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Co-benefit Analysis of Carbon Emission Reduction Measures for China, Japan and Korea

SU Xuanming, ZHOU Weisheng, REN Hongbo, NAKAGAMI Ken'ichi

CONTENTS

Keywords: Co-benefit, Low-carbon community, SO_2, NO_x, G-CEEP

Ⅰ. Introduction

Transition to a low-carbon community is recognized as a common goal in the world including both developed and developing countries. Using energy model is an efficient way to analyze this challenging issue. In addition, some air pollutants are released in various industrial processes, such as SO_2 and NO_x, which are able to form acid rain and have significant impacts upon human health. Because both these air pollutants and carbon emission derive from the consumption of fossil fuels, carbon abatement strategies usually achieve two aims simultaneously. One that reduces carbon emission as what the abatement strategies want to; the other alleviates the air pollutants as well. In order to measure the alleviation degree of SO_2 and NO_x emissions with the abatement strategies, we build an integrated evaluation model, the G-CEEP model to evaluate the effects of the abatement strategies on SO_2 and NO_x emissions for China, Japan and Korea.

Reducing SO_2 and NO_x emissions usually relies on the abatement technologies or related environmental policies. Nurrohim and Sakugawa (2004) discussed the possible impacts of the greenhouse gas abatement measures on the NO_x and SO_2 emissions from manufacturing industries in Hiroshima Prefecture and the predictions showed that NO_x and SO_2 emissions might decrease from 18.9 and 21.5 kt in 1990 to 15.1 and 14.2 kt in 2010, respectively, if Japanese energy policy and targets in voluntary action plans were successfully implemented. Chang et al. (2006) investigated the impact of strengthening vehicle emission regulation on economic activities and focused on the economic impact of reducing sulfur content in diesel fuel quality standard. Graus and Worrell (2007) gave an overview of the effects of SO_2 and NO_x pollution control on the energy efficiency of fossil-fired power generation for several countries and distinguished the levels of desulphurisation and denitrification for the stated countries. Lu et al. (2010) estimated the annual SO_2 emission in China after 2000 using a technology-based methodology and showed that the trend of estimated SO_2 emission in China was consistent with the trends of SO_2 concentration and acid rain pH and frequency in China, as well as with the increasing trends of background SO_2 and sulfate concentration in East Asia. As to an entire country like China, Japan or Korea, current literature seldom involved the co-benefit effects of the carbon abatement measures on the SO_2 and NO_x emissions.

This study aims to discuss the possible impacts of these abatement measures on the SO_2 and NO_x emissions. The carbon abatement targets here use greenhouse gas reduction proposals for the year 2020 in the Copenhagen Accord, which is a document that delegates at the 15th session of the Conference of Parties (COP 15) to the United Nations Framework Convention on Climate Change (UNFCCC) in 2009. Furthermore, this study discusses the co-benefit effects of carbon taxes on SO_2 and NO_x emissions, respectively, to illuminate the emission trend by the marginal abatement cost curve.

This paper begins with the methodologies of the development of G-CEEP model. Section III introduces the framework of G-CEEP model. Then Section IV states macroeconomic and technological assumption for the model. Subsequently, section V discusses the projected results and analyzes the co-benefit effects of carbon taxes, when section VI gives the conclusions of this paper.

Ⅱ. Methodologies

1. Macroeconomic input

Currently, most macroeconomic models with respect to energy or energy models with macroeconomic description are based on two-level CES production function. The GREEN model (Burniaux, J. et al., 1992) nested capital and energy with a low elasticity of substitution, and this aggregation was combined with labor by a higher elasticity of substitution. The model GLOBAL 2100 (Alan S. and Richard G., 1992) used a capital and labor nesting against energy. We follow the macroeconomic model with two-level CES production function proposed by Alan S. and Richard G.(1992), which adds energy as factor input to the traditional two-input CES production in the second level.

In G-CEEP model, Energy consumption is further subdivided to electricity (EN) and non-electricity (NN). Thus there are four inputs: capital stock (KN), labor (LN), electricity and non-electricity. The two-level CES production function can be written as:

$$\mathrm{YN} = \gamma\left[\delta\left(\delta_1 KN^{-\rho_1} + (1-\delta_1)LN^{-\rho_1}\right)^{\frac{\rho}{\rho_1}} + (1-\delta)\left(\delta_2 EN^{-\rho_2} + (1-\delta_2)NN^{-\rho_2}\right)^{\frac{\rho}{\rho_2}}\right]^{-\frac{1}{\rho}} \qquad (1)$$

Where *YN* is the output. 0 < a, b < 1 are distribution parameters. ρ (ρ_1, ρ_2) ≥ -1 are substitution parameters. The elasticity of substitution is specified as:

$$\sigma = \frac{1}{1+\rho} \qquad (2)$$

σ is a constant depending on the substitution parameter, ρ (ρ_1, ρ_2). When the estimation of ρ (ρ_1, ρ_2) < -1, the elasticity of substitution σ will become negative which is a theoretical impossibility (see Prywes, M., 1986). If substitution elasticity $\sigma < 0$, the related two input factors can be interpreted as complements when $\sigma > 0$ the related two input factors are substitutes.

G-CEEP model describes the relationship between capital stock, labor and energy with the two-level CES production function. This introduces non-linearity to the large-scale optimization model, which increases computational complexity but makes the model a more integrated and economic meaningful one. Besides the two-level CES production function, this model introduces another non-linearity: technological learning.

2. Technological learning

Recently, technological learning is widely used as a key factor to analyze the decreasing cost in specific technology. Although the introduction of endogenous technological change will inevitably increase the computational complexity due to the non-linearity associated with the learning curve, this study tries to incorporate the technological learning method in order to analyze the prospects of specific technological options and related cost decrease potential.

The one factor learning curve is written as following (Sondes, 2008):

$$C_t(Q_t) = a_t Q_t^{-\alpha} \tag{3}$$

Where t is defined as a specific technology, C_t denotes the cost per unit of production, a is the cost of the first unit produced, Q_t is the cumulative production and α is learning by doing parameter.

The parameter a is determined by one given point of the learning curve, commonly the initial point:

$$a_t = \frac{C_{t0}}{(Q_{t0})^{-\alpha_t}} \tag{4}$$

Thus the progress rate is given by:

$$p_t = 2^{-\alpha_t} \tag{5}$$

And the learning rate is given by:

$$l_t = 1 - 2^{-\alpha_t} = 1 - p_t \tag{6}$$

The progress rate is the rate at which the cost declines each time when the cumulative production doubles, which is sometimes considered as the slope of the learning curve.

3. Implementation of macroeconomic model

The application of macroeconomic model in G-CEEP model bases on the two-level CES production function with four inputs: capital stock, labor, electricity and non-electricity. Their relationship can be implemented by the following equations.

Production output and new production output:

$$Y_{t,r} = Y_{t-1,r} \times (1-\mu)^5 + YN_{t,r} \tag{7}$$

Labor force and new labor force:

$$L_{t,r} = L_{t-1,r} \times (1-\mu)^5 + LN_{t,r} \tag{8}$$

Electricity and new installed electricity:

$$E_{t,r} = E_{t-1,r} \times (1-\mu)^5 + EN_{t,r} \tag{9}$$

Non-electricity and new non-electricity:

$$N_{t,r} = N_{t-1,r} \times (1-\mu)^5 + NN_{t,r} \tag{10}$$

New capital:

$$KN_{t,r} = 5/2 \times [(1-\mu)^5 I_{t,r} + I_{t+1,r}] \tag{11}$$

Capital and new capital:

$$K_{t,r} = K_{t-1,r} \times (1-\mu)^5 + KN_{t,r} \tag{12}$$

Two-level CES production function:

$$Y_{t,r} = f(KN_{t,r}, LN_{t,r}, EN_{t,r}, NN_{t,r}) \tag{13}$$

Cost function:

$$Y_{t,n} = C_{t,n} + I_{t,n} + EC_{t,n} \qquad (14)$$

Terminal condition:

$$K_T \times (\omega + \mu) \le I_T \qquad (15)$$

- t, r are t period and r region, respectively, and T is the last period in this model.
- YN, KN, LN, EN and NN represent new production output, new capital stock, new labor, new electricity and new non-electricity, respectively.
- μ is defined as annual depreciation rate, the power 5 represents 5 years per period, ω is annual growth rate.
- New capital is the annual investment I.
- $YN_{t,r}$ equation is the two-level CES production function.
- C is consumption and EC is energy cost.

To ensure the rate of investment is adequate to provide for replacement and net growth of capital stock during the subsequent periods, a terminal constraint (15) is applied at the end of the planning horizons (A. Svoronos, 1985).

4. Environmental evaluation output

The environmental evaluation output is to calculate the emissions of CO_2, SO_2 and NO_X under specific scenarios, through emission factors of different energy, subject to relevant environment policy constraints.

Energy emission factors can be different from region to region in accordance with sectors of energy consumption, as well as the characteristics of fuels. The emissions are defined as energy consumption volume multiplied by emission factors.

The CO_2 emission in specific period, region and sector can be estimated according to the following equation:

$$E_{CO_2,trec} = Q_{trec} EF_{CO_2,rec} \qquad (16)$$

- $E_{CO_2,trec}$: CO_2 emission volume in specific period, region and sector.
- Q_{trec} : Energy consumption volume in specific period, region and sector.
- $EF_{CO_2,rec}$: CO_2 emission factor in specific region and sector.

Annual carbon emission limit is defined as following:

$$\sum_{e\in ET}(cece_{t,r,e} \times PE_{t,r,e}) + \sum_{e\in NT}(cecn_{t,r,e} \times PN_{t,r,e}) - CIM_{t,n} + CEX_{t,n} \\ \le CLIM_{t,n} + NENC_{t,n} \qquad (17)$$

$cece_{t,r,e}$ and $cecn_{t,r,e}$ are carbon emission coefficients for electricity and non-electricity. $PE_{t,r,e}$ and $PN_{t,r,e}$ are electricity and non-electricity supply. $CIM_{t,n}$ and $CEX_{t,n}$ provide for carbon import and export. The constant in the right-hand side $CLIM_{t,n}$ is the carbon limit in region r and $NENC_{t,n}$ represents non-energy uses of some fossil fuels.

SO_2 emission is estimated according to the following equation:

$$E_{SO_2,trec} = 2Q_{trec} S_{trec} \alpha_{s,trec} (1 - R_{trc}) \qquad (18)$$

- $E_{SO_2,trec}$: SO_2 emission volume in specific period, region and sector.
- Q_{trec} : Energy consumption volume in specific period, region and sector.
- S_{trec} : sulfur content in specific period, region and sector.
- $\alpha_{s,trec}$: SO_2 emission factor in specific period, region and sector.
- R_{trc} : Desulfurization rate in specific period, region and sector.

Coefficient 2 means that the atomic weight of SO_2 is twice as S.

The calculating equation of NO_x Emission is defined as following:

$$E_{NO_x,trec} = Q_{trec} \cdot EF_{ec} \cdot (1 - RE_{tc}) \cdot (1 - DE_{tc} \cdot PR_{tc}) \tag{19}$$

- $E_{NO_x,trec}$: NO_x emission.
- Q_{trec} : Energy consumption.
- EF_{ce} : Emission factor of NO_x.
- RE_{tc} : Reduction efficiency of NO_x emission.
- DE_{tc}: DeNO_x efficiency of DeNO_x equipment.
- PR_{tc} : Popularization ratio of DeNO_x equipment.
- Here, $DR_{tc} = DE_{tc} \cdot PR_{tc}$ is called DeNO_x rate.

5. Objective function

The objective of this model is to maximize the discounted consumption. The output production is indicated as the sum of consumption, investment and energy cost. When considering the impact of environmental taxes on the energy system, it takes environmental taxes as a part of the energy cost, maximizes the objective function of discounted consumption, and figures out the level of each decision variable under optimized state.

$$UTIL = \sum_{r=1}^{R} \sum_{t=1}^{T} \left(5 \times \prod_{\tau=0}^{t-1} (1 - udr_\tau)^5 \times \log(C_{t,r}) \right) \tag{20}$$

- $UTIL$: Discounted consumption.
- C: Annual consumption.
- udr: Utility discount rate.

Ⅲ. Framework of G-CEEP model

G-CEEP model is an improved version of pre-developed optimization model (Su et al., 2011), with the following features updated: ① The model has been converted from linear to nonlinear planning model by embedding the two-level CES production function as macroeconomic constraint condition. ② Time period has been changed from 10-years per period to 5-years per period, from 2010 to 2100, capable of assessing short-term, mid-term and long-term energy projection and planning. ③ Endogenous technological change has been introduced in order to analyze the prospects of specific technological options and related cost variation trend. ④ Co-benefit analysis of carbon emissions abatement measures for SO_2 and NO_x was added. ⑤ Marginal abatement cost curve analysis with detailed technological description and related implementing cost at the same time was added.

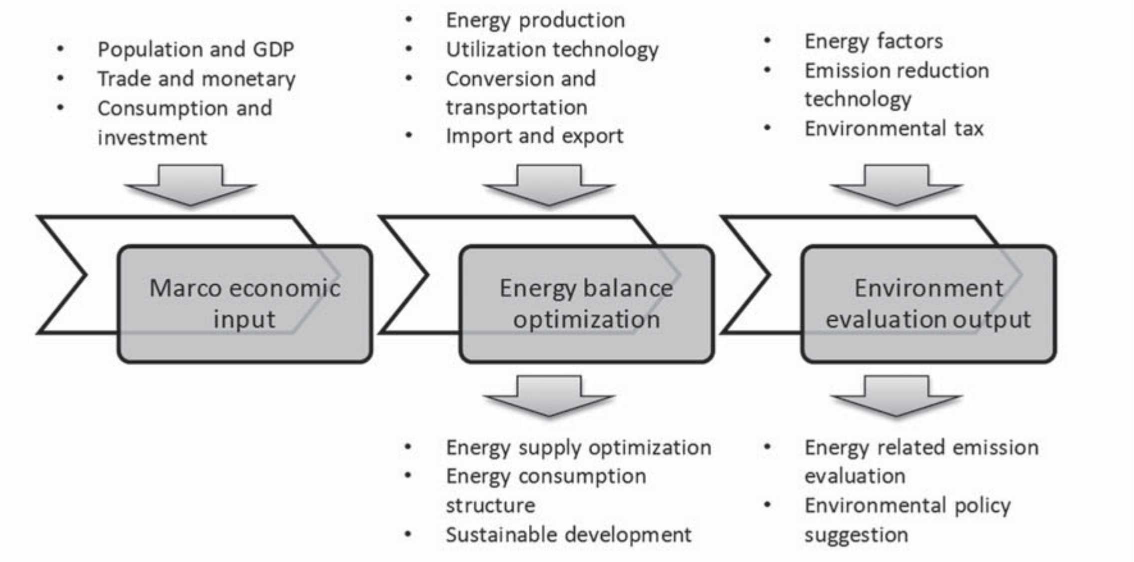


Figure 1: Flow chart of G-CEEP model

G-CEEP model mainly consists of three sub-models: the macroeconomic input sub-model, energy balance sub-model and environmental evaluation output sub-model. The objective of the model is to maximize the discounted consumption. The output production is indicated as the sum of consumption, investment and energy cost. The investment is determined by the initial investment and the annual growth rate. The relationship of the production, capital stock, labor, electricity and non-electricity are carried out by the two-level CES production function. The linkage between macroeconomic input sub-model and energy balance sub-model are energy demand, namely electric energy demand and non-electric energy demand. In addition to energy demand, energy cost in the macroeconomic input also comes from energy balance sub-model. The key constraint in the energy balance sub-model is the demand and supply balance. Also, the depletion fossil fuels, such as coal, oil, natural gas and the annual available renewable energy are considered as strictly constraints. The environmental evaluation output is to calculate the emissions of CO_2, SO_2 and NO_x under specific scenarios. Details are shown in figure 1.

Ⅳ. Macroeconomic and technological assumption

G-CEEP model bases on a series database related to macroeconomic assumptions, energy production and technologies, and environmental data with respect to emissions. The energy data of initial year comes from IEA (2011a) and IEA (2011b), and greenhouse gas emission factors are estimated from IEA (2011c).

The population and GDP data are adopted from the B2 scenario of Special Report on Emissions Scenarios (IPCC, 2001). SRES was a report prepared by the IPCC for the Third Assessment Report (TAR) in 2001. There are mainly 4 different families of scenarios, each making different assumptions for future greenhouse gas pollution, land-use and other driving forces. The B2 scenarios are of a world more divided, but more ecologically friendly. The population is continuously increasing, but at a slower rate than in A2, and will reach 10 billion by 2100 in B2 scenario. To evaluate local environmental sustainability under regionalization, this model assumes that population and GDP base on B2 scenario of SRES. All data are shown in figure 2.

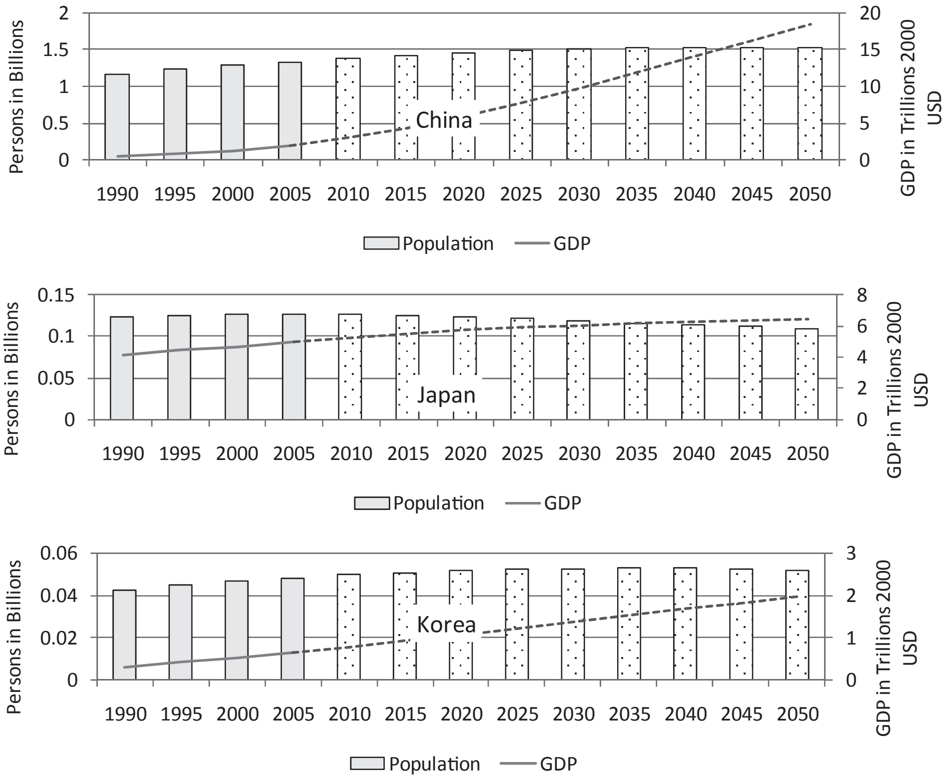
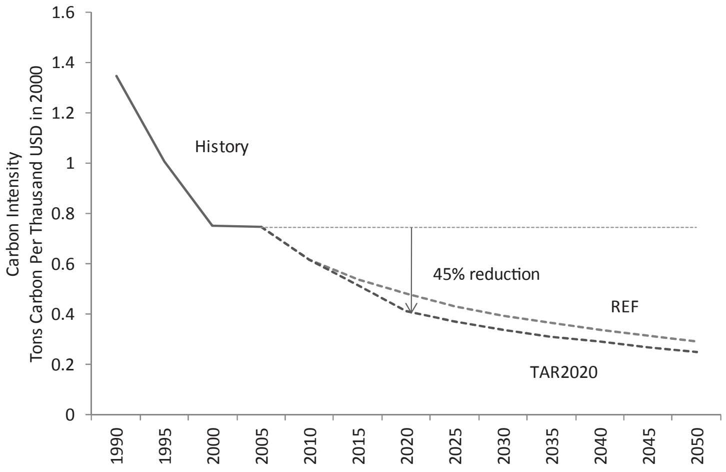
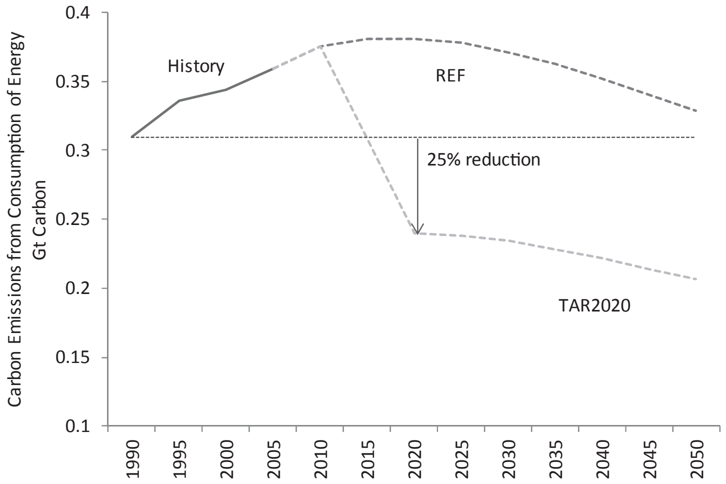


Figure 2: Population and GDP assumptions

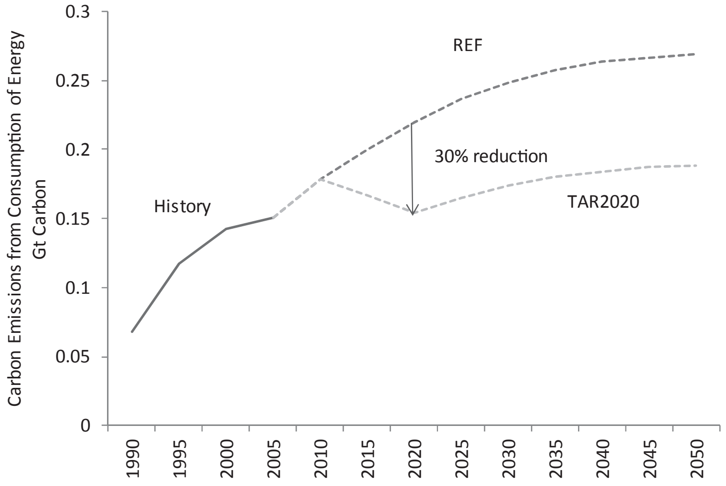
The carbon reduction targets stem from COP 15, which are defined as: China reduces the intensity of carbon emissions per unit of GDP in 2020 by 45% compared with the level of 2005; Japan slashes carbon emissions in 2020 by 25% under the level of 1990 and Korea cuts 30% base on the reference level. Although the bases of the carbon reduction targets are different for China, Japan and Korea, they are the targets to be achieved by 2020. All targets are shown in figure 3(a), 3(b) and 3(c). The emission constraints from 2010 to 2020 are defined as linear between the year of 2010 and 2020, and after 2020, adopt a homology proportion as in 2020 against reference scenario.



(a) China



(b) Japan



(c) Korea

Figure 3: Policy constraints on carbon emissions

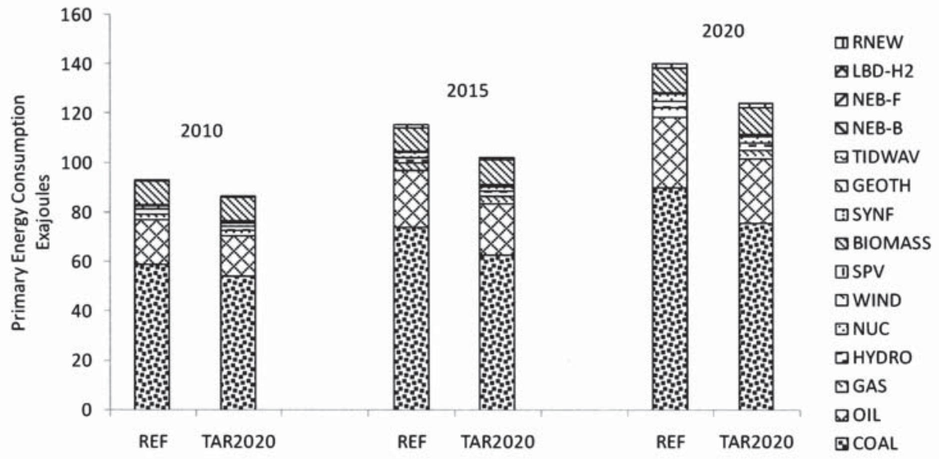
Ⅴ. Results and discussion

According to the population and GDP development assumptions illustrated in section IV, firstly, the reference (REF) scenario is generated, which bases B2 scenario in SRES (IPCC, 2001). Because the emission reduction target in 2020 of Korea bases on the REF scenario, this study defines the carbon emission constraint of Korea subjecting to REF scenario with reduced carbon emission. The carbon emission constraints of China and Japan are defined according to the history data. Thus, the target scenario (TAR2020) is generated.

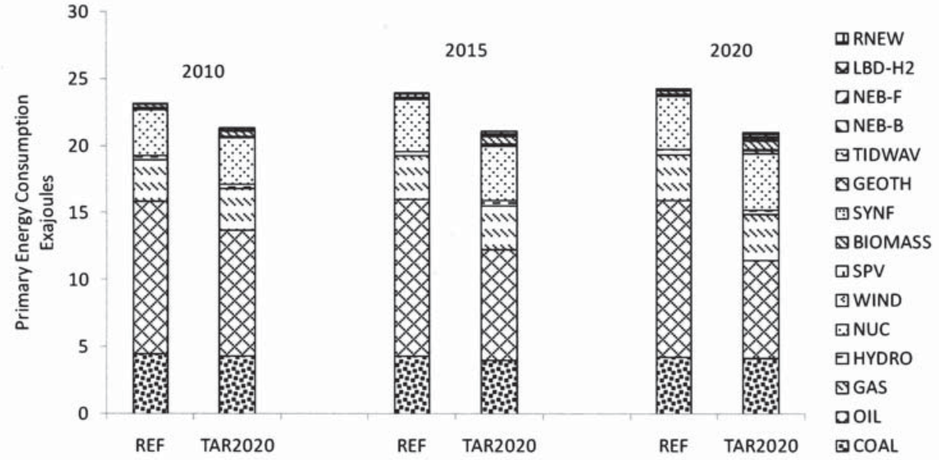
1. Primary energy consumption

The primary energy consumption of REF and TAR2020 scenarios are given by figure 4(a), 4(b) and 4(c). Total primary energy consumption in REF scenario will reach 140.4, 24.2, 13.1 exajoules for China, Japan and Korea, respectively, in 2020. The results here are close to the projection of EIA (2011). Coal is still the most important fuel for China, which will account for 64.1% in 2020 in REF scenario. Oil and natural gas will take 20.6% and 2.6% in 2020 in REF scenario. Despite China is attempting to increase nuclear energy in future, because of the relatively small installed capacity of nuclear power currently, its share in total primary energy consumption will be 2.1% in 2020 in REF scenario. In addition, hydro and other renewable energy consumption will take a share of 10.6% in 2020 in REF scenario. The primary energy consumption will not change a lot for Japan in the REF scenario, because of its relatively low economic growth rate. The share of coal, oil and natural gas will be 17.2%, 48.4% and 14.2%, respectively, in total primary energy consumption by 2020. The nuclear will account for 16.4% with 3.97 exajoules in 2020. Hydro and other renewable energy will take about 3.8% in 2020. The total primary energy consumption of Korea will increase by 23.4% from 2010 to 2020 in the REF scenario and the coal, oil and natural gas will share 23.6%, 46.3% and 13.4%, respectively in 2020. Nuclear power will account for 14.9% and hydro and other renewable energy take about 1.6% in total primary energy consumption in 2020.

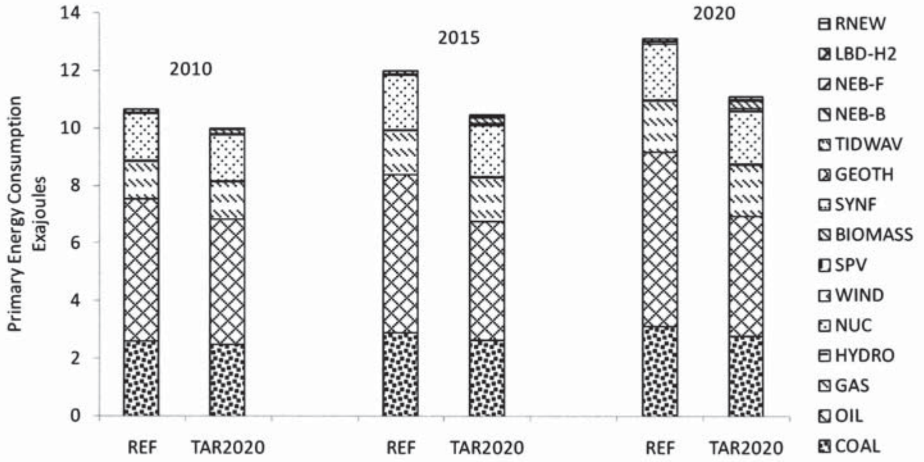
As to the reduction of carbon emissions, high carbon intensive fuels are switched to low carbon intensive fuels or carbon free fuels. For the case of China, in 2020, coal consumption in China will decrease from 64.1% in the REF scenario to 60.9% in the TAR2020 scenario. Oil will increase from 20.6% in REF scenario to 21.0% in the TAR2020 scenario. Natural gas will increase from 2.6% in REF scenario to 2.9% in the TAR2020 scenario. Nuclear will shift from 2.0% in REF scenario to 2.1% in the TAR2020 scenario. Hydro and renewable energy will shift from 10.6% in REF scenario to 12.7% in TAR2020 scenario. For Japan, energy sources are apt to shift to cleaner fossil fuel (natural gas) or renewable energy due to widely use of various emission abatement technologies. Coal consumption in Japan will decrease from 4.16 exajoules in the REF scenario to 4.12 exajoules in the TAR2020 scenario. Oil will decrease from 48.4% in REF scenario to 34.7% in the TAR2020 scenario. Natural gas will increase from 14.2% in REF scenario to 16.4% in the TAR2020 scenario. Nuclear will shift from 16.4% in REF scenario to 20.1% in the TAR2020 scenario. Hydro and renewable energy will shift from 3.8% in REF scenario to 7.9% in TAR2020 scenario. Coal consumption in Korea will decrease from 3.10 exajoules in the REF scenario to 2.75 exajoules in the TAR2020 scenario. Oil will decrease from 46.3% in REF scenario to 37.8% in the TAR2020 scenario. Natural gas will increase from 13.4% in REF scenario to 15.8% in the TAR2020 scenario. Nuclear will shift from 14.9% in REF scenario to 16.4% in TAR2020 scenario. Hydro and renewable energy will shift from 1.6% in REF scenario to 4.4% in TAR2020 scenario.



(a) China



(b) Japan



(c) Korea

Figure 4: Primary energy consumption of China, Japan and Korea

2. Scenario study of carbon, SO_2 and NO_X emissions

Carbon, SO_2 and NO_X emissions with respect to energy consumption in 2020 are shown in figure 5. For China, it planned to reduce the intensity of carbon emission per unit of GDP in 2020 by 45% compared with the level of 2005. If compared with the reference scenario in 2020, carbon emission will be reduced by 14.7% in the TAR2020 scenario. At the same time, the SO_2 will benefit from the carbon reduction effort, which will be cut by 15.1% from REF scenario. NO_x will be reduced by 13.3% compared with REF in the TAR2020 scenario. As to Japan, carbon emission will be reduced by 37.0% compared with REF in the TAR2020. But the SO_2 emission will be reduced by only 5.0% compared with REF in the TAR2020 due to widely use of desulphurization technologies and industrial processes, namely with high removal rate. NO_x will be reduced by 26.32%, which means the carbon reduction policy will have relatively large co-benefit effect on NO_x reduction in Japan. The carbon reduction target for Korea in 2020 is reducing 30% carbon emission compared with REF scenario. Achieving this emission target, the SO_2 emission will be reduced by 27.5% and NO_x will be reduced by 21.3% compared with REF scenario.

The carbon reduction effort will not only reduce carbon emissions, but also reduce SO_2 and NO_x as well. Because the emission sources usually are fossil fuels, although emission volume varies with different fossil fuels, by consuming the same unit of heat value. SO_2 usually comes from the consumption of variety of coal products, including both coal products as energy source and as non-energy source, like derived coal, coke. The consumption of variety of oil products also emits SO_2 and it is the second major SO_2 emission source. A small amount of SO_2 comes from the consumption of natural gas and biomass. NO_x mainly comes from the consumption of oil products, especially gasoline and other light fractions of oil, medium distillates (diesel, light fuel oil) and heavy fuel oil. The consumption of coal and natural gas releases a small amount of NO_x. This cannot be ignored if the consumption volume of energy is large, like the case in China, of which coal is a major energy source.

Since the reduction effort of carbon emissions will result in saving energy, switching among fossil fuels, switching from fossil fuels to renewable, less- or non- emission energy such as nuclear, wind, solar, biomass, etc. The effort will also reduce SO_2 and NO_x emissions due to similar energy sources. Co-benefit effects of carbon reduction vary from different countries because of different energy consumption structures and different existing removal rate. If the existing removal rate is low, the carbon abatement effort will have larger reduction effects on SO_2 and NO_x, as the case of China and Korea. Otherwise, the co-benefit effects become less, as the co-benefit reduction of SO_2 in Japan. The existing removal rate of SO_2 is relatively high in Japan and carbon reduction has limited impact on the SO_2 emission in Japan.

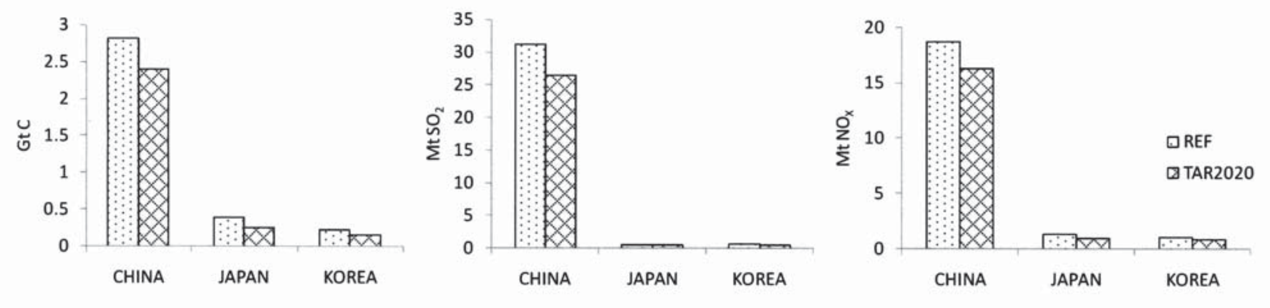


Figure 5: Scenarios of carbon, SO_2 and NO_X emissions in 2020

3. Marginal abatement cost

Marginal abatement cost reflects the cost of one additional unit of carbon emission that is abated. To plot the marginal abatement cost curve, this study introduces progressively higher carbon taxes from 0 to 200 USD/tC and records the quantity of reduced carbon emissions. The reduced emissions of SO_2 and NO_x are also recorded so as to analyze the co-benefit effects of carbon taxes. Marginal abatement cost of carbon emission reduction and co-benefit effects for SO_2 and NO_X are shown in figure 6.

According to the results, the carbon emission in China mainly comes from the consumption of coal, which accounts for 60.9% in 2020 of the REF scenario. For reducing carbon emission, coal consumption will decrease as the carbon taxes increase from 0 USD/tC to 160 USD/tC in China. If carbon taxes go on increasing, then new low-carbon technology of coal consumption will be introduced, e.g. more pulverized coal power plants will be built since the carbon emission rate of pulverized coal power is 0.20 kg-C/kWh, lower than the existing coal power 0.28 kg-C/kWh, although the generating cost for pulverized coal power is 40 mills/kWh, far higher than existing coal power generating cost, 20.3 mills/kWh. This makes the carbon abatement become easier, if carbon taxes are above 160 USD/tC but this will not affect the abated amount of SO_2 much, SO_2 emission even increases to a certain extent because of expansion of coal consumption. The NO_x emissions in China are manly from coal consumption, especially the hard coal. In addition, oil products are also a large source of NO_x emissions. Thus the carbon abatement effort will also have critical effect on the NO_x abatement in China. Carbon taxes also have co-benefit effects on the SO_2 and NO_x abatement in Japan. But the SO_2 abatement will not benefit as much as the abatement of NO_x from carbon taxes due to existing desulfuration technologies or related industry processes are widely used in Japan. This result is consistent with the result derived from COP 15 previously. Also, coal consumption will only account for 17.2% in total primary energy consumption in 2020 of REF scenario and the change in coal consumption will not be as significant as the case of China. For Korea, carbon taxes have similar effect on the carbon, SO_2 and NO_x abatement which means that similar percentage of emissions will be abated by imposing carbon taxes.

To sum up, carbon taxes not only play an important role in reducing carbon emissions, but also reduce SO_2 and NO_x as well because of deriving from the same energy sources. The co-benefit effects vary from different energy consumption structures, the switching among fossil fuels or to non-fossil fuels, energy technologies, etc. The increased carbon taxes make new energy technology be introduced and this may have different effects on the carbon, SO_2 and NO_x abatements. Existing emissions with high removal rate will be less effected by the carbon taxes. In this case, to further reduce this kind of emission, relying on the abatement technology itself will be a feasible way, besides benefitting from other emissions' abatement efforts.

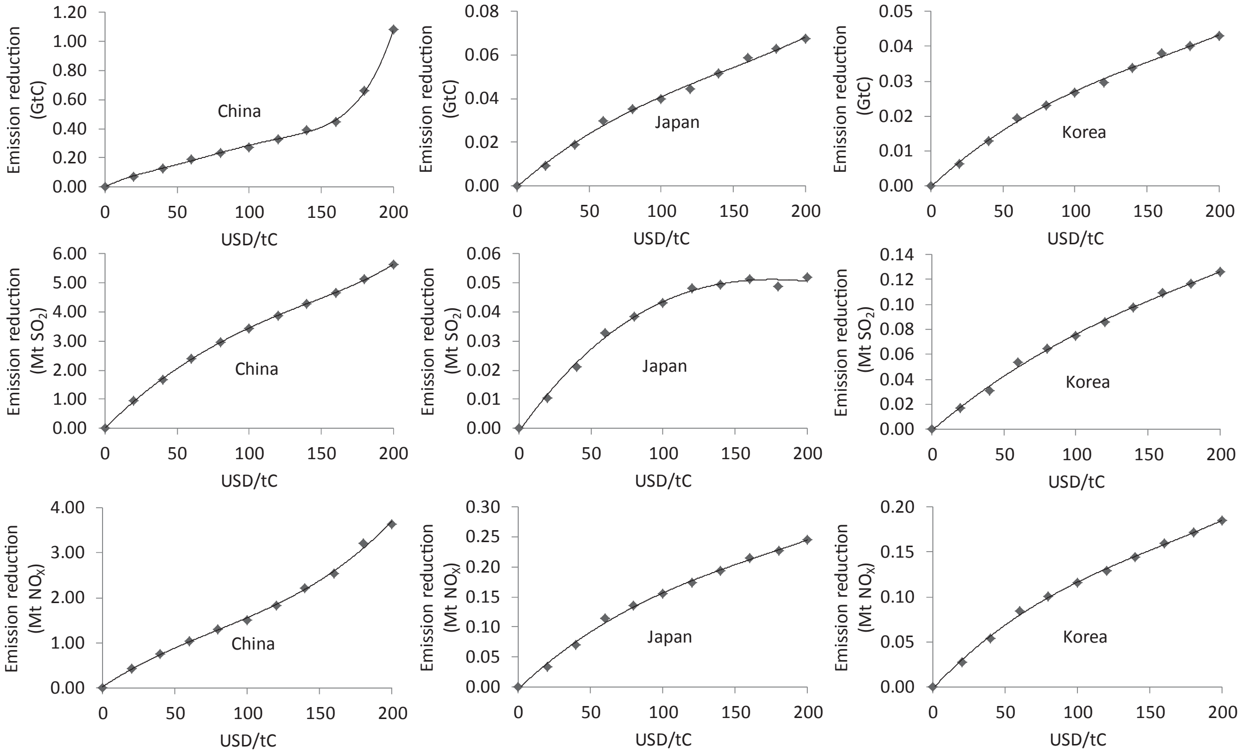


Figure 6: Marginal abatement cost of carbon emission reduction and co-benefit effects for SO_2 and NO_x (2020)

Ⅵ. Conclusions

In this study, a model named G-CEEP is built, to provide an approach to analyze possible energy consumption structures in future, co-benefit effects of carbon abatement strategies on SO_2 and NO_x emissions, roadmap to implement carbon emission target etc., to put forward corresponding suggestion and policy for policymakers.

Two scenarios are carried out in this study: reference scenario and carbon reduction target scenario deriving from COP 15. The primary energy consumption structures, emissions of carbon, SO_2 and NO_x are determined with respect to the two scenarios, for China, Japan and Korea, respectively. The results show that, coal is still the most important fuel for China, which will account for 64.1% in 2020 in REF scenario and will decease to 60.9% in the TAR2020 scenario. Hydro and renewable energy will shift from 10.6% in REF scenario to 12.7% in TAR2020 scenario. The primary energy consumption has little change for Japan in the REF scenario due to its relatively low economic growth rate. The share of coal, oil and natural gas will take 17.2%, 48.4% and 14.2%, respectively, in total primary energy consumption by 2020, and will shift to 19.7%, 34.7% and 16.4%, respectively, in the TAR2020. The total primary energy consumption of Korea will increase by 23.4% from 2010 to 2020 in the REF scenario and the coal, oil and natural gas will share 23.6%, 46.3% and 13.4%, respectively, in 2020.

This study provides an analysis of co-benefit effects under carbon abatement strategies. Co-benefit effects vary from country to country because of different energy structures and different existing removal rate. For China, the abatement of SO_2 and NO_x will benefit much from carbon abatement strategies because of its large consumption of fossil fuels and low removal rates of SO_2 and NO_x. The co-benefit effect becomes less if existing removal rate is high, as the co-benefit reduction of SO_2 in Japan.

According to the marginal abatement cost analysis, carbon taxes not only play an important role in reducing carbon emissions, but also contribute to SO_2 and NO_x. The co-benefit effects are determined by energy consumption structures, the switching among fossil fuels or to non-fossil fuels, energy technologies, etc. When carbon tax reaches to a certain level, it will make new energy technology be introduced and thus has different effects on the carbon, SO_2 and NO_x abatement. Existing emissions with high removal rate will be less effected by carbon taxes. In this case, we need to seek to related abatement technologies and measures with respect to the emissions, to further reduce the emissions.

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