China's CO_2 Emission Peaking and Leakage

-- A Decomposition for Direct and Indirect Carbon Leakage

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Abstract

China pledge to peak its CO_2 emission by 2030. With a GTAP-E based dynamic CGE model, we analyzed its domestic and global implication. Results indicated that China need a 12% yearly growth of carbon price to meet the target, which will lead to 10% of carbon leakage. With reference to GVC literature, we managed to decompose and trace the path of leakage and identify its driving forces.

From a demand perspective, India, US and South Africa consume have increases in their CO_2 demand while world total (other than China) decreases by 2%. From a production perspective, substitution and relocation effect lead to a 22% of carbon leakage, among which developed regions plus India are the main contributor. Autonomous adjustment in global trade flow mitigate half of this effect.

In a "post Kyoto era", developing economies' participation in GHG mitigation will complicate the transmission of carbon leakage through horizontal (to other developing countries) and vertical leakage (to developed countries). This paper integrated CGE model with carbon flow analysis, and enables us to quantify the driving forces of leakage on a bilateral level, and provides us with an in-depth perspective to understand the global effect of climate policies.

Key words

Carbon leakage, China emission peaking, dynamic CGE, global value chain, decomposition

1. Introduction

Noticing its responsibility for being one of the world's largest economies and greatest emitters of greenhouse gases (GHG) in the global effort against climate change, China has pledged its intension to achieve the peaking of CO_2 emissions around 2030 and to make best efforts to peak early. The announcement covered about a third (29.3%, EDGAR 2014[1]) of the global CO_2 emission from China to date, and it's the first time that China has agreed to set a ceiling, albeit an undefined one, on overall emissions. Previously China had only ever pledged to reduce the rapid rate of growth in its emissions. Although the exact emission cap of China and its reaching path, as well as its implementation process remain unknown, we have more than good reasons to expect significant impact on both domestic and global GHG emission and economy.

Domestically, China is striving to push forward industrialization of its economy to lift more people from poverty, which raises both the intensity and rigidity in energy demand, and in the growth of CO_2 embodied in consumption as well. Capping total emission on the other hand, would thus have significant impact on production costs and industrial structure. Eyes up from domestic economy, China is gaining its influence on international markets since its opening-up policy in 1990s, and is by all means a key link in global industrial chain with its massive and growing export nowadays. In recent years, China is pushing up its exports toward upper-ends along global industrial chains, which tightens the economic linkage between China and developed economies, while in the meantime, the competition in lower-end products intensifies with growing producing capacity in other developing economies. From this perspective, tightening emission targets in China would lead to change in domestic emission and production not only domestically, but also globally, and cause carbon leakage across borders.

Carbon Leakage Effect addresses the situation that, given the global nature of GHG emission, if only one group of countries commits to abate their emissions, the effect of their efforts can be partially offset by increased emission in other countries, and thus lowers the efficiency of climate policies (Monjona and Quirion, 2011). Currently, carbon leakage is mainly referred to from the perspectives of developed economies (Annex 1 countries in Kyoto Protocol), since they are the ones obliged, according to the Kyoto Protocol, to take stringent unilateral climate mitigation policies. But now China also joined this group with its pledge on emission peaking. Estimation (see section 3 of this paper) indicated that in order to peak its CO_2 emission in China by 2030, the corresponding cost (in the sense of marginal abatement cost, MAC) would increase rapidly in the following 15 years to a level much higher than current carbon price/carbon tax rate in developed economies. Considering the significance of Chinese share in both global total CO_2 emission and economic production, as well as its integration in international market, the leakage effect of Chinese climate policy deserves studying in-depth.

It's noteworthy that China, as a developing economy, is highly differentiated from developed economies in its economic structure, which can alter the path of carbon leakage. On one hand, China is a heavy exporter of low-end products which are exposed to intensive competition of substitutable products from other developing economies. And thus, tightening emission target in China would deteriorate the competitiveness of Chinese products, and lead to horizontal carbon leakage from China to other developing countries. On the other hand, as the fastest growing

[1] http://edgar.jrc.ec.europa.eu/

developing economy, China is adopting industries transferred from developed economies and exports products back. Higher producing costs would lead to reversal relocation of corresponding industries, and cause vertical carbon leakage to developed countries. The coexisting horizontal and vertical leakage path interconnected with each other by international trade flow in a net-structure. Carbon emission may be directly leaked to a country, and indirectly through trade from a third, or more countries. Comparatively, the carbon leakage from developed economies are more likely in a radiative-structure with one-directed leakage from developed countries to less developed countries.

At the approaching of the Paris Climate Summit in 2015, China have shown its will in constraining GHG emission in the following decades. But the story is not about China alone: in "post Kyoto era", some of the developing economies will be participated in global climate mitigation, and their participation will significantly complicates the pattern of international carbon flow. But unfortunately its impact on international market and global CO_2 emission haven't been studied in-depth. From this perspective, China's emission peaking has raised new questions for carbon-leakage related research. It's important to trace the path of carbon leakage by analyzing carbon emissions embodied in international trade, and decomposing the direct and indirect leakage enables us to shed light on the driving forces behind the net of carbon flow and leakage. Take China as an example, we hope that our study could unveil the paths of international carbon flow and leakage, and narrow the gap in understandings on the demand of a universe climate change mitigation arrangements.

In this paper, we establish a global CGE model to simulate the implication of China's emission peaking on domestic and global economic performances, as well as carbon emission. On that basis, we calculate both direct CO_2 emission and the emission embodied in final consumption as well as international trade. With reference to Koopman et al. (2014), we further decompose the international carbon flow into direct and indirect carbon flow, and compared the decomposition results across scenarios to analyze the path of carbon leakage from China.

The paper is organized as follows: in section 2, we reviewed the literature on carbon leakage, and put forward our contribution. In section 3 we establish a GTAP based dynamic CGE model to analyze the implication of China's emission peaking in 2030 on economic performances and CO_2 emission. According to the simulation results of the CGE model, we establish and decompose the international carbon flow matrix in section 4. We analyze and discuss the results in section 5, and conclude in section 5.

2. Literature Review

Carbon Leakage Effect has been studied and assessed extensively since 1990s (for early references, cf. Hoel, 1992; Felder and Rutherford, 1993; Carraro & Siniscalco, 1993; for recent surveys, cf. Gerlagh and Kuik, 2007; Droege et al., 2009; etc.) Three main channels of carbon leakage have been identified in the literature (Reinaud, 2008):

- Eenergy price leakage channel – emission reduction policies decrease domestic energy demand which may lower energy prices in international markets; hence they increase energy consumption in other regions without or with less stringent climate policies.

- International trade channel – climate policies increase producing cost of domestic producers. Assuming that international market prices are not affected, deteriorated trade conditions would lead to lower production, exportation and higher import. Both decreased exportation and increased importation would stimulate production in foreign countries, and lead to higher emission.
- Industrial transfer channel – if producers cannot fully pass through cost change to international market, higher producing costs erode producers' profitability. With international mobility of capital, some producers may choose to relocate their production to countries without climate policy, and the relocation would also cause production, as well as emission increase.

The estimation for leakage ratio ranges considerably from 2% to 130% (Droege et al., 2009), varying with respect to assumptions on preference structure for imported commodities, elasticity of substitution between energy and non-energy inputs, possibility of cross-border commodity and capital flow (Babiker, 2001), etc. Some other researches have been devoted to analyze the driving forces of carbon leakage by decompose the total leakage effect into different factors. Using the well-known Kaya identity, change in total emission can be disentangled into changes in production scale, energy intensity and carbon intensity of energy. On that basis, Kuik and Gerlagh (2003) present a decomposition procedure to attribute emission reduction to changes in economic scale and producing technology. Both these assessment and decomposition were mainly focused on direct leakage, i.e. the change in physical GHG emission, while few were devoted to analyze the emission embodied in final demand. Bollen et al. (2000) split up CO_2 emission embodied in domestic final demand and net exports, and concluded that most leakage was implicitly used for final demand in Annex 1 regions. While research by Aldy and Pizer (2009) indicated the opposite. They concluded that decrease in domestic consumption contributed the major part of emission reduction while leakage due to international trade adjustments was only trivial. Bollen et al. (2000) was one of the early attempts to find the driving forces behind emission leakage by comparing and linking production based and consumption based accounting of carbon emission. However, simply account the total carbon emission embodied in exportation provides limited insights into the actual source of emission, since it includes both emissions from domestic production and emissions embodied in imports. In a highly integrated global market, intermediates are dominating in both volume and value in international trade, so that it would lead to severe double-counting problem. Without well-developed database and methodology to integrate international trade on bilateral level and embodied emission flows into a unified conceptual framework, it was difficult to implement more detailed analysis on the path of carbon leakage.

The emerging of the literature on Global Value Chain (GVC) provided accounting methodologies for value-added in global trade, which can be integrated with accounting for embodied carbon emission. Koopman et al. (2014) and Wang et al. (2014) proposed a framework for decomposing trade flows into various value-added components by source and additional double counted terms at the sector, bilateral, or bilateral sector level. On that basis, Meng et al. (2014) combined value-added and emissions accounting in a consistent way, and estimated the potential environmental cost (emission with per unit of value-added created) along GVCs. Based on this unified accounting method, they traced CO_2 emission in global production and trade network among 41 economies in 35 sectors from 1995 to 2009 based on the World Input-Output

Database (WIOD) database. With reference to their work, we can use the accounting methodology to trace the source of CO_2 emission embodied in bilateral international trade, and thus trace the detailed path of carbon leakage.

3. The CGE Model

The recursive dynamic global CGE model used in this paper is developed on the basis of GTAP-E model. We replicate and modify the GTAP-E model in the General Algebraic Modeling System (GAMS) with reference to the GTAPinGAMS Package V5.4 (Rutherford, 2005).

The model includes all the 57 GTAP commodities and industries; the total 129 regions are aggregated into 9, including 5 developing economies, namely China (CHN), India (IND), Russia (RUS), Brazil (BRZ) and South Africa (ZAF); 3 developed economies, namely United States of America (USA), European Union Countries (EUN), East Asia developed countries (ASD); and one Rest-of-the-World (ROW) region. The model is calibrated with GTAP database (version 8) for the base year, 2007, and was solved recursively onwards to 2030. Statistics on global and regional economic growth, CO_2 emission during 2007 -2013 were used to calibrate the dynamic growth path.

3.1 Modifications of GTAP-E Model

Modifications of the GTAP-E model is made in nesting structure of CES production functions, capital accumulation, fossil fuel reserve and supply and energy technology improvements.

(1) Nesting structure of CES production function

Producing technology is specified by nested CES (Constant Elasticity of Substitution) function according to GTAP-E model with a KLEM nesting structure, where labor (D), land (L), capital (K) and natural resource (R) compose the value-added nest ($DKLR$), and is then nested with energy composition ($ECOMP$) which is composed by different energy product. The value-added and energy ($DKLRE$) composition is then nested with intermediates composition (M) to produce the final product (Y). A general expression of CES functions is as follows:

$$y = A\left(\sum_i \alpha_i x_i^{-\rho}\right)^{-1/\rho};\ \sum_i \alpha_i = 1 \qquad \text{eq.1}$$

where y is final output, and x are inputs or input bundles which are further composed by inputs in lower nesting level; α is the cost share of inputs; and σ=1/(1+ρ) is elasticity of substitution between inputs.

The energy composition structure was also set according to GTAP-E model for all but two industries: electricity and transportation. According to the actual fuel mixture in electricity and transportation sector, their energy composition structures are set different from ordinary energy consuming sectors, as illustrated in fig. 1 and fig. 2 respectively.

Another important feature of the energy composition is the emerging importance of renewable energies in their fuel mixture. An extra energy input, renewable energy, is introduced respectively to catch this trend. Since there's no renewable energy or renewable energy resource in GTAP model, we refer to the RCP6 by IPCC to set the share of renewables in the fuel mixture of power generation and transportation energy structure. Their initial prices are set identical to the price of household consumption so as to implicate the environment benefits. The extra income of renewable resources is transferred to household in lump sum manner. Carbon emissions are calculated according to energy input simulated in the model and emission factors provided by GTAP-E database, by fuel type, region and sector.

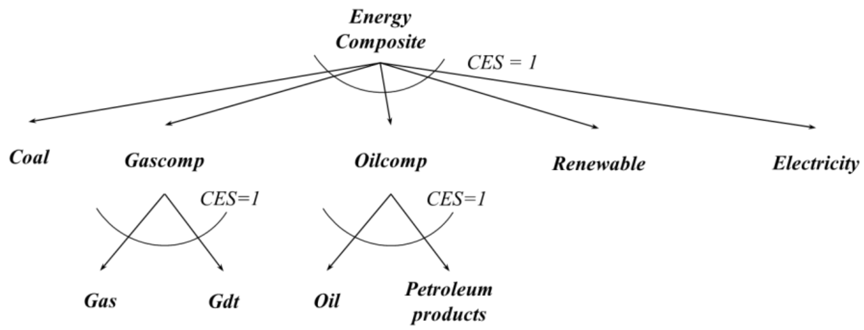

Fig. 1: Energy composite structure for electricity sector

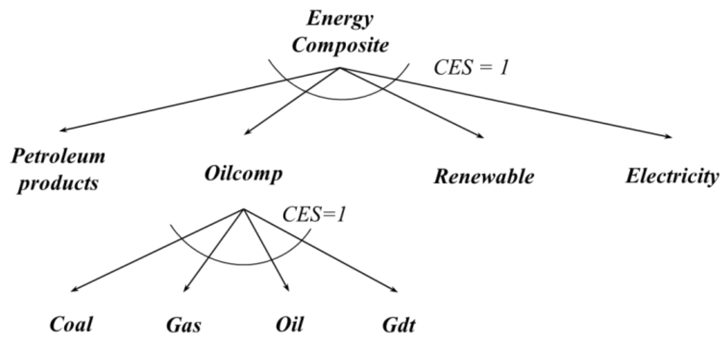

Fig. 2: Energy composite structure for transportation sector

(2) Dynamic module

The dynamic module of model specifies the capital accumulation and labor supply and natural resource supply. Capital accumulation mechanism is specified in a quasi-putty-clay manner, meaning that capital stocks are set as sunk and non-flowable while newly formed capital is flowable across regions and sectors. Industrial structure could then be changed gradually through depreciation of old capital stocks and formation of new stocks. Capital accumulation rate is linked to expected rate-of-return of investment in each sector and region, and the total investment is bounded by the total saving which is determined endogenously by a CET (Constant Elasticity of Transformation) utility function. Referring to the MONASH model (Dixon, 2002), we use the following Logit function to map expected capital rate of return to capital accumulation rate:

$$KR_i = \left(\overline{\overline{KR}}_i - \underline{\underline{KR}}_i\right) \frac{\dfrac{\overline{KR}_i - \underline{\underline{KR}}_i}{\overline{\overline{KR}}_i - \overline{KR}_i} \cdot e^{c\left(r_i^e - \overline{r}_i\right)}}{1 + \dfrac{\overline{KR}_i - \underline{\underline{KR}}_i}{\overline{\overline{KR}}_i - \overline{KR}_i} \cdot e^{c\left(r_i^e - \overline{r}_i\right)}} + \underline{\underline{KR}}_i \qquad \text{eq.2}$$

where $\overline{\overline{KR}}$ and $\underline{\underline{KR}}$ stand for the upper- and lower-limit of capital accumulation; $\overline{KR}$ and $\bar{r}$ are the average level of capital accumulation and rate-of-return; e is the base of the natural logarithm.

The growth rate of population is recalculated from a World Bank's report, World Population Ageing: 1950-2050, as shown in table 1.

Table 1: Labor endowment growth rate. Unit: %

	2005-2025	2025-2030	2030-2045	2045-2050
CHN	0.5	0.2	0.0	-0.3
USA	0.8	0.7	0.5	0.5
EUN	-0.3	-0.4	-0.5	-0.6
BRA	1.0	0.7	0.5	0.3
RUS	-0.6	-0.7	-0.7	-0.8
IND	1.1	0.8	0.6	0.4
ZAF	-0.1	0.1	0.3	0.5
ASD	0.0	-0.2	-0.4	-0.5
ROW	1.1	0.8	0.6	0.5

Natural resource reserves are another important endowment input in CGE model. Primary energies such as crude oil, gas and coal are all produced by natural resources. However, these kinds of natural resources are exhaustible, so dynamic input in production structure will not be stable, natural resources share in the production of primary energy will decrease over time. We use Reserves-to-Production (R/P) ratio from BP World Energy Statistics to predict exogenous natural resource endowment path with assumption on growth in resource exploration and extraction rate according to *World Energy Outlook 2012* (Refer to Appendix 1 for detail).

(3) Autonomous energy technology improvements

Energy technology improvements are represented by autonomously energy efficiency improvements, emission factor decrease, raising in the share of less carbon-intensive and renewable energy in the fuel mixture of electricity generation and transportation sector, etc. And these technology factors are set according to the RCP6 scenario by IPCC. Please refer to Appendix 1 for detail.

3.2 Simulation for China's 2030 Emission Peaking

Although China announced its target to achieve the peaking of CO_2 emissions around 2030, basic information for analysis like the peaking emission level, and the emission path to reach the peak was left undefined. With our CGE model, our first intension in this paper is to find out the emission reduction path that satisfies the target of peaking in 2030, and detect its implication on domestic and global economic performances, as well as global CO_2 emission.

(1) Climate policy scenarios

Carbon/energy tax and emission cap-and-trading are two of the most prevailing climate policy schemes. It's noteworthy that in a market with perfect information (no uncertainty), carbon tax and emission trading have identical effect where each producer has the same MAC (with carbon tax, MAC=tax rate; with emission trading, MAC=carbon price). For simplification and comparability, we use only carbon tax to model climate policies in the model. Differentiated regional carbon tax rates indicate different stringency, and thus emission reduction costs in each region. Denominate carbon tax rate as τ (USD/tCO_2), the actual carbon tax expenditure T^C of a producer is:

$$T^{C}_{r,i} = \tau^{r,t}_{i} \sum_{E} x^{r,t}_{Ei} ef^{r}_{Ei} \qquad \text{eq.3}$$

where x_E is the quantity of energy E input in production; ef is the emission factor; suffix r and i indicates region and sector.

Current carbon tax rate and carbon price in regional ETS are used to set BAU regional carbon policy. China has established 7 pilot emission trading project in 7 cities and provinces since 2011, including Beijing, Shanghai, Guangzhou, Tianjin, Shenzhen, Hubei and Chongqing. The emission targets are set according to their provincial target assigned in the 12^{th} Five-Year-Plan (FYP) of China. The 7 piloting cities covers samples for high, mid and low income regions, including agricultural, industrial and service oriented economic structure. So the average price of these pilot projects can be used to reflect the general abatement costs under current emission reduction target. From this perspective, we use the monthly average price of Dec. 2013 in the seven pilot projects to calculate the average carbon price for China, weighted with monthly trade volumes. Carbon tax is set as 8 EUR for EU region, with reference to the average carbon price of EU-ETS in 2013; and that for US is set as 15 USD according to the carbon price in California Carbon Emission Trading Market. Carbon tax rates for other regions are set according to their actual carbon policy. Carbon taxes are assumed to be levied since 2015 for all the regions. Table 2 lists the detail.

Table 2: Carbon Price in BAU Scenario. Unit: USD/tCO_2

Region	Carbon Tax Rate (BAU Scenario)
CHN	32.2 (RMB Yuan)/6.1 = 5.278
IND	15 USD
RUS	/
BRA	/
ZAF	120 (Rand)/11 = 10.9
USA	15
EUN	8 (EUR)/0.82
ASD	2
ROW	/

(2) Economic implication of 2030 emission peaking for China

Using the carbon tax rate in table 2, we can solve the BAU scenario with our CGE model recursively. The simulation results indicate clearly that the current carbon policy is far from sufficient to reach the target of emission peaking in 2030 for China. As fig 3 shows, in BAU scenario, CO_2 emission of China in 2030 will be 10.7 billion ton, which 60% higher than 2014. It will be 3.86% lower than No-Carbon-Tax (NULL) scenario, but no sign of convergence in the growth of emission.

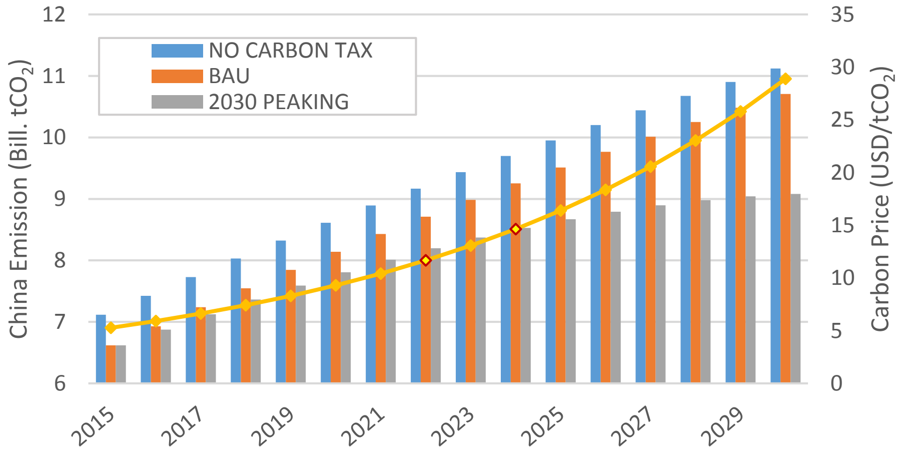

Fig. 3: CO2 Emission Trajectory in China

In order to peak its CO_2 emission in 2030, China needs higher carbon price. Assuming a fixed yearly growth rate of carbon price, we can test for the corresponding trajectory of carbon price increase. Model simulation indicated that a 12% yearly increase in carbon price is required for 2030 emission peaking, and that will lead to a 9.08 bill. ton of CO_2 emission in China in 2030, which is 37% higher than 2014. There're two time points to be noticed in this scenario, 2022 and 2024, when China surpass EU and US successively in carbon price, and without policy adjustment, Chinese carbon price will be the highest after mid-2020s.

Soaring abatement cost dampens economic growth in China. In 2030 PEAKING scenario, yearly growth rate of total output during 2015~2030 is decreased by 0.083%, which lead to an economic loss in 2030 of 2.46% in 2014 GDP.

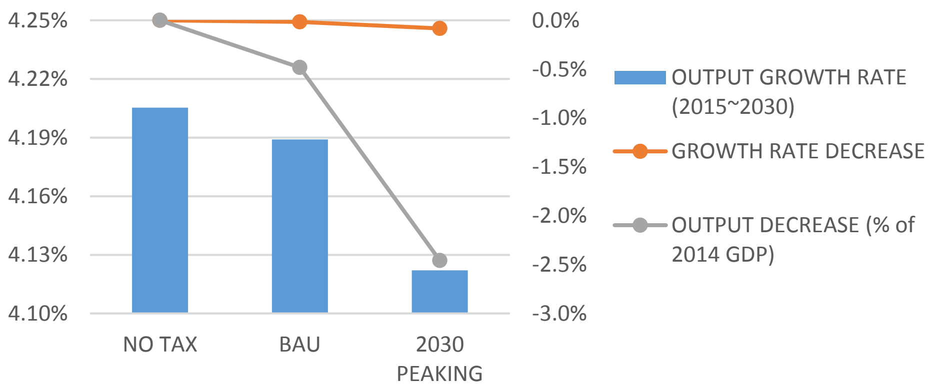

Fig. 4: Impact of Climate Policies on Economic Output (2015~2030)

More stringent climate policy also deteriorate competitiveness of Chinese products in international markets. Model simulation indicated that in 2030 peaking scenario, higher producing cost would lead to 1.93% decrease in exportation in 2030. Although import also decreased by 1.04% due to dampened domestic demand, trade surplus will be decreased by 5.94% in 2030 (as shown in fig. 5).

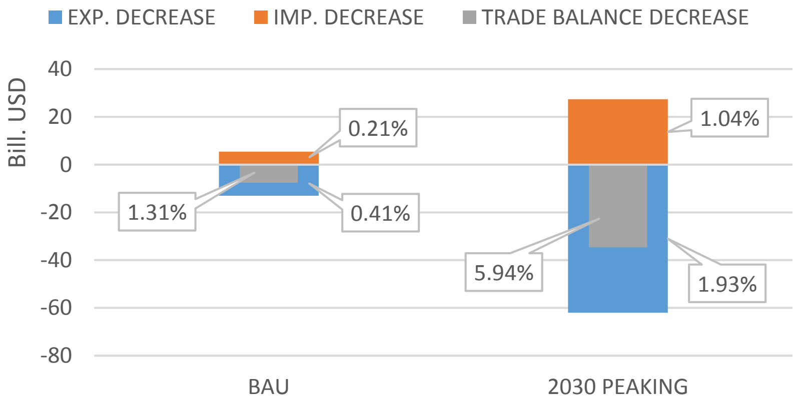

Fig. 5: Impact of climate policy on Chinese International Trade

In an integrated global market, decreased exportation from China is to some extent substituted by increased exportation from competing producers in other regions, and lead to carbon leakage. Detailed analysis of carbon leakage can be found in the following section, but here we simply compare the regional emission under different policy scenario to grab a general idea of the magnitude of leakage effect. Leakage rate is defined as emission increase in regions other than China compared to NULL scenario, divided by the emission reduction in China, i.e.:

$$\ell_{r\neq CHN,t} = \frac{E_{r,t}^{D,peak} - E_{r,t}^{D,bau}}{E_{CHN,t}^{D,bau} - E_{CHN,t}^{D,peak}};\ \ell_{TOT,t} = \frac{\sum_{r\neq CHN}\left(E_{r,t}^{D,peak} - E_{r,t}^{D,bau}\right)}{E_{CHN,t}^{D,bau} - E_{CHN,t}^{D,peak}} \quad \text{eq. 4}$$

where $\ell_{r,t}$ and $\ell_{TOT,t}$ stands for regional and total leakage rate respectively; E^D is the direct emission, the results are list in table 3. From the table, we can see that total leakage rate increases from 13.41% in 2015 to 18.38% in 2030, while US and India are the biggest leakage destination.

Table 3: Direct Carbon Leakage Rate (2030 PEAKING vs. BAU)

	USA	EUN	ASD	IND	RUS	BRA	ZAF	RoW	TOT
2016	1.69%	0.70%	0.32%	1.92%	0.32%	0.06%	0.21%	2.61%	7.83%
2017	1.75%	0.71%	0.32%	2.00%	0.32%	0.06%	0.22%	2.64%	8.01%
2018	1.84%	0.72%	0.33%	2.10%	0.33%	0.06%	0.23%	2.69%	8.30%
2019	1.95%	0.73%	0.33%	2.22%	0.33%	0.06%	0.24%	2.75%	8.61%
2020	2.05%	0.75%	0.34%	2.32%	0.33%	0.06%	0.25%	2.82%	8.93%
2021	2.16%	0.76%	0.35%	2.42%	0.34%	0.07%	0.26%	2.88%	9.23%
2022	2.25%	0.78%	0.36%	2.51%	0.34%	0.07%	0.27%	2.93%	9.50%
2023	2.35%	0.79%	0.37%	2.59%	0.34%	0.07%	0.28%	2.98%	9.75%
2024	2.43%	0.80%	0.37%	2.65%	0.34%	0.07%	0.29%	3.02%	9.97%
2025	2.51%	0.80%	0.38%	2.70%	0.34%	0.08%	0.29%	3.05%	10.15%
2026	2.57%	0.81%	0.39%	2.74%	0.34%	0.08%	0.30%	3.08%	10.30%
2027	2.63%	0.81%	0.39%	2.76%	0.33%	0.08%	0.30%	3.11%	10.42%
2028	2.68%	0.81%	0.40%	2.77%	0.33%	0.08%	0.31%	3.13%	10.51%
2029	2.72%	0.81%	0.40%	2.78%	0.33%	0.09%	0.31%	3.14%	10.57%
2030	2.75%	0.81%	0.41%	2.77%	0.32%	0.09%	0.31%	3.15%	10.60%

4. Tracing Carbon Flow Embodied in International Trade

Trade in an integrated global market enables disentangling of production and consumption – the same idea applies for GHG emission: gas emitted in one region could be used to produce product that is consumed in another region, which could further be traded to a third region. Although international trading itself does not emit GHG gas, the emission embodied in traded commodities determines the international carbon flow. These affects are growing over time, and the net emission transfer (production minus consumption) via international trade from developing countries to developed countries increased form 0.4 Gt CO2 in 1990 to 1.6 Gt CO2 in 2008, which exceeds the Kyoto Protocol emission reductions (Peters et al., 2011). It imply that a country's direct emission from producing activity, and indirect emission embodied in final consumption is crucially subject to its position and the extent of its participation in GVC through international trade directly or indirectly (Meng et al., 2014).

In order to analyze the path and find the driving forces of carbon leakage, we'll have to trace the embodied emission in trade, and further decompose it to find its actual source and ultimate destination. This task is implemented in three steps: 1) accounting for the emission embodied in trade according to model results and draw the international carbon flow matrix; 2) decompose the carbon flow matrix to find origin and ultimate destination of emission; and 3) compare between scenarios to sort out the path of carbon leakage due to emission reduction in China, and find the driving forces behind it.

4.1 Embodied emission and carbon flow matrix

In our model, we account GHG emission from fossil energy combustion. Aside from direct consumption of fossil fuel, production would also consuming fossil fuel indirectly by consuming non-energy commodities which consumes fossil energy in their production. This indirect consumption exists for infinite rounds, and its normalized summation can be expressed by Leontief inverse (Leontief, 1936):

$$\mathbf{B} = (\mathbf{I} - \mathbf{A})^{-1} - \mathbf{I} \qquad \text{eq. 5}$$

where $\mathbf{A}$ is an $i \times j$ ($i=j$) matrix of Direct Consumption Coefficient (DCC), whose element a_{ij} indicates the amount of intermediate i (x_{ij}) directly consumed for producing one unit of output j (y_j), i.e.: $a_{ij} = x_{ij}/y_i$. $\mathbf{B}$ is the matrix for CCC, whose element b_{ij} indicates the amount of x_{ij} consumed totally for producing a unit of y_j. With the CCC matrix, we can calculate the embodied CO_2 emission coefficient of each commodity:

$$\theta_i^{r,t} = \sum_E b_{Ej}^{r,t} x_{Ej}^{r,t} ef_{Ej}^{r} \qquad \text{eq.6}$$

Then the CO_2 emission embodied in bilateral trade between region r and rr can be expressed as:

$$F_{r,rr}^{t} = \sum_i \theta_i^{r,t} X_{i,r,rr}^{t} \qquad \text{eq.7}$$

where $X_{i,r,rr}^{t}$ is the exportation or commodity i from region r to rr. Table 4 list the carbon flow matrix in different scenarios.

Table 4: Carbon flow matrix (2030) Unit: Mill. tCO2

BAU Scenario

BAU	USA	EUN	ASD	CHN	IND	RUS	BRA	ZAF	RoW	CNS
USA		74.62	29.8	41.34	8.73	3.03	8.38	1.59	194.96	2276.53
EUN	52.75	430.53	15.93	29.64	8.47	19.6	6.23	3.88	150.34	1550.04
ASD	28.82	23.19	11.93	53.22	2.52	4.67	1.33	0.94	59.76	623.69
CHN	188.91	180.07	111.9		23.53	24.71	10.86	5.77	289.66	3658
IND	17.52	26.57	4.14	10.2		1.14	1.5	1.22	55.51	664.05
RUS	3.29	23.26	4.24	8.05	0.68		0.3	0.08	22.14	290.94
BRA	2.75	3.64	0.82	3.57	0.21	0.4		0.18	7.48	112.19
ZAF	3.03	8.59	2.44	3.1	2.55	0.18	0.31		14.21	67.32
RoW	163.73	162.55	66.08	151.24	35.34	15.26	12.4	5.93	213.99	2276.17
PRD	2178.18	1334.39	562.79	4193.06	699.83	284	89.91	82.13	2094.67	

2030 PEAKING Scenario

	USA	EUN	ASD	CHN	IND	RUS	BRA	ZAF	RoW	CNS
USA		74.43	29.86	41.34	8.67	3.01	8.23	1.59	193.72	2277.64
EUN	52.64	428.59	15.94	29.53	8.45	19.47	6.2	3.86	149.68	1544.99
ASD	28.67	23.07	11.91	52.87	2.52	4.63	1.32	0.94	59.46	621.51
CHN	175.9	167.46	104.25		21.84	22.96	10.08	5.36	269	3437.43
IND	17.68	26.79	4.19	10.26		1.14	1.52	1.23	55.96	669.65
RUS	3.32	23.21	3.93	7.93	0.68		0.3	0.08	21.83	290.53
BRA	2.74	3.63	0.82	3.54	0.21	0.39		0.18	7.45	111.64
ZAF	3.09	8.57	2.46	3.16	2.36	0.18	0.31		13.91	68.47
RoW	163.86	162.95	65.04	147.31	34.99	15.17	12.42	5.92	213.79	2271.96
PRD	2190.59	1340.65	568.49	3918.35	708.71	284.85	90.22	83.34	2108.6	

The 'PRD' row is the amount of CO_2 directly emitted from domestic production ($E_r{}^D$), and the 'CNS' column is the CO_2 emission embodied in final consumption ($E_r{}^C$). The row summations give total emission embodied in domestic and external demand of each region ($E_r{}^{TOT}$), which equals corresponding column summations, i.e. the total source of CO_2 emission – either imported or domestically emitted. Cells in table 4 are colored to indicate magnitude of inter-regional carbon flow. From table 5 we can find that the carbon flows among developed regions are active (the red cells in upper-left corner of each carbon flow matrix), while the flow among developing regions other than China, as well as the carbon flow between them and developed regions are limited. China is an important chain linking the developing and developed regions, indicated by the fact that the carbon flows from (and to) China to (and from) both developed and developing regions are both relatively high.

Since Chinese carbon price is the only changed variable in each scenarios, comparing direct and embodied emission and carbon flow matrix across scenarios can reveal the path of carbon leakage due to Chinese emission reduction. Table 6 shows the comparison between scenarios, and it provides information on two aspects. Firstly, direct emission and emission embodied in final consumption of China respond to climate policy differently, which is the main driving force for carbon leakage. Secondly, the decreased exportation of emission from China due to stringent emission reduction targets are partially substituted by increase in carbon exportation from other developing regions, and the destination of these exportation are mainly developed regions (see the blue cells on the lower-left corner of each set of comparison).

Table 6: Carbon leakage (2030)

2030 PEAKING - BAU

BAU	USA	EUN	ASD	CHN	IND	RUS	BRA	ZAF	RoW	CNS
USA		-0.19	0.06	0	-0.06	-0.02	-0.15	0	-1.24	1.11
EUN	-0.11	-1.94	0.01	-0.11	-0.02	-0.13	-0.03	-0.02	-0.66	-5.05
ASD	-0.15	-0.12	-0.02	-0.35	0	-0.04	-0.01	0	-0.3	-2.18
CHN	-13.01	-12.61	-7.65		-1.69	-1.75	-0.78	-0.41	-20.66	-220.57
IND	0.16	0.22	0.05	0.06		0	0.02	0.01	0.45	5.6
RUS	0.03	-0.05	-0.31	-0.12	0		0	0	-0.31	-0.41
BRA	-0.01	-0.01	0	-0.03	0	-0.01		0	-0.03	-0.55
ZAF	0.06	-0.02	0.02	0.06	-0.19	0	0		-0.3	1.15
RoW	0.13	0.4	-1.04	-3.93	-0.35	-0.09	0.02	-0.01	-0.2	-4.21
PRD	12.41	6.26	5.7	-274.71	8.88	0.85	0.31	1.21	13.93	

Carbon flow matrix is a starting point for analyzing the path of carbon leakage, since the carbon flow accounts carbon emission both imported to and directly emitted in the exporting country, which generates the double counting problem. In order to analyze the path of carbon leakage, we need to further decompose the carbon flow matrix to identify the actual origin and ultimate destination of CO_2 emission, and thus, to link the production based direct emission and consumption based embodied emission of each region.

4.2 Decomposition of carbon flow[2]

The carbon flow matrix introduced in last section can be interpreted as an international Input-Output table with only one sector – CO_2 emission. From this perspective, we can refer to Leontief (1936) and rewrite the vector of regional total CO_2 "supply" or region *r* ($\boldsymbol{E}_r^{TOT}$), which is defined as direct emission ($\boldsymbol{E}_r^{D}$) + indirect emission embodied in import ($\Sigma_{rr}\boldsymbol{F}_{rr,r}$), as follows:

$$\mathbf{E}^{TOT} = \mathbf{f} \cdot \mathbf{E}^{TOT} + \mathbf{E}^{C} = \mathbf{fb} \cdot \mathbf{E}^{C} \qquad \text{eq. 8}$$

Where $\mathbf{f}$ is the matrix for international carbon flow coefficients, whose elements $f_{r,rr}$ are defined as $F_{r,rr}/E_{rr}^{TOT}$, and $\mathbf{fb}=(1\text{-}\mathbf{f})^{-1}$.

Denominate the share of direct emission in total CO_2 supply as $e^D{}_r=E_r{}^D/E_r{}^{TOT}$, then following the same logic in equation 8, we can define a complete demand coefficient matrix for direct emission as $\hat{\mathbf{e}}^D\mathbf{fb}$, where $\hat{\mathbf{e}}^D$ is a $r\times r$ matrix with $e^D{}_r$ for diagonal elements and 0 for non-diagonal elements. Each element of the complete demand coefficient matrix, $eb_{r,rr}$ indicates the amount of direct emission from region *r* required for a unit increase in embodied emission in final consumption of region *rr*. Given the amount of CO_2 emission embodied in final consumption of each region calculated in section 4.1, we can finally decompose total emission into:

[2] For more detailed information about the methodology, please refer to Koopman et al. (2014), Wang et al. (2014) and Meng et al. (2014). The decomposition procedure was originally developed to analyze the flow of value-added in Global Value Chain, but the basic logic can also be used to analyze carbon flow through international trade linkage.

$$\hat{\mathbf{e}}^D\mathbf{fb}\hat{\mathbf{E}}^C = \begin{bmatrix} e_1^D & 0 & \cdots & 0 \\ 0 & e_2^D & & 0 \\ \vdots & & \ddots & \\ 0 & 0 & \cdots & e_r^D \end{bmatrix} \begin{bmatrix} fb_{11} & fb_{12} & \cdots & 0 \\ fb_{21} & fb_{22} & & 0 \\ \vdots & & \ddots & \vdots \\ fb_{r1} & fb_{r2} & \cdots & fb_{rr} \end{bmatrix} \begin{bmatrix} E_1^C & 0 & \cdots & 0 \\ 0 & E_2^C & & 0 \\ \vdots & & \ddots & \\ 0 & 0 & \cdots & E_r^C \end{bmatrix}$$

$$= \begin{bmatrix} e_1^D fb_{11}E_1^C & e_1^D fb_{12}E_2^C & \cdots & e_1^D fb_{1r}E_r^C \\ e_2^D fb_{21}E_1^C & e_2^D fb_{22}E_2^C & & e_2^D fb_{2r}E_r^C \\ \vdots & & \ddots & \vdots \\ e_r^D fb_{r1}E_1^C & e_r^D fb_{r2}E_2^C & \cdots & e_r^D fb_{rr}E_r^C \end{bmatrix} \quad \text{eq. 9}$$

Each element of $\hat{\mathbf{e}}^D\mathbf{fb}\hat{\mathbf{E}}^C$, $e^D_r fb_{r,rr} E_{rr}^C$ indicates the amount of CO_2 that is originally emitted in region r and ultimately consumed in region rr. By its definition, the columns in the matrix trace backward linkages of emissions embodied in each regions final consumption to their original source. In other words, each column represents a "consumption oriented" decomposition which shows where the directly and indirectly consumed CO_2 in each region's final consumption are originated from. A consumption oriented decomposition can be normalized as $\hat{\mathbf{e}}^D\mathbf{fb}$, whose column sums all equal 1. Similarly, the rows in the matrix trace forward linkages of direct emissions across all downstream countries from a "production oriented" perspective, and split direct emission of each country with respect to their ultimate destination of final consumption. Denominate the consumption coefficient matrix as $\hat{\mathbf{e}}^C$, whose diagonal element $e_r^C = E_r^C / E_r^{TOT}$, then the production oriented decomposition can be normalized as $\mathbf{fb}\hat{\mathbf{e}}^C$, with each of its row sum equals 1.

Table 7: Consumption oriented decomposition of carbon flow (2030, BAU Scenario)

$\hat{\mathbf{e}}^D\mathbf{fb}$

	USA	EUN	ASD	CHN	IND	RUS	BRA	ZAF	RoW
USA	***0.831***	0.041	0.039	0.011	0.013	0.013	0.062	0.019	0.061
EUN	0.018	***0.733***	0.020	0.007	0.010	0.043	0.041	0.031	0.041
ASD	0.010	0.012	***0.709***	0.009	0.004	0.012	0.011	0.009	0.017
CHN	0.078	0.109	0.147	***0.940***	0.036	0.080	0.101	0.067	0.110
IND	0.008	0.016	0.007	0.003	***0.896***	0.005	0.014	0.013	0.019
RUS	0.002	0.011	0.005	0.002	0.001	***0.806***	0.003	0.002	0.007
BRA	0.001	0.002	0.001	0.001	0.000	0.001	***0.686***	0.001	0.002
ZAF	0.001	0.004	0.003	0.001	0.003	0.001	0.003	***0.808***	0.005
RoW	0.050	0.072	0.069	0.027	0.036	0.039	0.080	0.049	***0.738***

Table 7 lists the $\hat{\mathbf{e}}^D\mathbf{fb}$ matrix, i.e. a "consumption oriented" decomposition of international carbon flow. The non-diagonal cells are colored to show their relative magnitude. In each column, we can find the "CHN" cell colored red, indicating that China is an important source for all the regions; on the other hand, the self-sufficiency of China is very high (94.0%). Therefore, the emission of China is relatively more demand driven by other regions.

Tables 8 lists the matrix $\mathbf{fb}\hat{\mathbf{e}}^C$, i.e. a "production oriented" decomposition. From the decomposition, we can find that the US and European Union are the two main importers of CO_2

emission, indicating that a relatively large proportion of CO_2 emission from other regions are used to satisfy final demand of these regions. It's also noteworthy that the demand for imported CO_2 emission in China increase significantly from 2007 to 2030, and makes China the third biggest importer of carbon emission, following the US and EU. Considering the facts that the carbon self-sufficiency of China is remained high since 2007, and even higher in 2030, the increased influence on foreign carbon emission can only be attributed to its rapid growth in the scale of total demand from 2007 to 2030.

Table 8: Production oriented decomposition of carbon flow (2030, BAU Scenario)

$\mathbf{fb}\hat{\mathbf{e}}^{C}$

	USA	EUN	ASD	CHN	IND	RUS	BRA	ZAF	RoW
USA	***0.869***	0.029	0.011	0.018	0.004	0.002	0.003	0.001	0.063
EUN	0.031	***0.851***	0.009	0.019	0.005	0.009	0.003	0.002	0.070
ASD	0.039	0.033	***0.785***	0.060	0.004	0.006	0.002	0.001	0.069
CHN	0.043	0.040	0.022	***0.820***	0.006	0.006	0.003	0.001	0.060
IND	0.025	0.034	0.007	0.016	***0.851***	0.002	0.002	0.001	0.062
RUS	0.015	0.061	0.012	0.024	0.003	***0.825***	0.001	0.000	0.058
BRA	0.024	0.029	0.007	0.026	0.002	0.003	***0.855***	0.001	0.051
ZAF	0.039	0.083	0.024	0.036	0.024	0.003	0.004	***0.662***	0.125
RoW	0.055	0.053	0.020	0.047	0.011	0.005	0.004	0.002	***0.802***

With the decomposition of carbon flow, we can compare the change in different components and across scenarios and periods according to alternative decomposition criterion so as to analyze the paths and driving forces of carbon leakage, as well as its trend.

5. Decomposing Carbon Leakage

According to equation 4 in section 3.2, carbon leakage is defined as the increase in CO_2 emissions (or decrease as negative leakage) outside China due to the domestic mitigation action taken in China. Leakage rate is then defined as the amount of leakage divided by the reduction in the emission in China due to the same domestic mitigation activity. With reference to equation 9, we can decompose leakage as follows:

$$\mathbf{L} = \hat{\mathbf{e}}^{D,peak}\mathbf{fb}^{peak}\hat{\mathbf{E}}^{C,peak} - \hat{\mathbf{e}}^{D,bau}\mathbf{fb}^{bau}\hat{\mathbf{E}}^{C,bau} \qquad \text{eq. 9}$$

5.1 Consumption oriented decomposition

From a consumption oriented perspective, equation 9 can be rewritten as:

$$\underbrace{\left(\hat{\mathbf{e}}^{D,peak}\mathbf{fb}^{peak}\right)\left(\hat{\mathbf{E}}^{C,peak} - \hat{\mathbf{E}}^{C,bau}\right)}_{\text{consumption change}} + \underbrace{\left(\hat{\mathbf{e}}^{D,peak}\mathbf{fb}^{peak} - \hat{\mathbf{e}}^{D,bau}\mathbf{fb}^{bau}\right)\hat{\mathbf{E}}^{C,bau}}_{\text{trade flow change}} \qquad \text{eq.10}$$

The first part of equation 10 in the part that can be attributed to changes in foreign consumption (denominated as $\mathbf{L}^{DMD}$), while the second part can be attributed to changes in carbon flow embodied in international trade (denominated as $\mathbf{L}^{TRD}$) which reveals the path of leak. Table 9 shows the decomposition results. Since the column sums of $\hat{\mathbf{e}}^{D}\mathbf{fb}$ matrix all equal 1, the column sums of $\mathbf{L}^{DMD}$ (the upper part of table 9) are thus, by definition the change of CO_2 emission embodied in final consumption. And the row sums shows the sources of direct emission that is used to satisfy the changed consumption.

Table 9: consumption oriented decomposition

$\mathbf{L}^{DMD}$

	USA	EUN	ASD	IND	RUS	BRA	ZAF	RoW	Change in Source
USA	***0.93***	-0.21	-0.08	0.07	-0.01	-0.03	0.02	-0.26	0.43
EUN	0.02	***-3.73***	-0.04	0.06	-0.02	-0.02	0.04	-0.17	-3.87
ASD	0.01	-0.06	***-1.57***	0.02	0.00	-0.01	0.01	-0.07	-1.67
CHN	0.08	-0.51	-0.30	0.19	-0.03	-0.05	0.07	-0.43	-0.99
IND	0.01	-0.08	-0.02	***5.04***	0.00	-0.01	0.01	-0.08	4.88
RUS	0.00	-0.06	-0.01	0.01	***-0.33***	0.00	0.00	-0.03	-0.42
BRA	0.00	-0.01	0.00	0.00	0.00	***-0.38***	0.00	-0.01	-0.40
ZAF	0.00	-0.02	-0.01	0.02	0.00	0.00	***0.94***	-0.02	0.90
ROW	0.06	-0.37	-0.15	0.20	-0.02	-0.04	0.06	***-3.14***	-3.40
$\Delta\mathbf{E}^C$	1.11	-5.05	-2.18	5.60	-0.41	-0.55	1.15	-4.21	-4.54
$\frac{\Delta E_r^C}{\Delta E_{DHN}^C}$	0.50%	-2.29%	-0.99%	2.54%	-0.19%	-0.25%	0.52%	-1.91%	2.06%

$\mathbf{L}^{TRD}$

	USA	EUN	ASD	CHN	IND	RUS	BRA	ZAF	RoW
USA	***1.23***	-0.16	-0.02	-0.15	-0.07	-0.02	-0.11	0.01	-0.69
EUN	0.07	***0.08***	-0.01	-0.09	-0.01	-0.02	-0.01	0.01	-0.03
ASD	-0.02	-0.03	***0.19***	-0.07	-0.01	-0.01	0.00	0.00	-0.04
CHN	-1.18	-1.40	-0.69	***6.09***	-0.28	-0.18	-0.12	0.00	-2.24
IND	0.02	0.00	0.00	-0.06	***0.01***	0.00	0.00	0.01	0.02
RUS	0.01	0.00	-0.20	-0.09	0.00	***0.44***	0.00	0.00	-0.15
BRA	0.01	0.01	0.00	-0.01	0.00	0.00	***-0.02***	0.00	0.01
ZAF	0.00	-0.08	-0.01	-0.01	-0.14	0.00	0.00	***0.51***	-0.26
RoW	0.33	0.41	-0.53	-1.95	-0.18	-0.02	0.02	0.03	***1.91***
Column Sum	0.46	-1.17	-1.28	3.67	-0.69	0.17	-0.24	0.57	-1.49

It's interesting to see that there're actually no leakage (negative leakage rate 2.06%) in the sense of consumption – world consumption (out of China) in total is decreased in response to Chinese climate policy. However, there're some countries that can benefit from it. The US, India and South Africa (especially India) are the contributor of global demand for CO_2 since the emission embodied in their final consumption increase, corresponding to CO_2 mitigation activities in China. This is mainly because that producers from these three regions are main competitors of Chinese producer in global market, and they can increase their income by substituting their Chinese counterparts. Since India has similar comparative advantage and trade structure, and plus India and China are geologically close, there're direct competition between these two countries in international. Once Chinese producers' competitiveness are deteriorated by climate policy, their Indian competitors can easily substitute them. That makes India the major source for extra emission: the leakage to India accounts for about half of the total leakage in absolute value. One of the effects of leakage is higher production, which in turn leads to higher income, and thus, higher consumption. This reasoning line applies for all the regions, and explains the positive correlation between change in $\boldsymbol{E}^C$ and emission source, as fig. 5 shows.

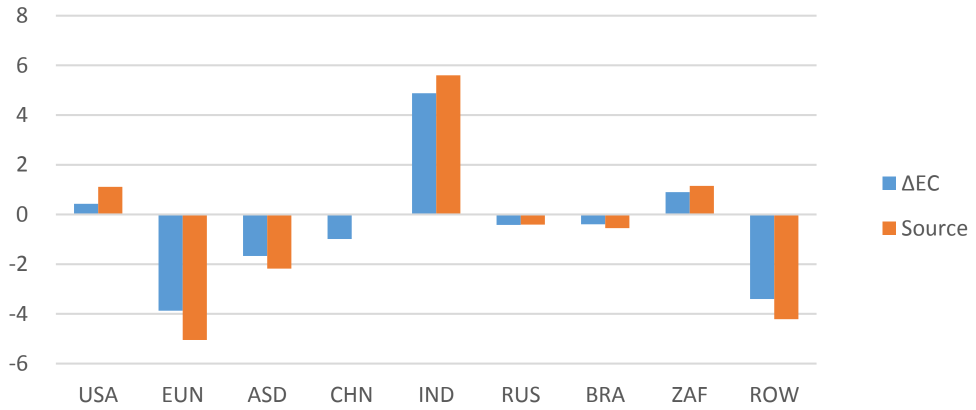

Fig. 5: Decomposition of leakage due to consumption change

The change in international trade also have impact on total leakage, as shown in the $\mathbf{L}^{TRD}$ matrix (lower-part of table 9). The decomposition results indicates that embodied emission flow from EU, Asian Developed Regions, India and Brazil to US, Russia and South Africa, which further decrease the leakage in the first group of regions, while increase the leakage in the last group.

5.2 Production oriented decomposition

Similarly, carbon leakage can also be decomposed from a production oriented perspective. Define $\hat{\mathbf{E}}^{D}$ as a matrix whose diagonal elements are regional direct emissions E_r^{D}, then production oriented decomposition of carbon leakage is:

$$\underbrace{\left(\hat{\mathbf{E}}^{D,peak}-\hat{\mathbf{E}}^{D,bau}\right)\mathbf{fb}^{peak}\hat{\mathbf{e}}^{C,peak}}_{\text{production change}}+\underbrace{\hat{\mathbf{E}}^{D,bau}\left(\mathbf{fb}^{peak}\hat{\mathbf{e}}^{C,peak}-\mathbf{fb}^{bau}\hat{\mathbf{e}}^{C,bau}\right)}_{\text{trade flow change}} \qquad \text{eq.11}$$

The first part of equation 11 is the part of leakage attributed to production change, i.e. change in direct emission (denominated as L^{PRD}), while the second part is also the part attributed to changes in trade flow (L^{TRD}). Table 10 list the transposition of $\mathbf{L}^{PRD}$ and $\mathbf{L}^{TRD}$ matrices.

Table 10: Production oriented decomposition

$(\mathbf{L}^{PRD})^{T}$

	USA	EUN	ASD	IND	RUS	BRA	ZAF	ROW	Change in Desti-nation
USA	***10.79***	0.19	0.22	0.22	0.01	0.01	0.05	0.76	12.26
EUN	0.36	***5.33***	0.19	0.31	0.05	0.01	0.10	0.75	7.09
ASD	0.14	0.06	***4.48***	0.06	0.01	0.00	0.03	0.28	5.05
CHN	0.22	0.12	0.34	0.14	0.02	0.01	0.04	0.64	1.52
IND	0.05	0.03	0.02	***7.55***	0.00	0.00	0.03	0.16	7.85
RUS	0.02	0.06	0.03	0.02	***0.70***	0.00	0.00	0.08	0.92
BRA	0.04	0.02	0.01	0.02	0.00	***0.27***	0.00	0.06	0.42
ZAF	0.01	0.01	0.01	0.01	0.00	0.00	***0.81***	0.02	0.87
RoW	0.78	0.44	0.39	0.55	0.05	0.02	0.15	***11.18***	13.56
$\Delta\mathbf{E}^{D}$	12.41	6.26	5.70	8.88	0.85	0.31	1.21	13.93	49.55
$\frac{\Delta E_r^{D}}{\Delta E_{DHN}^{D}}$	5.52%	2.78%	2.53%	3.95%	0.38%	0.14%	0.54%	6.19%	22.03%

$(\mathbf{L}^{TRD})^T$

	USA	EUN	ASD	CHN	IND	RUS	BRA	ZAF	RoW
USA	***11.09***	0.24	0.19	-12.88	0.23	0.02	0.01	0.05	1.04
EUN	0.41	***9.14***	0.22	-11.87	0.39	0.11	0.02	0.04	1.53
ASD	0.20	0.10	***6.23***	-6.35	0.07	-0.18	0.00	0.03	-0.10
CHN	2.55	1.62	2.44	***-13.04***	0.78	0.36	0.15	0.23	4.91
IND	-0.09	-0.04	0.00	-2.02	***2.53***	-0.01	0.00	-0.13	-0.22
RUS	0.00	0.05	0.03	-1.66	0.02	***1.47***	0.00	0.00	0.07
BRA	-0.04	0.04	0.01	-0.80	0.03	0.00	***0.63***	0.00	0.12
ZAF	0.00	-0.01	0.00	-0.37	0.00	0.00	0.00	***0.38***	0.00
RoW	0.35	0.58	0.43	-18.10	0.65	-0.08	0.03	-0.10	***16.22***
Column Sum	14.46	11.73	9.55	-67.09	4.70	1.71	0.86	0.50	23.56

We can see from table 10 that from a production perspective, direct carbon leakage is much more significant – total leakage rate is about 22.03% in 2030, in which developed regions plus India contributed the majority. And due to their economic scale, they are also big importers of CO_2 emission who have significant influence on other countries' emitting activity. From a production perspective, the change in international trade flow are adjusted to compensate the decrease in Chinese exportation and amplifies total leakage, as shown in lower part of table 10.

6. Concluding Remarks

China has pledge to peak its CO_2 emission by 2030. With a GTAP-E based dynamic CGE model, we analyzed the effect of domestic CO_2 mitigation policies, and simulated the corresponding emission reduction path. Our model simulation indicated that started from the current average carbon price China would have to increase its carbon price by 12% per year to achieve the emission peaking target. Soaring carbon price increases domestic production costs, which not only decrease domestic output and demand, but also deteriorate Chinese producers' competitiveness in global markets, and lead to carbon leakage in other countries. Model simulation indicated that a tenth of Chinese mitigation effort to peak its emission in 2030 will be offset by emission increase in other regions, or more specifically, the leakage rate in 2030 will be 10.6%.

With reference to Koopman et al. (2014), we managed to decomposed international carbon flow and carbon leakage by two alternative criterion, namely production oriented decomposition and consumption oriented decomposition. By this decomposition, we can trace the path of carbon flow and identify the driving forces behind carbon leakage.

From a demand perspective, our decomposition traced forward linkage of carbon emission to its final consumption, and concluded that although total world consumption decrease by 2.06% at response to China's CO_2 mitigation activity, India, US and South Africa can gain extra income by substituting Chinese exportation, and thus increase their final consumption. India accounted for almost half of the total leakage in absolute value, while decrease in emission embodied in final consumption in EU regions accounts for more than 100% of net leakage, meaning that decreased Chinese economic output and consumption, as well as more expensive and less exportation from China will lead to losses in final consumption in EU regions. CO_2 flow from EU, East-Asia developed countries, Russia, Brazil and the rest of world to satisfy the increased consumption in the US, India and South Africa.

From a production perspective, carbon leakage is more significant – total leakage rate will be 22.03%.The decomposition of direct emission represents relocation of production caused by Chinese climate policy. From the regional decomposition, we find that the main contributors are developed regions plus India. And the majority of the increased CO_2 emissions are consumed ultimately also in developed regions. This result corresponds to the development of Chinese exporting industry. China's participating in global market integration and GVC has been intensified and deepened. In recent years, China has strived to push its industries up along value chain in recent years which tightens the linkage and interaction between Chinese industries with those in developed countries. On the other hand, development in Chinese domestic market enabled China to adopt more and more industries transferred from developed regions. Therefore, considering the completeness in industrial structure and advance in producing technology, developed countries are more flexible in adjusting its industrial production according to external shock and substitute for the production decreased in China.

In this paper, we integrated CGE model simulation with carbon flow analysis. With the value-added decomposition methodology of GVC analysis, we managed to trace the carbon leakage from direct emission in production to embodied emission in final consumption. In a "post Kyoto era", developing economies will surely be more actively and intensively participated in global GHG mitigation. Their participation will highly complicate the transmission path and pattern of carbon leakage across countries, since they will trigger leakage in two inter-correlated and cross-determining directions: horizontal leakage (leaking to other developing countries due to competition and substitution in global market) and vertical leakage (leaking to developed countries due to reversal relocation of industries). From this perspective, it is crucial to develop a methodology to trace carbon leakage through international trade systematically, so as to assess the effect of climate policies more precisely. The decomposition procedure established in this paper enables us to integrate the accounting for carbon emission with trade flow on a bilateral level, so that we can identify the path of carbon leakage and quantify its driving forces. And this provides us with an in-depth perspective to understand the global effect of climate policies.

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Appendix 1: Autonomous Energy Technology Improvements

A1.1. Emission factors

Emission factors are different for each energy type according to EIA (including CO_2, CH_4, N_2O). The dynamic emission factors are weighted average value based on different energies' consumption reported by EIA, and the emission factors are divided to two different types – stationary and mobile. Here, stationary type emissions refers to those emissions which come from factories, offices and etc. Mobile type emissions come from transportation sectors.

$$ef_{s,t} = \sum_{si} w_{si,t} \times coef_{barrel2btu,si} \times coef_{btu2kg,si}$$

$$ef_{m,t} = \sum_{mi} w_{mi,t} \times coef_{barrel2btu,mi} \times coef_{btu2kg,mi}$$

These two equations are used to calculate historical emission factor during year 2004 to 2010, where *s* and *m* stand for stationary and mobile respectively, and w_i stands for share of petroleum products in each category. Subscript *t* is time periods. From year 2011 to 2050, we use an exponential function to predict their trends.

$$ef_{s,r,t^*} = ef_{\min} + e^{(t^*-2011)\times\hat{\beta}_{s,r}\div\gamma_s} \times \left(ef_{s,r,2010} - ef_{\min}\right)$$

$$ef_{m,r,t^*} = ef_{\min} + e^{(t^*-2011)\times\hat{\beta}_{m,r}\div\gamma_m} \times \left(ef_{m,r,2010} - ef_{\min}\right)$$

ef_{min} is the minimum emission factor can be achieved in 2050, which is assumed 2.7 Mt CO_2/Mtoe; β is the OLS estimator for each region from $ef_t=\alpha+\beta t+\varepsilon_t$. Generally, $\beta<0$, it reflect the trend that each region's emission factor decreases with time. This trend is not the result of any pledges, it is just the historical regression results that some coefficient between time and emission factor are negative. Just keep in mind that the emission factor is a weighted average of different petroleum products. It is true that each product's emission factor is quite stable over time which is denoted as *coef* above, but if the energy demand structure changes in one country, the aggregated emission factor index ef_t will also change. It is also true that it is hard to tell the trend in the BAU case, and generally, we should get those energy demand weight value from the result of CGE model. However, in our model and also in GTAP database, there are only one aggregated petroleum product sector, so we can't use the above equations to calculate new ef_t. Under this situation, I use the trend from historical regression analysis and extrapolate it to the future. For several exceptional regions that $\beta>0$, in these cases, I set an upper bound at zero for β. γ is the adjustment speed parameter.

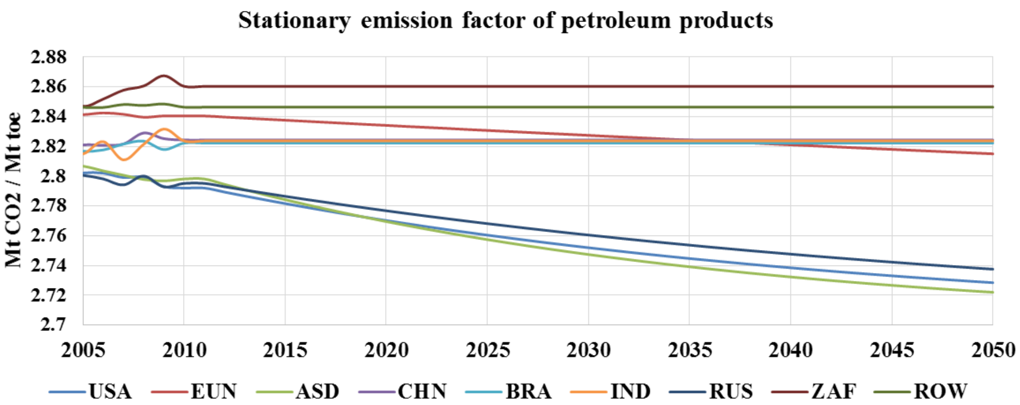

Fig. A1: Stationary emission factor

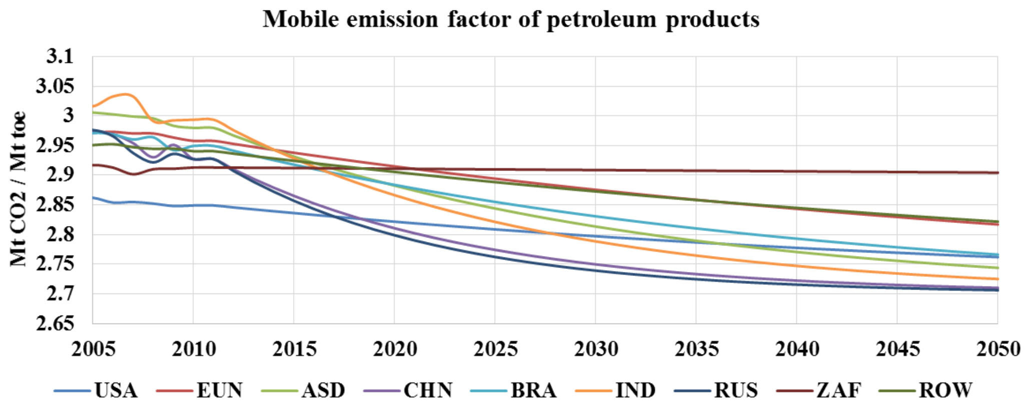

Fig. A2: Mobile emission factor

A1.2. Fuel mixture of electricity sector

Technologies in electricity and transportation sectors are referenced from IEA's report, *Energy Technology Perspectives 2012* (ETP 2012). ETP 2012 introduces two extra low carbon scenario, RCP2 and RCP4, to compare the result with the baseline scenario, RCP6. IEA provides predicted electricity generation from different technologies for different scenarios as follows:

Table 1. Electricity generation from coal

OECD	2009	2020	2025	2030	2035	2040	2045	2050
6DS	3 620	4 037	4 163	4 179	4 228	4 311	4 519	4 664
4DS	3 620	3 556	3 258	2 896	2 290	1 799	1 391	1 210
2DS	3 620	3 422	2 223	1 075	205	48	49	39
Non-OECD	**2009**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
6DS	4 498	8 321	9 624	11 072	12 932	14 627	16 182	17 755
4DS	4 498	6 978	7 379	7 892	8 636	9 240	9 580	10 098
2DS	4 498	5 929	4 645	3 093	1 761	898	807	590

Table 2. Electricity generation from gas

OECD	2009	2020	2025	2030	2035	2040	2045	2050
6DS	2 361	2 894	2 989	3 223	3 518	3 663	3 646	3 517
4DS	2 361	2 974	3 289	3 406	3 772	4 072	4 257	4 251
2DS	2 361	2 773	2 922	2 773	2 453	1 591	927	561
Non-OECD	**2009**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
6DS	1 938	3 038	3 578	4 300	4 890	5 516	6 202	6 901
4DS	1 938	3 381	4 057	4 526	4 881	5 098	5 386	5 599
2DS	1 938	3 079	3 561	3 701	3 443	3 106	2 775	2 629

Table 3. Electricity generation from oil

OECD	2009	2020	2025	2030	2035	2040	2045	2050

6DS	324	183	144	133	127	121	114	110
4DS	324	140	106	102	97	88	77	69
2DS	324	118	73	68	60	50	40	29
Non-OECD	**2009**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
6DS	703	594	554	489	480	460	440	418
4DS	703	561	507	439	429	413	398	384
2DS	703	518	417	320	289	245	180	91

Table 4. Electricity generation from total

OECD	**2009**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
6DS	10 394	12 345	12 984	13 638	14 268	14 815	15 246	15 646
4DS	10 394	12 131	12 672	13 147	13 561	14 001	14 376	14 812
2DS	10 394	11 997	12 336	12 697	12 950	13 475	13 994	14 561
Non-OECD	**2009**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
6DS	9 649	16 747	19 472	22 340	25 606	28 409	31 009	33 637
4DS	9 649	16 008	18 214	20 514	22 942	25 089	27 164	29 274
2DS	9 649	15 168	16 774	18 421	20 173	22 309	24 579	27 003

Using above tables' data, I can get electricity generated from renewable energies. (Subtract coal, gas and oil from total.) However, in GTAP 8 database, there is no electricity generated by renewable energies. So the share of renewable energies is 0% in base year. So I use the data in year 2050 from IEA's predicts and the data in year 2007 from GTAP 8 to smooth the ratios in this period. This method will neglect predict data from 2020 to 2045, thus cause the technology path to be smoother without any kink point. In IEA's report, it only divides the whole world into two regions, OECE and Non-OECD. So the technology changes are not precise. Only if we can get these share data from our own global TIMES model or get them from IEA internally, we can set up a more precise scenario.

The smoothed technology share can be seen from Figure 9 to Figure 12. As mentioned above that there are only two region categories, OECD and Non-OECD, so share data converge to two points (two direction of converge path) in 2050.

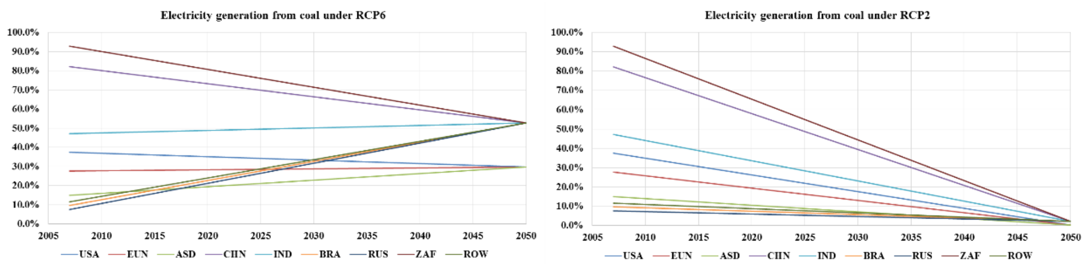

Figure 9. Electricity generation from coal under RCP6 (left) and RCP2 (right)

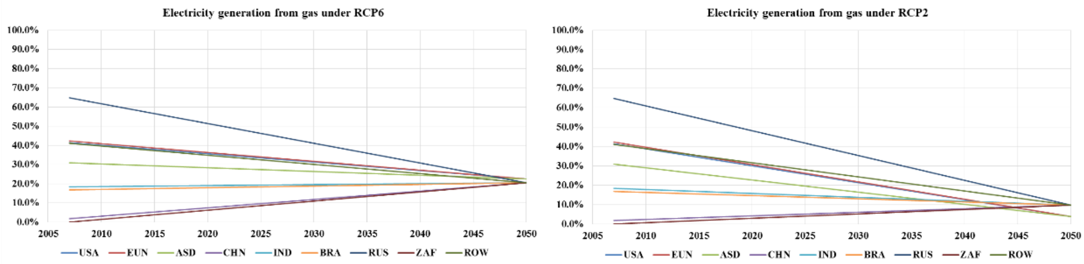

Figure 10. Electricity generation from gas under RCP6 (left) and RCP2 (right)

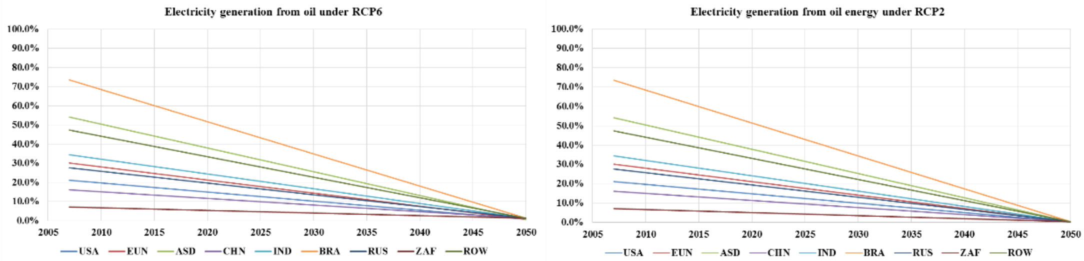

Figure 11. Electricity generation from gas under RCP6 (left) and RCP2 (right)

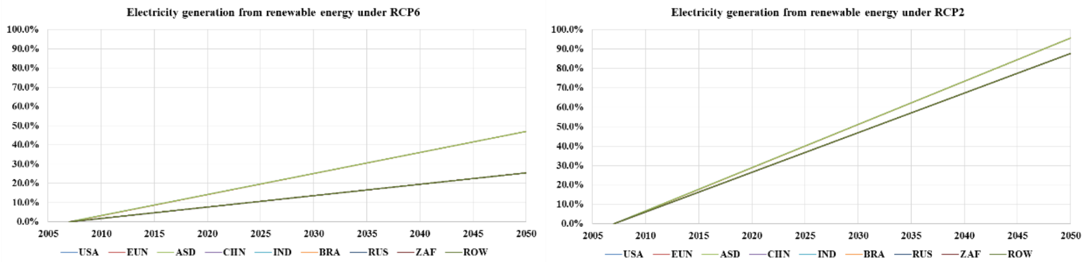

Figure 12. Electricity generation from renewable under RCP6 (left) and RCP2 (right)

A1.3. Fuel mixture of transportation sector

Technology changes are calculated from the data in IEA's report, Energy Technology Perspectives 2012. In this report the transport share provides a global portfolio of technologies for passenger LDVs and stock of passenger LDVs in most major markets. I use these data to calculate different technology share in transportation sector. The assumptions I made is:

Table 5. Assumptions made to predict technology share in transportation sector

Assumption	Value/Label
Depreciable life	5 years
Liquid driven	Gasoline, Gasoline hybrid, Diesel, Diesel hybrid, CNG/LPG
Electricity driven	Electricity
Renewable driven	Plug-in hybrid gasoline, Plug-in hybrid diesel, H2 Hybrid ICE,

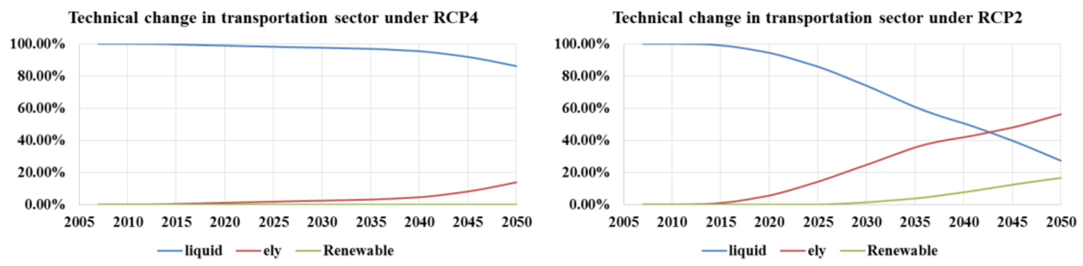

Figure 13. Tech share in transportation sector under RCP4 (left) and RCP2 (right)

Technology share under RCP6 does not change over time. So liquid driven cars account for nearly 100% from 2007 to 2050. The reason for this assumption is that the report does not give the number in RCP6 case, and from those numbers given in RCP4 case, the percentage of liquid driven cars decreases very slowly, so it is reasonable to assume a stable 100% value to 2050.

A1.4. Energy reserve change

Natural resource reserves are another important endowment input in CGE model. Primary energies such as crude oil, gas and coal are all produced by natural resources. However, these kinds of natural resources are exhaustible, so dynamic input in production structure will not be stable, natural resources share in the production of primary energy will decrease over time. For this reason, I use R/P value (Reserves to Production) from BP statistics to predict exogenous natural resource endowment path. I made the assumption that natural resource input do not change from 2007 to 2011. The total reserves in 2011 equal to:

$$M = X_{2011} \times B/P_{2011}$$

M stands for total reserves, X stands for natural resource input. Each year's new discover of natural resource reserves will account for 40% of that year's input and each year's input will decrease according to an exponential relationship. This 40% figure comes from IEA's report, World Energy Outlook 2012, which I think is just a statistical value. But the trend of this cover rate value is hard to predict for the future, so here I make a very rough assumption that it will remain the same until 2050. Then the following condition must be satisfied:

$$\begin{aligned} M &= X_{2011} \times 0.6 + X_{2011} \times (1-\alpha) \times 0.6 + \cdots + X_{2011} \times (1-\alpha)^{T-2011} \times 0.6 \\ &= X_{2011} \times 0.6 \times \frac{1-(1-\alpha)^{T+1}}{\alpha} \\ &\approx X_{2011} \times 0.6 \times \frac{1-\left(1 - C_{T+1}^{1}\alpha + C_{T+1}^{2}\alpha^2 - C_{T+1}^{3}\alpha^3\right)}{\alpha} \\ &= X_{2011} \times 0.6 \times \left(C_{T+1}^{1} - C_{T+1}^{2}\alpha + C_{T+1}^{3}\alpha^2\right) \end{aligned}$$

T stands for the end year that natural will be totally exhausted. Then we can solve the decrease rate α as:

$$\alpha = \frac{C_{T+1}^{2} - \sqrt{\Delta}}{C_{T+1}^{3}}; \quad \Delta = \left(C_{T+1}^{2}\right)^{2} - 4 \times C_{T+1}^{3} \times \left(C_{T+1}^{1} - \frac{M}{X \times 0.6}\right)$$

Figure 14 shows the endowment input (which is the technique structure mentioned above) for oil production as an example.

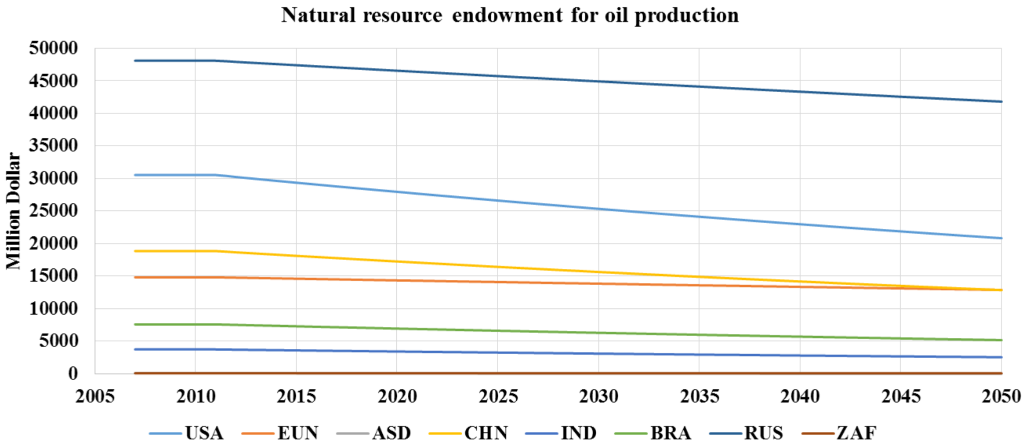

Figure 14. Natural resource endowment for oil production