Assessing Environmental Impacts Embodied in Manufacturing and Labor Input for the China−U.S. Trade

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Previous studies on environmental impacts embodied in trade have paid little attention to the impacts of labor input, or environmental overhead of labor input (EOLI). EOLI occurs to support lifestyles both in the purchase of goods and services and in the consumption of fuels and electricity by workers. This research investigates both supply chain manufacturing and EOLI energy use and carbon dioxide (CO_2) emissions embodied in the 2002 China−U.S. trade. EOLI is substantial in scale: 24% of manufacturing energy in the U.S. and 6% for China. The higher share of EOLI in the U.S. is the result of higher energy use to support worker lifestyles. Analysis shows China's EOLI is dominated by the manufacturing of products consumed by workers, while EOLI on the U.S. side is primarily from workers' direct consumption. The total manufacturing and EOLI energy and CO_2 embodied in the eastbound trade from China to the U.S. are 6.5 exajoules (EJ) of energy (6% EOLI) and 440 million tons (Mt) of CO_2 (8% EOLI). The total manufacturing and EOLI energy and CO_2 embodied in the westbound trade from the U.S. to China are 424 petajoules (PJ) of energy (19% EOLI) and 25.3 Mt of CO_2 (21% EOLI).

Introduction

International trade is recognized as a mechanism to optimally allocate resources including capital, labor, and materials at the global scale (*1*). Nowadays, globalization induces corporations in developed countries to shift their manufacturing activities to developing countries because of lower costs of labor and resources. Recently there has been increasing interest in the embodied environmental impacts of international trade (*2*), especially in emissions embodied in trade (*3, 4*). Instigated by globally increasing attention on climate change, energy and carbon dioxide (CO_2) emissions embodied in trade has been investigated in particular, primarily at national (*5*−*7*), but also bilateral (*8, 9*) and global levels (*10, 11*).

From a development perspective it is often argued that international trade from developing to developed countries is a key strategy to improve the lives of workers in the developing world. Studies of the environmental aspects of trade have primarily focused on impacts embodied in manufacturing-related processes. The environmental overhead of labor input (EOLI) or the environmental impacts of individual consumption by workers, is typically excluded from environmental assessments (*12*). There are two main arguments (usually implicit) to exclude EOLI. One is that labor is a social benefit and thus should not be imputed with negative environmental impacts. Essentially this amounts to weighting labor with zero environmental impacts because of its other benefits. A second argument is that environmental assessments are often used to assign responsibility for impacts in a manufacturing chain. The consumption of workers is, by and large, outside of the domain of the firms that employ them, and thus should not be included in this responsibility (*13, 14*). However, counterarguments do exist and argue that there are contexts in which EOLI should be included in environmental impact assessment. In a globalizing world, environmental issues play an increasing role in the debate and management of trade. Manufacturing processes are, generally speaking (and there are many exceptions), held to a higher environmental standard in the developed world as compared to the developing. One could thus argue that from an environmental perspective it is preferable to manufacture in the developed world. However, workers making goods in the developed world enjoy comparatively lavish lifestyles versus their counterparts in the developing world, a lifestyle which in many cases induces substantial environmental impacts. It is thus worth asking the question whether including the total environmental cost of manufacturing, including supporting the lifestyle of workers, might provide a different perspective on the environmental preferability of the location of manufacture. It can thus be argued that employees' work and life styles and associated environmental impacts are essential to the understanding of environmental impacts embodied in trade.

The value of U.S. imports is 21.6% of its gross domestic product (GDP) in 2007. The largest share, about 16.6% of its imports and accounting for 323 billion dollars, is from China. At the same time, China ranks as the third-largest export partner of the U.S. and the second-largest in terms of total trade (*15*). While there are debates between China and the U.S. as to which nation tops global CO_2 emissions (*16*), undoubtedly the two countries dominate the world's CO_2 emissions, as well as energy use and other environmental impacts. Li et al. investigated embodied energy in China's international trade and quantified its impact on ecological footprint (*7*). Shui and Harriss studied manufacturing-related CO_2 emissions embodied in the China−U.S. trade from 1997 to 2003 and found about 7%−14% of China's CO_2 emissions are the result of making exports for consumption in the U.S. (*8*). There are studies on direct and indirect environmental impacts of household consumption for various countries or regions including China (*17*) and the U.S. (*18, 19*). Companion research investigated energy use and air emissions embodied in the eastbound trade from China to U.S. from 2002 to 2007 (*20*). To date, however, there is no study on environmental impacts embodied in the China−U.S. trade taking both manufacturing and labor input into account.

In this article, we quantitatively examine energy use and CO_2 emissions caused by both manufacturing and labor input embodied in trade with the case of 2002 China−U.S. bilateral trade. Given the dramatic difference between and the

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political, economic, environmental, and geographical importance of the two countries, this case is a good candidate for the exploration of the complex issue of environmental impacts embodied in trade. For the sake of simplicity, the energy (CO_2) embodied in the manufacturing is denominated as manufacturing energy (CO_2) while the energy (CO_2) associated with the labor input is called energy (CO_2) EOLI.

Methods

Assuming employees work full time, their lifestyle consumption, either in working time or in leisure time, is fully supported by their jobs. It thus can be argued that employees' annual labor input is equivalent to their annual lifestyle consumption including that in working time, as well as that in leisure time. In this research, EOLI embodied in trade contains two components, the impacts directly caused by workers' individual consumption and the indirect impacts occurring in the life cycle of the products and services consumed by workers. The total EOLI embodied in trade, the sum of the direct and indirect, represents the accumulated environmental impacts resulting from the labor input embodied in trade. Usually, environmental impacts embodied in the manufacturing of trade are quantified using the method of input−output analysis (IOA) (*21*). By incorporation of employment data, existing IOA models can be updated to quantify labor input embodied in trade. In this research, an integrated IOA model is developed to quantify the energy and CO_2 EOLI embodied in the China−U.S. trade.

In an IOA model, there are n sectors (or commodities) and m categories of environmental impacts. Therefore, the EOLI embodied in trade from an exporting country can be expressed as

$$\boldsymbol{P} = \boldsymbol{ce}(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{T} \tag{1}$$

where $\boldsymbol{P}$ is a $m \times n$ matrix, whose element p_{ij} indicates the ith environmental impact of labor input embodied in the export of commodity j, $\boldsymbol{c}$ is a $m \times 1$ vector of environmental impacts indicating an average worker's household consumption on annual basis, $\boldsymbol{e}$ is a $1 \times n$ vector of labor, with the unit of capita-year, required to produce unit total output in each sector, $\boldsymbol{I}$ is the $n \times n$ identity matrix, $\boldsymbol{A}$ is the $n \times n$ matrix of export country's direct requirements, and $\boldsymbol{T}$ is a $n \times n$ diagonal matrix of exports sorted by commodities. Background information on IOA can be found in ref *22*.

One can classify three different boundaries of environmental impacts associated with trade:
1.manufacturing only (type I in terminology of (*25*))
2.manufacturing plus direct labor
3.full integration of manufacturing and labor (type II in terminology of ref *25*)

These three different boundaries are illustrated pictorially in Figure 1. The first type assesses impacts associated just with manufacturing supply chain for exports, the boundary previously studied in ref *20*. The second boundary adds the life cycle impacts from goods, services, and fuels supporting the lifestyles of workers in the supply chain producing the exports. This is boundary considered in this analysis and is mathematically expressed in equation 1. The third definition includes the labor and accompanying EOLI needed to produce the goods supporting the workers in the export supply chain. Implementing the third definition is based on a type-II social accounting matrix (SAM) by considering household consumption as a sector of the input−output economy (*23*−*25*).

While the third boundary (a type-II SAM model) is broadest, we argue that the second boundary is an appropriate starting point. The second boundary reflects "direct EOLI", the third "direct + indirect EOLI". By and large, the second boundary implies a broader sense of "manufacturing",

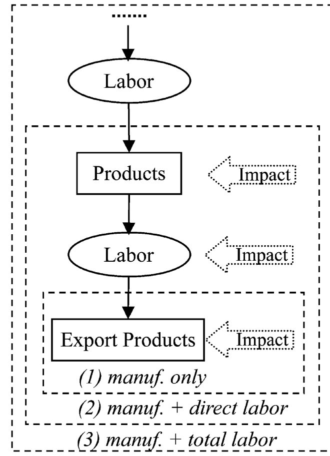

FIGURE 1. Boundary choices in analysis of environmental impacts embodied in trade. This study uses boundary 2.

including manufacturing itself and direct labor input. We argue that workers' individual consumption and associated environmental impacts are outside of the manufacturing processes thus the inclusion of indirect labor input could dilute the accounting of manufacturing-related impact. Given that this is the first attempt to characterize EOLI associated with trade, we begin with assessing its direct impacts and leave incorporation of indirect effects for future work.

Data. For both China and the U.S., the most recent input−output data ($\boldsymbol{A}$) are for 2002. Therefore, the model built in this research is based on the 2002 data. Moreover, data and models for quantifying energy use and CO_2 caused by manufacturing of commodities are also available for China (*26*) and the U.S. (*27*).

Although the China−U.S. bilateral trade data ($\boldsymbol{T}$) are available (*28*), there are obvious discrepancies between data reported by the two countries, for example, the value reported in U.S. statistics of exports of a commodity to China will often differ from the amount reported in Chinese statistics of import of the same commodity from the U.S. Without careful adjustment, choosing data reported by either country will undoubtedly generate huge uncertainties. Scholars have found that the discrepancies are primarily the result of the re-exports and markups occurring in Hong Kong and adjusted statistics to estimate a real trade value, mainly by top-down statistical analysis (*29*−*31*). In this paper, however, we use a novel estimation from a bottom-up perspective based on the fact that the physical quantity of goods does not change regardless of markups made through re-exportation (*32*). Our results are in the range of previous estimations and provide comprehensive China−U.S. trade data on a "free on board (FOB)" basis, officially known as "custom value" in the U.S., which excludes import duties, freight, insurance, and other charges beyond loading onto the cargo vessel. Adjusted trade data disaggregated to the 6 digit level of the Harmonized Commodity Description and Coding Systems (the Harmonized System or HS, see ref *33*) are available and more details can be found in refs *20 and 32* and the Supporting Information. Given that the customs records export values based on the exchange rate between currencies of China and the U.S., we used annual exchange rates reported by the International Monetary Fund (*34*).

Constructing the employment vector ($\boldsymbol{e}$) requires the numbers of workers in each sector in both countries. Such data are obtained from government statistics (*35, 36*), in particular the employment statistics for U.S. agriculture sectors are approximated by the 2000 Census data (*37*).

The environmental impacts vector ($\boldsymbol{c}$) contains energy use and CO_2 emissions occurred in the life cycle of the individual consumption of an average worker in each country

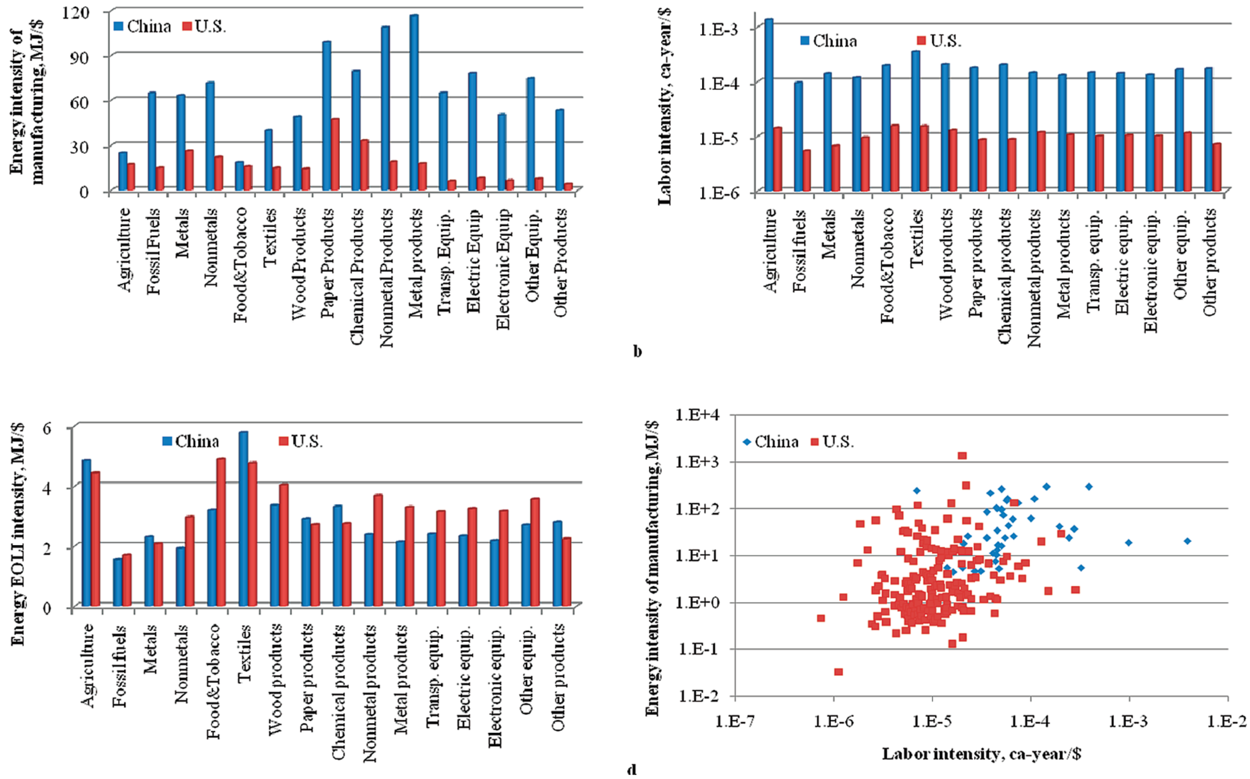

FIGURE 2. (a) Intensities of manufacturing energy, (b) labor input intensities, (c) energy EOLI, and (d) correlations between intensities of manufacturing energy and labor for 16 sectors in China and the U.S. in 2002.

on annual basis. Such data for China can be obtained from Wei et al. (*17*), which quantifies energy use and CO_2 emissions due to Chinese urban and rural residents' living activities in 2002 including residence, home energy use, food, travel, and education, cultural, and recreation services using the IOA method. Moreover, given differences between in urban and rural lifestyles in China, the results in reference (*17*) for rural residents are used to estimate agriculture-related EOLI while results for urban residents are adopted for EOLI of other products. The U.S. data are from Shui and Dowlatabadi (*18*), who used the same method as ref *17*, although study was carried out using 1997 data. Detailed information can be found in the Supporting Information.

The Chinese input−output matrix contains 122 sectors, while the employment data can only be allocated into a 45-sector format and the bilateral trade data has 4,988 entries. Similarly, the U.S. input−output matrix has 428 sectors, while the employment vector distinguishes 188 sectors. Appropriate transposition is thus required. The results are illustrated by aggregating to a 16-commodity-category format in the following sections while the Supporting Information contains results in more detail.

Results

Environmental Intensity of Economic Activities. Because of the division of labor at the global scale, it is usually expected that developing countries such as China specialize in resource and labor intensive manufacturing, while developed countries such as the U.S. specialize in high value-added industries (*38*). Our results confirm this by quantifying the embodied environmental and labor intensities of economic activities in the two countries. As shown in Figure 2a, more manufacturing energy is required to produce the same amount of output in China than in the U.S. for all 16 economic sectors in the IO model. These gaps are driven by in differences in manufacturing technology and the intrasector composition of bulk versus high-value added goods. Note that the energy intensity of manufacturing, measured by manufacturing energy required for per unit economic output, in producing transportation equipment, electric equipment, and other equipment in China is about two times of that in the U.S.

Labor input can be measured in capita-years (ca-years), representing the labor input of one typical worker over one year. Figure 2b shows that labor intensity, measured by labor input embodied in per unit economic output, is generally one magnitude higher in China than that in the U.S. Particularly, labor input embodied in the same value of agriculture products in China is about 100 times of that in the U.S.

Because of globalization, resource and labor intensive industries in developed countries are increasingly transferred to developing countries. Therefore, industries in the U.S. generally need much less resources than industries in China. In contrast, as shown in Figure 2 (c), the energy EOLI embodied in per unit economic output in China is the same magnitude as in the U.S. This is because American lifestyles implies far higher embodied energy than Chinese lifestyles.. In particular, although China uses about 100 times more labor than the U.S. to produce the same value of agricultural products, the associated energy EOLI for the two countries are in the same magnitude because of the huge difference between lifestyles of Chinese rural residents and average American residents.

Figure 2 (d) illustrates intensities of total, including direct and indirect, energy and labor embodied in the manufacturing of each sector for China and the U.S. in 2002. In general, the manufacturing in the U.S. requires less labor and energy than manufacturing in China. Similar findings have been reported elsewhere and strongly suggested that an increase in employment can be achieved by shifting consumption from energy-intensive to labor-intensive products (e.g., refs *14 and 25*).

Figure 2 represents our analysis for labor and manufacturing energy intensities in China and the U.S. in 2002, similar results for manufacturing CO_2 intensity can be found in the Supporting Information. In short, the differences in manu-

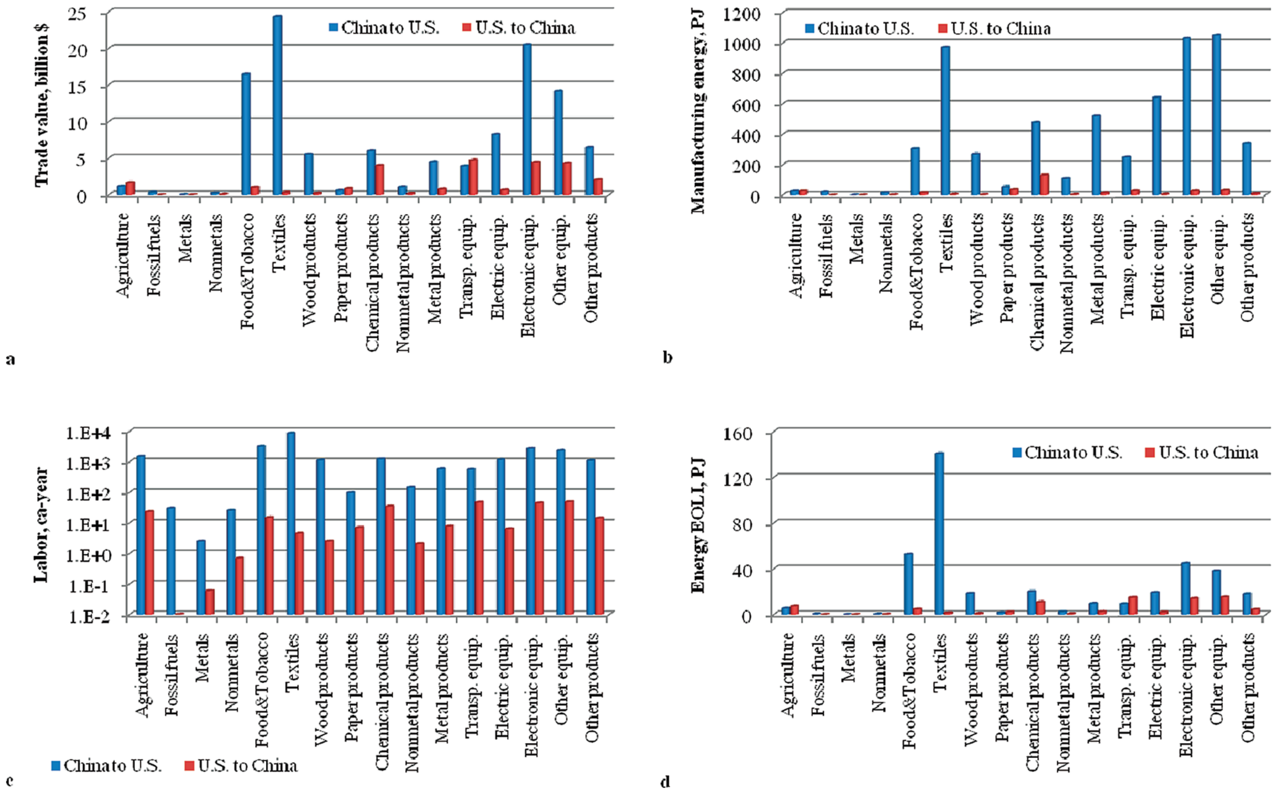

FIGURE 3. (a) Trade value, (b) embodied manufacturing energy, (c) labor input embodied in the manufacturing, and (d) embodied EOLI energy for the 2002 China-U.S. trade.

facturing technology and industrial structure between the two countries imply that China needs more labor and induces higher environmental impacts in manufacturing the same amount of economic output than the U.S. However, EOLI embodied in the same amount of economic output in the U.S. is in the same magnitude with that in China because of the higher energy requirement and CO_2 emissions of average worker's individual consumption in the U.S.

Environmental Impacts Embodied in the 2002 China−U.S. Trade. China has run a bilateral trade surplus with the U.S. since the late 1980s. In 2002, the eastbound (from China to the U.S.) and the westbound (from the U.S. to China) trade values are 113 and 24.9 billion dollars, respectively. As illustrated in Figure 3a, food and tobacco, textiles, electronic equipment, and other equipment count for 66.7% of the total eastbound trade. On the other hand, transportation equipment, electronic equipment, other equipment, and chemical products take 69.8% of the total westbound trade. Overall, energy and CO_2 embodied in the manufacturing of the 2002 eastbound trade are 6.1 exajoules (EJ) and 405 million tons (Mt) respectively while 343 petajoules (PJ) energy use and 20.0 Mt CO_2 emissions occur in the manufacturing of the westbound trade. The eastbound trade implies a labor input of 24.6 million ca-year, 380 PJ energy EOLI, and 34.6 Mt CO_2 EOLI, while the westbound trade required 0.3 million ca-year labor input, 81.0 PJ energy EOLI, and 5.3 Mt CO_2 EOLI in 2002.

Manufacturing energy embodied in the 2002 China−U.S. trade is illustrated in Figure 3b. In particular, the eastbound trade requires 6.1 EJ, or 16.6% of the total energy consumption, in China, while the westbound trade implies 342.6 PJ, or only 0.5% of the total energy consumption, in the U.S. Manufacturing energy embodied in textiles, electronic equipment, and other equipment accounts for 50.2% of the total manufacturing energy embodied in eastbound trade. On the U.S. side, manufacturing energy embodied in chemical products alone takes 38.3% of the total embodied manufacturing energy, followed by paper products, transportation equipment, and other equipment.

The composition of manufacturing CO_2 embodied in the 2002 China−U.S. trade is shown in Figure S4 in the Supporting Information. The manufacturing CO_2 embodied in the eastbound trade is 405.1 Mt, 11.3% of the total CO_2 emitted by China in 2002. The manufacturing CO_2 embodied in westbound trade is 20.0 Mt, only 0.5% of the total emissions in the U.S. Manufacturing CO_2 embodied in textiles, electronic equipment, and other equipment accounts for 51.7% of the total manufacturing CO_2 embodied in the eastbound trade. Chemical products contribute the most of the manufacturing CO_2 embodied in the westbound trade, accounting for 44.4% of the total.

Overall, labor input embodied in China for westbound trade is to 1.9% of total labor and for the eastbound trade 0.1% of total labor in the U.S,. To produce one million dollar products to trade with each other in 2002, China needs 218 ca-years, while the U.S. only requires 10.5. Figure 3c compares the labor input required by the China−U.S. trade in 2002. Generally, the labor input required for the eastbound trade is about 2 or 3 orders of magnitude more than that for the westbound trade. For the eastbound trade, textiles require the most labor, 8.7 million ca-years, followed by food and tobacco (3.2 million) and electronic equipment (2.8 million). For the westbound trade, other equipment needs 0.05 million ca-years in 2002, followed by transportation equipment and electronic equipment, both requiring 0.05 million.

When comparing the energy EOLI, the huge imbalance of labor required for the China−U.S. trade is offset by the difference of lifestyle between the two countries. For example, although labor intensity in China is much higher than that in the U.S., energy EOLI for one dollar eastbound trade, 3.4 MJ, is close to that for the same value of westbound trade (3.3 MJ). As showed in Figure 3d, textiles require the most energy EOLI, 140.6 PJ, and account for 37.0% in the eastbound trade, while other equipment needs more energy EOLI, 15.3 PJ, than any other commodity category in the westbound trade.

Figure S5 in the Supporting Information shows CO_2 EOLI embodied in the 2002 China−U.S. trade. On average, one dollar of exports by China can be associated with 0.3 kg of CO_2 emissions resulting from workers' consumption, while the U.S. exports of one dollar lead to 0.2 kg of CO_2 EOLI.

Discussion

More advanced technology usually implies higher energy efficiency and lower labor requirements. Therefore, it is expected that the manufacturing in developed countries, such as the U.S., requires less energy and labor input than in developing countries such as China. On the other hand, residents in developed countries usually consume more resources and generate more emissions than those in developing countries. It thus can be argued that the energy and emissions savings resulting from technological improvement in developed countries have been partially shifted to household consumption of residents. The results of our research confirm this. First, China requires about 30 times more labor than the U.S. to produce the same value of exports. However, the Chinese lifestyle is so different from the American one that energy use and CO_2 emissions associated with the household consumption of an average Chinese worker is much less than those of an average American worker. As a result, the energy and CO_2 EOLI embodied in the same value of exports in China are of the same magnitude as those in the U.S. Second, taking the 2002 trade into account, the total embodied energy EOLI in the U.S., 81.0 PJ, is 23.7% of the manufacturing energy embodied in those goods. The total embodied CO_2 EOLI is 5.3 Mt accounting for 26.4% of manufacturing CO_2. However, the energy and CO_2 EOLI are only 6.3% and 9.0%, respectively, of the manufacturing energy and CO_2 embodied in the eastbound trade. Finally, the westbound energy and CO_2 EOLI are only about 0.1% of the total energy consumption and CO_2 emissions in the U.S, while the shares in the eastbound trade rise to 1.0% for both energy and CO_2, respectively. The manufacturing energy and CO_2 embodied in the westbound trade are both 0.5% of the energy consumption and CO_2 emissions in the 2002 U.S. However, the manufacturing energy and CO_2 embodied in the eastbound trade take 16.6% and 11.3% of the total energy consumption and CO_2 emissions in China in 2002. This notable difference can be explained by that the 2002 eastbound trade value is about 7.8% of the Chinese GDP, while the westbound trade value is only 0.2% of the American GDP. Overall, to produce the same value of goods for trade, China requires more manufacturing energy (generates more manufacturing CO_2) and labor input than the U.S. However, American workers need more energy and generate more CO_2 in their individual consumption than Chinese workers. Moreover, the role of the bilateral trade with the other country is more important for Chinese economy than for the U.S. economy. The interaction between these factors brings notable complexity to environmental consequences of the China−U.S. trade. By quantifying the energy and CO_2 EOLI embodied in the China−U.S. trade, this research reveals this complex issue from the aspect of labor input and provides useful information for both countries' policy-making in international trade, energy, and carbon mitigation.

Manufacturing in developed countries is generally more environmentally benign than that in developing countries because of better technology and enforcement of regulations. However, additional environmental overhead of labor input could lead to situations where manufacturing is actually more environmentally intensive in the developed world. A preliminary comparison between China and the U.S. in terms of energy use and CO_2 emissions embodied in manufacturing and labor input provided in the Supporting Information suggests that the manufacturing of some products in the U.S. could have higher energy or CO_2 intensity than that in China if taking labor input into account. However, this preliminary result has significant uncertainties primarily due to the aggregation of products or services using economic value rather than physical quantities, that is, goods produced in China and the U.S. with the same value in the same sector may represent totally different compositions of products. Therefore, future research should study the manufacturing and labor input of specific products in developing and developed countries and compare the environmental impacts embodied in per unit physical quantity.

Policy Implications. In economics, the energy consumption and CO_2 emissions embodied in trade can be regarded as external costs in the sense that prices do not reflect the full costs in the production of a product by ignoring the associated ecological and environmental damages. Although the external costs can be compensated by economic instruments such as a Pigouvian tax (*39*), developing countries such as China usually have poorer environmental regulations than developed countries, which some argue has partially contributed to the shift of manufacturing from developed to developing countries. From a human development perspective, it is often argued that manufacturing should be placed where more people are employed. Taking environmental consideration into account, one may suspect that EOLI might be larger in China than in the U.S. given the huge employment in China, thus argue to keep manufacturing in the U.S. However, our analysis shows the resource intensive lifestyle in the U.S. highly offsets the efficiency gain brought by better technologies.

For the China−U.S. trade, overall, the eastbound trade implies 6.5 EJ of energy (6% EOLI) and 439.7 Mt of CO_2 (8% EOLI), while 423.7 PJ of energy (19% EOLI) and 25.3 Mt of CO_2 (21% EOLI) embody in the westbound trade. Obviously, the U.S. has benefited from the trade with China in terms of reducing energy consumption and carbon emissions, perhaps because of two reasons. First, the energy and carbon intensities in China are higher than those in the U.S. Second, the eastbound trade volume is higher than the westbound trade. Yet from a global point of view, it is not clear that international trade is directly beneficial in the short term. Countries that have lower cost labor and resources are likely to have poorer environmental performance in manufacturing. For example, if China and the U.S. produce what has been imported from the other in 2002 domestically, the total energy use and CO_2 emissions, including those caused by both manufacturing and workers' consumption, can be reduced by 56.1% and 58.5%, respectively. However, the bilateral trade is always a primary focus of Sino-American relations, not only because of the economy itself but also because of the political, legal, and cultural tensions between the two countries. A typical example is eastbound textile trade whose value is almost as much as the entire westbound trade from 2002 to 2007. In 2004, the China−U.S. trade fight regarding textiles led to a decrease in eastbound textile exports by 12.8%, which reduces the manufacturing energy and CO_2 by about 20% and energy and CO_2 EOLI by about 5%. Although the trade fight was settled through negotiation by November 2005, both China and the U.S. might rethink the trade-offs if taking the embodied environmental impacts into account, or use this information to take advantages in the negotiation. Moreover, the study on EOLI embodied in trade is also useful for domestic policy-making, especially for China. Particularly, our research clearly shows that China's energy use and CO_2 emissions are dominated by manufacturing but not household consumption. Therefore, energy consumption in manufacturing stage is crucial for China's ambition in improving energy efficiency. On the other hand, however, the U.S. should make more efforts in improving energy efficiency in household consumption.

At the global scale, one of the focuses in international negotiation on climate change is the responsibility of developed and developing countries. It has been argued that the country consuming products should be responsible for the carbon emissions occurred in the manufacturing no matter where the products are produced (*40*). EOLI, however, has not been taken into account in the argument. From an environmental protection perspective, developed countries should be also responsible for the EOLI embodied in the manufacturing in developing countries. In contrast, one may also argue that the carbon savings in developing countries associated with labor input can be regarded as the contribution of developed countries in reducing carbon emissions; thus can be used to offset developed countries' carbon debt.

Uncertainties. The inherent uncertainties of the IOA method include aggregation, time-lag, and assumptions of linear intersector relationship and homogeneity of products. Although detailed uncertainty analysis from these aspects is rarely done primarily because of the lack of information within input−output tables, theoretical analysis on uncertainties has been extensively discussed (*41*). In this research, there are addition uncertainties associated with the variation between the two countries, trade data, the estimation of average worker's consumption, and the system boundary.

First, China and the U.S. are different in terms of various variables, such as demographic composition, population size, development stage, and policies and regulations, which significantly affect the environmental impacts embodied in trade. For example, the income level of Chinese population is highly diverse among regions. Therefore it is hard to accurately estimate EOLI just using a national average to approximate employees' consumption. The large size of Chinese population also determines the higher labor intensity of the manufacturing in China. Additionally, policies and regulations regarding environmental protection and employment in China and the U.S. are greatly different. To avoid taxes (e.g., the Pigouvian tax), some manufacturers may pay less environmental costs, which may underestimate the true environmental impacts embodied in trade.

Second, given the nature of IOA, monetary values of products must be used rather than physical amounts. Therefore, we use nominal exchange rate rather than purchasing power parity suggested by other studies (*42*) to convert currencies because customs simply record export values according to exchange rate. Uncertainties also come from the bilateral trade data. In particular, using trade data officially reported by China and the U.S. can change the results on manufacturing energy and CO_2 embodied in the 2002 China−U.S. trade by up to 18% increase and 38% decrease. Given the contents and characteristics of the government statistics, it is inappropriate to directly use these data without further adjustment. Besides our adjustment, there are other studies dealing with this issue from different perspectives (*29, 30*), which can increase the results of this research by 10% or decrease by 16%. Moreover, the adjustment of bilateral trade data in this research has not taken re-imports (e.g., China exports raw materials to and imports final products from the U.S.) into account. Given that the processing of raw materials or intermediate products happens in another country, it is necessary to improve the adjustment we made in this research by identifying re-imports between China and the U.S.

Third, uncertainties associated with quantifying environmental impacts of average worker's consumption exist in this research. Among various studies on energy use and CO_2 emissions caused by residents' consumption, we adopt the results from Wei et al. (*17*) for China and Shui and Dowlatabadi (*18*) for the U.S. because other studies usually focus on only impacts of household consumption but rarely investigate energy use and CO_2 emissions occurring in residents' personal travel. For the eastbound trade, uncertainties are still high even if considering energy use and CO_2 emissions for only household consumption. Particularly, energy EOLI embodied in the 2002 China−U.S. trade could decrease by 26% if using results from other studies (*43, 44*). Using the result from Peters et al. (*42*) would lead to a 45% decrease in CO_2 EOLI without considering personal travel. Furthermore, this uncertainty can be even higher if taking the huge lifestyle difference between China's urban and rural residents into account. For example, using the data for rural residents from the same research (*17*), the energy and CO_2 EOLI can be decreased by as much as 86% for rural workers. On the other hand, such uncertainties on the U.S. side are much lower, even considering the data used in our research are on the 1997 basis. For example, direct energy EOLI embodied in the westbound trade without taking personal travel into account only increases by 10% if using 2001 data from the Energy Information Administration (EIA) (*45*). The total CO_2 EOLI calculated by using a research for 2004 U.S. household carbon footprint (*19*) only increases the result of our research by 10%. Obviously, the EOLI results in this research are more uncertain for the eastbound trade than for the westbound trade, possibly because that American residents' lifestyles are relatively stable so that the associated environmental impacts do not change significantly over time.

Finally, the system boundary of this study can be extended to include the impact caused by indirect labor input to the manufacturing of export goods as shown in Figure 1. A full integration of manufacturing and total labor input will certainly increase the amount of EOLI in both countries. However, given that workers' individual consumption and associated environmental impacts are, outside of the domain of the firms where manufacturing occurs, the inclusion of indirect impacts of labor could dilute the impact caused by manufacturing, including manufacturing itself and direct labor input, which is the purpose of this study.

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Supporting Information Available

Details about the trade data adjustment and supplementary analysis are included. This information is available free of charge via the Internet at http://pubs.acs.org.

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