RESEARCH REPORT

No. 2011-RR6

Co-control of Air Pollution and GHGs in China's Iron and Steel Sector: an Integrated Modeling Assessment of Policy and Technology Options

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China is currently facing a major air pollution challenge and must make significant reductions in its emissions of conventional air pollutants (AP) and greenhouse gases (GHGs). This is especially the case for the iron and steel sector, which is one of the country's biggest polluters. To help find the best way to address this problem, a new EEPSEA study has looked at policies that will help reduce both GHGs and APs at the same time - so called, co-control policies.
The study is the work of a team led by Liu Zhaoyang from the School of Environment, Beijing Normal University. It finds that a carbon tax regime can reduce both carbon and local pollutants from the iron and steel sector (and so deliver maximum benefits) . However, it finds that Command and Control and End of Pipe policies produce conflicting effects in the reduction of local pollutants and CO_2. It recommends that a high-rate carbon tax should be brought in. This should be done within a framework of environmental tax reform and alongside other policy measures to reduce any negative impacts the move might have on businesses and society.

Published by the Economy and Environment Program for Southeast Asia (EEPSEA)
22 Cross Street, #02-55 South Bridge Court, Singapore 048421 (www.eepsea.org)
Tel: +65-6438-7877, Fax: +65-6438-4844, Email: eepsea@idrc.org.sg

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ISBN: 978-981-07-0905-1

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October, 2011

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EEPSEA is supported by the International Development Research Centre (IDRC); the Swedish International Development Cooperation Agency (Sida); and the Canadian International Development Agency (CIDA).

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ACKNOWLEDGEMENTS

This research is funded by EEPSEA, IDRC (Grant No. 106269-00000000-008). We would like to acknowledge the support and suggestions from EEPSEA staff and researchers, especially Dr. Herminia FRANCISCO and Dr. David JAMES.

We are grateful for Dr. HU Tao and other researchers from Policy Research Center of Environment and Economy (PRCEE), Ministry of Environmental Protection (MEP). They shared their experience from the view of policy makers and consultants, and helped to implement the investigations at China Iron and Steel Association and several plants.

We are also thankful that Dr. Mark JACCARD from Simon Fraser University approved us to use CIMS (Canadian Integrated Modeling System) model. We should as well give sincere thanks to Ms. YANG Shuqian from Beijing Normal University for her help with the CIMS modeling work.

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CO-CONTROL OF AIR POLLUTION AND GHGS IN CHINA'S IRON AND STEEL SECTOR: AN INTEGRATED MODELING ASSESSMENT OF POLICY AND TECHNOLOGY OPTIONS

LIU Zhaoyang[1] MAO Xianqiang[2] LIU Shengqiang[3] Kevin Jianjun TU[4]

EXECUTIVE SUMMARY

Nowadays China is faced with increasing pressure of emission reduction of conventional air pollutants (AP) and greenhouse gases (GHGs) emission, especially in iron and steel sector, which has a great share in total industrial emission and suffers from an expensive abatement cost. Co-control policies of AP and GHGs emission are generally supposed to be cost-effective due to the co-benefits from the synergetic emission reductions of different pollutants. This research quantitatively evaluates and compares some co-control policy options through an Integrated Assessment Model (IAM) in order to provide environment and industry policy suggestions in China's 12^{th} and 13^{th} Five Year Period (2011-2020).

The major assessment tool is an IAM framework, which is established through a one-way soft-linkage between a top-down Computable General Equilibrium (CGE) sub-model and a bottom-up CIMS sub-model, to quantitatively simulate policy effects on economy development, technology evolution, energy demand and pollutant emission. The CGE sub-model is independently developed as a single-region, 12-sector and recursive dynamic model with a 2007 Social Accounting Matrix (SAM) of China as its database, representing the development of an economy system in which demands equal supplies in all the different commodity markets. The CIMS sub-model is focused on technology details of iron and steel sector, including six production processes and 37 technologies with different attributes involving Life Cycle Costs (LCC), energy consumptions and pollutant emissions, simulating technology competitions and substitutions. For each policy scenario, variations of production scales and energy prices simulated by the CGE sub-model, are input into the CIMS sub-model to achieve the integration.

Policy options include carbon taxations (ranging from 10 to 100 CNY/ton CO_2), and mandatory applications of End-Of-Pipe (EOP) control technologies for CO_2, SO_2 and NO_x, which are referred to as Command and Control (CAC)-EOP

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policy. These policies are quantitatively evaluated in terms of cost and effectiveness and compared through the IAM framework. According to the simulation results, carbon tax under an environmental tax reform framework is more cost-effective compared with other carbon tax policy scenarios, presenting co-control effects on different pollutants and leading to double dividend in both economic and environmental welfare. However, the carbon tax rate designed in this research is not high enough to ensure China's iron and steel industry to achieve significant emission reduction in the next decade. Meanwhile, mandatory application of PAFP-FGD is a relatively more cost-effective countermeasure with a CAC-EOP policy. For most of the EOP countermeasures, though significantly cutting of SO_2 and NO_x emissions is expected, they usually cause extra CO_2 emissions, presenting contradictory effects on AP and GHGs emissions.

Based on the foregoing discussions, some policy suggestions are provided, including, (1) accelerate the implementation of carbon tax under environmental tax reform framework, (2) impose higher carbon tax rates, (3) cushion the negative impacts of carbon tax to economy with discriminated tax rates and governmental guidance on energy pricing, and (4) prudently design or implement more CAC-EOP policies.

1.0 INTRODUCTION

1.1 Research Problem

1.1.1 Background

Along with the rapid growth of economy and population in the past several decades, currently China is faced with pressing environmental problems, among which one of the most important issues is the enormous consumption of energy and the following emission of conventional air pollutants (AP) and green house gases (GHGs). In this research, conventional or local air pollutants are defined as those pollutants with a significant relationship between emission source location and pollution target, referring to harmful materials in industrial waste gas directly threatening the health of humans in the neighborhood area of emission source, such as SO_2, CO, NO_x and particles, etc. Comparatively speaking, GHGs have different characteristics: the negative effects on human society are relatively indirect through climate change; the influence is worldwide, which is independent from the space locations of emission sources. In China, local air pollutants are in charged by Ministry of Environmental Protection (MEP) while GHGs by National Development and Reform Committee (NDRC, used to be National Planning Committee). There are different control targets and strategies of the two categories of emissions. That is one of the most important reasons why they are distinguished from each other in this research.

Among all the industries in China, iron and steel industry is one of the largest emitters, with a share of 9.2% in CO_2, 7% in SO_2 and 15% in PM out of the total industrial emission (China Iron and Steel Association, 2009). China's 11^{th} five year (2006-2010) environment plan, released in November 2007, aimed at 10% reduction of SO_2 emissions and 20% reduction of the macro energy intensity. In the 12^{th} five year (2011-2015) plan, emission reduction targets of SO_2 and NO_x is respectively 8% and 10%, leading to huge pressure on iron and steel industry.

In iron and steel sector, some of the emission control technologies, especially end-of-pipe (EOP) control measures, seem to result in a conflict between CO_2 and AP emission reductions. For instance, the operation of desulfurization facilities in iron and steel plant results in extra costs due to larger consumption of electric power, the generation process of which is often combined with large scale of CO_2 emissions. On the other hand, out of the consideration of economy revenue, some enterprises prefer to shut down those pollution control facilities, achieving energy consumption and CO_2 emission reduction at the expense of more intensive AP pollution. Results of a survey in 2008 imply that 90% of China's enterprises admit the existence of such a conflict (Hu and Wu, 2008), which could probably lead to expensive but poor abatement.

Apart from technical reasons, the present environment policy instruments in China, which often focus on the EOP emission control instead of the production process, should be partly responsible for the dilemma in CO_2 and AP emissions reduction.

Iron and steel industry's enormous emissions and offsets between GHGs and AP emission abatement calls for more effective policy incentives which could bring down GHGs and AP emissions at the same time.

1.1.2 Co-control

Recently the concept of integrating the control (or co-control) of AP and GHGs is becoming more and more popular, which offers a significant potential of savings in abatement costs and additional benefits while meeting emission reduction targets compared to separate instruments. Varieties of AP and GHGs have common sources. For instance, Fossil fuel combustion typically results in emissions of both CO_2 and other pollutants such as SO_2. Furthermore, these emissions interact in the atmosphere and, separately or jointly, cause a variety of environmental effects at the local, regional and global scales (IPCC, 2008). That is why it is feasible and important to capture synergies and avoid trade-offs when addressing the two problems simultaneously through a single set of policies or technologies.

Nowadays co-control of AP and GHGs has moved beyond a notion to applications in national regulations and international treaties. The Integrated Environmental Strategies (IES) operated by US EPA is designed to build capacity to conceptualize co-control measures, analyze their potential co-benefits, and encourage the implementation of promising policy instruments in developing countries. The program has involved eight developing countries, resulting in numerous assessments at the urban and national levels of co-benefits, and has facilitated the formation and implementation of policies leading to an efficient control over local pollution and GHGs together. The European Commission, in its European Climate Change (ECCP) and Clean Air for Europe (CAFE) program, explores the interactions between the European Union's climate change and air pollution strategies and examines harmonized strategies that maximize the synergies between both policy areas.

Despite of benefiting from the international experience in integrated management, China is still in an early stage of developing effective environmental policy instruments and accelerating technological improvements under the concept of co-control. In the future, such policy and technology options will probably offer important solutions to GHGs and AP emission control in China's iron and steel sector.

1.2 Literature Review

1.2.1 AP and GHGs emission reduction of iron and steel industry

Since the 21st century, more and more researches are carried out into AP and GHGs Emission reduction of China's iron and steel Industry, which can be classified into three categories. Some of these researches try to make estimations of CO_2

emission in this sector based on material and energy flow analysis over the whole production process, such as Sha and Liu et al., (2008) and Kim and Worrell, (2002). Other scholars focus on advanced production technologies in iron and steel industry which can bring down GHGs or AP emission, mainly including varieties of energy saving and desulfurization technologies. Typical researches include Shangguan and Li et al., (2009) and Huang, (2007) . The third group of researchers devote to simulations of AP and GHGs emissions in China's iron and steel industry under certain policy scenarios, based on economy or energy models, such as Wang and Wang et al., (2006) and Liu, (2008).

Among international researches on this topic, one of the classic literatures would be the work of Clifford S. Russell and William J. Vaughan. This study presents a methodology for investigating the implications that alternative public policies, especially but not exclusively environmental policies, will have for industrial costs and resource use of iron and steel sector. As well it summarizes some information about resource use, pollutant emission, production process and technologies of the sector (Russell and Vaughan, 1976).

1.2.2 Co-benefits and co-control assessment

As for the evaluation of co-benefits of policy and technology options, the Fourth Assessment Report released from IPCC in 2007 collected most of the scientific case studies at that time conducted with different methodologies (Metz and Davidson et al., 2008).

Case studies from Europe, US and China have demonstrated the significance of such co-benefits for different countries, such as (Syri and Amann et al., 2001), (Van Harmelen and Bakker et al., 2002), (Van Vuuren and Cofala et al., 2006), (EIA, 1998), (Burtraw and Krupnick et al., 2003), (Cao and Ho et al., 2008) and (Amann, 2008).

Compared with previous literatures, this study takes the next step by researching into how to achieve such co-benefits with cost-effective co-control policies and technologies. It is a specific sectoral study focused on China's iron and steel industry, which is infrequent up to now. The evaluation and comparison of co-control measures are based on an Integrated Assessment Model (IAM) which combines a top-down economy model and a bottom-up energy model.

1.3 Research Objectives

This study is designed to find cost-effective co-control policies in China's iron and steel industry based on an integrated modeling work. The specific objectives are twofold.

- Find out the most cost-effective co-control policies for China's iron and steel industry, based on quantitative evaluations and comparisons among a bunch of policy options, mainly including different carbon taxations, and

Command-And-Control (CAC) policies of mandatory applications of End-Of-Pipe (EOP) pollution control technologies.

- Establish an Integrated Assessment Model (IAM) for policy assessments, which is a soft-linked framework connecting a Computable General Equilibrium (CGE) model and a Canadian Integrated Modeling System (CIMS).

1.4 Research Contents

In this research the quantitative assessment of co-control policies for China's Iron and Steel sector relies on an IAM established through a one-way soft-linkage between CGE and CIMS model. The research process is presented as follows.

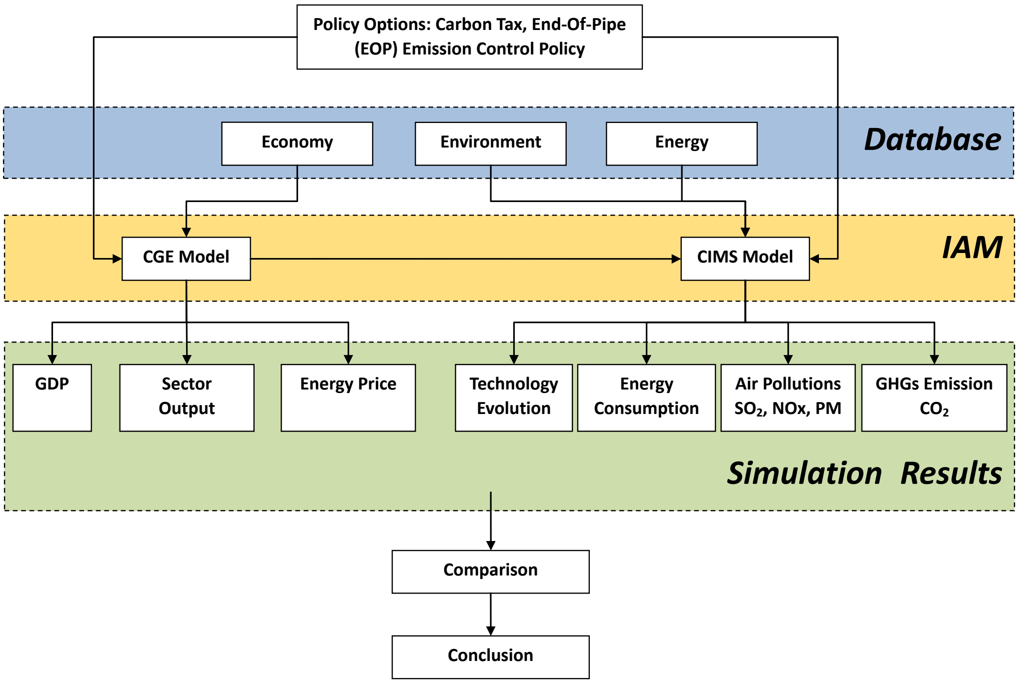

Figure 1. Research process

First of all, co-control policy options are identified. In the next step, statistics involving national economy, iron and steel sector production, energy consumption, pollution emission are collected to establish a database for the modeling work that follows. After that, the CGE and CIMS sub-model are independently developed. The outputs of the CGE sub-model represent the policies' economic effects on both national and sectoral level, some of which are input into CIMS sub-model as exogenesis parameters. Then the CIMS sub-model runs simulations under the same policy scenario, the outputs of which represent the policies' effects on the sector's technology substitutions, energy consumptions, AP and GHG emissions, which are referred to respectively as technology, energy and environment effects. The following part involves a comparison between those policy options for the relatively effective package or combination. Finally, recommendations and suggestions are rendered, based on the foregoing simulation results and analysis.

2.0 METHODOLOGY

2.1 Chain Reaction Assessment Method and Integrated Assessment Model

As anthropogenic energy consumptions and pollutant emissions emanate from economic activities, here it is assumed that Economy-Energy-Environment (3E) policies such as carbon tax would first change the scale and technology of industrial production and then lead to corresponding change of energy consumptions and pollutant emissions. In other words, in the Environmental Impact Assessment (EIA) of 3E policies, there is a dose-response or causal relationship from policy to production and consumption, and then to energy and environment. Such a Chain Reaction Assessment Method (CRAM) (Liu and Mao et al., 2011) serves to be the logical framework of the evaluation of carbon tax in this study.

Various modeling works have been developed to quantitatively research into 3E policies. Based on the difference of modeling approaches, 3E models can be classified into three categories: top-down, bottom-up and integrated models. Top-down models commonly adopt broader economic frameworks taking account into the interaction and spillover effects between markets as well as income effects for various economic agents such as private households or the government. Typical top-down models include Input-Output (IO) model (Hawdon and Pearson, 1995) and Computable General Equilibrium (CGE) model (Shoven and Whalley, 1992). Those models have significant advantages in estimating a policy’s impact on national economy. However, as a matter of fact, the high degree of endogenous in economic responses to policy shocks typically goes at the expense of simplifying the representation of energy system and leaving out specific sector or technology details. On the other hand, in bottom-up models, different energy production or consumption technologies combine following certain patterns to meet a given demand for final energy or energy services. Well known bottom-up models include Market Allocation (MARKAL) model (Zonooz and Nopiah et al., 2009), and Greenhouse gas-Air Pollution Interaction and Synergies (GAINS) model (Amann and Jiang et al., 2008). Such models are famous for their capacity to capture the details of technology evolutions and energy effects in a certain sector when a policy incentive is implemented, but omit the interaction with the rest parts of the economy. The specific strengths and weaknesses of the top-down and bottom-up models bring in the need of combining economic richness of the former with technological explicitness of the later to form integrated models. To achieve such an integration there are three major approaches (Böhringer and Rutherford, 2005), which include: (1) linking existing independently developed bottom-up and top-down models together to establish soft-linked models, (2) focusing on one model type and developing an extra part as an abridge version of the other, and (3) creating completely integrated models. Nowadays such inspirations have been put into practice. Representative integrated modeling works from abroad and China include MENSA-MERG system (James and Musgrove et al., 1986), Integrated Global System Model (IGSM) (Sokolov, 2005), Emissions Prediction and Policy Analysis (EPPA) model (Paltsev, 2005) and Integrated Policy Assessment Model for China Emission (IPAC-E) (Hu and Jiang, 1997).

In the Integrated Assessment Model in this study, a top-down CGE model and a bottom-up Canadian Integrated Modeling System (CIMS) model are combined through a one-way soft-linkage in which simulations will be carried out in each model separately, and CGE simulation results, including steel production scales and energy prices in both baseline and policy scenario, are input into CIMS, as shown in the following diagram. Policy shocks are imposed only on CGE model, since its simulation results which are cited by CIMS model already count for policy shocks in the latter.

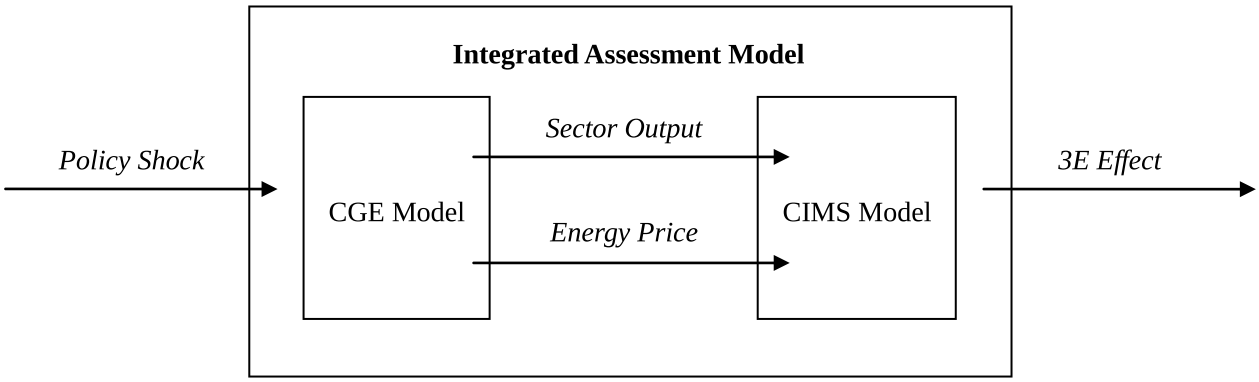

Figure 2. The soft linkage between CGE and CIMS model

2.2 CGE Sub-model

CGE models combine the abstract general equilibrium structure developed by Walras with realistic economic data to solve numerically for a set of prices and levels of production in each industry such that the market demand equals supply for all commodities. When a policy shock is imposed on the system, the original general equilibrium status moves to a different one, with variations of equilibrium prices and supply (or demand) scales, through which the impacts of the policy are observed (Zheng and Fan, 1999).

In this research, a single-region, recursive dynamic CGE model is established independently to quantitatively assess the impact of carbon tax on China's macro-economy. This model includes 12 sectors (agriculture, ferrous ore mining, coking, iron-smelting steel-smelting, other heavy industries, other light industries, coal, petroleum, natural gas, electric power and service industry), assuming that each of them produces only one single kind of commodities.

In production block, the model assumes perfect competitive market, constant return to scale and zero pure profit. Producers make input decisions to minimize production costs, with the supply scales given by general equilibrium status. Production function is a multi nested structure as depicted in the following figure. On the first level, domestic (QDF) and imported (QIF) commodities, which are assumed to be able to perfectly substitute for each other, are combined to form intermediate inputs (QF) of a certain production sector. Meanwhile, production factors (QFE), including capital and labor force, are aggregated by a Constant Elasticity of Substitution (CES) function to form added value (QVA). On the second level, intermediate inputs are combined with added value through Leontief function to produce final output (QO) of the sector, indicating that a certain output quantity given by equilibrium condition is produced by intermediate inputs and added value with fixed proportions.

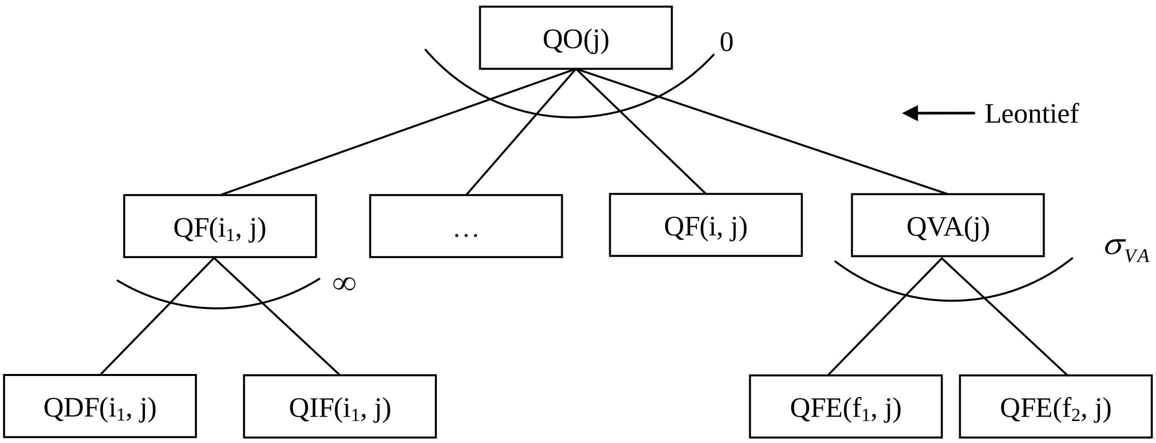

Figure 3. The structure of production function

On the consumption end, the model discriminates three categories of final demands, including private household consumption, government consumption and investment. The three accounts separately make consumption decisions to maximize their utilities with budget constraint. Cobb-Douglas form is chosen for the utility functions. Taking private household as an example, as presented by the following graph, domestic (QDP) and imported (QIP) commodities first form aggregates (QP), which are then combined by the utility (UP) function. The modeling work with government and investment is almost completely analogous to that of private household, with difference merely in income sources. Government income is mainly generated from value added taxation (VAT) and tariffs. Exogenous proportions of incomes of private household and government go to savings, which are then completely transferred to investment. Gross Domestic Production (GDP) is calculated through income approach to represent the scale of national economy. Equivalent Variation (EV) is expressed as $EV = E(P^0, U^1) - E(P^0, U^0)$ to measure the welfare change (Varian, 2010), where $E(P,U)$ denotes the minimum expenditure with a given level of utility (U) and price (P).

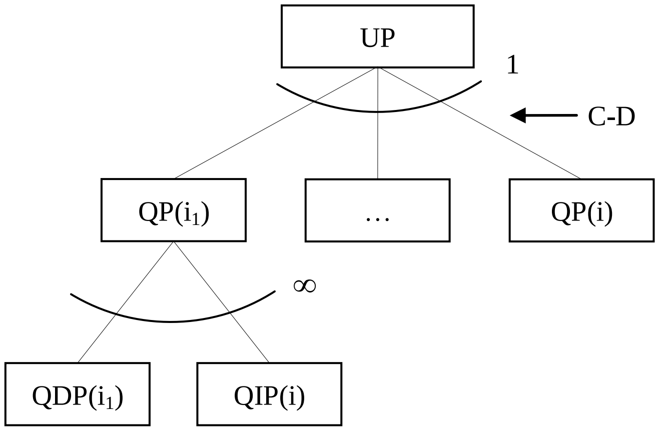

Figure 4. The structure of utility function of private household

As for the international trade, the model nets out the two-way trade from the gross flows and replace the data with net trade only. China is modeled as a large economy by introducing a fictitious factor, owned by foreign countries, and employed by China's production sector to produce export commodities, and thus the price elasticity of export demand is no longer infinite as in small economy (Markusen and Rutherford, 2004).

The market clearance block involves commodities and factor market. In labor force market, full employment, exogenous total labor endowment, free transfer among sectors and equal wage rate at equilibrium point are assumed. Assumptions in capital market are parallel.

Recursive dynamic technology implicates that economic behaviors in the system are based only on current period situations. The economy system evolves through capital accumulation and labor growth in the pattern of Solow model (Romer, 1996). Saving in each period is equal to investment, which both compensates for capital depreciation in the current period, and contributes to capital stock in the next period. Moreover, the amount of labor grows with an exogenous rate over the time series.

The major database of the CGE model is the 2007 China SAM based on 2007 China IO table (National Bureau of Statistics of China, 2009), China Finance Year Book 2008 (Ministry of Finance of China, 2008), China Flow of Funds Accounts Table 2008 (National Bureau of Statistics of China, 2009), etc. Some parameters of the model are derived from SAM, such as share parameters, transfer parameters and saving rates. Others are cited from previous literatures and data sources. For instance, the substitution elasticity parameters in CES functions are cited from GTAP 7 Database (Hertel, 1997; Hertel and Walmsley, 2008). Labor growth rate is calibrated based on China Statistical Yearbook 2009 (National Bureau of Statistics of China, 2009). The price elasticity of export demand faced by China is cited from (Fan and Wang et al., 2004). The model is mathematically expressed as a mixed complementary problem, coded in Mathematical Programming System for General Equilibrium (MPS/GE) (Rutherford, 1998) and implemented in General Algebraic Modeling System (GAMS) (Rosenthal, 2008).

2.3 CIMS Sub-model

The CIMS model in this research refers to its sub-model of technology substitution system, leaving the macro-economic simulation to the CGE sub-model of the IAM framework. The technology evolution starts with the retirement of old technology stock and the growth of the total stock, both measured by the quantity of iron and steel related products. Different technologies compete with each other for new stock based on Life Cycle Cost (LCC) comparison. A technology with relatively lower LCC takes a larger share of new stock while an exogenous variance parameter gives how advantaged the technology is. The mathematical expression of CIMS model is explicated in (Jaccard and Nyboer et al., 2003).

In the CIMS model in this research, iron and steel production technologies are categorized into six classifications according to different stages and corresponding products in the production process, including coke production, iron ore agglomeration, iron making, steel making, casting and steel processing. Technologies from different stages do not compete with each other. The technology structure of iron and steel sector in this research is presented by the following chart.

The technology parameters of the CIMS model, including initial production shares, energy consumptions, capital and operation costs, are obtained from (China Iron and Steel Association, 2009). Some model databases will also be included as supplements, such as MARKAL China, AIM and GAINS model **(**Liu, 2008). Cost variance parameters are cited from the original version of CIMS Model Database. Coefficients of energy consumptions, pollutions and GHGs emissions are cited from (IPCC, 2006; National Development and Reform Commission of China, 2007; China Environment Yearbook Editorial Committee, 2009; China State Council Leading Group of Pollution Source Census, 2009; National Bureau of Statistics of China, 2009). The model is coded and solved using a Java program.

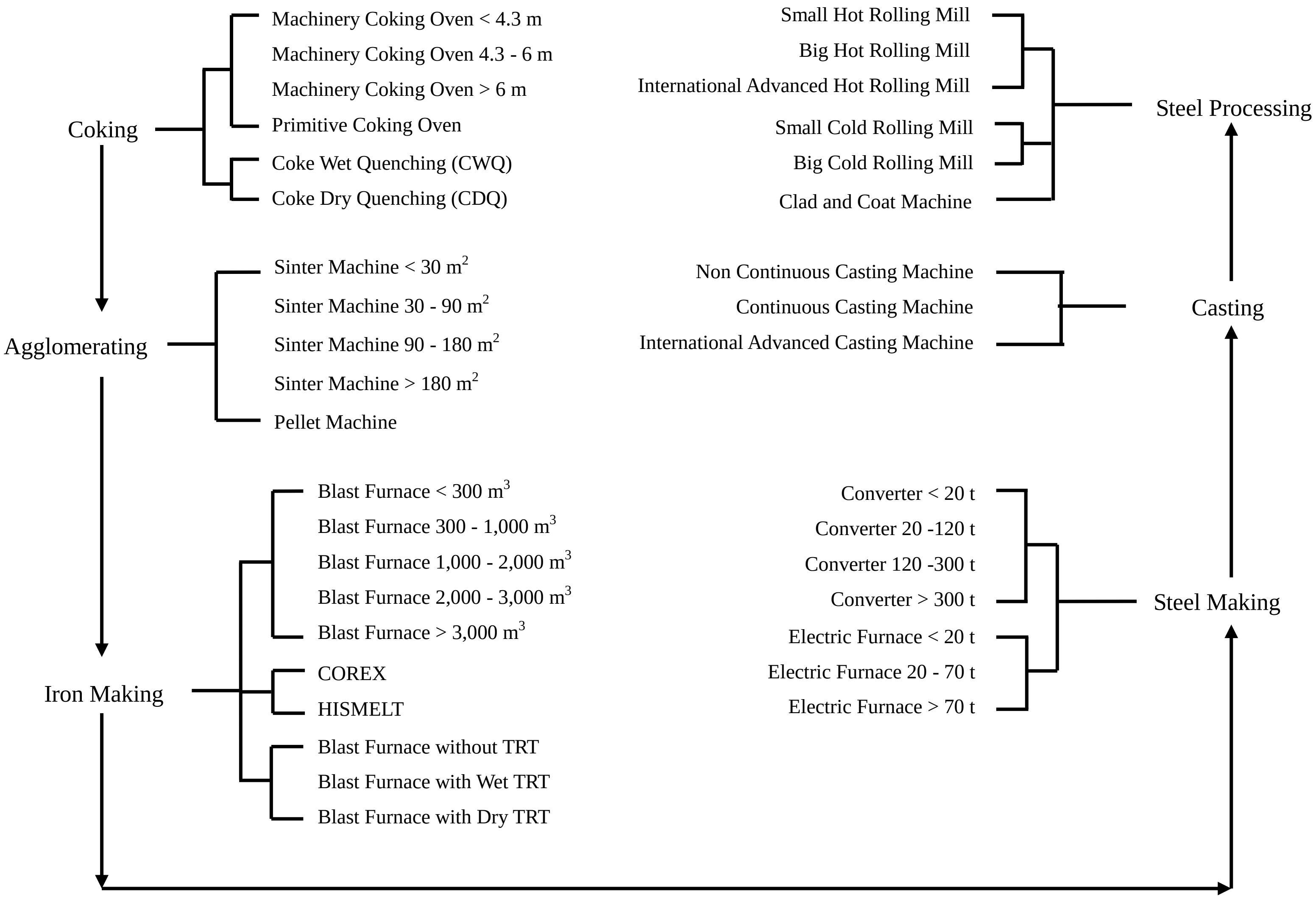

Figure 5. The technology structure of iron and steel sector in the CIMS sub-model

3.0 SIMULATION RESULTS AND DISCUSSIONS

3.1 BAU Simulation Results

In Business as Usual (BAU) Scenario, China's economy system evolves along the original trajectory without any policy shocks. Simulation results from the IAM are summarized as follows, mainly involving economy development, technology evolution, energy demands and pollutant emissions in the next decade.

3.1.1 Economy development

According to the simulation results, China's GDP keeps increasing in the simulation period between 2007 and 2020, but with lower growth rates, as illustrated by Figure 6. That is because the recursive dynamic system of the CGE model follows the method of Solow growth model. Given exogenous labor force supply, capital accumulation driven by savings, and leaving out technology progress, macro-economic growth can be expected to converge to a balanced grow path (Romer, 1996), in which the GDP indicator is growing at the same rate with labor force. Between 2015 and 2020, the average annual growth rate of GDP is lower than the counterpart simulation results of NRDC (ERI, NDRC, 2009) and some other academic works (Cao and Ho et al., 2008). The best explanation would be the assumption of labor force supply, which summits at 2015 and decreases since then (Jiang, 2010).

Energy sectors will keep expanding and take larger shares in China's GDP due to the increasing energy demands, such as coal, petroleum, gas and electricity, etc. It is indicated that China's economy will become more resource-intensive, if no regulations are implemented to accelerate the improvement of economy structure, as in BAU scenario. The CGE model in this research assumes perfect substitution between domestic and imported products. Based on the current situation, it can be inferred that China's rising demands for natural resources are likely to be solved by international supply. In that case, China's economic development is unsustainable and insecure.

Due to higher capital revenues, service industry enjoy larger growth rates throughout the simulation period, and will occupy a larger share in China's GDP in 2020, suggesting that there is still a chance for China's economy structure to become less energy-intensive.

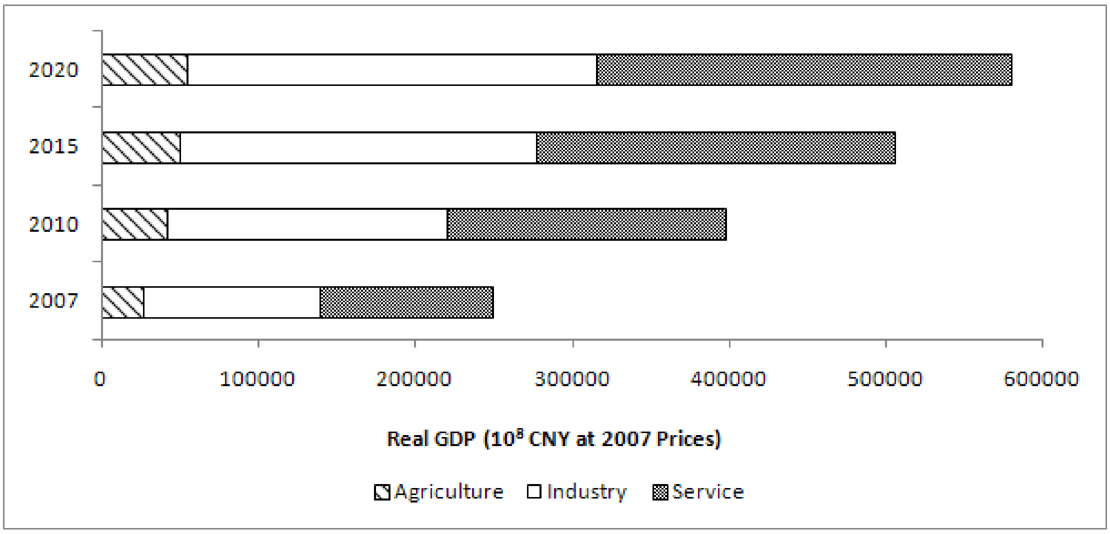

Figure 6. Variations of GDP volume and composition

The development trajectories of production scales of iron and steel related sectors are presented by the following figure, in which the output in 2010 is set as one. The total supply includes both domestic and imported products, which are especially important in ferrous ore market. These simulation results are input into CIMS model as exogenous stock parameters. The simulation results indicate that the steel production scales of China will keep expanding in the next decade. China's 12th Five Year Plan of iron and steel industry aims at a stable steel production scale, although the specific amount has not been identified. On the other hand, the international society tend to believe that the expansion of China's iron and steel industry will not stop, especially those ferrous ore suppliers such as Rio Tinto, stating that China's steel production will be doubled by 2020. In that case, the simulation result of China's steel production in this research is an intermediate prediction compared with the voices from China and abroad.

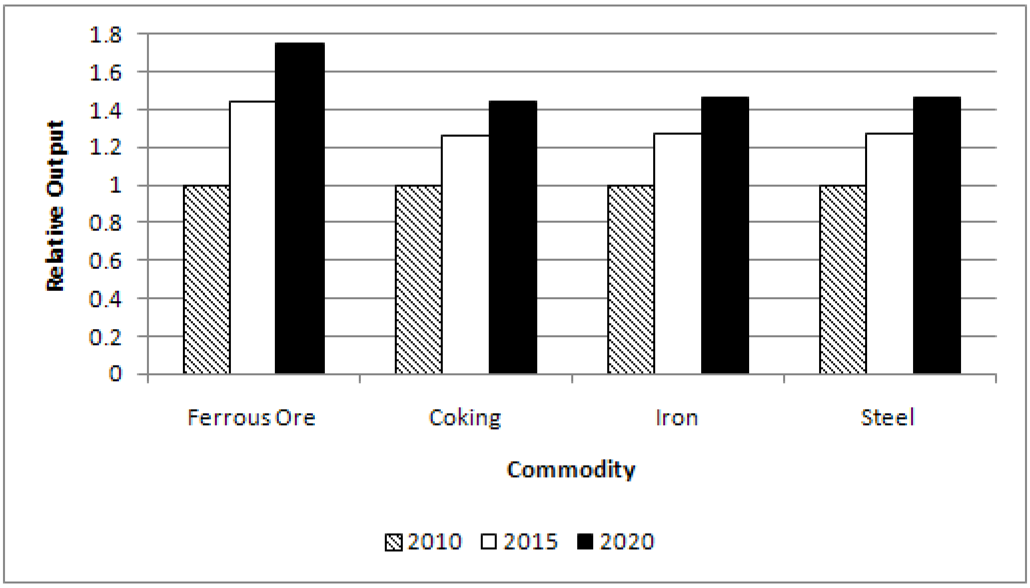

Figure 7. Variations of supply in iron and steel related sectors

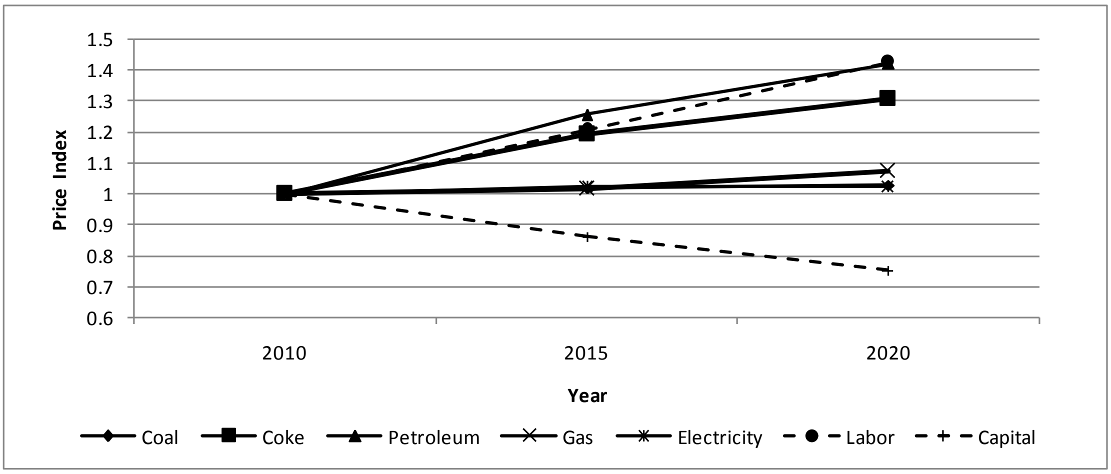

Figure 8. Variations of energy and factor prices

Figure 8 summarizes the price variations of energy and production factors throughout the simulation period in BAU scenario. The price indexes are relative prices in which all the prices in 2010 are set as one. These simulation results are input into CIMS model as exogenous price parameters. Each energy price is transformed into the price of per unit thermal value of the energy and measured in CNY/GJ.

Capital price gradually drops due to capital accumulation and decreasing capital revenues. On the other hand, labor price or wage rate sharply rises. That's because factors are combined in a CES production function, which partly allows substitution among them. When capital is accumulated with larger rates, labor force becomes relatively scarce, which then results in a rising price.

Energies are modeled as intermediate inputs, the prices of which are aggregated prices of both domestic and imported products. For some energy such as coal, electricity and coke, the supplies in China mainly rely on domestic production, and their prices are thereby determined by equilibrium status and production costs under zero pure profit assumption. Specifically, coal mining sector is relatively more labor-intensive. In 2007 its production costs on labor and capital was separately 216 and 160 billion CNY. Thus the producer price of coal tends to go up due to the rising price of labor force. Consequently, the producer prices of coke and electricity are also raised because coal is a major intermediate input of the two production sectors. For other energy such as petroleum, foreign supplies are important in meeting the domestic demands of China. Recalling the large country assumption of the CGE model, the prices in the world market are affected by China's supplies and demands through elasticity parameters. Thus to a large extent the increasing price of petroleum in China can be attributed to the higher price in the world market caused by the demand expansions in China.

The foregoing simulations of prices have nothing to do with currency supply or liquidity because the CGE model assumes neutrality of money and neglects monetary system.

3.1.2 Technology evolution

In BAU scenario, in iron and steel related sectors, technology evolves following the default mechanism of CIMS model without any policy effects, in which different technologies compete with each other for new stock based on Life Cycle Cost (LCC) comparison. However, according to industrial policies such as the *Guidance Catalog for Adjustment of Industrial Structure* issued by NRDC, technologies with higher energy efficiencies are encouraged to be equipped in new plants with advantaged credit support, while those with lower efficiencies are discouraged. In this guidance, available technologies are classified into three categories including encouraged list, restricted list and prohibited list. Financial institutions are supposed to stop any form of credit support for prohibited technologies right away or before some deadlines, such as primitive coking technology. In order to represent such industrial policies in CIMS model, unavailable years are set for some disadvantaged technologies. Those technologies will not compete for new stock since unavailable years, but their old stock will be replaced by counterpart technologies along the original trajectory, instead of being mandatorily retired right away.

The inter-temporal variations of technology shares in coke production in BAU scenario are shown in Figure 9. The explanation of that trajectory is twofold, including, (1) the low energy efficiency of primitive coking technology suggests its disadvantage in the competition for new stock based on LCC comparison, and (2) primitive coking technology is set to be unavailable for new coking plants since 2010 to represent the relevant industrial policies, and the evolution process merely involves the retirement of old stock of the technology. For the same reason, a similar variation tendency occurs for small machinery oven. By the end of the simulation period, big machinery oven will be the most prevalent technology in coke production process, which will occupy 66% of the total technology stock.

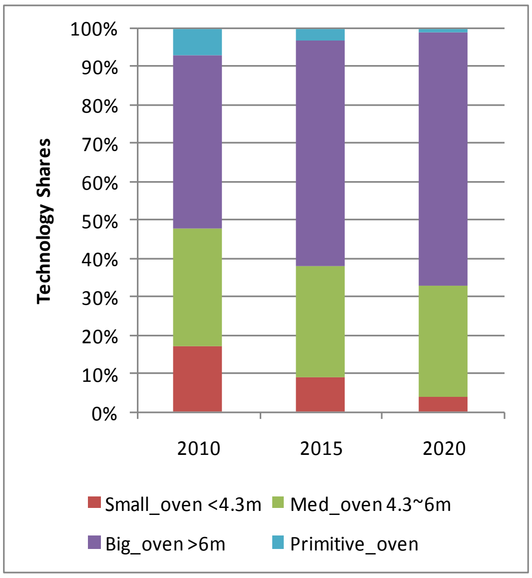

Figure 9. Coking technology evolution

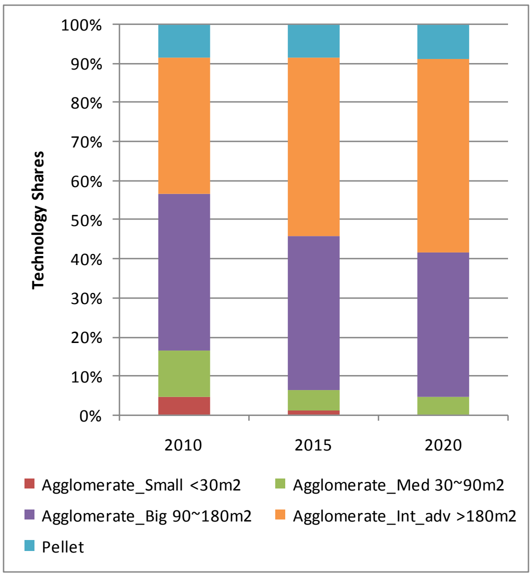

Figure 10. Agglomeration technology evolution

The agglomeration technology evolution trajectory in BAU scenario is indicated in Figure 10. There are notable decreases in both the stocks and market shares of small and medium sinter machine throughout the simulation period, and the former will become insignificant in 2020, which is a parallel variation to that of primitive coking technology. The stock of big sinter machine will expand from 481.74 Mt in 2010 to 644.19 Mt in 2020, but its market share will slightly shrink from 40% to 37%. That is because the international advanced sinter machine is much more competitive, the stock of which will rise from 411.69 Mt in 2010 to 871.55 Mt in 2020, and the market share from 35% to 49%. Meanwhile, pellet technology is assumed to be responsible for a constant share of roughly 9% out of the total technology stock. That is because normally a furnace uses both sintered and pelleted iron ores with certain proportions. Meanwhile, the input-output relationship in the whole iron and steel production is maintained stable.

In iron making process, as presented in Figure 11, small and medium blast furnace with a volume smaller than 1,000 m^3 will be almost completely replaced by other technologies since 2010. The total stock of the two technologies will descend to less than 2 Mt in 2020. Medium furnace with a volume between 1,000 and 2,000 m^3 as well suffers from a stock shrink from 86.54 Mt in 2010 to 60.76 Mt in 2020, and the according market share is separately 15% and 7%. Both big furnace and international advanced furnace enjoy a stock increase during the simulation period, but the latter is popularized more rapidly and will take up a share of 55% in total technology stock in 2020. Smelt reduction is a cutting-edge technology in iron making industry, in which COREX is currently the major production line in industrial-scale use. COREX is an environment-friendly technology because it use non-coking coal and iron ore to produce liquid iron, skipping the production and consumption of coke with severe environmental pollutions (Zhou and Qian et al., 2009). However, all the coke-free part aside and focusing merely on the iron making process, COREX is neither advantaged in production costs nor energy efficiency compared with blast furnace technology. Consequently, the practical application scale of COREX is still limited, with only five production lines in the world so far equipped by iron plants, one of which is built by Baoshan Iron and Steel Company in China. HISMELT technology is mainly discriminated from COREX by the feature that the former can directly take use of iron ore fines while the latter still needs agglomerated iron ores, which means HISMELT technology suggests the possibility of even skipping the agglomeration process. In spite of that, as much attractive as HISMELT appears to be, there is still a long way to go before the technology is put into industrial-scale practice. Taking into account all the foregoing facts, the CIMS simulation in this research sets up an up-limit of approximately 0.1% for the market share of smelt reduction iron making technologies.

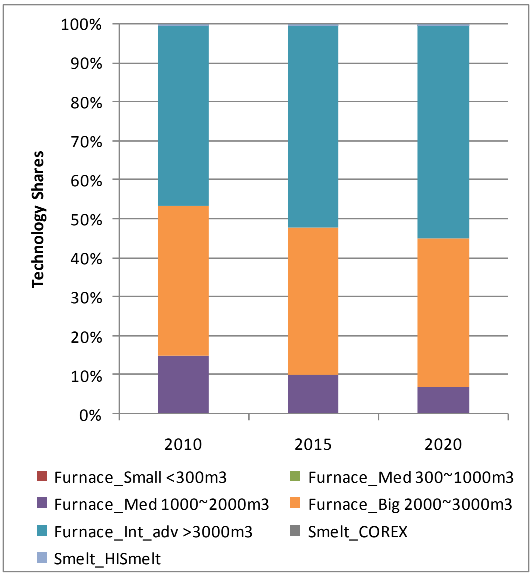

Figure 11. Iron making technology evolution

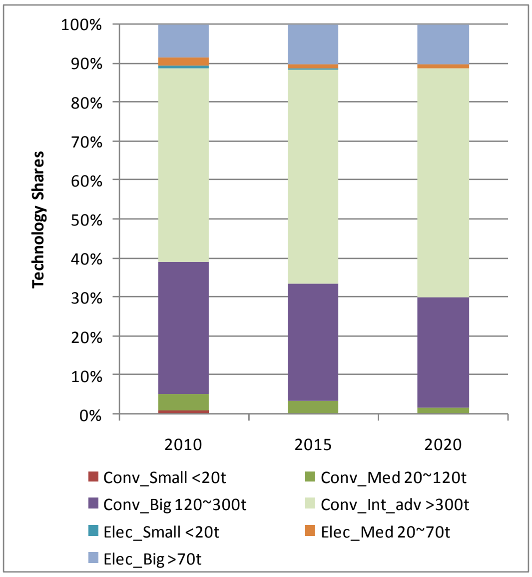

Figure 12. Steel making technology evolution

The technology substitution in steel making process is as well self-explicit, which is shown in Figure 12. In general, between the technology group of converters and electric furnaces, there is a fixed total stock proportion for each of them which is respectively 89% and 11% because the input-output coefficients and output features of the two technology groups are remarkably different. As for the specific technology, small converters will be off the market in 2015. The stock of medium converter will only be slightly decreased but its market share drops significantly as the total production scale expands. The stock of big converter will climb from 202.49 Mt in 2010 to 248.41 Mt in 2020 but its market share will decrease from 34% to 28%. Comparatively, international advanced converter is the real winner here, the stock of which will dramatically increase from 303.82 Mt in 2010 to 522.09 Mt in 2020, and the corresponding share is respectively 47% and 59%. Small and medium electric furnace will be insignificant in 2020, the total stock of which will be less than 10 Mt. Meanwhile, big electric furnace is relatively advantaged, the stock of which will rise from 50.55 Mt in 2010 to 90.79 Mt in 2020, and its market share will grow from 8% to 10%.

Technology evolutions in casting and steel processing are not to be discussed in details. In casting process, continuous caster dominates technology stock throughout the whole simulation period. The energy consumption and pollutant emission coefficients do not vary that much from common continuous caster to international advanced continuous caster. In steel processing part, hot rolling is a necessary preceding process of cold rolling. Additionally, the physical characters of hot rolled and cold rolled products are significantly different from each other. Comparatively, cold rolled products have advantages in size precision, surface smoothness and rigidity, but have disadvantages in flexibility. Features of hot rolled products are in the other way around. There are demands for both categories of steel products in different occasions thus hot and cold rolling mills are assumed to occupy fixed proportions in the total technology stock. Similar to continuous casters, the difference of energy and pollution intensity is insignificant among different kinds of hot rolling mills, and so are cold rolling mills.

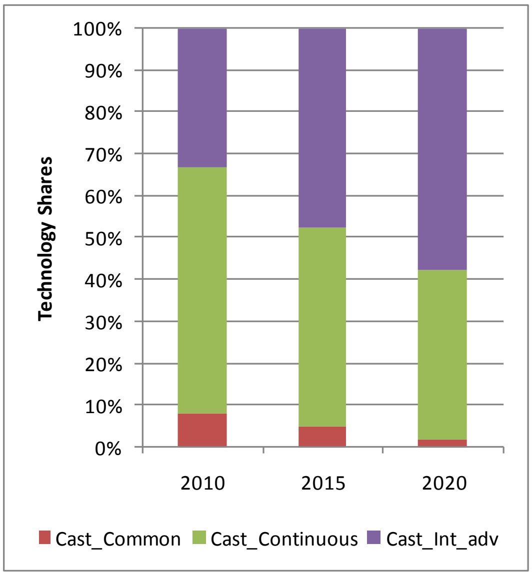

Figure 13. Casting technology evolution

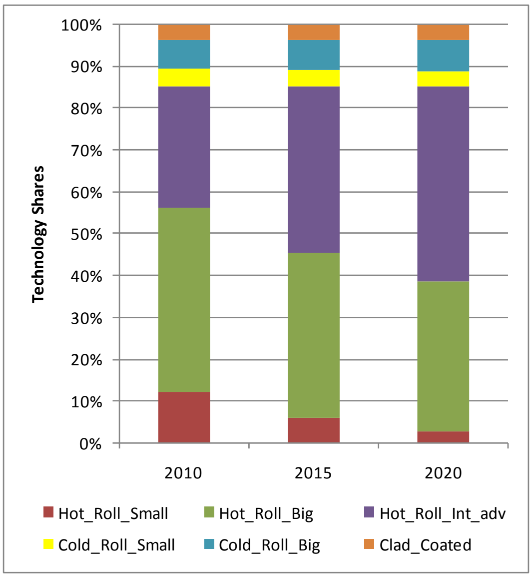

Figure 14. Steel processing technology evolution

As for coke quenching process, wet quenching is replaced by dry quenching to a large extent, which will be dominant since 2015, taking up almost the whole market. Blast Furnace Top Gas Recovery Turbine Unit (TRT) is set to be mandatorily equipped since 2010. Since then, the share of wet TRT equipment goes up from 70% to 74%, with dry TRT responsible for the rest.

In summary, technology composition in iron and steel sector will evolve towards the direction of higher energy efficiency even in the absence of additional policy incentives.

3.1.3 Energy-environment outlook

During the simulation period, the total energy demand and its composition in China's iron and steel sector are illustrated by the following figure. According to the simulation results, although energy efficiency has been raised by technology substitutions, apparently the total energy demands will expand along with the development of production scales in the sector, indicating that scale effects outweigh technology effects in the determination of total energy demands. Additionally, it is worth mentioning that the energy structure will not be significantly changed in the sector.

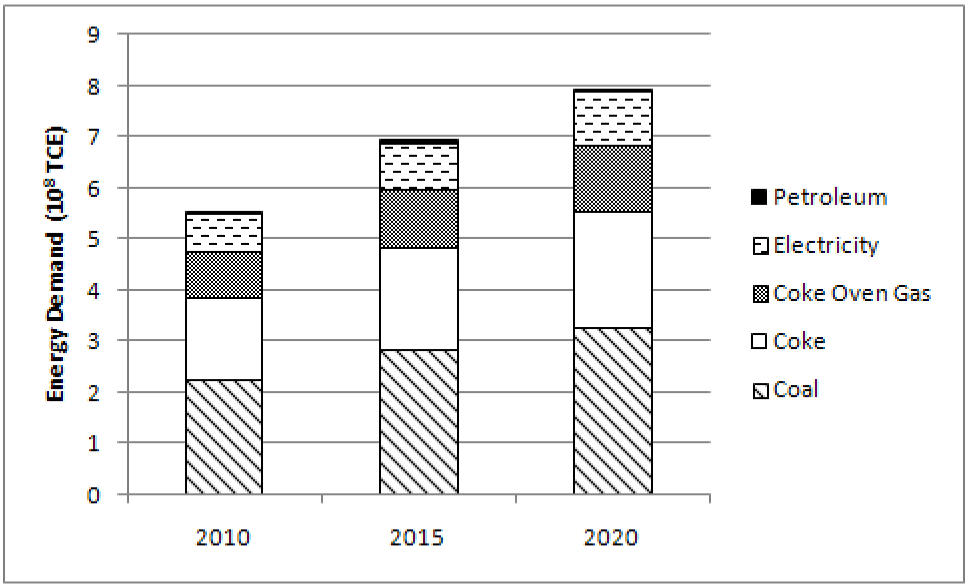

Figure 15. Total volume and composition of energy demand in iron and steel related sectors

An Emission Index (EI) is introduced to quantitatively measure the total emission scale of different categories of pollutants, which is calculated by $EI = \sum_i [W(i) \cdot E(i)]$, indicating a weighted summation of each pollutant emission. This research tries to find appropriate pollution prices as corresponding weight parameters. In that case, EI is actually a monetized quantity of total emission. The essential element of Pigovian tax is to internalize such negative externality of environmental pollutions into production or consumption process by pricing the pollutions, correct the market failure and achieve more efficient allocations of resources. The optimized rate of environmental tax, pollution charge or market price is the difference between private and social cost, in other words, the externality of environmental pollution (Baumol, 1972). In that sense, the welfare economics explanation of EI is a monetized total externality caused by different pollution emissions. Currently pollution charge rates of SO_2, PM and NO_x emissions in China have been legislated by the State Council, which are respectively 0.63, 0.28 and 0.63 CNY/kg. The charge rates were designed years ago and imposed on the quantity of pollutant emission, which are thereby generally regarded to be too low to fully internalize the social costs of environmental pollutions. Since 2010, several SO_2 trading or auction cases in China suggest that the market price of SO_2 is approximately 5 CNY/kg. Although such a pollution price is still lower than the counterpart in developed countries, it is apparently closer to the actual pollution damage compared with the current pollution charge rate in China. In that case, the pollution charge rates are scaled up through the market price of SO_2 in China, which is respectively 5.00, 2.18 and 5.00 CNY/kg for SO_2, PM and NO_x emissions. The weight parameter of CO_2 emission is cited from the lower limit of CO_2 price in China's CDM market, given by NRDC, which is 76.22 CNY/ton.

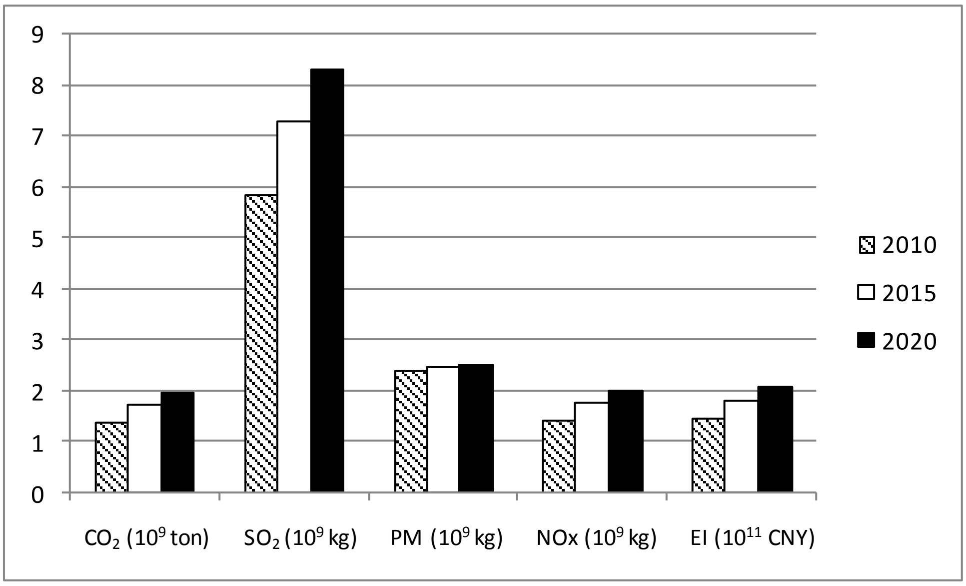

Figure 16. Variations of pollutant emissions in iron and steel related sectors

SO_2 and NO_x emission reduction rate in the 12th FYP environmental plan are respectively 8% and 10%. In that case, iron and steel sector in China will be faced with great challenge of emission reduction in the next decade. The augment of PM emissions between 2010 and 2020 is the least remarkable compared with other pollutant emissions, which is mainly caused by the popularity of dust removing equipment, such as electrostatic precipitator and filter separator, etc., which have been regulated to be mandatorily equipped by iron and steel plants since 2008.

Table 1. Scale and technology contributions to pollutant emissions in iron and steel related sectors between 2010 and 2020

	CO_2	**SO_2**	**PM**	**NO_x**
Scale effects	46.25%	46.25%	46.25%	46.25%
Technology effects	-3.67%	-4.61%	-41.49%	-4.67%

During the decade between 2010 and 2020, the variations of pollutant emissions in iron and steel related sectors can be attributed to the variations of production scales and the substitutions of technologies. Given unchanged technology conditions, production scale expansions alone lead to a homogeneous increase in different emissions. Meanwhile, given unchanged production scales, the enhancement of energy efficiency results in discriminated decreases in different emissions.

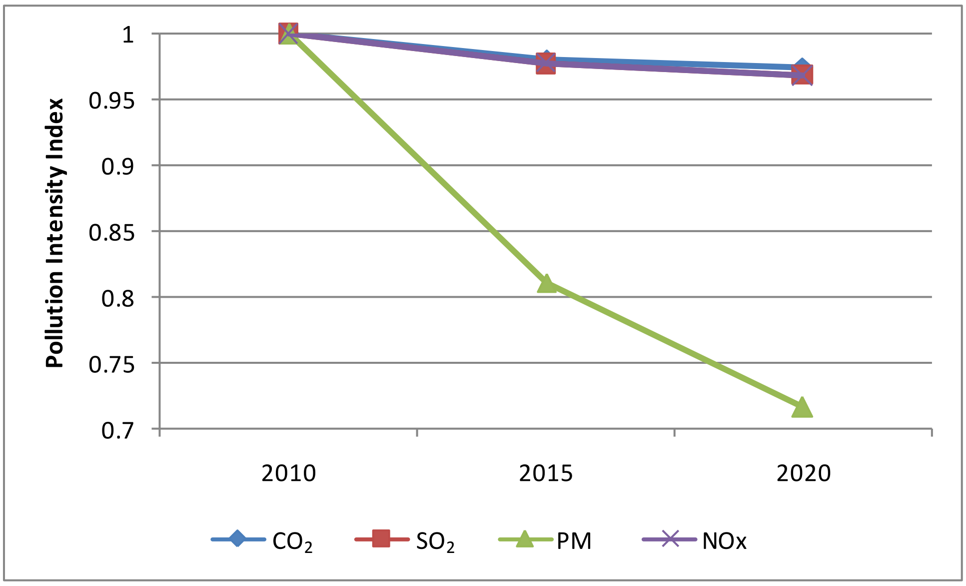

Figure 17. Variations of pollution intensity in iron and steel related sectors

3.2 Carbon Tax Simulation Results

Carbon tax is an environmental taxation levied on the carbon content of fuels. Carbon tax can be implemented by taxing the burning of fossil fuels in proportion to their carbon content (Hoeller and Wallin, 1991). Thus carbon tax could decrease the competitiveness of fossil fuels intensive industries, and accelerate energy substitution from fossil fuels to non-combustion energy sources such as wind, sunlight, hydropower and nuclear. Since fossil fuels consumption is an important source of both AP and GHGs, carbon tax could probably lead to co-control of both emissions. Nowadays carbon tax has been implemented in many developed countries, typically including Sweden, Norway and some areas in Canada and US (Mao and Yang, 2006).

In China, the feasibility and framework design of carbon taxation are under discussion by government consultant institutions. In 2009, Ministry of Finance issued the research report titled *Research into Carbon Taxation Issues in China*. In this report, it is stated that carbon taxation is likely to be imposed in 2012-2013, in order to achieve China's carbon emission reduction target, as well as to benefit China's international trade by avoiding carbon tariffs proposed by US (CRIFS, Ministry of Finance of China, 2009). In May, 2010, NDRC accomplished *China Carbon Taxation Framework Design*. According to this report, carbon tax might be implemented around 2012. It will be mainly imposed on CO_2 emission volume of energy sectors. Carbon taxation revenue will be shared by state and local government. The tax rate could begin with 10 CNY/ton CO_2, which might be raised to 20 CNY/ton CO_2 or even higher in the following years. This report achieves the general conclusion that carbon taxation's negative impact on China's GDP is less than 0.5% (ERI, NDRC, 2010).

Moreover, carbon taxation has long been a hot topic in China's academic circles, especially after Copenhagen climate conference in 2009 when China for the very first time made the public commitment of carbon emission reduction. Some scholars have carried out quantitative evaluations of the policy, typically based on CGE analysis, including (Zhang, 1996), (He and Shen et al., 2002), (Wang and Chen et al., 2005) and (Cao, 2009), etc. These researchers make similar conclusions that, in short term carbon tax could slightly slow down the macro economy development of China, meanwhile in long run deliberately designed carbon tax could lead to double dividend of environmental protection and economy development.

3.2.1 Scenario design

Six scenarios are designed as follows, which are discriminated by tax rates, tax revenue expenses and attached tax reform.

Table 2. Carbon tax scenario (CTS) design

Group	Scenario	Tax rate (CNY/ton CO_2)	Tax revenue expense	Attached tax reform
CTS_A	CTS_A1	10	Government consumption	NA
	CTS_A2	100	Government consumption	NA
CTS_B	CTS_B1	10	Refund to household	NA
	CTS_B2	100	Refund to household	NA
CTS_C	CTS_C1	10	Refund to household	VAT abatement
	CTS_C2	100	Refund to household	VAT abatement

In the six policy scenarios, carbon taxations with different attributes are imposed on all the industries since 2011, and levied on primary energy prices based on CO_2 emission coefficients. Taxed energies include coal, petroleum and natural gas. As for the different attributes, to start with, the tax rate of 10 CNY/ton CO_2 is recommended by NDRC, whereas 100 CNY/ton CO_2 is close to the optimal carbon tax rate recommended by IPCC, with reference to the current carbon price in CDM market. The two tax rates are designed to locate an 'impact range' of the possible carbon tax in China. Secondly, previous research on carbon tax indicates that different uses of the tax revenue might lead to different economy effects (Nurdianto, 2010). Thus Carbon Tax Scenario Group A (CTS_A) assumes that the government will gather and consume all the tax revenue. In other policy scenarios, the government will gather and reimburse all the tax revenue to private households for their consumption. CTS_C is designed following the double-dividend hypothesis of green tax shift (Bovenberg, 1999), in which carbon tax revenue replaces equivalent VAT (Value Added Tax) to keep the initial total tax revenue unchanged, while the VAT rate imposed on each production sector is cut down by the same proportion. Under such a green tax reform framework, there is supposed to be a double dividend rising from both economic development and environmental protection, which is why such an environmental tax is regarded as 'no-regret' option.

3.2.2 Simulation results

Parallel to BAU scenario, simulation results under carbon tax scenarios are summarized and interpreted from three aspects including economy effects, technology effects and energy-environment effects. In this part, simulation results are presented as comparisons between policy and BAU values in the same year of 2020, instead of inter-temporal comparisons as in the last section.

3.2.2.1 Economy effects

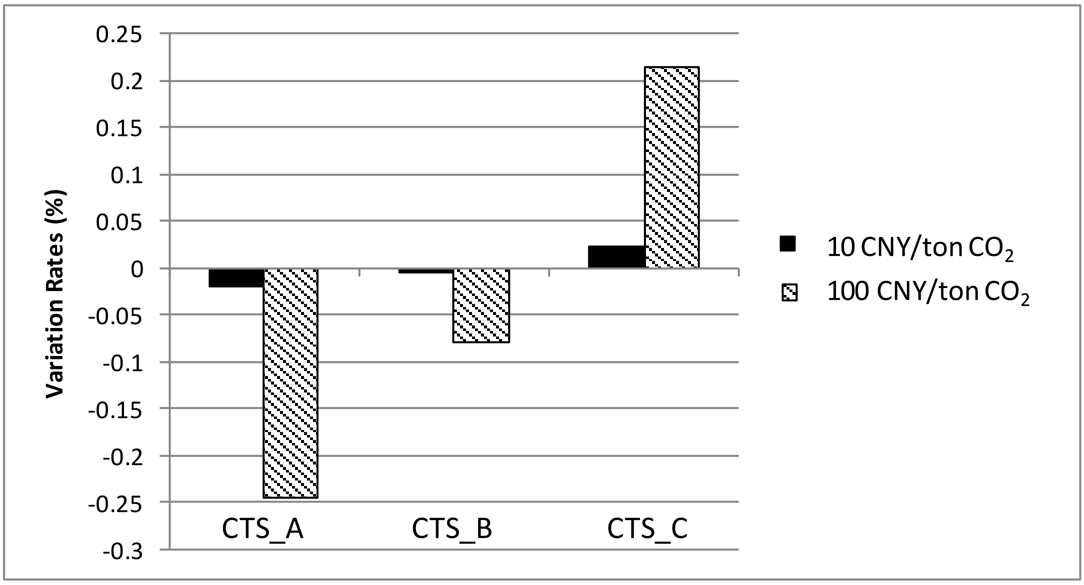

Figure 18. Impacts of carbon tax on China GDP in 2020

The impacts of carbon tax on China's national economy in 2020 are presented in the foregoing chart. Generally speaking, to start with, carbon tax designed in this research will lead to unremarkable influences on China's GDP in 2020, which are within a range of $\pm 0.25\%$. Secondly, CTS_A and CTS_B will impose slight negative impacts on China's GDP. When a tax rate is levied on energy prices, the production costs and output prices of energy-consuming industries are in turn brought up, which then causes shrinks successively on demand and supply end, especially in energy-intensive industries such as steel and power generation sector. In those policy scenarios, carbon tax revenues are consumed by government or private households, leading to increasing demands in final consumption, especially for services, agricultural products and light industry output. Therefore the production scales in corresponding industries will expand, as shown in the following graphs. However, the production increases in those benefited industries are not significant enough to offset the production decreases in energy-intensive industries, through which a slight GDP loss occurs. It is worth mentioning that under the same tax rate, when tax revenues are reimbursed to and consumed by private households, GDP loss is smaller than that when government consumes tax revenues.

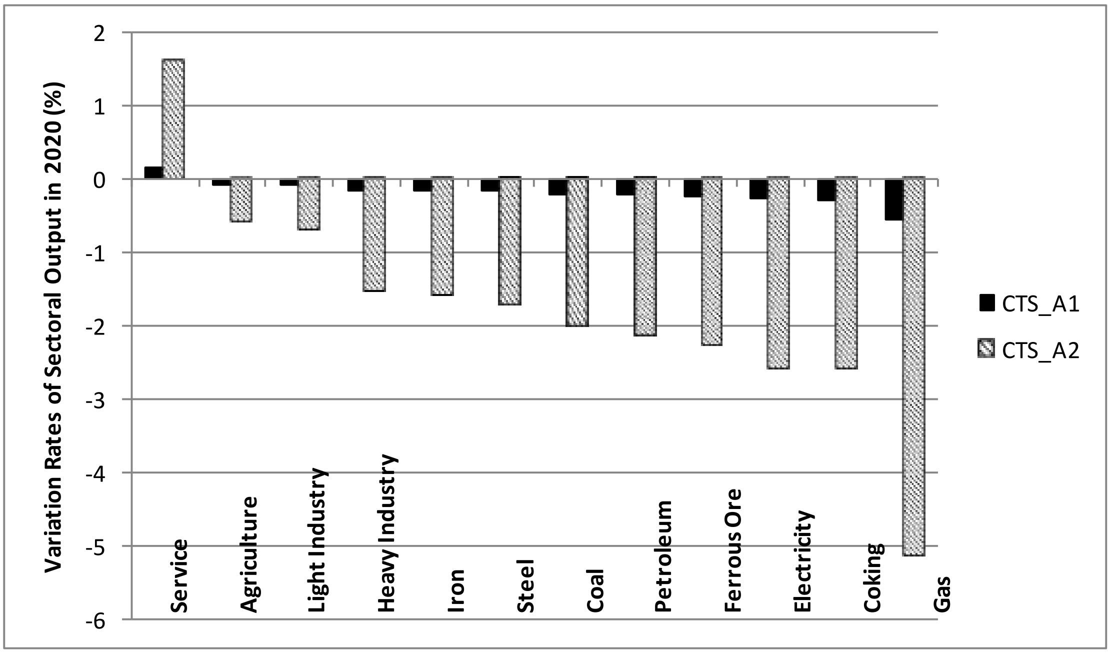

Figure 19. Variations of sector output in 2020 under CTS_A

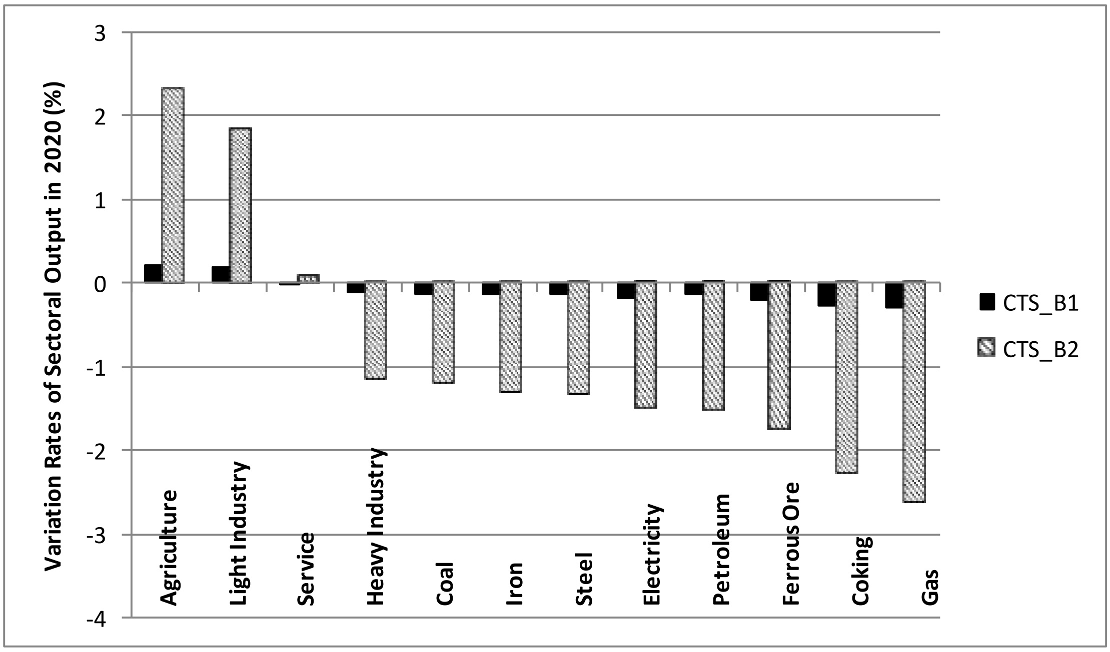

Figure 20. Variations of sector output in 2020 under CTS_B

Thirdly, in CTS_C, a GDP increase can be expected. In the two scenarios, when carbon tax is implemented, VAT rates are cut down by the same proportion for each industry to hold the total tax revenue unchanged in baseline year. Consequently, energy-intensive industries are faced with relatively higher production costs because they suffer from even larger energy expenditures compared with other industries, but do not enjoy larger VAT abatement. Since then, the composition of macro-economy has been shifted towards a less energy-intensive structure. In that process, the total tax revenue of government will reduce to some extent, but the growth of GDP volume, the improvement of economy structure and environmental benefits can be achieved simultaneously. Last but not least, carbon taxation’s impacts on macro-economy become more significant under larger tax rates. Therefore in the comparison of cost efficiencies of different carbon tax frameworks, more criteria or indicators should be included such as average and marginal abatement costs, aside from the total amount indicators of energy conservations, pollutant emission reductions and the accompanying opportunity costs. At this stage, based merely on the criterion of GDP variations, environmental tax reform is advisable, in which VAT is partly replaced by carbon tax.

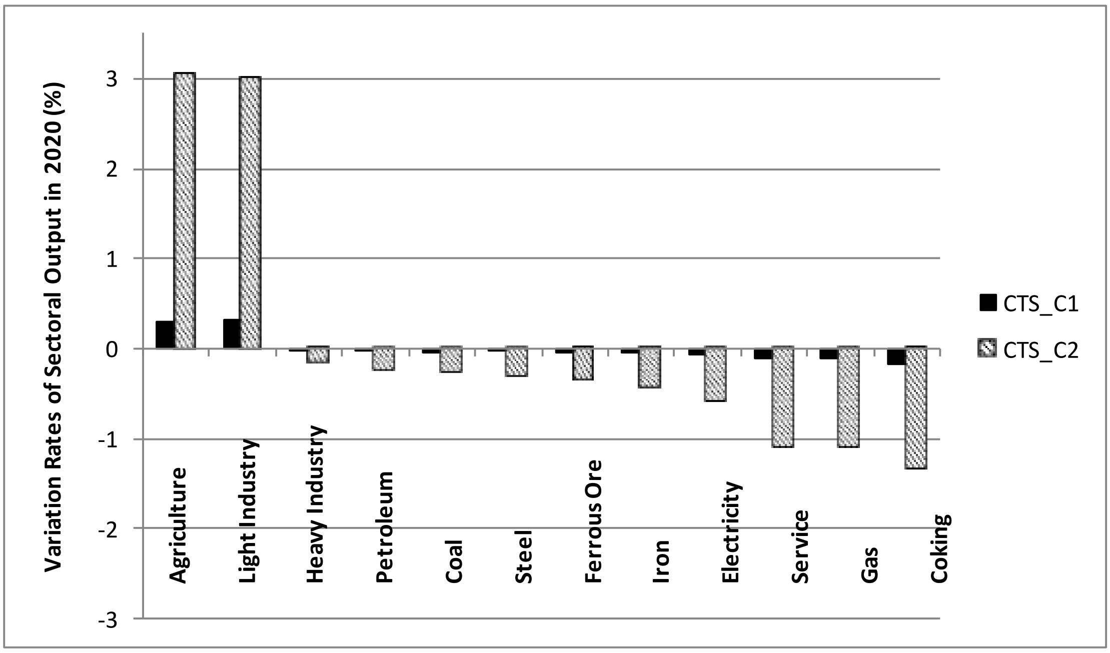

Figure 21. Variations of sector output in 2020 under CTS_C

Compared with BAU scenario, the variations of 2020 energy price index in carbon tax scenarios are shown in the following table. For some sectors, such as coking sector, carbon taxation will to a large extent raise the price of coal, which is an important intermediate input of the sector. Due to the more expensive production costs, recalling the zero pure profit assumption of the CGE model, it can be expected that the market price of the sector product will be brought up. However, on the demand end, higher market price results in the shrink of the demand, which in return bring down the market price. The two processes interact in an opposite way and the former plays a more important part in the pricing system. Hence when a new equilibrium is achieved, the corresponding price of the sector output is going up, but with a smaller increase rate compared with the carbon taxation rate. Similar situations occur in other energy industries such as power generation and gas sector. Contrarily, decreasing demands dominate the pricing process in other energy industries such as coal and petroleum sector, where there are slight price decreases in the corresponding energy products. Additionally, it is worth mentioning that inflation can be expected when the prices of up-stream commodities rise, such as energy. After the financial crisis in 2007, since 2011 China's government has turned to prudent monetary policy to curb inflation and even stagflation when exiting from the economic stimulus policy package. Under that background, tax reforms in this period should be discreetly designed.

Table 3. Variation rates of energy price index in 2020 (%)

	CTS_A1	**CTS_A2**	**CTS_B1**	**CTS_B2**	**CTS_C1**	**CTS_C2**
Coke	2.60	26.15	2.62	26.04	2.51	24.90
Coal	-0.10	-0.57	-0.06	-0.56	-0.09	-0.84
Petroleum	-0.11	-0.22	-0.08	-0.42	-0.17	-1.30
Electricity	1.30	12.05	1.23	11.85	1.22	11.73
Gas	1.06	10.60	1.09	10.41	1.08	10.18

The welfare effects of carbon tax are illustrated in the following table. Private households will suffer from welfare loss if the government collect and consume carbon tax revenue, as in CTS_A scenarios. Private consumers have to pay higher prices for most commodities because the production costs will be brought up by carbon tax, while their endowments of production factors are held unchanged in the same year among BAU and policy scenarios. At the same time, the government income will rise along with the increase of total tax revenue. In CTS_B scenarios, when the government reimburses carbon tax revenue to private households, the former will be faced with an income loss due to the decreasing total tax revenue because the production scale will shrink in most industries. On the other hand, household welfare will be improved because of the transfer payment of carbon tax revenue. When it comes to CTS_C, under the same tax rate, the equivalent variation ranges of household welfare and government income are remarkably larger than those in other scenarios. Government tax revenue and income will steeply drop because the VAT rate is cut down but the carbon tax revenue does not go to the government. In spite of that, private household welfare is significantly better off, indicating the positive welfare effects of expansionary fiscal policies.

Table 4. Equivalent variations of household welfare and government income at 2020 prices in carbon tax scenarios (10^8 CNY)

	CTS_A1	CTS_A2	CTS_B1	CTS_B2	CTS_C1	CTS_C2
Household welfare	-1273.09	-12700.15	234.68	2184.53	1459.26	14463.30
Government income	1183.48	11559.87	-256.32	-2546.37	-1350.06	-13455.00

The CGE model in this research estimates the added value variations in iron and steel related sectors in policy scenarios, as depicted in Figure 22. The added value includes production factor revenues and tax, which is calculated by subtracting intermediate input costs from the total output value. According to the simulation results, added value loss inevitably occurs throughout all the policy scenarios in iron and steel enterprises, which is becoming more remarkable when carbon tax rate goes up. The added value loss is comparatively smaller in CTS_C scenarios because the macro-economy situation is better off and the production scale in iron and steel sectors does not shrink as much as that in other policy scenarios. In other words, in CTS_C scenarios, carbon tax imposes relatively smaller negative influences on the added value of iron and steel enterprises. Such added value losses represent the energy conservation and pollution abatement costs faced with the producers of iron and steel industry, which are used to compare the cost-efficiency of different carbon tax policies in the next stage.

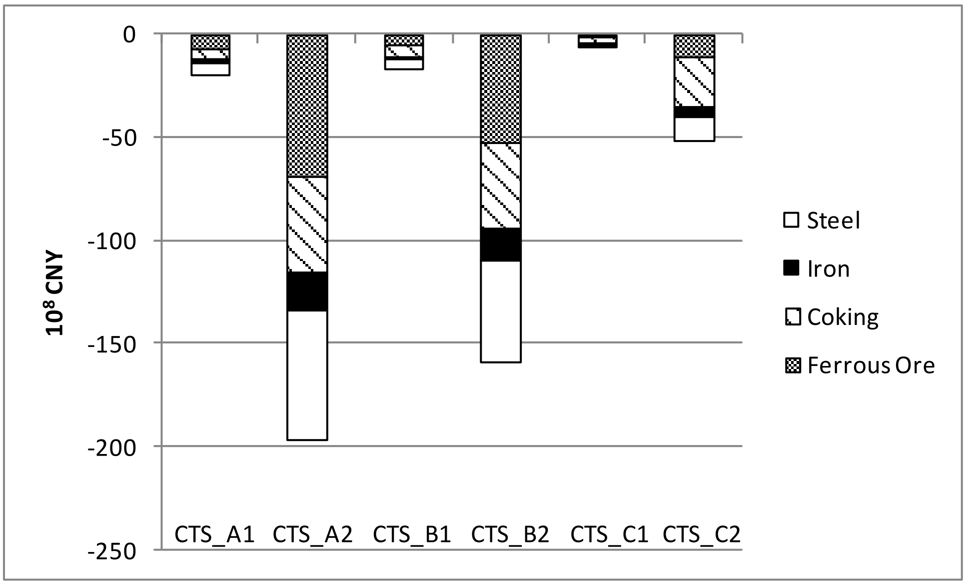

Figure 22. 2020 added value variations in iron and steel related sectors among different scenarios

3.2.2.2 Technology effects

According to the simulation results of CIMS model under carbon tax scenarios, technology composition evolves along similar trajectories under the same tax rate. In other words, technology evolutions in the three carbon tax groups (CTS_A, CTS_B and CTS_C) are not significantly different from each other, in which CTS_C is marginally faster. In that case, CTS_C1 and CTS_C2 are chosen to be representative policy scenarios in the comparison of technology compositions with BAU scenario.

In coke production, 2020 technology compositions of different scenarios are presented in Figure 23. Generally speaking, the implementation of carbon tax will accelerate technology evolution, which will become even faster when the tax rate goes up. Comparatively, technology composition in CTS_C2 is significantly improved, while CTS_C1 is not remarkably different from BAU scenario. Big machinery oven becomes even more advantaged in CTS_C2, which will have a stock of 474.37 Mt and occupy a market share of 78% in 2020, while in BAU scenario it is correspondingly 399.97 Mt and 66%. Meanwhile, other technologies will become even less competitive when carbon tax is levied. For example, the technology stock of small machinery oven in 2020 further falls from 24.36 Mt in BAU scenario to 12.97Mt in CTS_C2, and its market share shrinks from 4% to 2%.

There are similar tendencies in other production process in iron and steel sector, which are illustrated in the following charts. In one word, carbon tax will accelerate technology substitutions in iron and steel sector, improving its energy efficiency.

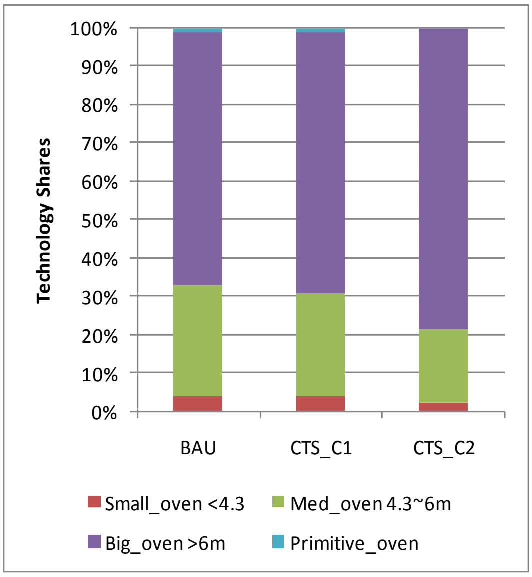

Figure 23. Coking technology composition in 2020

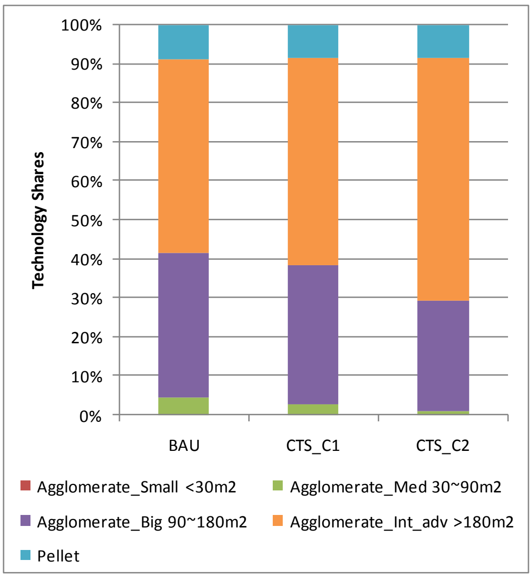

Figure 24. Agglomeration technology composition in 2020

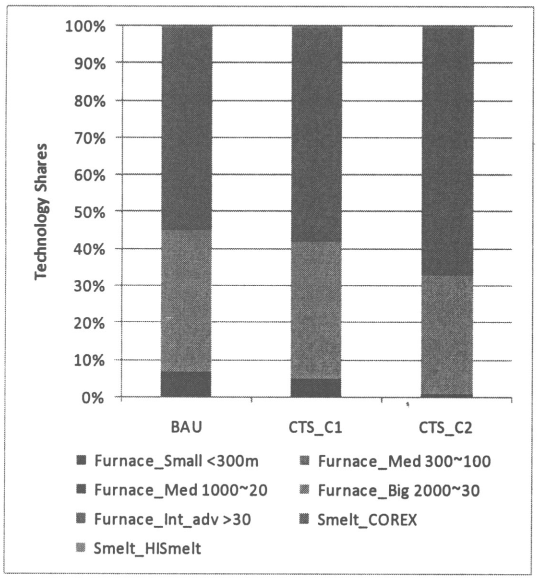

Figure 25. Iron making technology composition in 2020

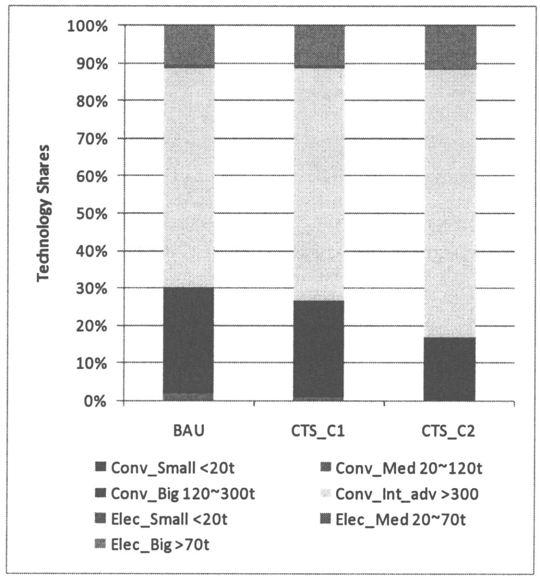

Figure 26. Steel making technology composition in 2020

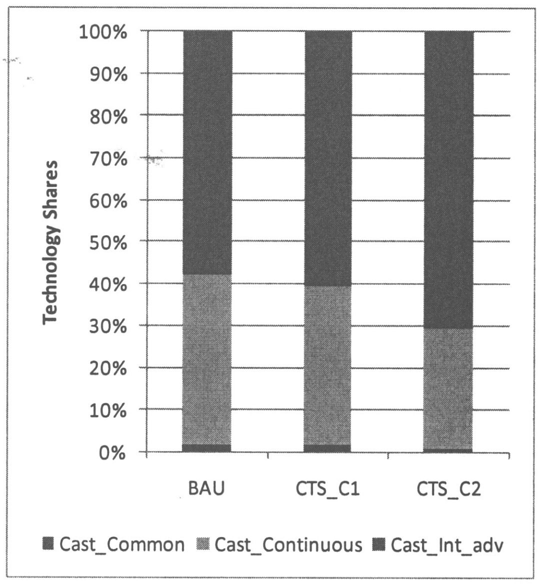

Figure 27. Casting technology composition in 2020

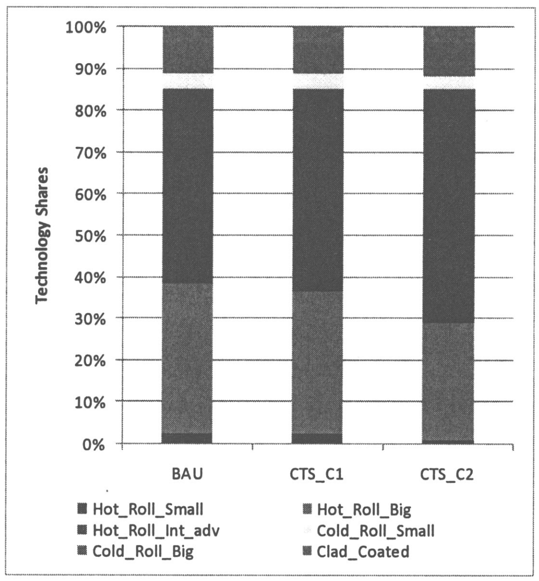

Figure 28. Steel processing technology composition in 2020

3.2.2.3 Energy-environment effects

Under carbon tax policy scenarios, the variations of 2020 energy conservation and emission reduction in iron and steel sector are presented in Table 5. First, carbon tax designed in this research will lead to co-control effects in CO_2, NO_x, PM and SO_2 emission. Secondly, PM emission reduction is the most significant among different pollutants, due to the rapid popularization of de-dusting equipment through technology substitution. However, recalling the emission control targets in 11th and 12th FYP environmental plan, according to the simulation results, carbon tax alone cannot ensure that iron and steel sector will meet the target of SO_2 and NO_x emission reduction in the next decade, if carbon tax rate is lower than 100 CNY/ton CO_2.

Table 5. 2020 energy consumption and emission variation rates (%) in iron and steel related sectors among different scenarios

	CTS_A1	**CTS_A2**	**CTS_B1**	**CTS_B2**	**CTS_C1**	**CTS_C2**
Energy consumption	-0.52	-2.78	-0.49	-2.42	-0.38	-1.40
CO_2 emission	-0.51	-2.76	-0.48	-2.40	-0.38	-1.38
NO_x emission	-0.59	-3.24	-0.56	-2.88	-0.45	-1.86
PM emission	-3.58	-13.42	-3.55	-13.10	-3.45	-12.19
SO_2 emission	-0.59	-3.27	-0.55	-2.91	-0.45	-1.90
Emission index	-0.61	-3.17	-0.58	-2.81	-0.48	-1.79

In policy scenarios, energy savings and pollutant emission reductions can be attributed to both production scale variations and technology evolutions caused by carbon tax. If energy consumption or pollutant emission is expressed as $E = \alpha \cdot \beta$, in which α is output scale and β is the intensity of energy consumption or pollutant emission, then a total differentiation of the equation indicate that $\frac{dE}{E} = \frac{d(\alpha \cdot \beta)}{\alpha \cdot \beta} = \frac{d\alpha}{\alpha} + \frac{d\beta}{\beta}$, through which the impacts of carbon tax on energy and environment can be disaggregated as the effects caused by production scale variations and technology evolutions, as summarized in Table 6. According to the simulation results, first, in 2020 the two factors have comparable contributions to the total energy-environmental effects of carbon tax, indicating that in a comparative dynamic analysis with a medium to long-term simulation period, the energy-environmental impacts of a policy could be significantly misjudged if technology evolution is neglected. Secondly, due to the availability of effective dust removing instrument equipped by advanced technologies, technology substitutions will cause more remarkable PM emission reductions compared with those on other energy-environmental index. Last but not least, technology effects on each energy-environmental index in CTS_C scenarios, without exception, outweigh scale effects, indicating that technology substitutions are more important drivers of energy conservation and emission abatement in an environmental tax reform.

Table 6. Scale and technology contribution rates (%) to 2020 energy conservation and emission reduction in iron and steel related sectors among different scenarios

		CTS1	**CTS2**	**CTS3**	**CTS4**	**CTS5**	**CTS6**
Energy consumption	Scale	-0.17	-1.71	-0.14	-1.32	-0.03	-0.31
	Tech	-0.36	-1.07	-0.35	-1.10	-0.36	-1.09
CO_2 emission	Scale	-0.17	-1.71	-0.14	-1.32	-0.03	-0.31
	Tech	-0.35	-1.05	-0.34	-1.08	-0.35	-1.07
NO_x emission	Scale	-0.17	-1.71	-0.14	-1.32	-0.03	-0.31
	Tech	-0.43	-1.53	-0.42	-1.56	-0.43	-1.55
PM emission	Scale	-0.17	-1.71	-0.14	-1.32	-0.03	-0.31
	Tech	-3.41	-11.71	-3.41	-11.78	-3.42	-11.88
SO_2 emission	Scale	-0.17	-1.71	-0.14	-1.32	-0.03	-0.31
	Tech	-0.42	-1.57	-0.42	-1.59	-0.42	-1.59

Figure 29 illustrates the cost curves of energy conservation and emission reduction in different policy scenarios. The opportunity costs marked on the vertical axis are measured by added value losses of iron and steel industry, as discussed earlier. The decrease of emission index can be regarded as the increase of environmental benefit, as marked by the horizontal axis. First, throughout all the carbon tax scenarios in this research, it seems that abatement costs are larger than environmental benefits. However, the current pollution market prices in China are not high enough to fully internalize the external costs of environmental pollution. For instance, in Sweden, the SO_2 tax rate, which is estimated according to the actual sulfur tax rate, and NO_x pollution charge rate is separately 10.73 and 28.60 CNY/kg, which is respectively 2 and 6 times higher than the counterpart pollution market price cited in this research. In that case, the environmental benefits of pollution abatement presented in Figure 34 are underestimated. If Chinese pollution market prices are replaced by environmental tax or pollution charge rates of developed countries to measure the benefits of pollution reduction, the environmental benefits will outweigh the abatement costs and positive net benefits are obtained. However, if the carbon tax rate is further raised, the increasing marginal abatement costs suggest that the abatement cost should equal to environmental benefits at some point, when pollution externality is fully internalized, and the optimized abatement volume and carbon tax rate could be in turn located. Secondly, an environmental tax reform like CTS_C will provide the most cost-effective carbon tax framework for both energy saving and emission abatement, compared with other carbon policy options scrutinized in this research. That is because the improvement of energy-environmental benefits in CTS_C is mainly caused by technology substitutions instead of production scale shrinks, which are major reasons for the added value losses of iron and steel industry. As well the optimized tax rate of expansionary carbon tax can be expected to be higher than that of other carbon taxes.

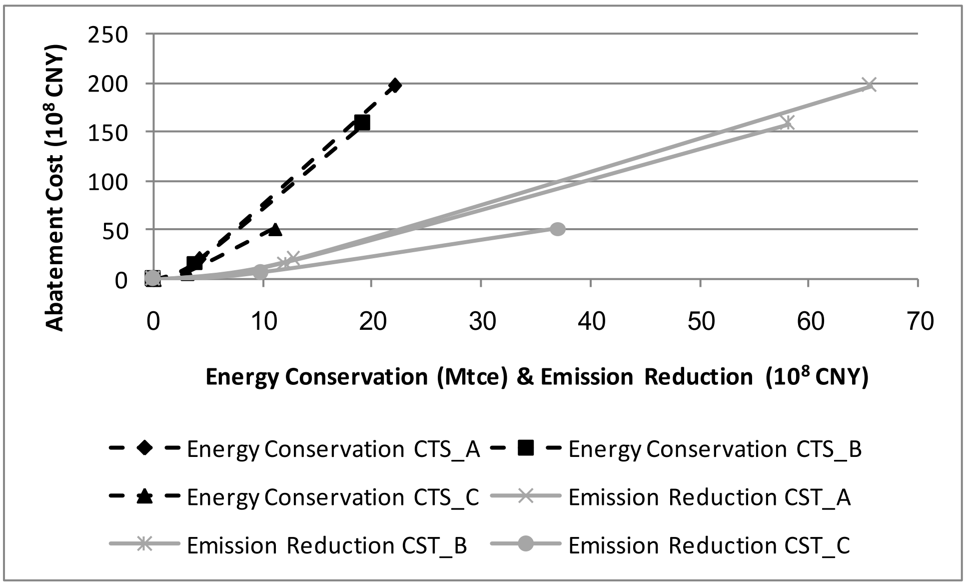

Figure 29. 2020 opportunity costs of energy conservation and emission index reduction in iron and steel related sectors among different policy scenarios

Finally, an economic-environmental impact assessment matrix is established to evaluate the overall effects of carbon tax policies on different criteria, as shown in Table 7. A carbon tax is graded at 3 on a criterion if it is the most advantaged compared with other policy scenarios, and 1 if the most disadvantaged. Given the same weight to each criterion, the overall evaluation of a policy is given by the summation of its scores on different criteria, indicating that CTS_C or an environmental tax reform is the most advisable option compared with other carbon tax policy frameworks.

Table 7. Economic-environmental impact assessment matrix

	CTS_A	CTS_B	CTS_C
GDP	1	2	3
Economic welfare	1	2	3
Technology substitution	3	3	3
Environmental welfare	3	2	1
Cost-effectiveness	1	2	3
Over all	9	11	13

3.3 CAC-EOP Simulation Results

Mandatory application of end-of-pipe (EOP) pollution control instrument is another important policy option to drive iron and steel sector to meet environmental requirements, which was regulated by many developed countries through their early-stage environmental legislation. Such command and control (CAC) policy has been highlighted by China's government at present, typically including mandatory application of EOP pollution control instrument, shutting down small-scaled plants and emerging into large ones, investment guidance and mandatory retirement of low energy efficiency technologies, etc. Although CAC policies have been widely accused of its expensive costs and flawed implementation and supervision, they are the major environmental policy instruments in China's 11th FYP, and are still likely to keep playing important roles in the 12th FYP.

During the 11th FYP, iron and steel plants in China have been required to equip and operate de-dusting instrument. According to the relevant policy from the Ministry of Environmental Protection (MEP) of China, iron and steel plants should 'always simultaneously equip and operate de-dusting instrument together with the corresponding production line, and the former should be at least as advanced as the latter' (MEP, 2008). The steep drop of PM emission intensity in BAU scenario suggests the effectiveness of the policy. As well, the Ministry of Industry and Information Technology (MIIT) of China has implemented a policy which requires iron and steel plants to cut down SO_2 emission in sintering flue gas by 25% through de-sulfur instrument by the end of 2011 (MIIT, 2009). That policy is still on the half way of fully implementation, and based on investigations into some advanced iron and steel plants in China, it is suggested that there is still a considerable potential of EOP control of SO_2 emission. Moreover, China's 12th FYP Environmental Plan also aims to achieve a 10% reduction of the total emission of NO_x. Recalling China's carbon intensity reduction commitment in COP15, iron and steel sector in the country are faced with new challenges of NOx and carbon emission reduction during the next decade. In that case, this research is focused on EOP control policy and technology options of SO_2, NO_x and CO_2 in China's iron and steel sector.

Sintering process is an important source of SO_2 emission in China's iron and steel sector. Desulphurization and de-nitration technologies are relatively more practical in this process. By 2009, only 8% of the sintering machines in China had equipped de-sulfur instrument (MIIT, 2009). There are different technologies currently available for industrial-scale use, the attributes of which are summarized by (Zhou, 2009), among which the most cost-effective one is the Limestone-Gypsum Wet (L-G W) FGD system. It is a well developed FGD technology taking place in a scrubber where $CaCO_3$ (limestone) absorbs SO_2, first forming $CaSO_3$ and eventually producing marketable $CaSO_4 \cdot 2H_2O$ (gypsum), with a desulfurization rate of 95% and an average cost of 19.12 CNY/ton steel. Meanwhile, synchronous desulphurization and de-nitration technology options are summarized by (Chen and Song et al., 2008), among which the most cost-effective one is Phosphate Ammoniate Fertilizer Process (PAFP) FGD system, in which SO_2 and NO_x is respectively adsorbed by active carbon and ammoniate. The technology could achieve a reduction rate of 98% for SO_2, and 80% for NO_x, with an average cost of 12.21CNY/ton steel.

Carbon Capture and Storage (CCS) is almost the only currently available EOP technology for carbon emission control, in which carbon is captured from emission sources and geologically stored so it does not enter the atmosphere. According to International Energy Agency (IEA), up to 2008 merely five large-scaled CCS projects had been built in the world, in which carbon capturing, transportation and storage are separately applied but have never been combined together (IEA, 2010). Specifically for iron and steel industry, some Swedish steel plants claim to have applied carbon capturing technology in small scales (Ribbenhed and Thorn et al., 2008). According to China Iron & Steel Association, CO_2 concentration in blast furnace gas is the highest among all the production processes, which is still not high enough for CCS, rendering the best explanation why CCS is not currently popular in that industry in China. In spite of that, experiments of commercial application of CCS have been carried out by some state-owned corporations in power generation, coal and petroleum extraction industry (The Climate Group, 2010). In some related research of NRDC, it is assumed that CCS could be commonly equipped in iron and steel industry after 2020 (ERI, NDRC, 2009). Moreover, IEA also claims that there should be demonstration projects of CCS in 2015 in China's industry such as iron and steel sector, and should be wider applied since 2025 (IEA, 2010). In this research, CCS application scenarios are designed with reference to the foregoing works.

Some essential economic and environmental parameters of those EOP technologies are summarized in Table 8 (Hu and Mao et al., 2010). Actually, each EOP technology alone cannot provide co-control effects for different pollutant emissions. For instance, PAFP-FGD technology can effectively cut down SO_2 and NOx emissions, while its electricity consumption suggests extra emissions of CO_2. That is the reason why the technology has positive reduction coefficients of SO_2 and

NO_x but negative ones of CO_2.

Table 8. Economic and environmental parameters of EOP technologies in iron and steel sector in China

Technology	**Emission reduction coefficient (kg/ton steel)**			**Total cost (CNY/ton steel)**
	SO_2	NO_x	CO_2	
L-G W FGD	1.62	-0.01	-3.92	19.12
PAFP FGD	1.78	0.69	-4.61	12.21
CCS	-1.05	-0.86	1335	546

3.3.1 Scenario design

Based on a primary comparison of emission control effects and economic costs among different EOP technologies, PAFP-FGD and CCS are selected as the major EOP technology options in this research. The mandatory application rates of the EOP technologies in different policy scenarios are designed as in Table 9. In CAC-EOP Scenario A (EOP_A), only PAFP-FGD technology is required to be further equipped by iron making plants since 2011, while EOP_A1 and EOP_A2 are discriminated by different variation trajectories of application rates, with reference to the related regulation of MIIT. In CAC-EOP Scenario B (EOP_B), only CCS technology is required to be equipped by iron making plants since 2015, while EOP_B1 and EOP_B2 are designed with different application rates of the technology. CAC-EOP Scenario C (EOP_C) assumes mandatory application rates for both PAFP-FGD and CCS technology to observe the joint effects when they are equipped simultaneously, in which EOP_C1 combines EOP_A1 and EOP_B1, while EOP_C2 aggregates EOP_A2 and EOP_B2.

Table 9. CAC-EOP scenario design

Group	Scenario	Technology	Application rate (%)		
			2011	2015	2020
EOP_A	EOP_A1	PAFP-FGD	25	50	75
	EOP_A2	PAFP-FGD	25	50	100
EOP_B	EOP_B1	CCS	0	5	10
	EOP_B2	CCS	0	10	20
EOP_C	EOP_C1	PAFP-FGD	25	50	75
		CCS	0	5	10
	EOP_C2	PAFP-FGD	25	50	100
		CCS	0	10	20

In some technology-specified CGE models, both EOP technologies and pollutant emissions are modeled as inter-changeable inputs of in the production structure (Rive, 2010), which is often a CES function. However, in the IAM of this research, economic and technological details are separately described in the CGE and a CIMS sub-model. Recalling the features of the CAC policy in the foregoing scenarios, in the CGE end, EOP technologies are modeled as intermediate inputs of sintering machines and blast furnaces, both in iron making process producers, and the technologies are supplied by environmental management industry, which is included in service sector. The environmental effects are left with CIMS sub-model through the variations of emission coefficients.

3.3.2 Simulation results

3.3.2.1 Economy effects

In CAC-EOP scenarios, the variation rates of 2020 GDP are summarized in Figure 30. As a whole, there is a GDP loss in 2020 in each EOP scenario within -0.15%. Generally speaking, such GDP losses are comparable with those in carbon tax scenarios. However, it is worth mentioning that the carbon tax in this research is imposed on all the industries while CAC-EOP policies merely on iron making industry. Thus the GDP losses of carbon tax are relatively overstated in such a comparison.

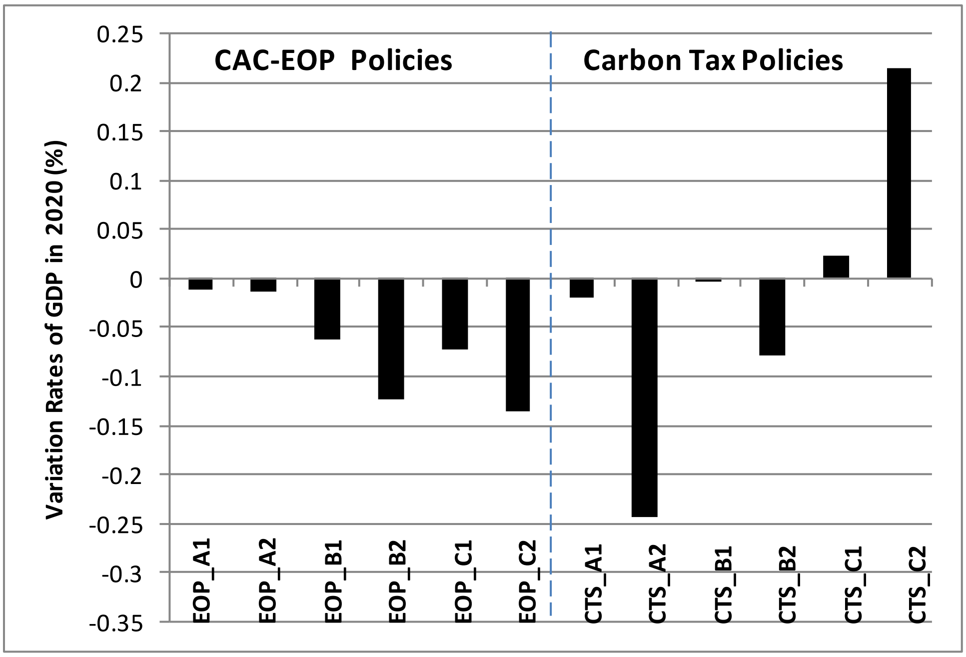

Figure 30. 2020 GDP variations in CAC_EOP and carbon tax scenarios

The variations of 2020 sector outputs are presented in the following graphs. CAC-EOP policies are directly imposed on iron making and service industry, and the variation rates of their production scales are more significant compared with those of other industries throughout different EOP scenarios. Production cost and output price of iron product are in turn brought up due to the zero pure profit assumption, as shown in Table 10. Simultaneously, on the demand end, higher price results in the shrink of the demand, which tends to bring down the market price of iron product. The two processes interact in an opposite way and the former plays a more important part. As a result, along demand and supply curves, both of the demand and supply scales shrink compares to those in BAU scenario. As for service industry, extra demands from iron making industry stimulate the expansion of its production scales, as mentioned in the foregoing analysis. In spite of that, the added value increases of service industry fail to offset the output shrinks in other industries, and national GDP losses thereby occur.

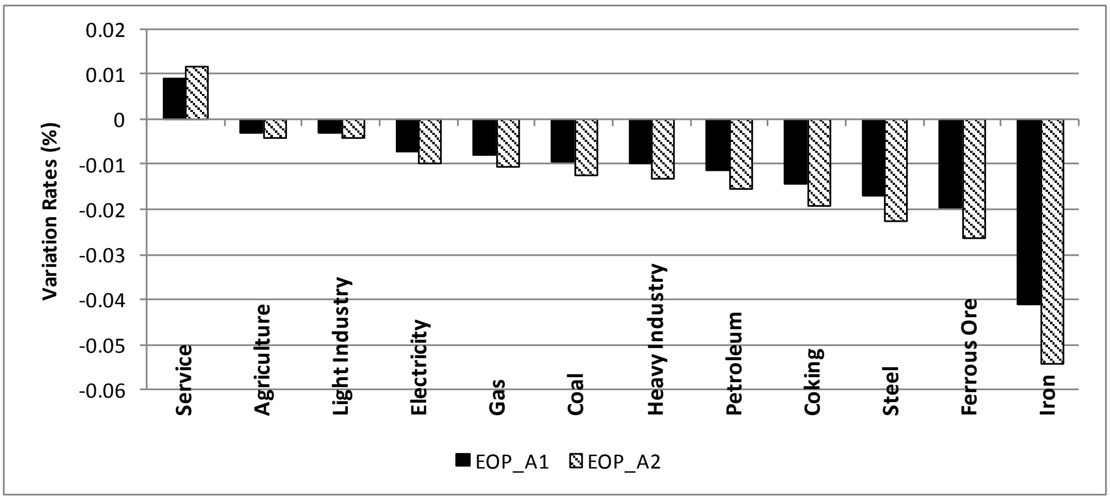

Figure 31. 2020 sector output variations in EOP_A scenarios

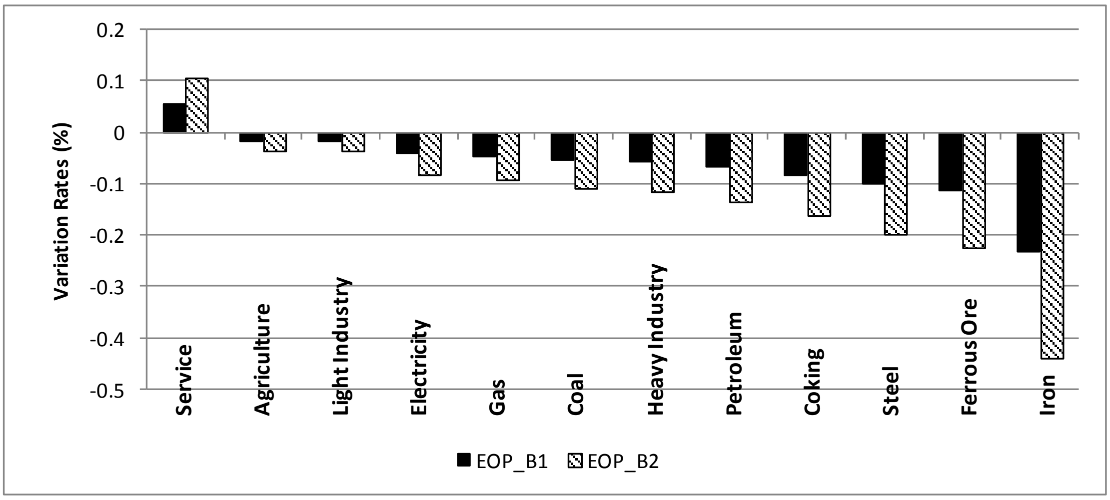

Figure 32. 2020 sector output variations in EOP_B scenarios

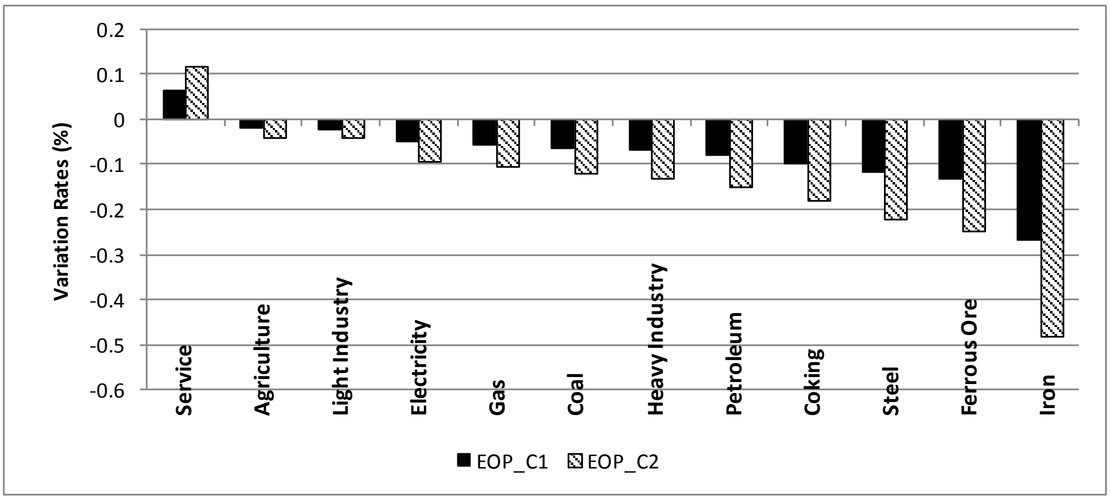

Figure 33. 2020 sector output variations in EOP_C scenarios

Table 10. Variation rates of price index in 2020 (%)

	EOP_A1	EOP_A2	EOP_B1	EOP_B2	EOP_C1	EOP_C2
Agricultural product	-0.01	-0.01	-0.04	-0.07	-0.04	-0.08
Ferrous ore	0.00	-0.01	-0.03	-0.06	-0.03	-0.06
Coke	0.00	0.00	0.00	0.00	0.00	0.00
Iron	1.44	1.91	8.56	17.12	10.00	19.04
Steel	0.23	0.30	1.35	2.71	1.58	3.01
Coal	0.00	0.00	0.00	-0.01	0.00	-0.01
Petroleum	0.00	0.00	-0.01	-0.01	-0.01	-0.01
Electricity	0.00	0.00	-0.01	-0.03	-0.02	-0.03
Gas	0.00	0.00	0.00	0.00	0.00	0.00
Light industry product	0.00	0.00	-0.01	-0.02	-0.01	-0.02
Heavy industry product	0.02	0.03	0.13	0.27	0.16	0.30
Service	0.00	0.00	0.02	0.04	0.02	0.04
Wage	0.00	0.00	-0.06	-0.12	-0.06	-0.12
Capital revenue rate	0.00	0.00	0.00	0.00	0.00	0.00

Some industries are indirectly affected by CAC-EOP policies, such as ferrous ore, steel, heavy industry and coal, which have very close input-output relationships with iron manufacture industry. For instance, when iron production scale shrinks, the demand and supply of iron ore is supposed to in turn decrease, and its market price is correspondingly brought down. Production scales of coke and coal decrease for similar reasons, but the variations of their prices are insignificant. On the other hand, steel and heavy industry are downstream industries using iron products as intermediate inputs. In that case, the production costs and output prices in those industries are successively raised by the remarkably rising price of iron product, as shown in Table 10. Consequently, demands for steel and heavy industry products are decreased by higher prices and the production scales are thus brought down.

Table 11. Equivalent variations of household welfare and government income at 2020 prices (10^8 CNY)

	EOP_A1	**EOP_A2**	**EOP_B1**	**EOP_B2**	**EOP_C1**	**EOP_C2**
Household welfare	-38.51	-57.77	-241.06	-462.87	-279.58	-520.64
Government income	-8.63	-11.74	-51.36	-101.89	-59.98	-113.59

Parallel to the discussions involving carbon tax, Equivalent Variations (EV) of household welfare and government income are introduced to measure the welfare effects of CAC-EOP policies, as presented by the foregoing table. Apparently both household welfare level and government income are decreased in policy scenarios, which are significantly worse off when CCS technology is required. The explanation of household welfare decrease is given in the foregoing discussions. As for the government income shrinks, the general tendency of national economy recession suggests decreasing tax revenues because the tax rates are constant while the output scales shrink in most industries.

Table 12. 2020 added value variations (10^8 CNY) in iron and steel related sectors among different scenarios

	EOP_A1	**EOP_A2**	**EOP_B1**	**EOP_B2**	**EOP_C1**	**EOP_C2**
Ferrous ore	-0.60	-0.80	-3.50	-6.84	-4.07	-7.57
Coking	-0.26	-0.35	-1.51	-2.95	-1.76	-3.26
Iron	-81.79	-109.05	-487.50	-974.71	-569.23	-1083.63
Steel	-0.62	-0.83	-3.70	-7.34	-4.31	-8.15
Total	-83.27	-111.02	-496.20	-991.84	-579.37	-1102.61

As well, the 2020 added value losses in iron and steel sector are calculated as the abatement costs faced by producers. Actually the current cost of CCS technology is extremely expensive, which should be responsible for the vast majority of abatement costs. The observed added value losses of producers given by the CGE model are mainly caused by the joint effects of the shrinks of production scales, the increases of production costs and output prices.

3.3.2.2 Environment effects

Under CAC-EOP scenarios, the variations of 2020 emission reduction in iron and steel sector are presented in Table 13. To begin with, EOP_A policies cause synergetic emission reductions of SO_2 and NO_x, which are much more remarkable compared with those in carbon tax scenarios, and offer better chances for iron and steel industry to meet the total emission control target of SO_2 and NO_x in the next decade. However, there will be extra emissions of CO_2 and the reduction rate of total emission index will thereby be brought down because larger weight is given to CO_2 emission, indicating the contradictory effects of CAC-EOP policies on conventional air pollution and greenhouse gas emissions. Similarly, EOP_B policies will cause emission reductions of CO_2, while increase SO_2 and NO_x emissions. In spite of that, the reduction rates of total emission index are greater than those in EOP_A scenario due to the remarkable CO_2 emission reduction. EOP_C policies seem to offer co-control effects on all the four emissions, but each reduction rate is smaller than that when the corresponding EOP instrument is solely equipped because PAFP-FGD and CCS technology partly offset some emission reduction effects of each other. In one word, CAC-EOP policies have contradictory effects on different emissions and cannot be regarded as ideal co-control policy options. Nevertheless, exclusively taking account into total emission control, CAC-EOP policies are considerable compared with carbon tax policies designed in this research.

Table 13. 2020 emission variation rates (%) in iron and steel related sectors among different scenarios

	EOP_A1	**EOP_A2**	**EOP_B1**	**EOP_B2**	**EOP_C1**	**EOP_C2**
CO_2 emission	0.14	0.19	-6.11	-12.20	-5.97	-12.01
SO_2 emission	-14.31	-19.08	1.02	2.05	-13.28	-17.00
PM emission	-0.02	-0.02	-0.10	-0.20	-0.12	-0.22
NOx emission	-23.09	-30.78	3.73	7.45	-19.33	-23.27
Emission index	-3.87	-5.17	-4.05	-8.09	-7.92	-13.24

As for technology evolution, under CAC-EOP policies, the variations of production scales and energy prices are too slight to impose significant effects on production technology evolution in CIMS model. Thus technology effects in CAC-EOP scenarios merely refer to the environmental effects of EOP pollution control instruments. The contributions of production scale variations and technology substitutions to the total environmental impacts of CAC-EOP policies are disaggregated as in Table 14, parallel to carbon tax scenarios. Throughout all the CAC-EOP scenarios, PM emission reductions are solely caused by the decreasing production scales, because no extra EOP technologies are mandatorily equipped in CAC-EOP scenarios. Besides, the contributions of scale variations are relatively insignificant compared with those of technology substitutions and the latter thereby dominate the total influences on pollutant emissions, especially when the two factors lead to contradictory environmental effects. In EOP_A scenarios, scale variations and technology substitutions simultaneously cause reductions of SO_2 and NO_x emissions, but contradictory effects on CO_2 emission. In EOP_B scenario, scale and technology variations lead to synergetic CO_2 emission reductions, but contradictory effects on SO_2 and NO_x emissions. In EOP_C scenario, both scale and technology variations cause emission reductions of CO_2, SO_2 and NO_x, but the latter are relatively more remarkable, especially for CO_2 and emission index, highlighting the carbon emission control effects of CCS technology.

Table 14. Scale and technology contribution rates (%) to 2020 emission reduction in iron and steel related sectors among different scenarios

		EOP_A1	**EOP_A2**	**EOP_B1**	**EOP_B2**	**EOP_C1**	**EOP_C2**
CO_2 emission	Scale	-0.02	-0.02	-0.10	-0.20	-0.12	-0.22
	Tech	0.16	0.21	-6.01	-12.00	-5.85	-11.79
SO_2 emission	Scale	-0.02	-0.02	-0.10	-0.20	-0.12	-0.22
	Tech	-14.30	-19.06	1.12	2.24	-13.16	-16.78
PM emission	Scale	-0.02	-0.02	-0.10	-0.20	-0.12	-0.22
	Tech	0.00	0.00	0.00	0.00	0.00	0.00
NO_x emission	Scale	-0.02	-0.02	-0.10	-0.20	-0.12	-0.22
	Tech	-23.07	-30.76	3.83	7.65	-19.22	-23.05
Emission index	Scale	-0.02	-0.02	-0.10	-0.20	-0.12	-0.22
	Tech	-3.86	-5.14	-3.95	-7.89	-7.80	-13.02

Figure 34 presents comparisons between carbon tax and CAC-EOP policies on abatement costs, which are measured by the added value losses of iron and steel industry. First of all, for all the CAC-EOP policies, the environmental welfare benefits of pollutant emission reductions cannot cover the abatement costs of producers in iron and steel industry, the explanation of which is still that the current pollution market values in China are too low to fully reflect the marginal social costs of pollutant emissions or the marginal social benefits of emission reductions. Secondly, among different CAC-EOP policies, the cost-efficiency of EOP_A is the highest and that of EOP_B is the lowest, suggesting that PAFP-FGD is relatively more cost-effective than CCS under the valuation system in this research.

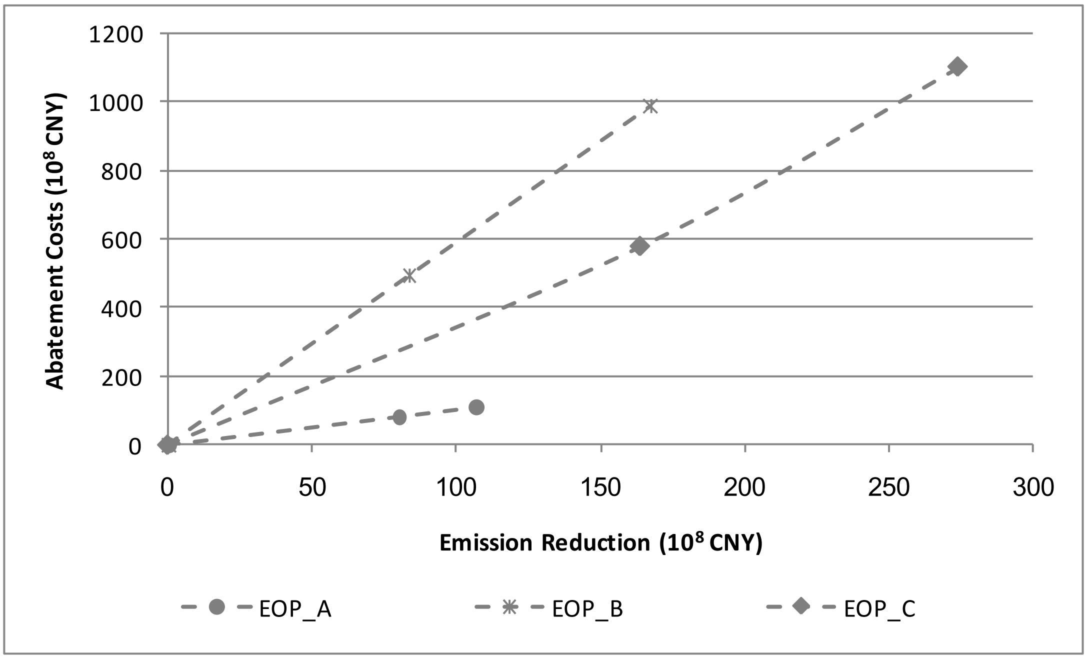

Figure 34. Abatement cost comparison among CAC-EOP scenarios

Moreover, a general comparison among different CAC-EOP policies is carried out through an economic-environmental impact assessment matrix on different criteria. A policy is graded at 3 on a criterion if it is the most advantaged compared with other policies, and 1 if the most disadvantaged. Given an identical weight of each criterion, EOP_A is relatively more advantaged in general.

Table 15. Economic-environmental impact assessment matrix of CAC-EOP policies

	EOP_A	**EOP_B**	**EOP_C**
GDP	3	2	1
Economic welfare	3	2	1
Environmental welfare	1	2	3
Cost-effectiveness	3	1	2
Over all	10	7	7

Last but not least, a primary comparison between carbon tax and CAC-EOP policies on cost-efficiency is given by the following chart. Recalling the assumption that carbon tax policies are imposed on all the industries, the abatement costs of carbon tax policies should be lower if they are merely imposed on one industry like CAC-EOP policies. Even so, the cost-efficiency of CTS_C is still significantly higher than that of EOP_B and EOP_C, and comparable with that of EOP_A.

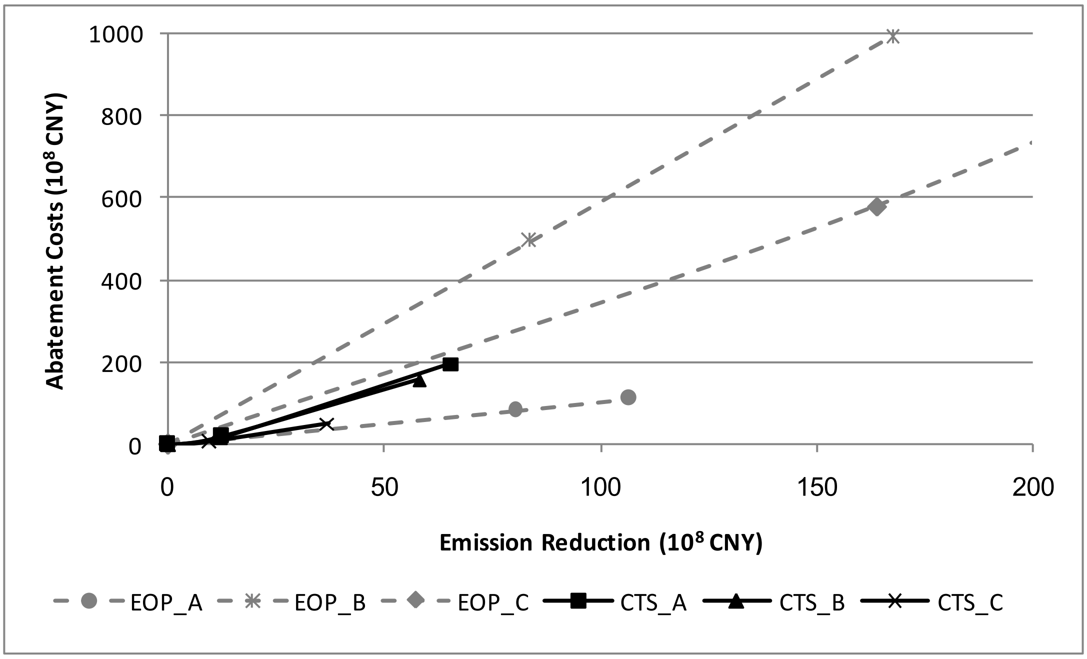

Figure 35. Abatement cost comparison between CAC-EOP and carbon tax scenarios

4.0 CONCLUSIONS AND POLICY IMPLICATIONS

4.1 Conclusions

This research evaluates and compares co-control policy options of conventional air pollutants and greenhouse gases in iron and steel sector in China, including carbon taxation, and mandatory application of End-Of-Pipe (EOP) pollution control technologies. Their effects on economy, technology and environment are major criteria in the comparative assessment. Such effects are quantitatively simulated through an Integrated Assessment Model, in which a top-down Computable General Equilibrium (CGE) sub-model and a bottom-up Canadian Integrated Modeling System (CIMS) sub-model is combined via a one-way soft-linkage. The CGE sub-model is responsible for the simulation of economic effects, such as the variations of production scales and energy prices, which will be input as exogenous parameters into CIMS sub-model, and used in the next stage to simulate technology, energy and environment effects.

Three categories of carbon tax policy scenarios are designed (each with tax rates from 10-100 CNY/ton CO_2). In Carbon Tax Scenario A (CTS_A), it is assumed that the government consumes all the revenues of carbon tax. In Carbon Tax Scenario B (CTS_B), it is assumed that all the revenues of carbon tax are refunded to households. In Carbon Tax Scenario C (CTS_C), it is assumed that the government imposes carbon tax and cut VAT rates to maintain the baseline total tax revenue unchanged, and all the revenues of carbon tax are refunded to households. According to the simulation results, major findings include: (1) CTS_C slightly improves GDP growth, while other carbon tax policies lead to marginal negative effects. (2) Macro-economy structure will be driven to a low energy and carbon intensity direction. (3) Social economic welfare will be enhanced in CTS_C, and brought down in CTS_A and CTS_B. (4) Technologies with higher energy efficiency will have larger shares of market, and technology evolution will be accelerated in iron and steel sector, which will become even faster under higher carbon taxation rates. (5) Synergetic reductions of CO_2, NO_x, PM and SO_2 emission will be achieved, but the reduction rates are not significant enough except for PM emission when carbon taxation rate is lower than 100 CNY/ton CO_2. (6) High energy efficiency technology substitution makes important contributions to energy conservations and pollutant emission reductions, especially in CTS_C scenarios, and should not be neglected in a medium to long-term simulation period. (7) The effects of carbon taxation on economy, technology, energy and environment will become more significant under higher tax rates. (8) CTS_C is more cost-effective, and is generally more advisable compared with other carbon tax scenarios.

Three categories of countermeasures (sub-scenarios) under CAC-EOP (Command and Control-End of Pipe) policy scenario are proposed, with different mandatory application rates of EOP control technologies for CO_2, SO_2 and NO_x. PAFP-FGD technology is solely required in EOP Scenario A (EOP_A) and CCS technology is solely required in EOP Scenario B (EOP_B). The two technologies are combined in EOP Scenario C (EOP_C). Major simulation results indicate that: (1) A GDP loss can be expected, which is comparable with that in CTS_A and CTS_B. (2) The economic welfare level of the society will be brought down. (3) Production technology substitution is not significantly accelerated because the variations of production scales and energy prices are not remarkable enough. (4) EOP technologies tend to have conflicting effects on different pollutant emissions but not of co-control effects. (5) If each pollutant emission is considered independently, the reduction rate under corresponding CAC-EOP countermeasure is considerable. (6) EOP_A is more cost-effective, and is generally more favored compared with other EOP scenarios based on a comparison of their economic and environmental effects.

When carbon tax and EOP policies are compared, it can be safely concluded that CTS can get co-control effects for reducing both carbon and local pollutants (co-benefit obtained), but CAC-EOP cannot get co-control effects with conflicting effects in reducing local pollutants and CO_2.

4.2 Policy Implications

On policy level, under the framework of environmental tax reform, it is possible that market-based policy instrument, such as carbon tax, leads to double dividend in both economic and environmental welfare. The ‘co-benefits’ are not merely embedded in ‘co-reduction’ of different pollutant emissions, but are also reflected on higher level of economic development, technology substitution, energy security and environmental protection.

Moreover, carbon tax provides a possible solution to the threat of carbon tariff proposed by the US and benefit the international trade interests of China. In order to cushion the negative impacts on certain industries, carbon tax should be implemented with other complement policies with reference to international experience, such as discriminated tax rates among different industries, and governmental guidance on energy price agreements among different energy sectors (Bruvoll and Larsen, 2004). Last but not least, carbon tax might rise energy prices and intensify inflation, and complement fiscal and monetary policies should be thereby taken account into.

Comparatively, CAC-EOP policies are in advantage in their relatively more significant pollution reductions in a shorter period, especially when single pollutant emission reduction target is set. But the incremental abatement costs are high and are also likely to be transferred from producers to consumers and in turn bring down social welfare levels. Secondly, different EOP technologies impose conflicting effects on different pollutant emissions, cutting down some of them while increasing the others. In that case, if different EOP technologies and different pollutions are considered as a whole, the environmental welfare benefits are much less than expected due to the offsetting effects. Additionally, some other problems have been observed during the implementation of CAC-EOP policies, and will probably still be there in the future. For instance, due to the flawed policy enforcement and supervision, together with weak penalty mechanisms, opportunity costs are low for the enterprises to violate CAC-EOP policies, and they are reluctant to equip and operate EOP pollution control technologies. Another example lies in the revival of mandatorily retired technologies with low energy efficiency and high pollutant intensity. Moreover, CAC-EOP policies have already been implemented in China for some years, and the marginal potential of pollution abatement is decreasing. Those factors should be taken account into before more CAC-EOP countermeasures are implemented.

On technology level, iron and steel technologies in China have been evolving towards the direction of larger scales and higher energy efficiencies, which will be accelerated under economic incentives such as carbon tax. Technology substitution and resource managements will be more effective if small-scale plants are shut down and merged into large ones, which is also indicated by the evolution history of iron and steel industry in developed countries.

As for Carbon Capture and Storage (CCS) technology, in spite of its considerable potentials of CO_2 emission reductions, its abatement costs are still rather expensive at present, which cannot be covered by environmental welfare benefits, leading to economic low-efficiency.

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