A Dynamic Model of Effects of Trade and Environmental Policies on Firms' Offshoring and Clean Technology Adoption Decisions

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Abstract

This paper develops a dynamic general equilibrium model to analyze firms' joint decisions on production offshoring and clean technology adoptions when facing different labor productivities and environmental regulations between home country and offshoring host country. During their decision processes, both workers' wages and emission levels of related countries are endogenously determined. Later this model is calibrated to match the data on manufacturing workers' wages in the U.S. and China's foreign invested enterprises and both countries' PM2.5 emissions over 1999-2013. This paper quantifies the offshoring levels which is measured by the share of total low-skilled labor-intensive manufacturing production processes shifted from U.S. to China. My paper also gives the long-run predictions on future offshoring level and environmental qualities in both countries. Besides, different counterfactual policy experiments are conducted and pollution haven effects on offshoring is estimated in this paper.

(*JEL* F18, F23, D21, J31, Q52, Q56)

1 Introduction

Since China and the U.S. reached a bilateral trade agreement in mid-November 1999 and China formally joined WTO two years later, both the FDI inflow and the export of China have risen dramatically.[1] The manufacturing sector attracts most FDI and contributes over 93 percent of total export in China.[2] The U.S. is one of the largest investors and most important export markets for China.[3] While the production offshoring from the U.S. and her top trading partners boosted the employment and wages of Chinese manufacturing workers, the air pollution level is high and increasing in China. On the other hand, the employment and wages in the U.S. manufacturing sector declines but the air quality improves over the past fifteen years (Figure 1).[4] More importantly, the emission intensities in both countries decline.

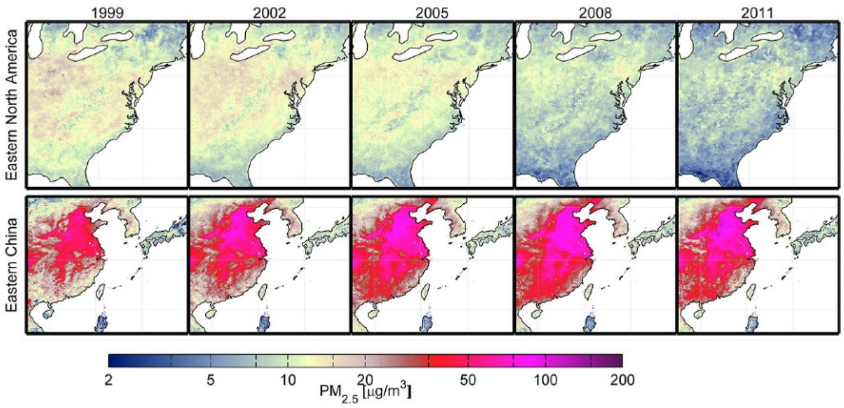


Figure 1: Trends of PM2.5 levels in US and China(van Donkelaar et al.,2015)

The main purpose of this paper is to analyze the interactions between China and U.S. labor market and environment outcomes through multinational firms' production location choices and their clean technology adoption decisions. The changes of two conditions around 1999 are the main contributions for production offshoring to China. First, as mentioned above, the

[1]The trade agreement signed in 1999 is the most important breakthrough in China's 15-year effect to join the WTO given the dominant and central role of U.S. plays in WTO. That's the reason why the time starts from 1999 in this paper. For the history of China's accession to WTO and the role played by the U.S., see Prime (2002), Morrison (2001) and Blancher and Rumbaugh (2004).

[2]From 2002 to 2005, the share of manufacturing FDI is around 70 percent and declined since then. In 2013, the share dropped to 38.7 percent. See the Figure A.1 on Share of FDI in manufacturing sector in Appendix for details. The data is from the multiple year report by Foreign Investment Committee of the Chinese Ministry of Commerence (2007).

[3]The total capital stock held by the U.S. in China was over $61 billion by the end of 2013 by U.S. BEA data(see Morrison (2015)). The share of China export to U.S. is declining from 41.9% in 1999 to 19.8% in 2013. See the Figure A.2 on the bilateral trade between China and U.S. in the Appendix for details.

[4]This paper focuses on fine particular matter measuring less than 2.5 microns in aerodynamic diameter(PM2.5). According to van Donkelaar et al. (2015), the population-weighted exposure to PM2.5 in China had increased from $38.1\mu g/m^3$ in 1999 to $54.4\mu g/m^3$ in 2011. The PM2.5 level for U.S. had decreased from $11.3\mu g/m^3$ to $7.6\mu g/m^3$ from 1999 to 2011. See the Data section for details.

China's accession to WTO reduces the trade barriers and the offshoring costs. Second, the pollutant PM2.5, which this paper focuses on, is the latest regulated one by EPA. In 1997, the U.S.EPA established new standards for allowable level of PM2.5 and started the implementation of the new standards in 2002.[5] However, the Chinese government didn't publish the standard for PM2.5 until November 2012. Therefore, the firms of the U.S. and her trading partners can reduce labor costs and enjoy the loose environmental regulations by shifting production to China. But there is some productivity loss from doing so.[6] Firms may invest in clean technology and their decisions are going to be affected by the different environmental regulations based on production locations.

After joining WTO, China has become a world factory and export platform.[7] Most production offshored to China are low-skilled labor intensive tasks because the majority of China export involve the processing trade. According to the China Foreign Investment Report by the Chinese Ministry of Commence, the processing trade accounting for 77.9 percent of total export by the foreign invested enterprises (FIEs)in China from 2002 to 2006.[8] And the FIEs play a crucial role in China's export.[9] Thus, as in Acemoglu et al. (2015), I assume that there are two sectors in the U.S. and only firms in the low-skilled sector can be offshored. The domestic export firms in China are treated as identical in productivity as offshored firms except the goods produced are different. A recent research by Wang and Wang (2015) finds no evidence on productivity improvement of foreign ownership by comparing the post-acquisition performance changes of foreign- and domestic-acquired firms in China. My model extends Acemoglu et al. (2015)in two main aspects. Acemoglu et al. (2015) focuses on the interaction between offshoring and horizontal technology (measured by the number of firms in a sector) changes. But the labor productivity growth and technology innovations are not considered. My paper adds clean technology adoptions and labor productivity growth into firms' production decision process.

By this paper's estimation, the total offshoring from U.S. to China reached the highest levels

[5]The litigation process for EPA's 1997 standards is not an easy way. The regulations on PM2.5 was first denied by the D.C. Circuit and later get support from United States Supreme Court. Finally EPA could implement the PM2.5 standards. For the detailed litigation history of EPA's 1997 PM2.5 standards, see EPA web site the litigation history part(http://www.epa.gov/pmdesignations/faq.htm)

[6]The labor productivity in manufacturing sector are based on the output per working hour by BLS data and calculated output per worker for China. See the Data section for details.

[7]For the literature on the relation between export-platform and multinational firms' vertical structure, see Ekholm et al. (2007) and Gordon H. Hanson (2005). Here I consider offshoring of intermediate goods production and all intermediate goods production are independent from each other.

[8]The processing trade by FIEs accounted for 79.6 percent of total export involving processing trade in China from 2002 to 2006.

[9]The FIEs account for about 54 percent of total China export. See the Historical Context section for more discussions about FIEs in China.

over 2002-2005 and the U.S. offshored about 11% of total types of low-skilled labor-intensive manufacturing production by importing from China, among which about 1.43% are directly offshored through U.S. multinational corporations' affiliates in China. The PM2.5 emission intensities for U.S. and China declined annually by 2.8% and 10.3% respectively.[10]The model of this paper suggest that if US tighten domestic PM2.5 regulations through increasing the pollution tax, the domestic firms will always invest more in clean technology to reduce the emissions but only increasing offshoring in the short run. That's because in the long run, the offshoring level is only affected by the relative labor endowments, productivity, and offshoring costs. That means the pollution haven effect in attracting FDI and boosting export vanishes with time due to firms' pollution abatement efforts. If US tighten the regulation by increasing the equivalent pollution tax by 5 percent, the total(or direct) offshoring to China will increase by 8.7%(or 1.1% for direct offshoring) which is comparable with the estimates by Levinson and Taylor (2008).[11] Besides, other counterfactual exercises such as government subsidy clean technology or reduction of offshoring cost are also discussed in this paper.

This paper builds on three strands of literature. First, this paper benefits most from recent research on production offshoring. The most related paper is Acemoglu et al. (2015) which builds a continuous-time dynamic model and use directed technology change to analyze the impact of offshoring on domestic wage inequality for both the short-run and long-run cases. But they exclude the effects of environmental regulations on firm's offshoring and emission reduction decisions. Feenstra and Hanson (2005) analyze the ownership in China's processing export firms. They find that foreign firms likely to have ownership of the Chinese plant but Chinese parties have control over input-purchase decisions. So they don't consider the production offshoring issues during foreign firms' decisions on ownership. Other Ricardian model of offshoring includes Grossman and Rossi-Hansberg (2008) and Rodrìguez-Clare (2010). The paper by Grossman and Rossi-Hansberg (2008) builds a single-country static model to analyze the effects of decreasing offshoring costs on the domestic labor wages where the decreasing offshoring costs can be referred to the rising productivity and trade liberalization in offshoring host country here. The paper by Rodrìguez-Clare (2010) analyzed both the short-run and long-run increasing of offshoring on both rich and poor countries. In the short run, increasing fragmentation and offshoring will

[10]By my estimation, the relative PM2.5 emission intensity in China relative to US has declined from 9.6 to 2.8 over 1999-2013. The high the emission per output today is easier to adopt clean technology by the assumption of builds-on-giants'-shoulders technology innovation process.

[11]Levinson and Taylor (2008) finds that 1% increase in pollution abatement cost is associated with 0.2-0.4% increase in importing from Mexico and 0.4-0.6% increase in importing from Canada.

hurt rich country and benefit the poor country. But those effects will be reversed in the long run because rich country will relocate resources towards research to make offshoring benefit them while the poor country can not derive direct gain from offshoring. The papers on offshoring and trade agreement are given by Antràs and Staiger (2012a) and Antràs and Staiger (2012b). Those papers discuss the challenges offshoring bring to the trade negotiations and WTO basic principles. Their suggested solution is that the trade negotiators should focus from market access to deep integration and sign more-individualized trade agreements. The literature on other contractual issues in offshoring are give by a series of paper by Pol Antràs and his co-authors especially Antràs and Helpman (2004),Antràs et al. (2006) and Antràs and Costinot (2011).

A second body of research analyzes the effects of trade liberalization on environments. Earlier papers on the intersection between trade and environment, such as Copeland and Taylor (1994), Grossman and Krueger (1995) and Copeland and Taylor (1995), discuss the impact of trade on environmental quality and the long-run trends. Antweiler et al. (2001) develop a theoretical model to divide trade's impact on pollution into scale, technique, and composition effects and apply their theory to the world sulfur dioxide concentrations. They find freer trade is good for the economy because the the trade-induced technique and scale effects reduce pollution while trade-induced changes in composition of national output has little effect on pollution concentration. A following paper by Levinson (2009) also decompose the air pollution drop in the U.S. manufacturing sector from 1987 to 2001 into those three effects. And he finds most reduction is due to technology advances and importing(composition effect)accounts at most 10 percent of total reduction. Because his paper only focus on U.S. manufacturing sector, the trade effects on U.S. trading partners are ignored. A recent research Shapiro and Walker (2015) using plant-level data finds that the decreasing of pollution intensity due to the rising environmental regulation explains the 60 percent air pollution reduction from U.S. manufacturing between 1990 and 2008. Recently literature on trade-induced pollution in China since China join WTO is given by Lin et al. (2014) which finds that in 2006, 36% of anthropogenic sulfur dioxide, 27% of nitrogen oxides, 22% of carbon monoxide, and 17% of black carbon emitted in China were due to production of exporting goods. Among those export-driven pollution, about 21 percent are due to the export to America. A similar paper by Weber et al. (2008) on carbon emission claims that about one third carbon emission in China are incurred by exports and about 27% of export-driven carbon emission are due to exporting to U.S. from 2002 to 2007. All of those papers consider the effects of trade rather than production offshoring on the environments of related countries. And they couldn't give proper policy implications especially for the trade between U.S. and China.

Third, this paper contributes to the recent literature on the effect of trade with China on U.S. labor market. Bernard et al. (2006)finds that manufacturing plants in the U.S. more exposed to imports from low-wage countries grew slowly and were more likely to exit over 1977-1997. Liu and Treffler (2008) finds that, from 1996 to 2006, U.S. outsourcing of services to China and India had minimal effects on employment or wages for U.S. workers. Autor et al. (2013) confirms that, over 1990-2007, the rising imports from China causes higher unemployment, lower labor force participation and wages in U.S. local labor market. Those literature missed the role played by the firms especially large firms because about half of the world trade involves multinational enterprises. In my paper, the share of related trade in total China exports are over 50 percent. And what's more, the production offshoring played a central role for China becoming the largest exporting country after join WTO. So my paper will help better understand the trade between China and her top trading partner–America.

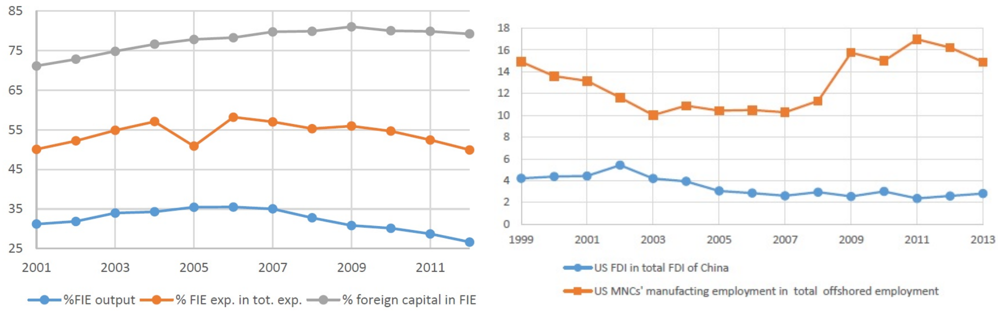
The rest of this paper is organized as follows. Section 2 reviews the role of FIE in China and the offshoring history. Section 3 presents the theoretical model which analyze both the short-run and long-run trends. Section 4 discusses the data and section 5 covers calibration results. Section 6 outlines the numerical results based on the calibrated parameters. Section 7 presents counterfactual exercise and gives policy implications. Section 8 concludes. All omitted proofs, figures and tables are in the Appendix.

2 Historical Context

As mentioned above, the FIEs have played a crucial role for the export of China and the share of FIE's export have been very stable at 54 percent(Figure 2.a). The share of FIEs' output in total manufacturing output of China is 31.8 percent from 1999 to 2012.[12] According to the Report, the share of FIEs' export to U.S. is roughly 24.2 percent of the total FIEs' export.[13] That's very close to the share of total export to U.S. from China (27.3 percent) from 1999 to 2013. And the share of foreign capital in total registered capital of FIEs is 76.6 percent from

[12]The share reached the highest level at over 35 percent between 2005 and 2007 and declined since then. The share is calculated based on the data about the industrial output in the China Statistical Yearbook.

[13]The Report doesn't include the information on FIEs export destination each year. The only data available for the share is 23.99% in 2003, 24.3% in 2004 and 24.38% in 2006.



(a) share of FIE export and foreign capital (b) share of US FDI and Employment

Figure 2

1999 to 2013 which is keeping rising over the time periods(Figure 2.a). The share of FDI flow directly from U.S. to China in total China FDI has been decreasing from 10.5 percent in 1999 to 2.4 percent in 2013. But by the BEA's data on activities of multinational enterprises, the total employment by U.S. multinational firms in China increased from 0.29 million in 1999 to 1.57 million in 2012 which is roughly 5.72 percent of total FIEs' employment in China. In particular, the total manufacturing workers employed by U.S. multinational firms in China increased from 0.23 million in 1999 to 0.70 million in 2012 which account for about 5.86 percent of total FIEs' employment in manufacturing sector(Figure 2.b).

By the EBA's benchmark survey of U.S. direct investment abroad for 1999 and 2004(Table A.2 in Appendix), about 10.3 percent of sales of Chinese affiliates of U.S. parent companies are shipped to U.S. market and in particular the share is 7.7 percent for manufacturing goods.[14] The share of the sales to the U.S. out of the total export by the Chinese branches of the U.S. MNCs dropped from 44.5 percent in 1999 to 28.5 percent in 2004.[15] Therefore, the Chinese branches of the U.S. MNCs are a little bit more likely to export to the U.S. than the general FIEs and exporters in China. But the difference is shrinking and is ignored in this paper. In the numerical part, after the total offshoring is obtained, the share of production offshoring through U.S. multinationals is based on its share of FDI and employment.

One of this paper's contributions is to explain the relation between the FDI in China and the export from China to the U.S. using the concept of generalized offshoring. According to the National Academy of Public Administration(2006), offshoring is defined as "U.S. firms shifting services and manufacturing activities abroad to unaffiliated firms or their own affiliates". [16]

[14]The likelihood of export is lower for FIEs with funds from the U.S. and European countries than the Asian investors.

[15]See the section on data for more information about the U.S. MNCs' operations in China.

[16]There also includes the detailed comparisons of different definitions of offshoring and outsourcing. See **?** for details.

In this paper, the concept of offshoring is generalized as "U.S. firms or previously offshored U.S. firms shifting services and manufacturing activities abroad". So the offshoring discussed in this paper includes both the direct offshoring by U.S. firms to China and indirect offshoring by previously offshored U.S.firms to China.

Since this paper is to interpret trade from the perspective of offshoring , the history of the trade between the U.S. and her top trading partners can be regarded as a history of production offshoring. This interpretation is consist with the product life-circle theory proposed in 1966 by Raymond Vernon who also played an important role in the post-world war development of the IMF and GATT organisations. In his seminal paper (Vernon (1966)), Vernon found the matured and standardized production processes were shifted abroad mainly to west European countries and Japan. And U.S. firms stopped producing those goods and imported them from offshore-host countries. In stead U.S. firms started to produce more innovative and technology advanced new goods.[17] According to the trade between U.S. and her top trading partners, the production offshoring first happened in the 1960's(or even earlier)to Japan and west European countries. During 1970's and 1980's, the labor intensive low-skill manufacturing production were offshored to South Korea, Taiwan and other southeast Asia countries. Then during 1990's and especially after China joined WTO in the early 21st century, there was a wave of manufacturing production offshored to China from U.S. and her top trading partners.[18]

3 Model

Consider a discrete-time and two-country model consisting of the east(developing) country and the west(developed) country. Each period, the only endowment in each country is labor which are treated as exogenous. At first, I assume the labor supply is changing from period to period. But when I'm considering the steady state, the labor endowment in each country will be treated as fixed. The east country has only low-skilled labor and its quantity is denoted as L_{et} at period t. The west country has both the low-skilled and high-skilled labor force which are denoted as L_{wt} and H_t respectively. Also assume the labor is immobile both across sector and across country and inelastically supplied. The only production input is labor.[19] The same

[17]For the literature on product life cycle, see Grossman and Helpman (1991a),Grossman and Helpman (1991b) and recent paper on product life circle and offshoring by Bilir (2014).

[18]The Figure A.7 in the Appendix illustrates the transaction history of production offshoring from US.

[19]The main reason for this paper to exclude the capital factor in production is the different capital investment situations facing the U.S. and Chinese firms,in particular, the different situations between the FIEs and domestic firms in China. No doubt that FDI can be treated as both the capital and technology transfers across countries.

type of labor in different country and different type of labor may have different productivity. As mentioned before, the labor productivity growth paths are treated as exogenous. Assume there is pollution emission during production precess which involves low-skilled workers.[20] The emission of a firm is proportional to its output and the emission coefficient(emission per output) is a measure of the clean technology. Firms can make investment in clean technology to reduce the emission intensities.

There is only one unique final goods for both consumption and investment which is treated as numeaire good. The final goods, Y, is produced using two types of intermediates: the low-skill sector aggregate goods Y_l and high-skill sector aggregate goods Y_h. From now on, the time indexes will be omitted unless this will cause confusions. The technology to produce the final goods is given by the the following constant elasticity of substitution(CES) function.

$$Y = (Y_l^{\frac{\epsilon-1}{\epsilon}} + Y_h^{\frac{\epsilon-1}{\epsilon}})^{\frac{\epsilon}{\epsilon-1}} \tag{1}$$

where $\epsilon > 0$ is the elasticity of substitution between the two sector inputs. If $\epsilon > 1$, the two sector inputs are gross substitutes and are gross complements if $\epsilon < 1$. If $\epsilon = 1$, then it's Cobb-Douglas production function and is ignored here. Actually most estimates of the elasticity of substitution between skilled and unskilled workers are in the range $[1.5, 2]$(see Ciccone and Peri (2005)). So I only consider the case $\epsilon > 1$ unless mentioned otherwise. Normalize $P_Y = 1$, then the inverse demand functions for two sector inputs are given by

$$P_l = (Y/Y_l)^{\frac{1}{\epsilon}}, \quad P_h = (Y/Y_h)^{\frac{1}{\epsilon}}, \quad \text{and } (P_l^{1-\epsilon} + P_h^{1-\epsilon})^{\frac{1}{1-\epsilon}} = 1 \tag{2}$$

The two sector aggregate inputs, Y_l and Y_h, are produced using intermediates from their own sector. In this paper, each firm is producing a single type of intermediate goods.[21] Each firm only need either the low-skilled workers or the high-skilled workers for production. So all firms are divided into low-skill sector or high-skill sector depending on the type of workers they

That makes the FIEs enjoy an advantage over the domestic firms if not mentioning the reduced exporting costs. In Song et al. (2011), the high-productivity firms in China tend to adopt advanced technology through internal savings rather than borrowing from financial institutions due to financial imperfections. Therefore to make the model simple, I ignore the capital factor in production.

[20] This assumption is based on two observations: first, the production workers in U.S. manufacturing is roughly the low-skilled workers by the NBER-CES manufacturing data; second, the pollution due to the China export to the U.S. is from the processing trade which only involves low-skilled production workers.

[21] For the multi-product firms, we can just divide the firm into a couple of firms depending on the number of products. This way is better to characterize the fact that only some tasks of whole production processes are offshored. This is insistent with the task offshoring assumption in the current literature(seeGrossman and Rossi-Hansberg (2008) and Acemoglu and Autor (2011)).

employ.[22] Denote A_l as the total measure of $low - skill$ sector firms and A_h for $high - skill$ sector firms in the west at the beginning. Assume that a fraction of k of $L - sector$ firms already shift their production from west to east in the sense that there is no such production any more in the west. Then the measure of $L - sector$ firms left in the west is $(1 - k)A_l$. But assume that there would be $\nu k A_l$ low-skill firms in the east with $\nu > 1$. That means the measure of additional business generated in the east country due to production offshoring is proportional to the offshored firms with the ratio $(\nu - 1)/\nu$. The main reason for this assumption is to capture the stable relations between the domestic exporters and the FIE exports in the east country.[23] Therefore, the total number of firms in the $low - skill$ sector is $(1 - k + \nu k)Al$ which is denoted as $Al(k)$. Now the production function of intermediate aggregate goods is given by

$$Y_l = B_l \Big(\int_0^{A_l(k)} x_{li}^{\alpha} di \Big)^{1/\alpha}, \quad Y_h = B_h \Big(\int_0^{A_h} x_{hi}^{\alpha} di \Big)^{1/\alpha}, \quad \alpha \in (0,1) \tag{3}$$

where x_{li} is the quantity of intermediate $i \in [0, A_l(k)]$ and similar interpretation for x_{hi}. And $\sigma = \frac{1}{1-\alpha} > 1$ is the elasticity of substitution between any two intermediates within the same sector.[24] As in Acemoglu et al. (2015), The measure of technology spillovers within the same sector

$$B_l = (A_l)^{\frac{2\alpha-1}{\alpha}}, \quad B_h = (A_h)^{\frac{2\alpha-1}{\alpha}} \tag{4}$$

which guarantee the existence of the balanced growth path for any σ if the free entry and exit condition holds here.[25] Even though free entry and exit are prohibited here, I use the same assumption here to compare my results with the results with Acemoglu et al. (2015). What's more, this assumption can help simplify the formulas.

By solving the profit-maximizing problems for the two sector inputs producers, I obtain the inverse demand function for the intermediate goods:

$$p_{li} = P_l B_l^{\alpha} Y_l^{1-\alpha} x_{li}^{\alpha-1}, \quad p_{hi} = P_h B_h^{\alpha} Y_h^{1-\alpha} x_{hi}^{\alpha-1} \tag{5}$$

[22]In the future, the two sectors are sometimes denoted as low sector(or L-sector) and high sector(or H-sector).

[23]For details, look back to the Introduction part. Later in the numerical part, the factor ν is determined by relative size of total export from China to the U.S. respective to the total FIEs' export.

[24]As in the review paper Anderson and van Wincoop (2004), the elasticity should lie between 5 and 10. In Broda and Weinstein (2006), the import demand elasticity is 4 across 3-digit SITC codes and 12 across 10-digit HTS sectors.

[25]In this paper, there is no balanced growth path but the steady state because the free entry and exit condition are not allowed here. For an alternative but equivalent approach without technology spillovers see Acemoglu et al. (012b) for detail.

By assumption, each low-skill sector intermediate goods $i \in [0, A_l(k)]$ is produced by a single monopolist using the low-skill labor($l_{li\theta}$) and the labor augmenting technology $z_{li\theta}, \theta \in \{e, w\}$ where θ indicate the country where it's produced.[26] Same assumption for high-skill sector except that the good production can not be offshored. So we can write down the production functions for a L-sector firm i and a H-sector firm j

$$x_{li\theta} = z_{li\theta} l_{i\theta}, \quad \theta \in \{e, w\}; \quad x_{hj} = z_{hj} h_j \tag{6}$$

During the production of the low-sector intermediates, there is also pollution emission. The emission function is proportional to the total output level and the emission index. Thus, the emission for L-sector firm i in country θ is

$$E_{i\theta} = e_{i\theta} x_{li\theta} = e_{i\theta} z_{li\theta} l_{i\theta}, \quad \theta \in \{e, w\} \tag{7}$$

Here $e_{i\theta}$ is the emission level per unit of output. So the inverse of $e_{i\theta}$ is a measure of the clean technology.[27] So firm can adopt more clean technology to reduce the per output emission level. Assume that clean technology adoption precess is of the builds-on-giants'-shoulders style,i.e., the cost of increase clean technology depends on the current emission intensity and the targeted emission level.[28] That is, if the current pollution emission index is e and the targeted level is e' then the one-time innovation cost is

$$C_e(e', e) = c_e[(e')^{-(n+1)} e - e^{-n}], \quad n \geq 0 \tag{8}$$

where c_e is a parameter which measures the overall cost to reduce emission and n measures how fast the technology innovation cost will rise.[29] The following lemma gives the property of the clean technology adoption cost function which satisfies the stand-on-shoulders-of-giants technology accumulation process.

[26]Also assume that the firms produced in the east and west may have different productivity due to the fact that the firms choose different productivity in response to the different wage rate. This topic is covered in Meng (2015).

[27]That is, $\frac{1}{e}$, gives us the current technical status: the higher it is, the better the clean technical becomes.

[28]It's straightforward to write the target emission level as a function the current emission level and the investment. And it's easy to derive the clean technology level is an increasing but concave function of investment. Here the technology innovation only involve investment but not innovators or scientists to keep the model simple. For the clean technology innovation involving scientists, see Acemoglu et al. (012a).

[29]If $n = 0$, then the cost to reduce emission is proportional to the percentage change of the emission intensity. When $n > 0$, the innovation cost increasing exponentially with the decrease of the target level.

Lemma 1. *The technology cost function satisfies*

(i) $\frac{\partial C_e}{\partial e'} < 0$ *and* $\frac{\partial C_e}{\partial e} > 0$

(ii) for any $e^* \in [e, e']$, $C(e', e) \geq C(e^*, e) + C_e(e', e^*)$, *and the equality holds iff* $e^* = e, e'$

(iii) the savings in dividing investment in clean technology increases in n *if emission intensities less than a certain level. If not, the opposite holds.*

The proof of this lemma is in Appendix. The second part of the above lemma says that it's better to divide the investment in clean technology in more times to save cost. That's one of the main driven forces for the firms' to adopt clean technology dynamically. The third part predicts that as the emission per output below certain level, the firms will be more likely to divide their investment in clean technology if the parameter n increases.

The total pollution in country $\theta \in \{e, w\}$ is given by

$$E_\theta = \int_{\text{all } i \text{ in country } \theta} E_{i\theta} di, \qquad \theta \in \{e, w\} \tag{9}$$

The accumulation of the stock of pollution $\mathscr{P}_{jt}$ of country j at period t will evolves according to the following equation

$$\mathscr{P}_{jt} = \eta_0 E_{jt} + \eta_1 E_{jt-1}, \qquad \eta_0, \eta_1 > 0 \tag{10}$$

By the formula, the current stock of pollution only depends on the current and previous period emissions.[30] In this paper, the stock of pollution will be measured by its concentration level in a unit space of air.[31] So the parameters (η_1, η_2) gives the ratio how the total amount of pollution will contribute to the increase of the concentration. From the above process, there is no rather pollution abatement from the government. Thus the only way to reduce pollution is through firms' clean technology adoptions.

Now I want to define how the firms change their production allocations. In this paper I only consider the symmetric equilibrium such that all firms in the same country should have identical clean technology. This way will avoid the multiple solutions and simplify analysis.

[30]The assumption on the pollution stock accumulation can be generalized to make it depend on previous history of any number of periods. Because this paper will only consider the atmospheric particulate matter with diameter of 2.5 micrometres or less which is generally called PM2.5. Due to data limitation and for simplicity, only previous period emission will affect the current accumulation level.

[31]In the numerical part of this paper, the pollutant PM2.5 is measured by its concentration within one cubic meters($\mu g/m^3$).

To make symmetric equilibrium possible, assume that if a firm choose offshoring, there will be a one-time offshoring cost which is measured as a fraction of the firm's value after offshoring. Here assume that the original firm owner can only own a share $\beta_o < 1$ of the new firm's value offshored to the east country.[32] That cost might due to the FDI regulation or the imperfect intellectual right protection. Similar for firms which want to move back, they have to pay the moving cost. Assume that moving cost will cost a faction of the total firm's value and a moving back firm will appropriate a share $\beta_m < 1$ of the firm moved back to the west. All firms which change locations will possess the same technologies as the local firms.[33] Each period, assume the equilibrium offshoring is reached when the firms in the west are indifferent about whether offshoring or not. [34]

Now define the ownership of the firms and cross-boarder borrowing and lending(trade deficit) in this model. Assume the domestic firms are owned by domestic people. The a low-skilled worker in the west own a share of s_{ll} of each low-sector firm(both offshored and not)and a share of s_{lh} for each high-sector firm.[35] Similarly each worker in the east also own a fraction s_{el} of each local L-sector firms. So to make the total share is one for each firm, the shares should satisfy the following equations:

$$s_{ll}L_w + s_{hl}H = 1 \tag{11}$$

$$s_{lh}L_w + s_{hh}H = 1 \tag{12}$$

$$s_{el}L_e = 1 \tag{13}$$

Denote the wage rates w_{lwt}, w_{ht}, w_{let} for the low and high skill workers in the west and workers in the east respectively. And denote $\pi^*_{lwt}, \pi^*_{ht}, \pi^*_{let}$ as the net profits flows for the low and high sector firms in the west and firms in the east.[36] So at period t, the total national income in the west is denoted as gnp_{wt} which is the sum of total wage income $w_{lwt}L_w + w_{ht}H$ plus the total

[32]Here the share β_o is closely related with the ownership allocation of the offshored firms which might be an endogenous decision of the original firm owners. Here this issue is not considered. For related literature see Feenstra and Hanson (2005).

[33]Because the only production factor is labor, so the firms' productivity and clean technology level are determined by the labor employed.

[34]It looks like this equilibrium path is a special case of the original dynamic systems. But this assumption will make the calculation easier and avoid the potential multiple solutions.

[35]Notice that the total ownership of offshored L-sector firms is β_o. Thus a western low-skilled(or high-skilled) worker own $s_{ll}\beta_o$(or $s_{hl}\beta_o$) of the offshored L-sector firms. Similarly for the eastern low-skilled workers's ownership of the offshored western L-sector firms.

[36]The net profit flow of a firm is revenue minus the labor and the technology innovation costs. See later of this section for details.

firm profits and similarly for the total national income gnp_{et} of the east country.[37] The cross country borrowing and lending of the final goods will be determined by the consumption and saving behaviors of the households and national incomes of the two countries.

All households(also workers) from both the west and the east countries supply labor inelastically and have the same preference[38]:

$$\sum_{t=0}^{\infty} \frac{1}{(1+\rho)^t} u(C_t, \mathscr{P}_t), \quad u(C_t, \mathscr{P}_t) = \frac{C_t^{1-\varphi}}{1-\varphi} - \gamma \frac{\mathscr{P}_t^{1+\phi}}{1+\phi}, \rho > 0, \gamma \geq 0, \varphi, \phi > 0 \tag{14}$$

$$\text{with budget constraint} \qquad C_t + B_{t+1} = (1+r_t)B_t + w_t + T_t + \pi_t^*$$

where the C_t is the consumption of the final goods and E_t denotes the accumulated stock of pollutants in the environment at time t, and ρ is the utility discount rate. The instantaneous utility function $u(\cdot, \cdot)$ is separable between the consumption and the pollution with γ as the weight on disutility from pollution. In the budget constraint equation at period t, w_t is the wage rate and π_t^* is the income due to the ownership of the firms and B_t is the savings or debt passed from last period. There is also the direct tax transfers from the government. The tax revenue is collected from the firms' emission of pollution. The standard Euler equation can be obtained

$$\frac{C_{t+1}}{C_t} = \frac{1 + r_{t+1}}{1+\rho} \tag{15}$$

The above equation determine the equilibrium interest rate each period given goods market clearance conditions. The transversality condition is given by $\lim_{t\to\infty} \frac{B_{t+1}}{R_t} = 0$ and $R_t = \prod_{m=0}^{t} (1 + r_m)$.

Finally, define the timing of this dynamic model. At beginning, both countries announce their pollution taxes which are fixed through out all periods.[39] Then in each period, the timing of this dynamic game proceeds as below:

1. At the beginning of each period, only L-sector firms make decisions on changing production locations or stay at the same country.

[37] The total firm profits is the sum of domestic firms profit($\pi_{lwt}^*(1-k_t)A_{lt} + \pi_{ht}^* A_{ht}$) and the offshored firms profit($\beta_o \pi_{let}^* k_t A_{lt}$). The total firms' profits in the east country is the sum of domestic firms($\pi_{let}^*((\nu-1)k_t A_{lt})$ and partial offshored firms($(1-\beta_o)k_t A_{lt}$)).

[38] The preference assumption is the same as in Acemoglu et al. (012a)

[39] In this paper, the strategic environmental regulations are not considered. Markusen (2013) analyze the strategic trade and pollution regulations between a north and a south country where the per-capita income level will affect their preferences and abatement decision.

2. Then, the L-sector firms need to determine the investment on clean technology.

3. All firms hire workers for production and labor market clears. Those L-sector firms emit pollution according to their obtained clean technology.

4. Goods market clears and current period ends.

The remaining of this section tries to solve this dynamic model. It's intuitive to solve the equilibrium for each period using backward induction.

3.1 Firm's Production Decision

Starting from step 3 of the period, the offshoring percentage k and the emission levels e's have already predetermined by the previous steps. First consider the firm's production decisions given the clean technologies. The profit-maximizing problem for the L-sector firm producing intermediate i and located in country $\theta \in \{e, w\}$ is given by

$$\max_{x_{li\theta}} p_{li} x_{li\theta} - w_j l_{i\theta} - \tau_\theta e_{i\theta} x_{li\theta}, \qquad \text{where } x_{li\theta} = z_{li\theta} l_{i\theta} \tag{16}$$

The demand function is given by equation(5). Notice the price elasticity of demand is $\sigma = \frac{1}{1-\alpha}$ so the optimal price $p_{li} = \frac{w_{l\theta}/z_{li\theta} + \tau_\theta e_{i\theta}}{\alpha}$ and profit flow function $\pi_{li\theta}$ are calculated below

$$\pi_{li\theta} = S_l \left(\frac{w_{l\theta}}{z_{li\theta}} + \tau_\theta e_{i\theta}\right)^{\frac{-\alpha}{1-\alpha}} \tag{17}$$

where $S_l = (1-\alpha)\alpha^{\frac{\alpha}{1-\alpha}} P_l^{\frac{1}{1-\alpha}} B_l^{\frac{\alpha}{1-\alpha}} Y_l$ given by the industry states and is treated as exogenous by the low-sector firm. It's obvious that the firm's profit flow function is increasing with clean technology level$(1/e)$. Because the relative pollution tax cost is much lower than the labor cost for production, the profit flow functions are assumed to be concave with clean technology.[40] It's easy to get $\frac{\pi_{le}}{\pi_{lw}} = (\frac{z_{le}}{z_{lw}} \frac{w_w + \tau_w e_{lw} z_{lw}}{w_e + \tau_e e_{le} z_{le}})^{\frac{\alpha}{1-\alpha}}$. Holding the other variables fixed, if the pollution tax τ_w increase or τ_e decrease, the relative profit of firms offshored will increase. Thus more firm want to relocate production from west to east countries.

Notice that the H-sector intermediate producers have no pollution and only produced in the west country. Hence just let $e = 0$ and we can obtain the price $p_{hi} = \frac{w_h}{\alpha z_{hi}}$ and the other

[40]Notice that the profit flow function π is concave with clean technology$(1/e)$ iff $(2\alpha-1)\tau e < 2(1-\alpha)w/z$. That is, the share of pollution cost in total production couldn't exceed a specific level $2(1-\alpha) = 2/\sigma$. Therefore, the concavity holds if the elasticity of substitution σ is no larger than 2. Actually most estimates of the substitutions across traded varieties are greater than 3. That's the reason why the cost function for technology adoption should be strictly convex.

corresponding solutions to profit-maximization problem for the h-sector firms.

$$\pi_{hi} = S_h(\frac{w_h}{z_{hi}})^{\frac{-\alpha}{1-\alpha}} \tag{18}$$

Similarly $S_h = (1-\alpha)\alpha^{\frac{\alpha}{1-\alpha}} P_h^{\frac{1}{1-\alpha}} B_h^{\frac{\alpha}{1-\alpha}} Y_h$ which are treated as given by the high-skill sector firms.

By assumption, if k is the fraction of total measure of $L-sector$ firms already offshored from west to east, there are $\nu k A_l$ firms producing $l-sector$ intermediates in the east country and $(1-k)A_l$ $l-sector$ firms remain in the west. Assume that the west country can produce all varieties of intermediate goods while the east country can only produce a fraction $\hat{k} = \frac{z_{le}L_e/\nu}{z_{le}L_e/\nu + z_{lw}L_w}$. That is, $k \leq \hat{k}$.[41] An interpretation is that, the total offshoring can not exceed the fraction of the production capacity reserved for offshored firms in east out of the total western(offshored and not)firms' production. In other words, the output of a offshored production firm is greater than the those not.[42] By the assumptions of symmetric equilibrium and the labor market clearance, it's straightforward to get the equilibrium employment

$$l_{ie} = \frac{L_e}{\nu k A_l}, \qquad l_{iw} = \frac{L_w}{(1-k)A_l}, \qquad h_i = \frac{H}{A_h} \tag{19}$$

By the labor productivity, the output of each type of firms is

$$x_{lie} = \frac{z_{le}L_e}{\nu k A_l}, \qquad x_{liw} = \frac{z_{lw}L_w}{(1-k)A_l}, \qquad x_{hi} = \frac{z_h H}{A_h} \tag{20}$$

By each sector aggregate function in equation(3), the aggregate production for each sector is

$$Y_h = A_h z_h H, \quad Y_l = A_l \hat{L} \quad \text{where } \hat{L} = \left[(\nu k)^{1-\alpha}(L_e z_{le})^{\alpha} + (1-k)^{1-\alpha}(L_w z_{lw})^{\alpha}\right]^{1/\alpha} \tag{21}$$

So the total output in $h-sector$ equal the measure of firms(A_h) multiple the productivity(z_h) of the high-skilled workers and the total number of high-skill workers(H). The term $\hat{L}$ looks like the weighted average of the production capacities of both countries. Now let's look at how

[41]This is a generalization of Krugman (1979)(corresponding to $z_{le} = z_{lw} = 1$ and $\nu = 1$) and Acemoglu et al. (2015)(corresponding to $z_{le} = 1, z_{lw} = t$ and ν), where the upper bound assumption will guarantee the lower equilibrium wage($w_{le}/z_{le} \leq w_{lw}/z_{lw}$) in the east country comparing with the west. But here, this condition alone is not enough because the worker's wages are affected by the pollution level and environmental regulation. However this condition can still guarantee the lower production cost in the east than west.

[42]In reality, generally larger and more productive firms are more likely to have production facilities abroad. This is a selection issues due to the offshoring cost.

the total $L - sector$ output changes as the offshoring changes.

$$\frac{d\hat{L}}{dk} = \frac{1-\alpha}{\alpha}\hat{L}^{1-\alpha}[\nu(\frac{L_e z_{l,e}}{\nu k})^{\alpha} - (\frac{L_w z_{l,w}}{1-k})^{\alpha}] \tag{22}$$

Thus the total $l - sector$ output increases in offshoring k if $k \le \hat{k}$. That's pretty intuitive that if the production cost in the east country is lower than those of the west, then increase offshoring will increase the total output in the $l - sector$. That's called *efficiency effect* of offshoring: improvement of efficiency as a result of reallocation of production toward the places with lower production cost.[43] As $k \to 0$, then $\frac{d\hat{L}}{dk} \to \infty$ and $\hat{L} \to L_w z_{lw}$. That is, the efficiency-enhancing effect of offshoring from west to east is extremely large at the beginning. As $k \to \hat{k}$, then $\frac{d\hat{L}}{dk} > 0$ due to the extra business generation effect.[44] To maximize the total output from $l - sector$, the critical offshoring is $\frac{\nu^{1/\alpha-1} z_{le} L_e}{\nu^{1/\alpha-1} z_{le} L_e + z_{lw} L_w}$ which can be denoted as $\hat{\hat{k}}$. [45]It's obvious that the larger the extra firms created due to offshoring, the greater the critical offshoring level. It's easy to get $\hat{\hat{k}} > \hat{k}$ and this paper usually require that $\hat{k}$ is the upper bound for offshoring unless otherwise mentioned. So it's easy to observe the efficiency effect is greater when the current offshoring k is small, the relative larger endowment of labor in the east(L_e/L_w), and relative rise of the productivity (z_{le}/z_{lw}). In a word, the greater the differences between the production costs, the larger the efficiency effect.[46]

Now turn to the ratio of relative production costs. By demand function of the intermediate goods given by equation(6) and the equilibrium price $p_{li} = \frac{w_j/z_{lj} + \tau_j e_{lj}}{\alpha}$ we get

$$\frac{p_{le}}{p_{lw}} = \frac{w_e/z_{le} + \tau_e e_{le}}{w_w/z_{lw} + \tau_w e_{lw}} = \left(\frac{x_{lie}}{x_{liw}}\right)^{\alpha-1} = \left(\frac{z_{le}}{z_{lw}}\frac{L_e}{L_w}\frac{1-k}{\nu k}\right)^{\alpha-1} \tag{23}$$

As long as $k \le \frac{L_e z_{le}/\nu}{L_e z_{le}/\nu + L_w z_{lw}}$, the intermediate goods are cheaper in the east than the west. And holding other factors fixed, increasing the offshoring k will reduce the equilibrium price differences of $l - sector$ intermediate goods between west and east. Also fix the offshoring and other factors, strengthen the domestic environmental policy will reduce relative wage for domestic low-skill workers comparing with foreign counterpart.

[43]This effect is quite similar as in Rodrìguez-Clare (2010) which also is adopted in Acemoglu et al. (2015).

[44]By calculation,at this time, $\hat{L} = (L_e z_{le} + L_w z_{lw})[(L_e z_{le} + L_w z_{lw})/(L_e z_{le}/\nu + L_w z_{lw})]^{(1-\alpha)/\alpha}$ and $\frac{d\hat{L}}{dk} = \frac{1-\alpha}{\alpha}(\nu-1)(z_{le}L_e + z_{lw}L_w)^{(1-\alpha)/\alpha}(z_{le}L_e/\nu + z_{lw}L_w)^{\alpha}$. If $\nu = 1$, then $\frac{d\hat{L}}{dk} = 0$ and $\hat{L} = z_{le}L_e + z_{lw}L_w$.

[45]Compare with Acemoglu et al. (2015), the results in their paper corresponds to the special case $z_{le} = 1, z_{lw} = t$ and $\nu = 1$.

[46]As in Acemoglu et al. (2015), by equation(5)and(7), we can obtain $P_l^{1-\sigma} = A_l^{\sigma-1}[\nu k p_{le}^{1-\sigma} + (1-k)p_{lw}^{1-\sigma}]$. Then $\frac{dP_l^{1-\sigma}}{dk} = A_l^{\sigma-1}(\nu p_{le}^{1-\sigma} - p_{lw}^{1-\sigma})$. Notice that both p_{le} and p_{lw} are proportional to production cost. Thus the greater the difference between the production costs, the lower the price of the aggregate $l - sector$ inputs.

Now we turn to the production costs which is proportional to the price of the intermediates. By equation(3),(5),(6) and (30),(31), we can solve

$$w_{le} = \alpha z_{le}\left[1+\left(\frac{A_h z_h H}{A_l \hat{L}}\right)^{(\epsilon-1)/\epsilon}\right]^{1/(\epsilon-1)} A_l \hat{L}^{1-\alpha}\left(\frac{z_{le}L_e}{\nu k}\right)^{\alpha-1} - z_{le}\tau_e e_e \tag{24}$$

Then similar to Acemoglu et al. (2015), I can decompose the effect of offshoring(i.e., increasing of k) on the production cost of low-sector intermediate into a labor supply effect, $\left(\frac{L_e}{k}\right)^{\alpha-1}$, an efficient effect $\hat{L}^{1-\alpha}$ and a relative price effect, $\frac{H}{\hat{L}}$. The first two effects increase the real price of intermediates also the production cost and east worker's wage in east country while the third one, the relative price effect will decease the production cost and the east worker's wage. But overall the wage of the east worker will increase due to an increase of offshoring. See the Proposition 1. and its proof for details.

Similarly, the wages of high-skilled workers is

$$w_h = \alpha z_h A_h\left(\frac{Y}{A_h z_h H}\right)^{\frac{1}{\epsilon}} \tag{25}$$

Then increase of offshoring will increase the final goods Y due to increase of the $l-sector$ inputs. Thus, the price of the $h-sector$ goods and the high-skill worker's wage will also increase.

Now turn to the production cost of the $l-sector$ intermediates and low-skill worker's wage in the west country

$$w_{lw} = \alpha z_{lw}\left[1+\left(\frac{A_h z_h H}{A_l \hat{L}}\right)^{(\epsilon-1)/\epsilon}\right]^{1/(\epsilon-1)} A_l \hat{L}^{1-\alpha}\left(\frac{z_{lw}L_w}{1-k}\right)^{\alpha-1} - z_{lw}\tau_w e_w \tag{26}$$

Similarly, the effect of offshoring(i.e., increasing of k) on the production cost of low-sector intermediate can be decomposed into a labor supply effect, $(L_w/(1-k))^{\alpha-1}$, an efficient effect $\hat{L}^{1-\alpha}$ and a relative price effect, $H/\hat{L}$. Offshoring will decrease the low-skill worker's wage in the west country through labor supply effect and relative price effect except the efficient effect. The result is the same as in Acemoglu et al. (2015) such that offshoring will lower the western low-skill worker's wage if $\sigma > \epsilon$ and the also $(\frac{A_h z_h H}{A_l \hat{L}})^{(\epsilon-1)/\epsilon} > \frac{\epsilon}{\sigma-\epsilon}$. Otherwise offshoring will first increase then decrease the west low-skill worker's wage. See appendix for proof.

Now look at the price ratio of $l-sector$ intermediates and $h-sector$ intermediates in the west country.

$$\frac{p_h}{p_{lw}} = \frac{w_h/z_h}{w_{lw}/z_{lw} + \tau_w e_w} = \left(\frac{A_h}{A_l}\right)^{\frac{\epsilon-1}{\epsilon}} z_h^{-1/\epsilon} \hat{L}^{\alpha-1} \left(\frac{\hat{L}}{H}\right)^{\frac{1}{\epsilon}} \left(\frac{L_w}{1-k}\right)^{1-\alpha} \tag{27}$$

Also the effect of offshoring can be decomposed of relative price effect, $(\hat{L}/H)^{1/\epsilon}$, the efficiency effect, $\hat{L}^{\alpha-1}$ and labor supply effect, $[L_w/(1-k)]^{1-\alpha}$. Therefore an increase of offshoring will increase the relative production cost of the $h-sector$ intermediates through relative price effect and labor supply effect and decrease it through efficiency effect. It's obvious that if $\sigma > \epsilon$, then the relative price effects will dominate the efficiency effect. So if the elasticity of substitute between the $L-sector$ intermediates(no matter produced in east or west) is greater than the elasticity of substitution between $L-sector$ and $H-sector$ inputs, then offshoring will increase the production cost ratio and also the relative wages between high-skill workers and low-skill workers. Otherwise, offshoring will first decrease then increase the relative production cost of the $H-sector$ intermediates. Meanwhile the wage differences will first decrease then increase as offshoring increases.

All results for exogenous technologies are summarized as below.

Proposition 1. *With fixed technologies and environmental policies, an increase of offshoring*

(i) *increases the equilibrium prices of the east $L-sector$ intermediates and the west $H-sector$ intermediates and the wages of the east low-skill workers and the west high-skill workers.*

(ii) *decreases the low-skill workers' wage differences between the east and west countries.*

(iii) *if $\sigma > \epsilon$, i.e., the elasticity of substitution between intermediates within sector is greater than that across sectors,*

  a) *increases the skill premium in the west.*

  b) *decreases the western low-skill worker's wage if the current offshoring is small and relative total output in the high-sector is large,i.e. $Y_h/Y_l \geq (\epsilon/(\sigma-\epsilon))^{\epsilon/(\epsilon-1)}$. Otherwise if $\sigma \leq \epsilon$, increase offshoring will increase the western low-skill worker's wage first but decrease it later.*

The proof is in the Appendix. Similarly we can analyze the effects of offshoring on firm's profit in each sector. First, the firms' profit functions can be obtained by plugging in employment condition condition(29) to equations (30)(4)(5).

$$\pi_{lie} = (1-\alpha)P_l\hat{L}^{1-\alpha}\left(\frac{z_{le}L_e}{\nu k}\right)^{\alpha}, \tag{28}$$

$$\pi_{liw} = (1-\alpha)P_l\hat{L}^{1-\alpha}\left(\frac{z_{lw}L_w}{1-k}\right)^{\alpha}, \tag{29}$$

$$\pi_{hi} = (1-\alpha)P_h z_{hi} H \tag{30}$$

Then the results about the effects of offshoring on firms' profits are summarized in the following proposition.

Proposition 2. *With exogenous technologies and policies, an increase of offshoring will*

(i) increase the firm's profit in the west high-skill sector.

(ii) decrease the firm's profit in the east low-skill sector if $\sigma \geq 2$.

(iii) increase the relative profit of the west low-skill sector firm with respect to their east counterpart.

(iv) increase the firm's profit in the west low-skill sector if either $\sigma < \epsilon$. Otherwise, increase of offshoring will decrease the western low-skill sector firm's profit when offshoring level is small but increase it when offshoring beyond some level.[47]

The proofs can be found in the Appendix. Combining with the discoveries in proposition 1, rising offshoring will increase both the east low-skill worker and west high-skill worker's wages. Thus the corresponding firms' profit levels will drop due to the rising production costs. The relative profit of west low-sector firms with respect to the offshored firms will rise because the relative production cost in the west is falling with offshoring levels. For the west low-skill sector firms, their profit will increase with offshoring levels if the substitution within sector is less than that across section. Otherwise, the west low-sector firms profit might decrease when offshoring level is small and increase when it's beyond some level. Those results come exactly from the changes of the production cost which are derived in Proposition 1.

3.2 Firm's Decisions on Offshoring and Technology

By the timing of the model, the firms will choose the production location and the clean technologies before production in each period. The state variables before firms' decisions are

[47] As in the corresponding case in Proposition 1, increasing offshoring will decrease western low-skill firm's profit if $\sigma \geq \epsilon$ and $Y_h/Y_l \geq (\epsilon/(\sigma-\epsilon))^{\epsilon/(\epsilon-1)}$.

the emission levels e_w, e_e. Denote state variables $e = (e_w, e_e)$. Also denote the western low-sector firm's value by V_w before making the offshoring decision at stage 1 and by v_w after that in stage 2. Similarly denote by V_e and v_e for the low-skill sector firms in the east country. The value of the high-skill sector firm is denoted by W. Then first analyze low-sector firms' technology adoptions at stage 2 which is given by the following Bellman equations.

$$v_w(k, e) = \max_{e'_w \leq e_w} \pi_{lw}(k, e'_w) - C_e(e'_w, e_w) + \frac{1}{1 + r'} V_w(e') \tag{31}$$

$$v_e(k, e) = \max_{e'_e \leq e_e} \pi_{lw}(k, e'_e) - C_e(e'_e, e_e) + \frac{1}{1 + r'} V_e(e') \tag{32}$$

Notice the net profit flow for the low-sector firms in both countries is denoted by $\pi^*(= \pi(\cdot) - C_e(\cdot, \cdot))$. So the value of low-sector firm staying in the west equals the sum of the net profit flow and the expected next period value.[48] Now back to stage 1, low-sector firms' decision on production offshoring is given by

$$V_w(e) = \max \left\{ v_w(k, e), \beta_o V_e(e) \right\} \tag{33}$$

$$V_e(e) = \max \left\{ v_e(k, e), \beta_m V_w(e) \right\} \tag{34}$$

Only consider the case that there is positive offshoring each period. That is, the equilibrium offshoring level is achieved when western $L - sector$ firms are indifferent about whether shifting production abroad or not. Therefore, at stage 1 of each period, the measure of offshoring $k^* = k^*(e)$ is determined by

$$V_w(e) = v_w(k^*, e) = \beta_o V_e(e) \tag{35}$$

Thus, together with equation(32) and (33), we can get

$$V_e = v_e > \beta_m V_w \tag{36}$$

Therefore, the positive offshoring assumption is characterized by the previous two equalities. That is, the offshoring level at stage 1 of each period will just make the western low-skill sector firms indifferent between offshoring or not and the offshored firm will prefer staying in the

[48]Notice the discounted period $t+1$ firm's value at period t is given by $1/(1 + r_t)V_{t+1}$ where the interest rate $1 + r_t$ is exactly the relative price of the final goods of period t respect to period $t + 1$.

east country. Combining with the Bellman equations, the positive offshoring assumption is equivalent to the assumption about the two countries' net profit flow satisfying the relation below

$$\pi^*_{lw}(k^*, e^*, e) = \beta_o \pi^*_{le}(k^*, e^*, e) \tag{37}$$

Then, the necessary and sufficient condition to have positive offshoring is that the relative net profit flow between the western and eastern low-skill firms is exactly equal to the parameter β_o which is the fraction of offshored firms' value belonging to the west country.

Then by rewriting the value functions, the standard Euler equations for the optimal choices of clean technology can be derived as below.

$$(n+1)c_e \frac{e_w}{e'_w} = \frac{c_e}{1+r'}[(\frac{e'_w}{e''_w})^{n+1} + n] + \frac{\alpha}{1-\alpha}(e'_w)^{n+1} S_l \tau_w (\frac{w_{lw}}{z_{lw}} + \tau_w e'_w)^{-\frac{1}{1-\alpha}} \tag{38}$$

$$(n+1)c_e \frac{e_e}{e'_e} = \frac{c_e}{1+r'}[(\frac{e'_e}{e''_e})^{n+1} + n] + \frac{\alpha}{1-\alpha}(e'_e)^{n+1} S_l \tau_e (\frac{w_{le}}{z_{le}} + \tau_e e'_e)^{-\frac{1}{1-\alpha}} \tag{39}$$

By the equilibrium production cost equation(23)and(25), together with the formula of S_l, the Euler equations can be simplified as below

$$(n+1)c_e \frac{e_w}{e'_w} = \frac{c_e}{1+r'}[(\frac{e'_w}{e''_w})^{n+1} + n] + (e'_w)^{n+1} \tau_w \frac{L_w z_{lw}}{(1-k)A_l} \tag{40}$$

$$(n+1)c_e \frac{e_e}{e'_e} = \frac{c_e}{1+r'}[(\frac{e'_e}{e''_e})^{n+1} + n] + (e'_e)^{n+1} \tau_e \frac{L_e z_{le}}{\nu k A_l} \tag{41}$$

The left side is the cost of emission reduction. The first term in the right side is the reduction of next period's cost due to the current period's clean technology adoption and the second term is the increase of current period's profit. Then the value for high-sector firms in the west is given by

$$W(e) = \pi_h(k^*, e^*) + \frac{1}{1+r'} W(e^*) \tag{42}$$

Then all firms' problems for current period have been solved and both the goods and labor market are clear. In the next period, the firms will solve the similar problems again. Now take a look at each country's gross national product(GNP) which includes the wage income, the firms' profits and environmental tax revenues. After calculations, the GNP for each countries is given below

$$GNP_w = (1-k)A_l(\frac{\pi_{lw}}{1-\alpha} - C_e(e'_w, e_w)) + \beta_o k A_l \pi^*_{le} + A_h \frac{\pi_h}{1-\alpha} \tag{43}$$

$$GNP_e = \alpha \nu k A_l \frac{\pi_{le}}{1-\alpha} + (\nu - \beta_o) k A_l \pi^*_{le} \tag{44}$$

For the west country, the first term gives the sum of low-skill workers' wages, the total tax revenues collected, and the total net profits of the low-skill sector firms not offshored.[49] The total profits of the offshored firms belonging to the west is given by the second term. The third term in equation of GNP_w is the sum of total high-skill workers' wages and the profits of the high-sector firms. Similarly for the east country, the first term gives the sum of total workers' wages and tax revenue. And the second term is the total profits of the firms for the east, which including the offshored firm from the west and the additional ones generated due to offshoring. By the equilibrium offshoring satisfying equation(36), the GNP of the west country can be simplified as

$$GNP_w = (1-k\alpha)A_l \frac{\pi_{lw}}{1-\alpha} - A_l C_e(e'_w, e_w) + A_h \frac{\pi_h}{1-\alpha} \tag{45}$$

By the form above, it seems that, in equilibrium, all productions take place domestically except that a fraction of $k\alpha$ of total revenue of the low-skill sector are paid to the west workers. Recall that an increase of offshoring will increase profits of both types of firms in the west. So if offshoring are treated as exogenous, increasing offshoring will benefit total domestic income through revenue increase while damage it because of more labor payment to the east country. Now consider the total output of the two countries and it's given by

$$GNP_w + GNP_e = Y - (1-k)A_l C_e(e'_w, e_w) - \nu k A_l C_e(e'_e, e_e) \tag{46}$$

That is, the total output is equal to the total final goods produced excludes the total clean technology adoption costs. To clear the goods markets, together with Euler equation(5), the interest rate r_t at period t satisfying

$$\frac{1+r_t}{1+\rho} = \frac{Y_t - (1-k_t)A_l C_e(e_{wt}, e_{w(t-1)}) - \nu_t k_t A_l C_e(e_{et}, e_{e(t-1)})}{Y_{t-1} - (1-k_{t-1})A_l C_e(e_{w(t-1)}, e_{w(t-2)}) - \nu_{t-1} k_{t-1} A_l C_e(e_{e(t-1)}, e_{e(t-2)})} \tag{47}$$

[49] By the CES production function, the total production costs count for a fraction of α of the total revenue while the profit counts for $1-\alpha$ of the total revenue. Therefore, the term $\pi_{lw}/(1-\alpha)$ is the total revenue of domestic low-sector firms.

Now this paper will only consider the competitive general equilibrium defined below.

Proposition 3. *The competitive general equilibrium path consists of the consumptions of all workers* $\{C_{lw}^t, C_{le}^t, C_h^t\}$*, the wages* $\{w_{lw}^t, w_{le}^t, w_h^t\}$*, the emission per output* $\{e_w^t, e_e^t\}$*, the offshoring levels* $\{k^t\}$ *and the interest rates* $\{r^t\}$ *such that*

(i) the consumptions solve each individual's problem given by (4) and satisfy Euler equation(5);

(ii) the wages clear the labor market and satisfy the equations(23)(24)(25);

(iii) the interest rates clear the good market and satisfy equation(46);

(iv) the emissions solve the Bellman equations for low-skill sector firms in both country and satisfy the equations(39)(40);

(v) the offshoring levels guarantee the positive offshoring each period and satisfy the equation(36).

After a close look at the equations which define the competitive equilibrium path, an intuitive and interesting result can be detected. If the model parameters such as the pollution tax τ_w, τ_e and the measure of firms A_l, A_h doubles, then the consumptions and the wage rates of all workers will also double. Meanwhile, the emission and offshoring levels and the interest rate will remains. The key is that double the firm numbers of both sectors will double the outputs of both sectors and also the final output. Thus the interest rate will remains to clear the goods markets. Due to the homogenous assumptions of the consumers of both countries, all will double their consumptions. By the Euler equations on optimal emission technologies, the marginal benefit of reduction of emission remains if both pollution taxes and the firm measures double. And thus the emission path will remain the same. Finally, the profits of all firms are the same as before so as the net profits of the low-sector firms of both countries. Therefore the offshoring doesn't change. Now this results are summarized below before talking about the steady state of the economy.

Proposition 4. *If multiply the pollution tax* τ_e, τ_w *and the firm measures* A_l, A_h *by a factor* λ (> 0)*, and assume the equilibrium path are denoted as in previous proposition, then the new equilibrium path consists of the same emissions, the same offshoring and interest rates but with consumptions and wages multiplied by* λ*.*

This simple observation is very helpful for the identification part. That's because we can just re-scale the wages first when it's very large.

3.3 The Steady State

Finally, the technology levels will reach the steady state. Also are the workers' wages and output levels. Denote the steady state technology and wages as $\bar{e}_\theta, \bar{w}_{l\theta}$ with $\theta \in \{e, w\}$. Then by the Euler equations,

$$\frac{\bar{r}}{1+\bar{r}} c_e(n+1) = \frac{\alpha}{1-\alpha}(\bar{e}_w)^{n+1}\bar{S}_l\tau_w(\frac{\bar{w}_{lw}}{z_{lw}} + \tau_w\bar{e}_w)^{-\frac{1}{1-\alpha}} \tag{48}$$
$$\frac{\bar{r}}{1+\bar{r}} c_e(n+1) = \frac{\alpha}{1-\alpha}(\bar{e}_e)^{n+1}\bar{S}_l\tau_e(\frac{\bar{w}_{le}}{z_{le}} + \tau_e\bar{e}_e)^{-\frac{1}{1-\alpha}} \tag{49}$$

Just take ratios, we can obtain

$$\frac{\bar{e}_w}{\bar{e}_e} = (\frac{\tau_e}{\tau_w})^{\frac{1}{n+1}}(\frac{\bar{w}_{lw}/z_{lw} + \tau_w\bar{e}_w}{\bar{w}_{le}/z_{le} + \tau_e\bar{e}_e})^{\frac{1}{(1-\alpha)(n+1)}} = (\frac{\tau_e}{\tau_w}\frac{L_e}{L_w}\frac{z_{le}}{z_{lw}}\frac{1-\bar{k}}{\nu\bar{k}})^{\frac{1}{n+1}} \tag{50}$$

The second equality is obtained by applying equation(25) where $\bar{k}$ is the equilibrium offshoring percentage. Therefore, in the final state of the economy, the ratio of the emission per output is negatively related with the pollution tax ratio but positively related with the production cost ratio. Besides, given the production cost are higher in the west country, the final pollution cost for the firm($\tau_\theta\bar{e}_\theta$)will be still higher in the west as long as its pollution tax is higher than the east country. By the second equality, the equilibrium offshoring can be solved out.

$$\bar{k} = \left(1 + \nu(\frac{\bar{e}_w}{\bar{e}_e})^{n+1}\frac{\tau_w}{\tau_e}\frac{L_w}{L_e}\frac{z_{lw}}{z_{le}}\right)^{-1} \tag{51}$$

That is, the equilibrium offshoring is negatively related with the clean technology, pollution tax, labor productivity and labor endowment ratios.[50] There's no doubt the production capacity of the west which are measured by the labor endowment and the labor productivity are negatively related with offshoring.

Now turn to the relation about net profits of $L-sector$ firms in both countries given by equation(35). In steady state, there is no clean technology adoption cost. Using the formulas about the profit flow functions in equation(16), the equilibrium unit product cost ratio is given

[50] I want to point out that, in the special case when $n = 0$, the final offshoring percentage is negatively related with the pollution cost.

by

$$\frac{\bar{w}_{lw}/z_{lw} + \tau_w \bar{e}_w}{\bar{w}_{le}/z_{le} + \tau_e \bar{e}_e} = \beta_o^{-\frac{1-\alpha}{\alpha}} \tag{52}$$

So in the steady state, due to the offshoring assumption, unit production cost ratio between the west and east country are only related with the offshoring cost. Any policy which can reduce offshoring cost(while increase the remaining part β_o), will decrease the relative cost of production in the west. That's because that there will be more offshoring due to cost reduction thus reduce the production cost in the west while increase the production in the east. Plug the above equation to equation(40), the equilibrium emission level ratio is given by

$$\frac{\bar{e}_w}{\bar{e}_e} = \beta_o^{-\frac{1}{\alpha(n+1)}} (\frac{\tau_e}{\tau_w})^{\frac{1}{n+1}} \tag{53}$$

Thus, the steady state emission ratios are positively related with the offshoring cost but negatively related with the pollution tax ratio. To make the equilibrium pollution rate lower in the west needs the pollution tax in the west exceeds that in the east by some certain level.[51] Now the results about the relative production costs and the relative emission levels are summarized in the following proposition.

Proposition 5. *The relative production costs and the relative emission levels of the low-skill sector between the west and the east country are given by equation(46)and(47)respectively. Reduction of offshoring cost will increase both the relative production cost of the low-skill sector and the relative emission level in the west. The emission ratio is negatively related with the pollution tax ratio.*

Now plug equation(47)to equation(45), the equilibrium offshoring is obtained as below[52]

$$\bar{k} = \left(1 + \nu \beta_o^{-\frac{1}{\alpha}} \frac{L_w}{L_e} \frac{z_{lw}}{z_{le}}\right)^{-1} \tag{54}$$

Therefore, the equilibrium offshoring is negatively related with the production capacity ratio between the west and east and also with the offshoring cost. Thus increase the production capacity in the west or reduce the offshoring cost in the east will boost production offshoring

[51] In this case, to make $\bar{e}_w \leq \bar{e}_e$ iff $\tau_w/\tau_e \geq \beta_o^{-1/\alpha}$.

[52] Another way to achieve this is take ratios of the equilibrium profit flow and use the equation(22)and(23). Be aware that it's still true that $\bar{k} \leq \hat{k}$ and equality holds iff $\beta_o = 1$. That is, the steady state offshoring will reach the most reasonable level only if there is no offshoring cost at all.

in the long run. Just notice the extra related industry generated in the east together with production offshoring are assumed to be proportional to the measure of firms offshored which is denoted by $\nu \geq 1$. It's straightforward that the more extra firms generated due to offshoring will reduce the equilibrium offshoring level. At last, notice that the final offshoring level does not depend on the environmental regulations of either country. That's because the pollution haven effects vanish with time due to firms' pollution abatement effects. As before, the results on the steady state offshoring level are summarized in the following proposition.

Proposition 6. *The steady state offshoring level is given by equation(48). Increasing the relative production capacity in the west or the offshoring cost will decrease the final offshoring level.*

Since the measure of firms in each sector A_l, A_h are fixed, so the output levels in each sector will also reach the steady state when both offshoring and the clean technology reach the steady state level. By the Euler equation of consumption given by equation(5) and the goods market clearance condition, it is easy to conclude that the consumption will also reach the steady state and the final interest rate is equal to the preference discount factor, i.e. $\bar{r} = \rho$. Then solve equation(38)and(39) by using the equations(6)(7)(16)(20)(26)(28)and(41) for the equilibrium emission levels of both countries.

$$\bar{e}_w = \left(\frac{\rho}{1+\rho} \frac{A_l c_e (n+1)}{\tau_w} \frac{1}{L_w z_{lw} + \nu^{-1} \beta_o^{\frac{1}{\alpha}} L_e z_{le}} \right)^{\frac{1}{n+1}} \tag{55}$$

$$\bar{e}_e = \left(\frac{\rho}{1+\rho} \frac{A_l c_e (n+1)}{\tau_e} \frac{\beta_o^{\frac{1}{\alpha}}}{L_w z_{lw} + \nu^{-1} \beta_o^{\frac{1}{\alpha}} L_e z_{le}} \right)^{\frac{1}{n+1}} \tag{56}$$

After taking derivatives, it's not difficult to obtain the following results on comparative analysis.

Proposition 7. *Given by the equation(49)and(50), the final equilibrium emissions per output of both countries can be reduced if*

(i) people are more patient, i.e. the utility discount factor ρ are smaller;

(ii) there are less firms in the low-skill sector;

(iii) the clean technology adoption costs are lower;

(iv) their domestic pollution tax is higher;

(v) the production capacity of either country($L_w z_{lw}$ or Lez_{le}) grows.

In particular, reduction in offshoring cost will lower the equilibrium emission level in the west while lift that in the east.

The conclusions on some factors above are very intuitive such as the effects of innovation costs and the government regulations on equilibrium emissions. When people are more patient, then more final goods are saved so the invest in clean technology will rise due to lower interest rate. Thus the final emission per output will be lower for both countries. If there are less low-skill sector firms in the low sector, the profit of each firm in the low-skill sector are higher and the marginal benefit from the emission reduction is larger. So low-sector firms will invest more in the clean technology and the final emission levels of both countries will be lower. Similar argument for the effects of either country's production capacity growing.[53] But for a reduction in offshoring cost, the number of firms offshored will increase. So there is a decrease of firms in the west and an increase of firms in the east. That means the profit and the marginal benefit of emission reduction will rise in the west but falls in the east. So finally the emission in the west will decline while it rises in the east.

At last, I want to mention the effects of the offshoring cost reduction on those firms' profits in the steady state. Notice that the equilibrium offshoring $\bar{k} < \hat{k}$. And together with the negative relation between the equilibrium offshoring and the the offshoring cost, all results about the firms' profits in Proposition 2 hold. And reducing offshoring cost will increase the offshoring level in the steady state. Therefore the profits of the high-skill sector firms will rise and the profit of offshored firm will decrease. Meanwhile the west low-skill sector firm's profit will either increase or decrease first then increase in the form of U-shaped function. But the relative profit between the west low-skill firms and their east counterpart are increasing with the reduction of the offshoring cost.

4 Data

In this section, the model developed above will be applied to analyze the offshoring and related environmental issues between the U.S. and China from 1999 to 2013. During this time period, there has been dramatic rise between the bilateral trade between those two countries while their environment experienced opposite changes. To solve the model numerically, this paper uses the employment and wages data in manufacturing sectors and the PM2.5 concentration levels of

[53]I want to point out that the labor productivity's growth are treated as exogenous and finally reach the steady state too. So the productivity growth has a positive externality for the clean technology adoption.

both countries.

This paper use the IPUMS-CPS data for US labor employment and wage(See King et al. (2010)). I only use employment and wages in the manufacturing sector for both U.S. and China. For US labor force, the low-skilled labor are defined as high school graduates or blow and high-skilled labor are those with some college or above. The manufacturing FIEs' employment and output in China are from NBS Department of Industrial Statistics (2014) and are based on the annual survey of state-owned industrial enterprises and non-state-owned enterprises with revenue from primary business above certain scale.[54] The manufacturing workers' compensation are from National Bureau of Statistics of China (2014). Here the firms which receive funds from Hong Kong, Taiwan and Macau and foreign countries are treated as FIEs in this paper. The total manufacturing employment due to production offshoring from U.S. to China is consisted of two parts: the U.S. MNCs' manufacturing employment(direct offshoring) and the other firms' employment for exporting to U.S.(indirect offshoring). The formula for calculating the indirect offshoring is given below

$$\begin{aligned}&\text{indirect offshored manufacturing employment} \\ &= \frac{\text{other FIEs' manufacturing employment} \times \text{Prob(export)} \times \text{Prob(export to US}|\text{export)}}{\text{share of FIEs' export in total China export}}\end{aligned} \tag{57}$$

The share of export in total sale for China domestic firms, firms funded by Hong Kong, Taiwan and Macau and foreign firms and FIEs are calculated using NBS Department of Industrial Statistics (2014)(See Figure in Appendix). The firms funded by Hong Kong, Taiwan and Macau are almost equally likely to export as the foreign funded firms and more than 5 times likely to export compared with China domestic firms. Conditional on export, the probability for FIEs export to U.S. is 0.24. And by Figure 2, FIEs' export account for about 54 percent of total China export. The data for manufacturing employment and compensation for both countries are summarized in Table 3, 4, and 5 in the Appendix.

The Figure illustrate the trends of employment and wages in both countries. By the data, there were annual reductions of 355 thousand low-skilled manufacturing workers and 103 thousand high-skilled manufacturing workers from 1999 to 2007. And the fractions of low and high skilled jobs in the manufacturing sector declined from 18.58% and 12.79% in 1999 to 14.32%

[54]The primary business revenue for surveyed non-state-owned industrial enterprises should be above 5 million RMB from 1998 to 2010, above 20 million RMB since 2011. Before 2007, all state-owned enterprises were surveyed and after that, the stat-owned enterprises are surveyed only if they satisfy the same requirement as the non-state-owned enterprises.

Figure 3: Employment(left) and Wage(right) Trend in US and China

and 9.91% in 2007. The financial crisis and the great recession broke out in December 2007 hit the low-skill jobs more than the high-skill jobs and caused much worse damages to the manufacturing sector than the overall economy. And up to 2013, the lost low-skill jobs hadn't come back. And the employment for the high-skill manufacturing workers didn't returned to the before-crisis level until 2012.

For the employment by foreign funded enterprises in China, both the number of workers employed and their wage rate are rising since 1999. Both the total and the manufacturing sector workers employed by the foreign firms grows over 12 percent annually before 2007. But the total offshored manufacturing employment reached the highest level at 2008 and declined since then. The wages for the manufacturing workers employed by FIEs in China grows annually over 7 percent. The financial crisis did less damage to the offshored manufacturing employment and wages compared with U.S. labor market.

Through out this paper, the labor productivity is treated as exogenous and assumed to be constant after 2013. The data on U.S.manufacturing labor productivity is published by BLS. I use the BLS data on output per working hour as the measure for labor productivity and calculate the output per worker for Chinese manufacturing labor productivity(Figure). From 1999 to 2013, the average U.S. manufacturing labor productivity grows by 3.24 percent annually.[55] While during the same time period, the annual growth rate for Chinese manufacturing workers is 12.85. Due to the rapid labor productivity growth, the total manufacturing output in China surpassed that of US in 2010 which made China as the largest manufacturing country since

[55]By the BLS data, the labor productivity dropped by only 0.44 percent during the 2008-2009 great recession. But some papers noticed the growth of the labor productivity during the past crisis. For details, see Lazear et al. (2013), McGrattan and Prescott (2014) and Fernald (2014).

then.[56] For calculation of the output per worker in China manufacturing sector, the total manufacturing employment in China are obtained from BLS International Labor Comparisons for 2002-2009.[57] For the other periods, the manufacturing employment data are from NBS Ministry of Labor and Social Security (2014).

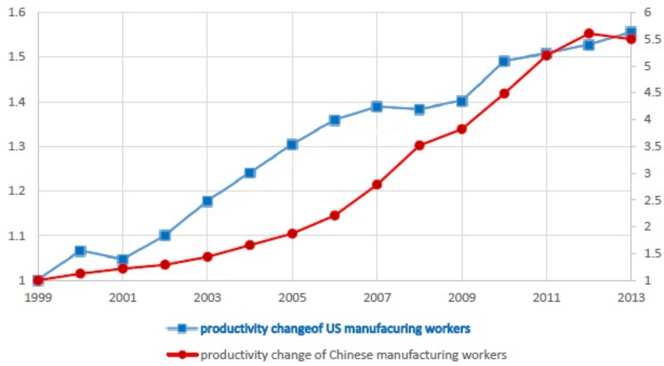


Figure 4: Productivity Growth in US and China

The data for PM2.5 concentration levels and emission in U.S. is from EPA website and National Emission Inventory(NEI) air pollutant emissions.[58]. Another source for PM2.5 data is the Atmospheric Composition Analysis Group of Dalhousie University in Canada. Their recent papers by Boys et al. (2014) and van Donkelaar et al. (2015), which are joint works with scientists from China and United States, develop a new algorithm to calculate a unified fifteen year time series(1998-2012) of the global ground-level PM2.5 concentrations using NASA satellite photos at a resolution of about 10km by 10 km. Those papers discovered that the world's four broad areas show significant and coherent annual trends: a consistent reduction of PM2.5 in Eastern U.S. and the rapid growth of PM2.5 in the Eastern China, South Asia and the Arabian Peninsula. The PM2.5 concentration level in Eastern U.S. decreases annually by about $0.39\mu g/m^3$ and that for Eastern China increases by about $0.79\mu g/m^3$ per year.[59] The changes in secondary inorganic aerosols formations, whose formation are due to all types of combustion activities and industrial processes, explain well the observed trends for Eastern China and US and South Asia while the mineral dust largely explain the trend in the Arabian

[56] See the Figure in the Appendix for the manufacturing output and total output of both countries over the past 15 years.

[57] The total employment in the manufacturing sector of China is consisted of the urban area and rural area where workers are employed by the town and village enterprise. The data published by China's Labor Ministry cover the urban area but missing some rural area employment. So the data on town and village enterprise manufacturing workers are reported by Ministry of Agriculture. For details, see Banister (2005).

[58] The PM2.5 level data can be download at the EPA website: http://www.epa.gov/airtrends/pm.html. And the NEI data is available at http://www3.epa.gov/ttnchie1/trends/.

[59] The PM2.5 concentration annual growth rates for South Asia and Arabian Peninsula are $0.93\mu g/m^3$ and $0.81\mu g/m^3$ according to Boys et al. (2014).

Peninsula. The second paper by van Donkelaar et al. (2015) derived the population-weighted global PM2.5 concentrations which is exactly the data my paper will use. According to their estimates, the global population-weighted PM2.5 concentration increased by $0.55\nu g/m^3$ per year due to the rapid growth in developing countries despite the reduction in developed regions. The figure below gives the three-year-average population-weighted PM2.5 levels which on average an American and a Chinese are exposed to from 1998 to 2012.

In the numerical part of this paper, the pollution stocks of PM2.5 are measured by the national PM2.5 levels. I compared the PM2.5 levels between the EPA measures and the estimates by van Donkelaar et al. (2015). The EPA's national PM2.5 concentration level is highly correlated with the estimates by van Donkelaar et al. (2015) but is on average $1.81\mu g/m^3$(or 18%) higher than the latter one.[60]The PM2.5 concentration levels decreased annually by $0.34\mu g/m^3$(2.9%) for U.S. and increased annual by $1.36\mu g/m^3$(2.86%) for China from 1999 to 2011. The proportion of population in Eastern China living above the World Health Organization(WHO) interim target level $35\mu g/m^3$ increase from 51 percent during 1998-2000 to 70 percent during 2010-2012. In contrast, the proportion of North America population living above the WHO air quality guideline $10\mu g/m^3$ dropped from 62 percent in 1998-2000 to 19 percent in 2010-2012.

5 Calibration

Some of the model parameters are predetermined based on literature. The utility discount factor $\rho = 0.04$ as in Acemoglu et al. (2015) which makes the steady state interest rate equal to 4 percent. [61] Here I choose the long-run elasticity of substitution between the low-skilled and high-skilled workers $\epsilon = 1.59$ which is consistent with the estimates by Ciccone and Peri (2005).[62] The elasticity of substitution within the same sector $\sigma = 5.63$ because it lies between the import demand elasticity estimate 4 across 3-digit SITC codes and 12 across 10 digit HTS sectors given by Broda and Weinstein (2006). By review paper Anderson and van Wincoop (2004), most estimates of elasticity of substitution between traded goods is between 5 and 10.

Some of the model parameters are chosen based on the data. The parameter ν which measures

[60]The concentration level calculated by the EPA is the average of the observations from total 533 monitoring stations and the distributions of the EPA's monitoring stations are highly correlated with the population concentration. The correlation between the two data sets is 0.94.

[61]In Acemoglu et al. (2015), they assume the 2 percent annual growth rate along the balanced growth path. Together with the 4 percent utility discount rate, the annual return on equity would be 6 percent. Those are the long-run growth rates and equity return rate in U.S..

[62]Most estimates of the elasticity of substitution between low- and high-skilled workers is between 1.5 and 2 according to Ciccone and Peri (2005).

the total exporting firms generated due to offshoring are based on the fact that all FIEs' export account for about 54 percent of total export from China to U.S. and the left are sold by domestic firms in China. So this paper chooses $\nu = 1/0.54 = 1.8519$. For the pollution level accumulation equation, I assume $N = 1$, that is, the PM2.5 accumulation level just depends on the current and previous period emissions. It's based on the observations that the PM2.5 levels are very easily affected by season, weather conditions and pollution control policy. [63] During the 2008 Beijing Olympic Games, which took place from August 8th to 24th, the fine particulate matter concentration decreased significantly when the implemented pollution control measures contributed to at least 43 percent reduction.[64] Then using the 16-year (1999-2014) data on U.S. PM2.5 levels and annual manufacturing emissions, the OLS regression gives the estimation of the coefficients[65]

$$\eta_0 = 0.00886136, \qquad \eta_1 = 0.00685536 \tag{58}$$

Then the total manufacturing emissions of PM2.5 in China can be solved out using the PM2.5 levels in China and the pollution accumulation equation.[66] Using the total manufacturing emissions, it's straightforward to calculate the emission per worker($e_\theta z_{l\theta}$) in both countries.[67]

Now the unknown parameters to calibrate include the innovation cost coefficients n, c, the pollution tax rates τ_w, τ_e, the measure of firms A_l, A_h and offshoring cost β_o. Besides, I also need to guess the starting values for the emission intensities e_w, e_e and productivities z_{lw}, z_{le} and z_h. The computing logic is to random pick the parameters and initial values for emission intensities and labor productivities and assume the steady state can be reached in finite period to generate the initial guess of the equilibrium path for the key variables offshoring level k and emission intensities e_w, e_e.[68] Then by the Proposition 3, update the grid points by solving

[63] By EPA estimates, the PM2.5 levels in the eastern half of the United States are typically higher in the third calendar quarter (July-September) because of the sulfur dioxide emissions from power plants in that region. But for the west part, Fine particle concentrations tend to be higher in the fourth calendar quarter in part because nitrates are more readily formed in cooler weather, and wood stove and fireplace produces more carbon. For more case studies on the influential factors on PM2.5 concentration see Tai et al. (2010) for US, Liu et al. (2015) for Beijing of China and Wang and Ogawa (2015) for Nagasaki, Japan.

[64] For details, see Yang et al. (2011).

[65] I use the manufacturing emissions instead of total emissions because the correlation between PM2.5 level with manufacturing emissions equal 0.96 but only equals 0.45 if with total emissions.

[66] In addition, I assume the manufacturing emissions are the same for 1999 and 1998 in China. Given the manufacturing outputs are close for those two years, it's not a strong assumption.

[67] Notice that only the low-skilled jobs involve emissions in U.S..See the Figure A.9 in the Appendix for the calculated PM2.5 emission per manufacturing worker in both countries.

[68] The total number of periods to reach the steady state is 500 in the calibration process. I also increase the time span and check that the change of the equilibrium path is very small.

backwardly for the optimal choice of the three key variables using the Euler equations for e_w, e_e and the equilibrium equation for k.[69] The iteration process stops when there is little change for the equilibrium paths. The optimal choices of parameters and the initial values for emission intensities and productivity levels are based on matching the following point values:

1. the emission per low-skilled worker in US $e_w z_{lw}$ over 1999 to 2014
2. the emission per worker in China $e_e z_{le}$ over 1999 to 2011
3. all workers' wages w_{lw}, w_{le} and w_h over 1999 to 2013

After picking a large number T and assuming the steady state can be reached after T periods, the basic algorithms for the computing process follow such steps:

1. randomly generate the model parameters and initial values for emission intensity and productivities;
2. for one set of parameters, calculate the steady state values for key variables $\bar{k}, \bar{e}_w$ and $\bar{e}_e$;
3. using the productivity growth rate, calculate the productivities paths z_{lw}, z_{le} and z_h;
4. generate the initial grids for offshoring k, the emission intensities e_w, e_e based on steady state and starting points;
5. solve the model backwardly and update the grids for the three key variables;
6. iterate the process to update the equilibrium paths;
7. iteration stops once the changes of the grid points are less than some criteria;
8. calculate the equilibrium wages and pollution levels for both countries;
9. select the optimal parameters and solutions by matching the moments above.

The calibrated parameters and initial values for the emission intensities and labor productivities are listed in the table below.

Among the calibrated parameter values, the share of the offshored firms(FIEs)in China held by the foreigners is equal to 75 percent and it's very consistent with the share of foreign fund in the total registered capital of the FIEs. According to the China Foreign Investment Report by

[69]While solving backwardly, by holding the previous and next period's key variable values fixed and solve the equations for the optimal current period key variables' values.

Table 1: Calibrated Model Parameters and Initial Values

Param.	Mfg.	Note
n	1.12	the exponetial increase of innovation cost
β_o	0.75	share of offshored firm's value left
c	99.32	clean technology innovation cost
A_l	14.72	measure of firms in low-skill sector(in thousand)
A_h	90.82	measure of firms in high-skill sector(in thousand)
τ_w	224.8	US tax rate on PM2.5 (in US dollars/ton)
τ_e	68.4	China tax rate on PM2.5 in US(in US dollars/ton)
z_{lw}^0	0.67	US low-skilled worker's productivity in 1999
z_{le}^0	0.03	China's worker's productivity in 1999
z_h^0	0.19	US high-skilled worker's productivity in 1999
e_w^0	107.65	US emission intensity in 1998
e_e^0	1035.6	China's emission intensity in 1998

Chinese Ministry of Commerce, the share of total registered capital from abroad is 73.4 percent from 1997 to 2013. The share increased from 65.9 percent in 1997 to 81 percent in 2009 and stayed at 79.6 percent since then(see the figure in the appendix for details). So the share of profits goes to foreign holders should be less than this number because there are a lot of other costs such as the transportation cost, the tariff and profit loss due to imperfect intellectual property rights protection issues, etc. Recently all those costs might account for between 4 and 5 percent of the total profit flow.

The pollution tax in U.S. is about 224.8 dollars per ton for PM2.5 emission. The corresponding pollution tax in China is 68.4 dollars which is roughly about 30.4 percent of the U.S. regulation. As mentioned as in the beginning, there is no specific regulation for PM2.5 in China until 2012[70]. The positive pollution tax in China mainly is because of the regulation of dust emissions including PM2.5. Another reason is the externality from the regulation and monitoring of other pollutants such as sulfur dioxide, carbon monoxide and nitrogen oxides which affects the formation of PM2.5..[71] Later, I will compare the simulated PM2.5 emission for both countries and it's very clear the real tax should be a little bit higher than the estimate for US and lower for China.

Last I want to compare the relative productivity and emission intensity between US and China's low-skilled workers. The relative productivity of US low-skilled manufacturing workers

[70]The Chinese government has environmental regulations on dust emissions which include the particles with an aerodynamic diameter below $75\mu m$.

[71]According to US EPA's report United States Environmental Protection Agency (2004), the PM2.5 are made up of different chemical components including carbon, sulfate and nitrate compounds, and crustal materials such as soil and ash. And by Klimont et al. (2013), the sulfur emission in China rose from 2000 and peaked in 2006 and declined sine then.

respective to China's manufacturing workers dropped from 22 to 6 over 1999-2013. This results is a direct outcome of the different productivity growth paths of two countries. Meanwhile, the relative emission per output between US and China's manufacturing production workers was 9.6 in 1998.[72] Given the build-on-giants'-shoulders style of the clean technology innovation process, it's easier for China to adopt clean technology because the current technology level is lower.

6 Numerical Results

In this section, I will first check the solution for the three policy variables: offshoring and two countries' emission intensities. After that, the comparison of simulated and true wages and pollution will be discussed.

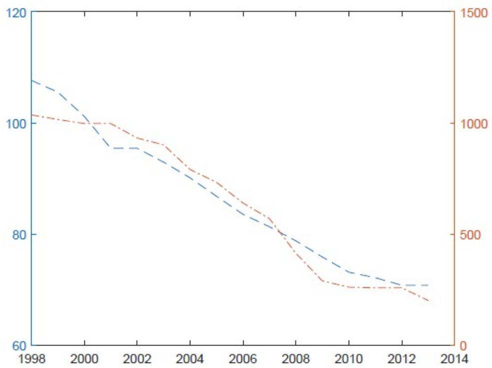


Figure 5: Emission Intensities in US and China

First the emission intensities are dropping in both countries over 1999-2013(Figure). On average, the emission intensity in US declined annually by 2.8 percent while it's 10.4 percent for China. That's because the emission intensity in China is about 7 times as that in US. Due to different decrease rates, the relative emission in China dropped from 9.6 to 2.8 over the time period. In the long run, the emission per output in US will drop to 22.44 ton which is roughly 32 percent of the current level. For China, the future emission intensity will drop by 83 percent of current level and reach 33.4 ton per output.

The offshoring levels are given by Figure. The share of total offshoring including both the direct and indirect ones in total L-sector intermediate goods production rises since 1999 and are above 10 percent between 2002 to 2004 and declines since then. Currently, about 5.3 percent

[72] Lin et al. (2014) gives the relative emission intensities for other main air pollutants between China and US which are between 5 and 32. For details, see Table S1 in the supplement materials of their paper.

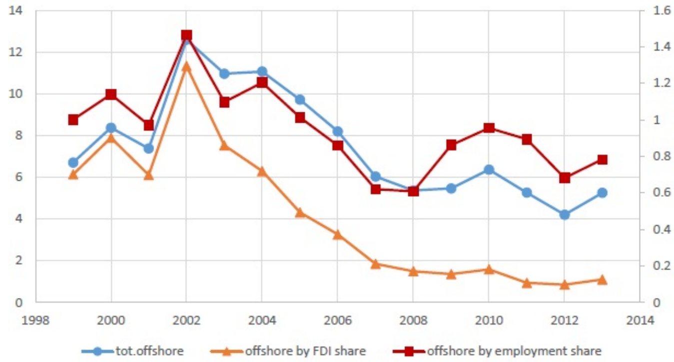


Figure 6: Total and Direct Offshoring from US to China

of total low-skilled manufacturing goods are produced in China. The direct offshoring through US multinational cooperations has the same trend and peaked at 1.4 percent of total low-skill manufacturing production and currently it drops to about 0.8 percent.[73]In the long run, the total offshoring share will drop to 3.6 percent.

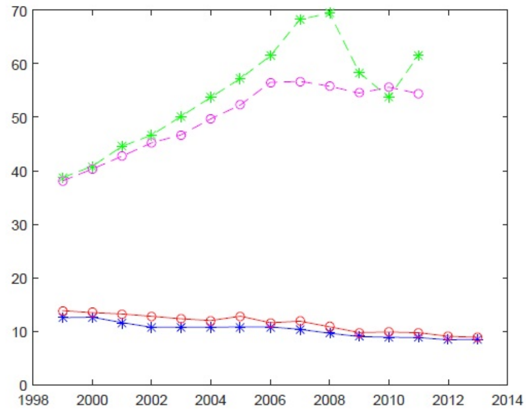


Figure 7: Simulated and Real PM2.5 Levels

Now I will check the simulated pollution level and wage rates. The trend of the simulated pollution level and the data matches well.[74] The simulated pollution level is higher than the data for China but lower than the observation for US. One reason mentioned before is due to the overestimation of regulation in U.S. and underestimate in China. Another reason is that there is measurement error for the data. Especially for China, the estimated population-weighted PM2.5 levels by van Donkelaar et al. (2015)cover all areas over China. As we know,

[73]According to a report by Bronfenbrenner and Luce (2004) which was submitted to the US-China Economic and Security Review Commission, about 58 plants announced to shift production to China, about 23 percent of total announcements between Jan 1, 2004 and Mar 31, 2004. In their earlier study Bronfenbrenner et al. (2001), from Oct 2000 to April 2001, the total number of announcements was 84 which accounted for 29 percent of total production shifts from U.S..

[74]The correlation coefficients between simulated level and data is 0.97 for US and is 0.93 for China.See the Figure A.9 in the Appendix for the simulated and matched data on emission per worker.

the offshored firms mostly are concentrated along the east coast.[75] And the pollution level are much heavier in the east coast than the national average.

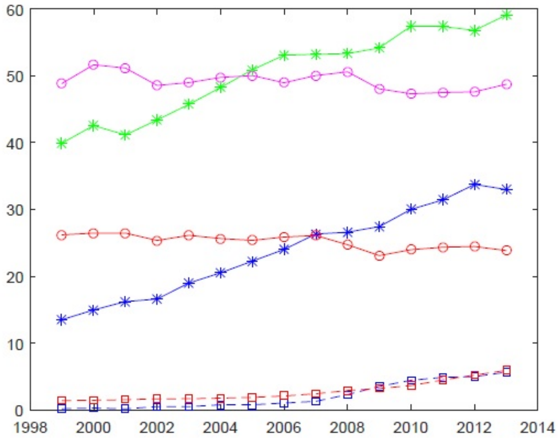


Figure 8: Simulated Wages(blue and green): from top US High- and Low-skilled and Chinese Workers

The simulated the wage for Chinese manufacturing workers matches well with the data.[76] I have to admit that there is different trend between simulated wages and true wage data in U.S..(See Figure A in the Appendix.) By simulated wages, there were annual growth rates of 2.9 and 6.7 percent for US High- and Low-skilled workers. But the data reveals little growth in wages. Even though the average annual labor productivity growth rate is 3.2 percent over 1999-2013. There are three reasons for the mismatch: first the two country model ignore the other countries which account for over 70 percent of production offshoring from US; second, this model doesn't consider the effect of the 2008 financial crises on employment and wages; last, the labor supply and frictions in the labor market are ignored in this paper. To solve this issues needs the data for other offshoring destinations or complicate this model which is beyond the scoop of this paper.[77]

7 Policy Analysis

Using structural approach, this paper can easily do counterfactual and policy analysis. Here three counterfactual experiment will be considered: first US would tight environmental regu-

[75]The top five provinces which attracted most FDI in China including Guangdong, Jiangsu, Shanghai, Shandong and Fujian are all located in the east part and the share of FDI goes to these five provinces reaches 64 percent of total FDI over 1999-2006.

[76]See Figure A in the Appendix.

[77]Another explanation is that the return to the capital are larger than the labor. So the labor productivity growth are not appreciated so much in the economy. For the issues of the departure between the return to capital and labor see Piketty (2014)and his other papers Piketty and Zucman (2013).

lations and increase the pollution tax; second, either US or China would subsidize the clean technology adoptions to reduce emissions; third, there is continuous decrease in the offshoring cost. For each scenario, the equilibrium path for emission, wages and offshoring levels are computed and compared with the benchmark case discussed before.

7.1 US Tighten Environmental Regulations

First consider the US EPA tighten the regulation of PM2.5 by increasing the pollution tax. Then the profit of the pollutant firms in the L-sector will decline and more firms will offshore production in the short run.[78] And the low-skilled workers in US will have lower wage than before due to the labor supply effect mentioned in the Model section. On the other hand, the Chinese workers' wage will rise. Then the profit of the offshored firms in China will decline than the benchmark case. I also do the numerical exercise and assume that US government increase pollution tax τ_w by 5 percent. Then offshoring will increase by 8.7 percent. That's the total offshoring increase and the direct offshoring increase will be around 1.13% because direct offshoring accounts for about 13 percent of the total manufacturing employment for production and export to US. Now comparing with the estimate of the pollution haven effects by Levinson and Taylor (2008). They find that 1% increase in pollution abatement cost is associated with a 0.2∼0.4% increase in net imports from Mexico and a 0.4∼0.6% increase in net imports from Canada. My estimation of the pollution haven effects on offshoring is comparable with theirs.

Due to the rise in offshoring, the US low-skilled workers' wage will decrease by 3.95% and Chinese workers' wages will rises by 1.7%. The 5% increase of PM2.5 tax in US make firms invest more in clean technology so the emission intensity and PM2.5 levels will drop by 0.03% compared with the benchmark case. Because of less pollutant firms left, the total abatement cost is lower and the national income level will increase by 0.04%. In China, the increase of total income due to offshoring is 1.25%.

7.2 US or China Subsidize Clean Technology Adoptions

First consider the case that the US government subsidize the cost for clean technology adoptions. Then US domestic L-sector firms' profits rise because of the reduced clean technology adoption costs. No doubt that there would be less firms offshored comparing with the benchmark case.

[78] As mentioned in the steady state part of Model section, the long-run offshoring are only affected with labor endowments, productivities and offshoring costs.

Due to the government subsidy, the clean technology level adopted by the US firms will be higher and emission intensity will be lower. So the pollution level would be lower and the US low-skilled workers' wages are higher. In the numerical exercise, I assume that US government subsidize 25 percent of firm's emission reduction cost. Then, the equilibrium net profit level of US low-skilled firms will be 2.24% higher and offshoring will be reduced by 0.9%. The emission intensity and PM2.5 level in US will be 0.01 percent lower than the benchmark case. The low-skilled worker's wage increases by 0.02%. On the other hand, the offshored firms in China increase their profit by 2.71 percent due to lower wages(1.4% decrease in Chinese workers' wage) and less investment in clean technology. Then in China, the emission intensity would increase by 1.9 percent and PM2.5 level will be 2.1 percent higher than the benchmark case. Finally the gross national income(GNP) will increase by 0.01 percent for US and decrease by 0.08 percent for China.

Now consider China subsidize 25 percent of firms' innovation costs. Then because the clean technology adoption costs are lower, the firms offshored in China will adopt more advanced clean technologies and make the emission intensity and PM2.5 levels about 0.21 percent lower over 1999 to 2013. The offshored firms' profits will rise by 3.3 percent and offshoring will increase by 0.81 percent. The Chinese workers' wages will increase by 0.49 percent and the wages of their US counterparts will decrease by 0.02 percent. The US Low-sector firms's profit will be 0.05 percent higher due to the reduction in labor cost. But the GNP for US will increase by 0.0002 percent while for China it will decrease by 0.15 percent due to the government subsidy expenditure.

Last, consider the scenario that both US and China subsidize 25 percent of firms' emission-reduction costs. Then firms of both countries's profit increase. But due to the innovation cost in US is higher than in China. So there would be less firms offshored to receive higher subsidy from US government. Then the low-skill workers's paycheck in US will be 0.02 percent higher while Chinese workers' wages are 1.4 percent lower. The environment in US will be a little bit better and PM2.5 in China will be 2 percent higher. Finally the national income for US will be 0.01 percent higher and for China will decline by 0.33 percent.

7.3 Offshoring Cost Declines

In this paper, offshoring cost is measured as a fraction of the firm's profit. So the share of left profit β_o will increase if offshoring cost decrease.[79] It's easy to observe that the profits of offshored firms rise so the offshoring will increase. Thus the wages of US low-skilled workers will decrease while the wages of their counterparts in China will increase. Then in equilibrium the net profits of US L-sector firms will increase but the net profit of China L-sector firms will decline.

I do the numerical exercise by assuming that the share of the left profit β_o increase by 1 percent. Then offshoring will increase by 0.27 percent. So the US low-skilled manufacturing workers' wages decline by 0.007% while Chinese manufacturing workers' wage increase by 0.31%. The changes of the profit flows for US and China are 0.02% and -0.43%. The firms located in both countries will invest more in clean technology for different reasons. For US firms, they can invest more in clean technology due to the decline in labor cost. The offshored firms want to reduce emission because the increasing of the marginal benefit of the reduction in pollution penalty due to the increased ownership. The emission intensity in US will decline by 1.7×10^{-5}% and in China decline by 0.16%. So are their PM2.5 levels. Finally, the national incomes of US and China decline by 3.6×10^{-5}% and 0.028%.

8 Conclusion

This paper propose a new frame work to analyze how different labor endowments and environmental regulations across countries will affect firms' dynamic production location choices and clean technology adoptions to reduce emission. The theoretical model characterizes the equilibrium paths for offshoring levels, emissions levels and wages rates of both offshoring source and host country. Also this model derives closed-form formulas for long-run offshoring and emission intensities which depends on the labor endowments, productivities, offshoring and technology adoption costs. So some comparative analysis could be easily done based on the steady states. For example, increasing the relative production capacity in the west or increasing the offshoring cost will decrease the final offshoring levels and decreasing offshoring cost will decrease the final emission level in the west while increasing emission in the east.

[79] As mentioned before, the share of profit flow left are also related with the ownership of the firms. If the western people increase the holding of the offshored firms, it's equivalent to the decrease of the offshoring cost here. See Feenstra and Hanson (2005) for discussion on the ownership of outsourcing firms in China.

Also the theory is applied to analyze the offshoring of low-skill manufacturing production between U.S. and China from 1999 to 2013. In order to fit the case into the two-country model, I used the generalized offshoring to includes all manufacturing production offshored to China by U.S. and her top trading partners for which China is an export platform. The assumption behind this concept is that all offshore source countries are choosing between China and U.S. for production location. This way will give the upper bounds for both the total offshoring to China and also the total low-skill manufacturing jobs held in U.S. without considering other offshoring host countries. My estimations give the highest offshoring levels happened over 2002-2005 when about 11% of total hypothetic low-skill manufacturing tasks are offshored to China. In the long run, the total share offshored will drop to 3.6% percent. And U.S. firms offshored about 1.0% of its low-skill manufacturing jobs in 1999 and dropped to about 0.8% in 2013. In the long run, it will drop to 0.5 percent. To my best knowledge, this is first estimate and prediction on U.S. manufacturing offshoring to China.

Besides, this paper is probably the first one to formally analyze the effects of U.S. EPA's regulation of PM2.5 since 1997 on manufacturing jobs offshoring. Also this paper gives the equilibrium path for both countries' PM2.5 concentration levels. In the long run, the PM2.5 concentrations for U.S. and China will be $2.8\mu g/m^3$ and $10.1\mu g/m^3$ respectively. During the counterfactual exercises, if U.S. government tighten the regulation of PM2.5 emission, a 5% increase in the tax will result in a 8.7% increase of total offshoring in China, among which about 1.1% are direct offshoring through US firms.

In this paper, all foreign invested enterprises and domestic export firms in China are treated as the same. But in reality, there are some FIEs which just produce for domestic market and don't export at all. In addition, those firms' reactions to environmental regulations are quite different especially between FIEs and domestic firms. A recent research by Howell (2015)finds that the domestic and joint-venture auto firms acted quite differently in response to China's higher fuel economy standards. The domestic auto firms didn't conduct technology innovation but to reduce quality and price while the joint ventures implemented fuel efficient technology. The proposed explanation is that the joint venture structure in the FIEs generated large rents but reduced domestic auto firms' innovation incentives. Then the future research could be about the effects of regulation of the ownership of the foreign invested firms on the foreign investment and technology transfer levels and domestic firms' innovation incentives.

APPENDIX

Proof of Lemma 1. The part 1) of the lemma is obvious. Now show the second part. Denote $e^* = \lambda e + (1-\lambda)e' \equiv e^*(\lambda)$ for some $\lambda \in [0,1]$. Then denote

$$f(\lambda) = C_e(e^*(\lambda), e) + C_e(e', e^*(\lambda)) - C_e(e', e)$$

Then $f(0) = 0 = f(1)$. Then by Fermat's theorem, there exist(s) interior local maximum or minimum for some point $\lambda^* \in (0,1)$. By the first order condition, we can get at λ^*

$$(\frac{e^*}{e'})^{n+1} + n - (n+1)\frac{e}{e^*} = 0$$

Then plug above equation into function f obtain

$$f(\lambda^*) = -c_e(n+1)(e^*)^{-n}(\frac{e}{e^*} - 1)^2 < 0$$

Thus the part ii) in lemma 1 follows. For the third part the lemma, take partial derivative of f with respect to n

$$\frac{\partial f}{\partial n} = (e - e^*)[(e^*)^{-(n+1)}log((e^*)^{-1}) - (e')^{-(n+1)}log((e')^{-1})]$$

Now denote $z = e^{-1}$. Then we just need to analyze the monotone of $g(z) = z^{n+1}log(z)$. Notice $g'(z) = z^n((n+1)log(z) + 1)$. So $g(z)$ is increasing if $z \geq e^{-\frac{1}{n+1}}$ and decreasing otherwise. Therefore f is increasing in n if $e' > e^{\frac{1}{n+1}}$ and decreasing in n if $e < e^{\frac{1}{n+1}}$. That means, as the deceasing of e, it's more likely the firms to invest less each period if n is larger.

Proof of Proposition 1.

First rewrite the expression of p_{le} as

$$p_{le} = A_l^{(1-\epsilon)/\epsilon} Y^{1/\epsilon} \hat{L}^{1-\alpha-1/\epsilon} \nu^{1-\alpha} k^{1-\alpha} (L_e z_{le})^{\alpha-1}$$

Notice that Y is increasing in k. So it suffices to show $\hat{L}^{1-\alpha-1/\epsilon} k^{1-\alpha}$ is increasing in k. Denote

$B = \hat{L}^{1-\alpha-1/\epsilon} k^{1-\alpha}$, then

$$\frac{d\ln B}{dk} = (1-\alpha)\Big[\frac{1-\alpha-1/\epsilon}{\alpha}\hat{L}^{-\alpha}\Big(\nu(\frac{L_e z_{le}}{\nu k})^{\alpha} - (\frac{L_w z_{lw}}{1-k})^{\alpha}\Big) + \frac{1}{k}\Big]$$

If $1-\alpha-1/\epsilon \geq 0$, i.e., $\sigma \leq \epsilon$. Then the results follows immediately because $d\hat{L}/dk > 0$. Otherwise, plug in $\hat{L}^{\alpha} = \nu k(\frac{L_e z_{le}}{\nu k})^{\alpha} + (1-k)(\frac{L_w z_{lw}}{1-k})^{\alpha}$ and we only need to show

$$\frac{\epsilon-1}{\epsilon}\nu(\frac{L_e z_{le}}{\nu k})^{\alpha}) + [\frac{\alpha(1-k)}{k} - (1-\alpha-\frac{1}{\epsilon})](\frac{L_w z_{lw}}{1-k})^{\alpha} > 0$$

which is of course true if $\sigma > \epsilon$. Next consider the equilibrium prices p_{lw}. Then take derivative

$$\frac{d\ln p_{lw}}{dk} = \frac{1}{\hat{L}}\frac{1-\alpha+(1-\alpha-1/\epsilon)(\frac{A_h z_h H}{A_l \hat{L}})^{(\epsilon-1)/\epsilon}}{1+(\frac{A_h z_h H}{A_l \hat{L}})^{(\epsilon-1)/\epsilon}}\frac{d\hat{L}}{dk} - \frac{1-\alpha}{1-k} = F\frac{d\hat{L}}{dk} - \frac{1-\alpha}{1-k}$$

So if $F \leq 0$, then $\frac{d\ln p_{lw}}{dk} < 0$. That is,

$$1-\alpha+(1-\alpha-1/\epsilon)(\frac{A_h z_h H}{A_l \hat{L}})^{(\epsilon-1)/\epsilon} < 0$$

Then $1-\alpha-1/\epsilon < 0$, i.e., $\sigma > \epsilon$.

$$(\frac{A_h z_h H}{A_l \hat{L}})^{(\epsilon-1)/\epsilon} > \frac{1-\alpha}{-(1-\alpha)+1/\epsilon} = \frac{\epsilon}{\sigma-\epsilon}$$

If $\sigma \leq \epsilon$, then $F > 0$. By $\lim_{k\to 0}\frac{d\hat{L}}{dk} = \infty$, then p_{le} is increasing when offshoring k is small. Notice that $\lim_{k\to\hat{k}}\frac{d\hat{L}}{dk} > 0$ and $\lim_{k\to\hat{\hat{k}}}\frac{d\hat{L}}{dk} = 0$, so p_{le} will decrease in k after some point which may beyond the usual bound $\hat{k}$.

Similarly for p_h/p_{lw} and we can get

$$\frac{d\ln(p_h/p_{lw})}{dk} = -\frac{1-\alpha-1/\epsilon}{\hat{L}}\frac{d\hat{L}}{dk} + \frac{1-\alpha}{1-k}$$

Therefore, if $\epsilon < \sigma$, the equilibrium price ratio increases in offshoring k. Otherwise, the skill premium will decrease at the beginning and increase after some point.

Proof of Proposition 2.

By equation(27), the profit function for east low-skill firms is $\pi_{le} = (1-\alpha)P_l\hat{L}^{1-\alpha}k^{-\alpha}\nu^{\alpha}(L_e z_{le})^{\alpha}$. Notice that the price of the low-skill sector aggregate goods P_l is decreasing with offshoring k.

It only needs to show the term $\hat{L}^{1-\alpha}k^{-\alpha}$ is a decreasing function. Denote this term as B. Then

$$\frac{dB}{dk} = \frac{\frac{\nu(1-2\alpha)}{\alpha}(\frac{L_e z_{le}}{\nu k})^\alpha - [\frac{(1-\alpha)^2}{\alpha} + \frac{\alpha(1-k)}{k}](\frac{L_w z_{lw}}{1-k})^\alpha}{\nu k(\frac{L_e z_{le}}{\nu k})^\alpha + (1-k)(\frac{L_w z_{lw}}{1-k})^\alpha}$$

Therefore, the term B is decreasing if $\alpha > 1/2$, i.e., $\sigma > 2$. For the case of π_{lw}, take derivative,

$$\frac{d\ln\pi_{lw}}{dk} = \frac{1}{\hat{L}}\frac{1-\alpha+(1-\alpha-1/\epsilon)(\frac{A_h z_h H}{A_l\hat{L}})^{(\epsilon-1)/\epsilon}}{1+(\frac{A_h z_h H}{A_l\hat{L}})^{(\epsilon-1)/\epsilon}}\frac{d\hat{L}}{dk} + \frac{\alpha}{1-k}$$

The first part is the exactly the same item as in $d\ln p_{lw}/dk$. So the same argument holds as there. It's easy to check the increasing of the ratio π_{lw}/π_{le}.

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Figures and Tables

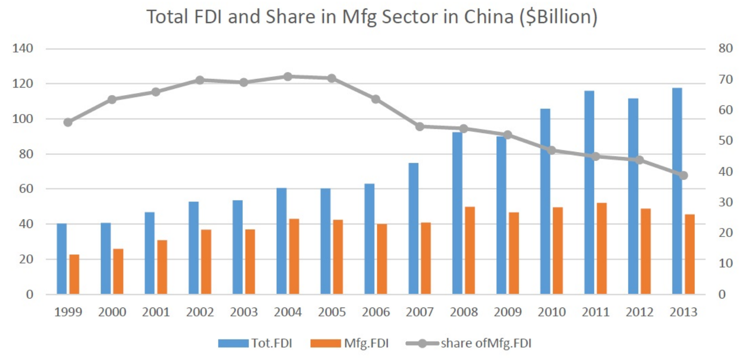

Figure A1: Total and Manufacturing FDI

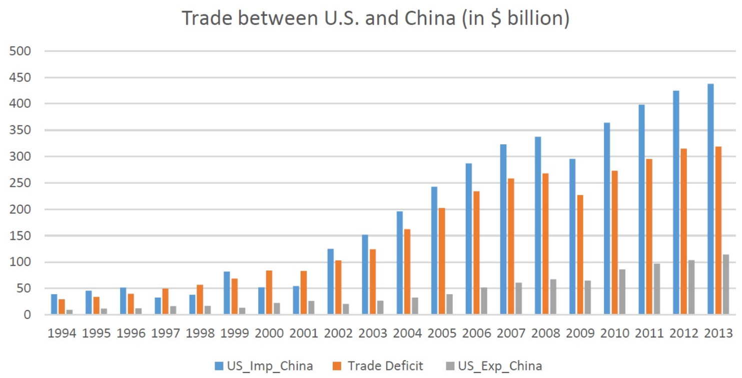

Figure A2: Bilateral Trade between U.S. and China

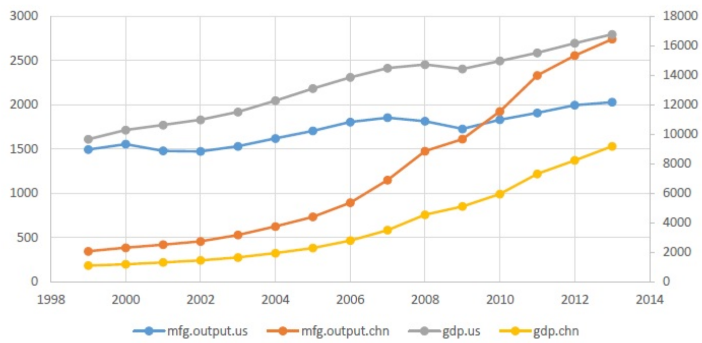

Figure A3: Manufacturing and GDP of US and China

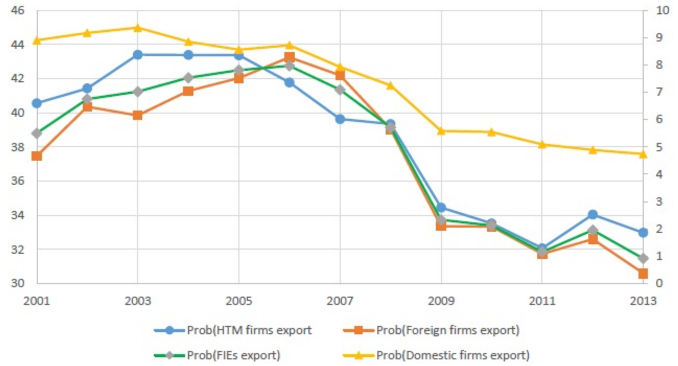

Figure A4: Export Probabilities Different Type of Firms: Based on China Annual Survey of Industrial Firms with Primary Revenue above Certain Scale

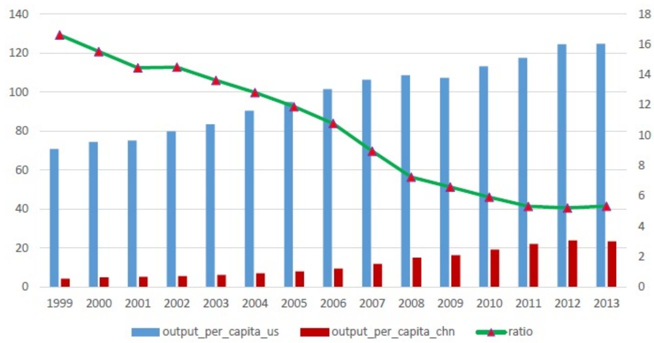

Figure A5

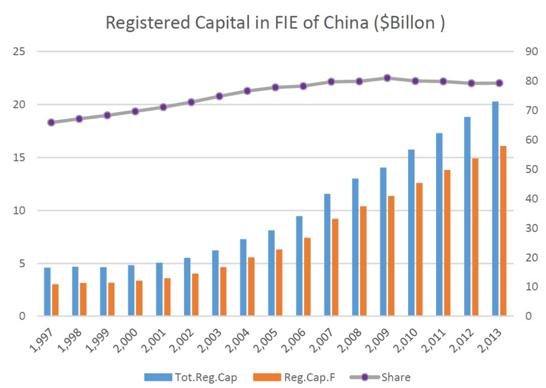

Figure A6

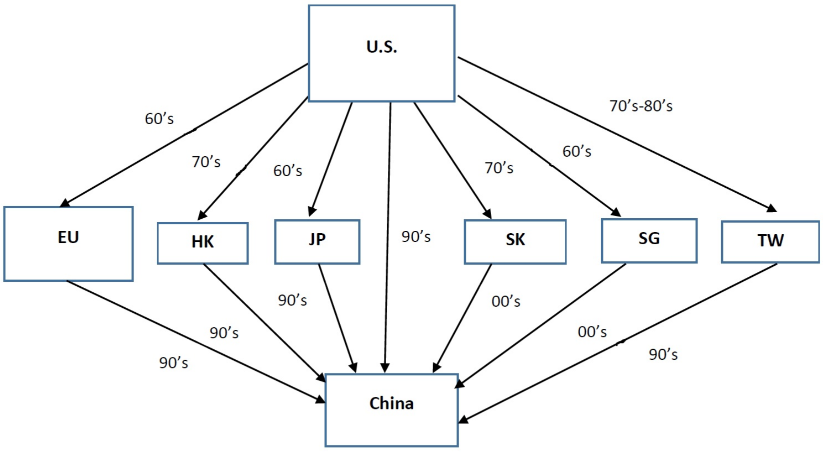

Figure A7: Transaction History of Manufacturing Offshoring from US

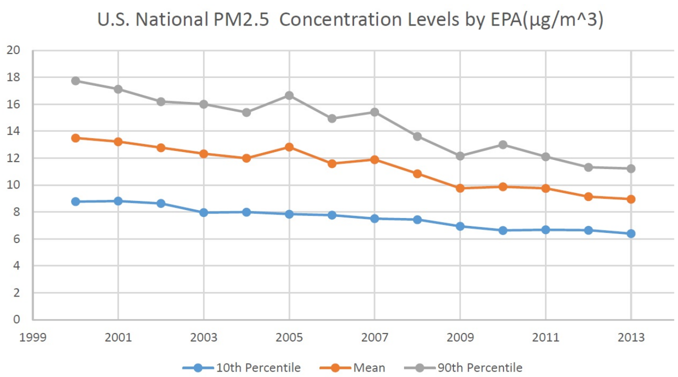

Figure A8

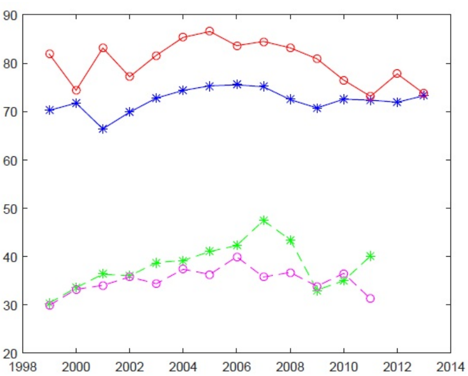

Figure A9: Calculated Emission Per Work(red and pink) and Simulated Values(blue and green):

Table A1: FDI Flow in China(Units: 1999 U.S. Billion Dollars)

Year	Agg.Lel			Main Contrib.						
	Tot.FDI	Mfg.FDI	% Mfg.	US	% US	HK	JP	SK	TW	SG
1999	40.32	22.60	56.06	4.21	10.45	16.36	2.97	1.27	2.59	2.64
2000	40.71	25.84	63.47	4.38	10.76	15.49	2.91	1.48	2.29	2.17
2001	46.88	30.91	65.93	4.43	9.45	16.71	4.34	2.15	2.97	2.14
2002	52.74	36.79	69.77	5.42	10.28	17.86	4.19	2.72	3.97	2.33
2003	53.50	36.93	69.03	4.19	7.84	17.70	5.05	4.48	3.37	2.05
2004	60.63	43.01	70.95	3.94	6.50	18.99	5.45	6.24	3.11	2.00
2005	60.32	42.45	70.37	3.06	5.07	17.94	6.52	5.16	2.15	2.20
2006	63.02	40.07	63.59	2.86	4.54	20.23	4.59	3.89	2.13	2.26
2007	74.76	40.86	54.65	2.61	3.49	27.70	3.58	3.67	1.77	3.18
2008	92.39	49.89	54.00	2.94	3.18	41.03	3.65	3.13	1.89	4.43
2009	90.03	46.77	51.94	2.55	2.83	46.07	4.10	2.70	1.88	3.60
2010	105.73	49.59	46.90	3.02	2.85	60.56	4.08	2.69	2.47	5.42
2011	116.01	52.10	44.91	2.36	2.04	70.50	6.32	2.55	2.18	6.09
2012	111.72	48.86	43.74	2.59	2.32	65.56	7.35	3.03	2.84	6.30
2013	117.58	45.55	38.74	2.81	2.39	73.39	7.05	3.05	2.08	7.22

Table A2: U.S. Affiliates Sales by Destination and Trade Activity(Units: Millions of U.S. Dollars)

	1989	1994	1999	2004 general	2004 Manufacturing
U.S. Multinational Affiliates Sales					
Sales to U.S.	1	219	2703	4528	3465
Sales in China	242	2520	14306	46207	30889
Sales to Other Countries	13	486	3371	11343	10500
U.S. Exports of Goods to Affiliates					
Total	39	371	3103	2919	2445
Shipped by U.S.parents	35	288	2529	2452	2053
Shipped by unaffiliated U.S. persons	4	83	574	467	392
U.S. Imports of Goods from Affiliates					
Total	1	448	2640	3130	NA
Shipped to U.S. parents	1	403	1778	2558	NA
Shipped to unaffiliated U.S. persons	0	45	862	572	NA

Those data above are from the final results of EBA's benchmark survey of U.S. direct investment abroad for 1989, 1994, 1999 and 2004. The data only cover the U.S. nobank MNC's majority-owned affiliates in China.

Table A3: Manufacturing Employment in US and FIEs of China(Units: in millions)

Year	US				China			
	Tot LS[a]	Mfg. LS	Tot. Hs	Mfg. HS	Mfg.FIE	Ind. Offsh.[b]	US MNC	Offshored [c]
1999	61.07	11.35	76.26	9.76	7.82	1.31	0.23	1.54
2000	61.55	11.26	79.08	9.65	8.42	1.42	0.22	1.64
2001	61.16	10.33	79.78	9.37	9.27	1.55	0.24	1.79
2002	60.89	9.76	81.61	8.72	10.41	1.84	0.24	2.08
2003	60.39	9.41	82.54	8.94	12.43	2.23	0.25	2.48
2004	61.05	9.17	83.24	8.73	14.29	2.61	0.32	2.93
2005	61.05	9.20	85.32	8.78	18.76	3.47	0.40	3.87
2006	61.70	9.06	87.26	8.72	20.93	3.89	0.46	4.35
2007	59.44	8.51	90.17	8.93	23.23	4.18	0.48	4.66
2008	58.85	8.17	90.68	8.55	25.46	4.34	0.55	4.89
2009	58.83	7.91	90.82	8.19	24.18	3.53	0.66	4.19
2010	56.82	7.85	92.63	8.33	26.13	3.78	0.67	4.45
2011	56.11	7.67	94.27	8.55	25.40	3.50	0.71	4.21
2012	54.88	7.21	96.05	8.82	25.21	3.61	0.70	4.31
2013	55.09	7.61	96.41	8.66	29.24	4.00	0.69	4.69

[a.] In the table, LS is short for low-skill workers similarly for HS.
[b.] The manufacturing employment due to indirect offshoring are calculated using the formula in the paper .
[c.] The total manufacturing employment due to offshoring is the sum of direct offshoring(Column 8) and indirect offshoring(Column 7).

Table A4: Wages in U.S. and China(Units: in 1999 US dollars)

Year	US[a]				China[b]	
	Tot LS	Mfg. LS	Tot. Hs	Mfg. HS	FIE	Mfg. FIE
1999	20100	26211	37392	48839	1552	1426
2000	20565	26460	39533	51628	1636	1484
2001	20709	26473	40310	51141	1742	1551
2002	20627	25359	39610	48547	1889	1684
2003	20656	26133	39042	48966	1994	1702
2004	20486	25648	39143	49739	2079	1794
2005	20388	25377	39141	50017	2189	1900
2006	20548	25878	39697	48946	2441	2118
2007	20612	26102	38765	50020	2810	2447
2008	19658	24728	38145	50575	3434	2935
2009	18937	23101	37965	48026	3785	3237
2010	18875	23981	36902	47302	4245	3666
2011	19196	24354	37180	47478	5081	4508
2012	19039	24458	37464	47582	5835	5242
2013	19472	23855	37283	48720	6571	5929

[a.] The US workers' wages are calculated using CPI data provided by U.S. Bureau of Labor Statistics.

[b.] The wage data for Chinese workers' in foreign funded enterprises are weighted average between the firms funded by Hongkong, Taiwan and Macao and foreign invested firms. The values in U.S. dollars are calculated using the same CPI data as above and the annual official exchange rate data provided by World Bank (http://data.worldbank.org/indicator/PA.NUS.FCRF).

Table A5: Employment and Wages in FIE and Overall Wages in China

Year	Hongkong,Taiwan and Macau		Frgn.Ent.		Overall	
	Employment[a]	Wage	Employment	Wage	Ave.Wage	Ave.Mfg.Wage[b]
1999	3.06	1371	3.06	1734	1225	1125
2000	3.10	1426	3.32	1832	1312	1190
2001	3.26	1473	3.45	1995	1414	1259
2002	3.66	1588	3.91	2171	1509	1345
2003	4.09	1657	4.54	2297	1622	1385
2004	4.69	1730	5.63	2371	1760	1518
2005	5.56	1856	6.88	2459	1911	1658
2006	6.11	2038	7.96	2750	2175	1887
2007	6.80	2387	9.03	3127	2565	2234
2008	6.79	2905	9.43	3815	3180	2718
2009	7.21	3195	9.78	4219	3565	3049
2010	7.69	3609	10.53	4710	4040	3488
2011	9.32	4397	12.17	5604	4738	4204
2012	9.69	5072	12.46	6428	5332	4790
2013	13.97	5765	15.66	7290	5937	5358

[a.] The data is from China Statistical Yearbook from 2000 to 2014. The unit for employment is million workers and for wage is 1999 U.S. dollars.

[b.] The overall manufacturing workers' wage refers to the manufacturing workers' wage in urban area.