Decomposition of Embodied Exergy Flows in the Manufactured Products and Implications for Carbon Tariff Policies

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Abstract

The paper proposes to use the concept of embodied exergy as metrics in designing incentive policy instruments to tackle the inefficiency of energy operations. Based on the second thermodynamic law and the energy's economic property as of both private commodity and public goods, it maintains that energy be measured by separating its useful exergy embodied in a manufactured product from its waste exergy (anergy) as emission and sunk waste in a production process. It is rational to benchmark the content of useful exergy embodied in products for any incentive polciy design to encourage green production. The paper uses the trade data between China, Japan and EU countries and compares the embodied exergy and waste exergy embodied in the traded manufactured products. The paper proposes to use negative value-added tax as an incentive instrument instead of fullscale carbon tariff to encourage green production and to fence against carbon evasion behaviour.

The analysis on embodied exergy flow in manufactured products is to find about how much useful energy left and embodied in a product, and what amount of emission and waste caused by energy depreciation at different point of production/consumption process should be assigned either to producers or to consumers for the mitigation duty.

The research methods adopted for this study include Literature Based Discovery (LBD) and Gtap-E simulation. The former is applied to expound and prove a theory about embodied exergy in traded products and an empirical analysis based on the trade data of EU and its major eastern Asian partners-China and Japan.

1.Introduction

1.1. Global energy consumption network and carbon emissions

The global fuel energy resources should be treated as common properties of the global community if we look at them from the perspective of environmental sustainability and greenhouse gas (GHG) mitigation. Despite the growing importance of international production networks in the world economy and a growing body of literature on embodied energy in trade, there is still limited literature on the effects of fragmentation of production and shifting trade patterns on energy consumption and greenhouse gas emissions. In contrast to the cross-boundary drive of industrial networking for fuel energy sourcing and consumption, the international community is still trapped in territory boundaries and confined the greenhouse gas mitigation efforts to segmented national commitments and policies, while being troubled with so called carbon leakages across the global production chains. Recognizing that much environmental damage is due to the increased scale of global economic activity, and the divide between industrial countries and emerging economies, especially China, on the issues about emission benchmarking methods and theories, this paper adopts a technical decomposition approach. By differentiating the useful energy (exergy) from its waste energy (anergy) of an energy form in the production process and tracking the emission routes of products flows across countries, it is found that the polluter-pay principle could be challenged in the context of global production chain and new trade pattern, as the border tariff or domestic tax in one country or region may well spin off a cross-chain effect along the global production value chain.

Energy consumption in industry commonly refers to the primary energy sources including biomass-based fuels, fossil fuels (coal, oil, natural gas) and renewable sources (sun, wind, water) used to power manufacturing processes. For economic analysis, the conventional way for accounting the energy consumption amount is based on the ratio of value of output to the quantity or cost of energy inputs, i.e. energy efficiency. One of the loopholes of this accounting method is that the cost of energy inputs counted may induce a plausible conclusion that the manufacturer is the polluter, who should take the liability for the unavoidable cost of the greenhouse gas emissions, therefore the polluter-pay principle targeting at suppliers applies and underpins policies such as an ecotax or carbon tax. Further, with the growth of global production value chain, the producers, especially those multinational companies (MNCs) will relocate the polluted sectors outside their home countries to circumvent the tax burden. The intentional carbon tax evasion rather than casual leakage will surely become an unavoidable case.

1.2. Embodied exergy analysis

The interest in studying about embodied exergy flow is triggered and developed roughly parallel in the same period in engineering (Georgescu-Roegen, 1971) and environmental and biological circles (Odum,1996;) and later it has been seen in the study about economics and international trade (Costanza,1980,Moran, et al, 2009). Different from the concept of embodied energy which is defined as the cumulative amount of commercial energy (fossil, renewable, nuclear) invested to extract, process and manufacture a product and transport it to its point of use, embodied exergy is defined as the amount of work the system can perform when it is brought into *thermodynamic equilibrium*[①] with the environment (Jørgensen,2004). Different from gross energy consumption data used in macroeconomic accounting and projection, embodied exergy is product-specific accounting methodology which aims to capture the consumption mode of energy embodied in an entire product lifecycle. The analysis on embodied exergy flow in manufactured products is to find about how much useful energy left and embodied in a product, and what amount of emission and waste caused by energy depreciation at different point of production/consumption process should be assigned either to producers or to consumers for the mitigation duty.

The research methods adopted for this study include *Literature Based Discovery* (LBD) to expound and prove a theory about embodied exergy in traded products and an empirical analysis based on the trade data of EU and its major eastern Asian partners-China and Japan. The analysis strives at defending three arguments: first, the border-confined institutional mechanism such as carbon tariff scheme based on the energy feedstock of individual countries' industries may cause "carbon evasion" behavior, that is, producers or even governmental decision makers may choose to segregate the production value chain across the borders and relocate those energy-intensive and heavy polluted production processes in other countries to circumvent the environmental and financial liabilities imposed by the international GHG mitigation commitments. Second, the energy as a traded goods

[①] It can be understood as a state in which an input of energy has been combusted to the full under set temperature and technical conditions.

should be treated as a commodity of dual property as possessing both features of non-exclusive public goods and tradable private goods. As feedstock input, its degradation property caused by its physical and dynamic effects can convert only a portion of energy into useful work (or exergy) and a certain amount of deadweight loss of energy (or anery) caused by entropy effects will either turn into waste or GHG. Therefore the focus of emission problem should be directed at how to maximize exergy efficiency. It would be misleading if we simply use total energy inputs as a base for calibrating carbon tariff rate. And the third, in the context of global production value chain and cross-border products flow, the incentives for joint GHG mitigation efforts is not triggered by levying tax on energy use rather by encouraging the exergy efficiency.

This study has two purposes. First, it explores the status quo of embodied exergy consumption flow in traded products between EU and its major East Asian partners. Second, it discusses the distributional impact of embodied exergy consumption and burden on both producers and consumers in different regions and countries the potential positive and negative effects as a result of carbon mitigation policies.

The following paper is divided into four sections. The second section gives a critical review about embodied exergy approaches and their applications. In the third section, the accounting methodology for embodied exergy flow for this paper is proposed and explained. The forth section followed is an empirical study on the embodied exergy in traded manufactured products flow between EU and its two major East Asian trading partners, China and Japan followed by GTAP-E simulation. The final section is the analysis based on the simulation findings for implications for carbon related trade policies.

2. A critical review about embodied exergy approaches

2.1. The concept of positive and negative values of embodied exergy

The exergy-based methods are grounded on the second-law of thermodynamics, which takes into account the unavoidable losses caused by the entropy effect[②]. When using energy we utilize the energy conversions along its way towards heat at environmental temperature. During this process not all the energy can be converted into work, only a certain available part of the energy, or the similar amount of mechanical work that could be extracted from it. This useful component of energy is called exergy, which is destroyed by every process or action, while the non-useful component of energy (anergy) increases, which can be in the forms of heat, gas and wastes to emit. Based on energy conservation law, energy flows into and out of components should be equal. Due to the entropy effect, exergy flows to and from components do not balance, because there is a conversion loss, or "consumption" of exergy. This may be explained as those components in the system consume exergy by virtue of the ineffectiveness of their ability to transfer available energy (Moore,1981).

In the past 20 years, there is an increasing application and recognition of the usefulness of exergy methods by those in industry, government and academia in many countries. Applications of exergy analysis can be found not only in thermodynamics field, it has also been applied to fields outside, particularly, various industrial systems and environmental impact assessment (Dincer, et al.,2011).

Conventional energy analysis based on the first-law of thermodynamics is essentially an

[②] The traditional qualitative description of entropy refers to changes in the status quo of the system and is a measure of "molecular disorder" and the amount of wasted energy in a dynamical energy transformation from one state or form to another.

accounting of the energies entering and exiting. When measuring a system's energy efficiency, it is measured by the ratio of a system's energy input to its output, but it cannot tell the causes, locations and magnitudes of process inefficiencies. The results of such energy analysis can often indicate the main inefficiencies to be within the wrong sections of the system, and a state of technological efficiency different than actually exists (Dincer, et al.,2011). But for exergy analysis, it highlights that although energy cannot be created or destroyed, it can be degraded in quality, eventually reaching a state in which it is in complete equilibrium with the surroundings and hence of no further use for performing tasks. The exergy efficiency is the ratio of the amount of thermodynamics work performed by a process (the numerator) to the maximum amount of work performed in theory (exergy). It is considered as a measure of potential to cause change, and may provide the basis for an effective indicator of the potential of energy form to impact the environment.

The exergy concept has mostly been used within heat and power technology, now its field of application is being extended to the analysis of energy production and consumption in relation to GHG emissions and mitigations. As exergy per unit quantity is in fact the physical value of a resource relative to the environment, the embodied exergy analysis can provide a more direct access to evaluate the emission intensity and technology efficiency.

Drawn on the thermo-economic and system ecological studies (Sciubba,2001; Rosen, 2003; Odum,1996), fuel energy can be considered to have a dual property of both public and private commodity. Just as systems ecological analysis reveals, the emission of energy use can be treated as a commodity of negative value (Chen, 2005, 2011). As the market value and material quantity of energy cannot reflect the hidden cost of negative utility caused by emissions, we have to resort to exergy analysis for a better understanding about how to reduce emission.

2.2. The basics of exergy analysis

Exergy analysis is a thermodynamic analysis technique of exergoeconomics, the branch of applied thermodynamics and optimization methods (Sciubba, 2004).It is suggested that exergy is the only rational basis for assigning monetary costs to the work actually performed by input energy. Based on the second law of thermodynamics[③], the exergy of an energy form or a substance is a measure of its usefulness or quality or potential to impact the environment. It is the maximum theoretical useful work (shaft work or electrical work) obtainable as a thermodynamic system is in a complete state of thermodynamic equilibrium under conditions of certain temperature and pressure (Tsatsaronis,2007).Some studies (Rosen & Dincer,2001, Dincer 2002) have proved that the deviation between energy-based and exergy-based analysis can be very large. It is found that the efficiency of a steam generator on an energy base can be 95%, if it is calculated by its input quantity but only 50% efficient on exergy base. Most of the exergy losses in the steam generators are associated with internal consumptions. This discrepancy implies that, although most of the input energy is transferred to the preheated water, the energy is degraded in the process.

In recent years many studies on environmental impact of a manufacturing process have adopted exergy analysis methods. Wall (1986) has proved by comparing energy and exergy losses in the manufacturing process and pricing differences between the two that exergy based analysis can be a

[③] i.e. the law of thermodynamic entropy production, is alternatively expressed in terms of exergy consumption, that is, exergy can never be created: it is always consumed in a real irreversible process in exception only for the idealized reversible or equilibrium process (Chen,2005), simple method and may develop conventions and standards for technical improvements for long-term planning. Based on Renaldi (2011), Wall (1986), Tsatsaronis (2007)'s definitions, and especially Szargut's breakthrough contribution to the calculation of exergy (2002), we are able to rationalize the proposed exergy approach as follows.

First, exergy is a general measure of the quality of natural resources. In a fuel combustion system, there are four different types of exergy *E*, denoted respectively as kinetic, potential, physical and chemical exergy. Kinetic and potential exergy have the same meaning as the corresponding energy terms can be disregarded for the purposes of analyzing most common industrial processes. Physical exergy is "the work obtainable by taking a substance through reversible physical processes from its initial state (temperature *T*, pressure *p*) to the state determined by the temperature T_o and the pressure p_o of the environment"(Szargut et al. 1988). Physical exergy assumes an important role for the purposes of optimization of thermal and mechanical processes, including heat engines and power plants. But it is of secondary importance, or even negligible when attention is focused on emissions of fuel combustion in the manufacturing processes. In this case, chemical exergy plays a major role for the purpose of embodied energy accounting and environmental analysis. Chemical exergy is "the work that can be obtained by a substance having the parameters (temperature *T* and the pressure *p* to a state of thermodynamic equilibrium with the datum level components of the environment" (Szargut et al.1988).

Second, energy is motion or ability to produce motion and exergy is work or ability to produce work (Wall,1986). That is, not all exergy output can be considered as useful output. Material wastes, emissions and heat losses are external exergy losses. To split embodied exergy in products E_P from the loss exergy (anergy) E_L , The equation (1) can be rewritten as:

$$E_P^x = E_R^x - E_L^X \tag{1}$$

Third, the exergy losses are the results of entropy generation partially caused by the fuel components, and partially caused by technological inefficiency. By distinguishing the inefficient causes from the deadweight losses of exergy, we can use exergy loss as a measure to calculate the ecological cost thus incurred and necessary incentive financial instruments for green production and GHG mitigation.

Most of the literature about exergy-based analysis is concentrated in thermo-engineering, environmental and ecological areas, producing quite well grounded formulations to calculate both positive exergy and negative exergy, however, it is found quite difficult and complicated to be applied directly in economic analysis. Of limited journal articles on the economic aspects, Sciubba (2011) focuses on macro space- and time integral of primary energy, and Bo Zhang et al (2012) uses exergy-based analysis for an empirical study on the emissions data of Chinese industrial sectors with clustering and disjoint principal component analysis(CDPCA) to calculate the exergy contents of the emissions. The methods they use are all based on thermodynamic tools, though very applicable, yet with stringent constraints, including temperature and operation environment parameters. To solve this difficulty, Szargut and Stanek (2002, 2008) introduce the index of ecological cost, defined as the cumulative consumption of non-renewable exergy in fabricating a particular product plus the compensation of environment losses caused by rejection of harmful substances to the environment. Based on thermo-ecological cost balance equation, the dimensionless index expresses the ratio of thermo-ecological cost of the *i*- th product related its specific exergy. The lower is the index value, the better from the ecological point of view, believing that we pay less cumulative exergy of natural resources per unit of exergy of particular useful products.

In theory, exergy analysis provides a more plausible way to evaluate the efficiency of energy conversion system in relation to GHG emissions. This method complements the widely used "energy intensity" based on the ratio of the quantity or cost of energy inputs to the value of output, which can only measure quantity, but not the quality. Exergy analysis enables us to determine the locations, types, and true magnitudes of wastes and losses. This actually lays a scientific basis for internalizing the cost of environmental recovery incurred by production emissions. Just as Zhang noted (2012), the measure of pollution was modified into embodied exergy or exergy emitted as "ecological cost" to make up for the polluted environment. As a special corollary, the maximum exergy production efficiency principle for production value chain can then turn to be the principle of maximum profit for sustainable economic development.

3. Accounting embodied exergy flow

3.1. Setting the boundary for embodied exergy analysis

There are two ways to define embodied energy consumption flow. First it may refer to the total input of fuel energy including the fossil fuel and non-fossil fuel in the production process for making products. Second, it may also refer to the aggregate input of all kinds of invested energy including fuels, materials and manpower. For the study purpose here, we adopt the first definition, with its complete definition quoted from UNIDO's Industrial Development Report (2011) as follow:

Embodied energy refers to the cumulative amount of commercial energy (fossil, renewable, nuclear) invested to extract, process and manufacture a product and transport it to its point of use. This accounting concept sums the energy physically embodied in the materials (which can be released by reversing the process) and the energy invested in creating the processing conditions and bringing the materials together (including transport).

It can be further inferred from this that embodied exergy consumption flow refers to the cumulative amount of useful energy invested in a production process minus its losses including heat, material waste and emissions.

Basically there are two types of research design, product-specific and process-based analysis methods, each of different analytical utility. For the product-specific analysis, which is now being applied in civil engineering and thermo-engineering industries, its measurement is based on the thermodynamic analysis of chemical compositions of specific products, and sets its boundary for example, starting with an input material as a final product (e.g. cement for building) and traces backward the direct energy inputs or sequestered energy of each contributing material (i.e. water, limestone,etc.) (Dixit, et al. 2010;). This method is also applied in principal components analysis for environmental emissions (Zhang, et al.,2012).

The second approach is process-based analysis or supply chain analysis (Nishimura,K., 1995; Seow, 2011;Bordigoni, et al,2012, Kara,S, et al, 2010,2011). This approach, based on the energy conservation law and life cycle theory, requires setting a system boundary as the process to be studied and take into account all possible direct energy inputs or sequestered energy of each contributing material in the process. There are mainly three analytical boundary setting techniques:

(1) 'Cradle-to-gate analysis', which includes all energy (in primary form) until the product leaves the factory gate.

(2) Cradle-to-grave analysis, which starts from the extraction of raw materials (including fuels)

until the end of the products life cycle (including energy from manufacturing, transport, energy to manufacture capital equipment, heating and lighting of factory, maintenance, disposal etc., and

(3) Cradle –to-site analysis, which includes all of the energy consumed until the product has reached the point of use (Production Cost+Freight).

3.2. Integrating embodied exergy into decomposition methods

Available decomposition methods are quite successfully in analyzing the sectoral energy consumption, yet it still cannot fully reflect the factors that determine energy usage from the technological aspects, to distinguish the positive work from negative work of energy usage. The discussion in this section is intended to make up this gap by integrating the embodied exergy analysis method with decomposition techniques into a pragmatic analytical tool.

Functions of different decomposition methods

There are already quite many discussions about decomposition techniques (Ang,1995; Sun,1998,). The general function of decomposition techniques is to study the impacts of structural differences and changes in sectoral energy efficiency improvements. Mainly three major approaches can be identified: the energy intensity approach, the energy consumption approach, and the energy coefficient approach.

The energy intensity approach studies about the effects of changes in sectoral production mix or activities, or changes in subsectoral energy intensities on the total sectoral energy intensity. Based on Greening et al (1997), the energy intensity approach has the advantage of ease of result presentation because the estimated effects are normally expressed in indices. The two index decomposition methods most commonly used are the Laspeyres or the simple average Divisia. The Laspeyres compares each of the components of energy usage patterns with a fixed base year, while holding the other components constant. As a result, this index does not have the time or factor reversal properties of an ideal price index (Fisher, 1972). As opposed to the Laspeyres index, the Divisia index, as with the Cobb-Douglas index forms, does have the time reversal property but does not have the factor reversal property.

The energy consumption approach involves decomposition of the change in industrial energy demand between two years or of the ratio of the energy consumption of one year to that of another. It studies about the effects associated with the changes in aggregate production level, structural change in production and changes in sectoral energy. A comparative study done by Greening et al (1997) shows that the result by using either fixed-year or time-series Laspeyres techniques tend to underestimate the effects for both energy intensity and activity mix on aggregate energy intensity, while using the simple average Divisia fixed base year technique tend to overestimates the effects of both energy intensity and activity mix on aggregate energy intensity.

The energy coefficient approach, is based on energy consumption approach and developed by Ang and Lee (1996) to study the impacts of structural change and changes in energy efficiencies in industrial sectors. Its major contribution is to break down the aggregate energy coefficient or elasticity for industrial energy demand into contributions from different factors including the industrial energy consumption, industrial production and energy intensity at both total and sectoral levels. By estimating the ratio of the fractional change in primary energy consumption in a specific industrial sector to the fractional change in total industrial national output, it is proposed by its inventors to identify the past evolving patterns of industrial energy consumption and the relative contributions of different factors to changes in energy demand. More importantly, Ang and Lee set up three parameters to reflect production effect (e_{pdn}), structural effect (e_{str}) and intensity effect (e_{int}) respectively for the energy consumption in a production process in a given period. They also for the first time brought into the decomposition analysis the concept of a residual term e_{rsd}, as they noticed there existed an efficiency difference between the changes in total industrial energy consumption efficiency (e_{ct}) and the total sum of the estimates of the three effects.

The factorization technique applied is calculated on the ratio changes of energy production ΔE to value production ΔP and between a time periods *0* to *t*. Their general mathematic expression is as follows:

$$(e_x)_{0,t} = [(\Delta E_x)_{o,t} / E_o] / \Delta P_{o,t} / P_o \quad (2)$$

where e_x represents the three different variables above mentioned. By using parametric estimation method, the three sub coefficients are each assigned with a quotient calculated with the Laspeyres-based parametric Divisia method. The coefficient approach draws attention to the different factors that might affect the energy consumption in the production process, it sets up an analytical causal linkage between energy consumption and production process.

In sum, those different decomposition approaches proposed and applied share the same study objective and have proved to be a useful tool in identifying the changes of industrial energy demand. But as what has discussed above, the merits of these three methods are confined to the aggregate energy consumption analysis and projection.

The exergy-based decomposition method

The major function of exery-based decomposition method is by differentiating positive energy from negative energy of energy in a production unit, it is able to determine the work efficiency of exergy and to estimate about emission impacts caused by engineering management inefficiencies. The exergy-based decomposition method is built on the concept of exergy and anergy as two components in energy, and exergy efficiency is a measure of GHG emissions. The main purpose is to break down the aggregate energy coefficient or elasticity for industrial energy demand into contributions from exergy and anergy factors. The proposed exergy-based decomposition procedures include defining time and scale scalars, parameters, factorized quotients, data synthesis and analysis.

(1) Time scalar. A periodwise (PW)-based or a time-series (TS)-based data analysis are two commonly used methods for time measurement. The choice between a periodwise analysis and a time-series analysis depends on data availability, depth of analysis and, to some extent, the decomposition approach used. As periodwise analysis is more likely to be used in multi-country analysis because less data is needed, and time-series analysis is more likely to be used together with the energy intensity approach because result presentation and interpretation are easier. For the purpose of this study, a one-year data analysis is adopted for empirical study sample.

(2) Data scale. Exergy-based analysis targets at specific sector and products. Of three different sector classification practices: (i) follow an international standard classification, (ii) group together industrial activities related in terms of energy use patterns, and (iii) single out a few major energy-intensive sectors, we choose to use sector disaggregation data for manufactured products for a selection of industrial sectors, which will enable us to compare the embodied-energy in intermediate products. This provides the advantages of linking energy consumption with pre-defined manufacturing processes and products.

(3) Parameters. This study is confined to sectoral industrial products and define the following variables:

Q_t = total industrial energy input

Q_i = energy input in industrial sector *i*

P_t = total industrial output

P_i = production output of sector *i*

V_{im} = the import value of products of sector *i*

V_{ex} = the export value of products of sector *i*

E_i^x = the exergy of energy input in sector *i*

$E_{p,i}^x$ = product exergy in sector *i*

$E_{a,i}^x$ = anergy in sector *i* , the sum of E_R^x , E_M^x , E_P^x , E_H^x , ΔE^x .

E_e^x = exergy production efficiency (= E_p^x / Q_i)

$E_{v,im}^x$ = embodied exergy in per unit value of import products

$E_{v,ex}^x$ = embodied exergy in per unit value of export products

(4) Exergy value accounting. The embodied exergy in products is decided by the system environment. In the case of fuels, namely coal, fuel oil and natural gas, the exergy content has been estimated by multiplying the net heating value by an appropriate coefficient. As more detailed treatment of the exergy formula is out of the scope of this work, we adopt, for convenience, Szargut's chemical exergy coefficient (2002) and Ayres' table (2006) for embodied exergy accounting as follows:

Table 1. Chemical exergy content of some fuels

Fuel	Exergy coefficient	Net heat value(kJ/kg)	Chemical exergy(kJ/kg)
Coal	1.088	21680	23587.84
Coke	1.06	28300	29998
Fuel oil	1.073	39500	42383.5
Natural gas	1.04	44000	45760
Diesel fuel	1.07	39500	42265

Source: Ayres. 2002

(5) For the decomposition formulation, we adopt the additive form and set one year period for "from-cradle-to-gate" production process. The decomposition procedures for computing the chemical exergy content in products include the following steps:

i. To compute the total exergy of energy input in a predefined industrial sector:

$$E_{i,j}^x = \sum_{i=1}^{n} \sum_{j=1}^{m} Q_{i,j,} \bullet \lambda_{i,j} \quad (3)$$

where $Q_{i,j}$ denotes the *j*-th fuel input in *i*-th sector. It has to be converted into thermo unit by net heat value. For λ, we adopt Ayres' coefficients in Table 1.

ii. Based on equation (2), the $E^x_{i,j}$ consists of the product exergy $E^x_{p,i}$ and the loss exergy $E^x_{a,i}$, the embodied exergy in products should be expressed as:

$$E^x_{p,i} = E^x_{i,j} - E^x_{a,j} = \left(\sum_{i=1}^{n}\sum_{j=1}^{n} Q_{i,j} \bullet \lambda_{i,j}\right) - E^x_{a,i} \tag{4}$$

As $E^x_{a,i}$ is subject to the energy property and production environment, therefore we just keep it as a variable, and because of these losses, only a certain percentage per unit of exergy supplied to a system can be usefully exploited. As it is the exergy losses that release into the environment and produce harmful effects, we adopt IPCC's CO_2 emission factors to calculate the losses cost.

iii. To compute the content of embodied exergy in per unit production output value:

$$E^x_{p,j}perunit = \frac{E^x_{i,j} - E^x_{a,i}}{P_{i,j}} \tag{5}$$

There are three options to for the calculation of $E^x_{a,i}$: in natural units using the quantities of substances, as IPCC has provided, or in monetary units resulting from the estimation of economic losses caused by harmful substances ejected into the environment, or in exergy units resulting from depletion of non-renewable resources required to prevent. For the purpose of this study, we adopt the exergy method by using emission factors ε = 4.4 MJ/kg in exergy provided by Stanek et al(2011).

$$E^x_{a,i} = E^x_{i,j} \bullet \varepsilon \tag{6}$$

iv. To compute the content of embodied useful exergy in per unit import/export products:

$$E^x_{p,im/ex}perunit = V_{im} \bullet E^x_{p,j}perunit \tag{7}$$

4. An accounting of the embodied exergy flow in traded manufactured products between EU and China, Japan

4.1. Data and synthetizing procedures

One of the big challenges in this study is synthetizing data from different sources. In order to best present the embodied exergy in intermediate products[4], we choose 2009 data from United Nation's Broad Economic Categories (BEC) as classification standard for this analysis.

It is found that China and Japan are the two top trading partners with EU from East Asian region, accounting for 72.5% imports from and 56.97% exports to EU. Over 80% of total EU exports are

[4] Intermediate goods can be parts and components or any other item used as an input in the production of manufactured goods for final consumers. Goods classified as "intermediate inputs" are by "product type" and not by "use" as in input-output tables. The former is used to approximate the latter since the latter is not available at the 6-digit HS commodity level.

manufactured products, and for the export to China and Japan, 52% more are made up by the intermediate products. Japan and China can be used as two contrasting sample for the analysis of embodied exergy flow between EU and East Asian region.

The industrial sector output data comes from UNIDO's Industrial Statistics Database (INDSTAT4 2012), and the energy data are mainly from International Energy Agency (IEA)'s sectoral energy consumption data. In order to match BEC's classification, we have adjusted certain items against the data issued by China statistical bureau and Japan Ministry of Economy, Trade and Industry.

For the convenience of comparison, we first convert all the energy carriers into unified oil equivalence unit, and use exergy coefficient and lower heating value of fuel oil to calculate the total chemical exergy of combustible energy The result of this calculation will indicate the total quantity of available or useful exergy in an energy carrier and more importantly to depict the portion of the waste exergy and its impact on the industrial and trade policy making. Second, we calculate the waste exergy of different energy carriers with reference of Stanek's energy loss ratio and properties of carbon-based fuels (2011) (Table 2). And third, the trade volume between EU and China, Japan is compiled to the BEC classification with the data from UN comtrade shown in Table 3.

Table 2 The decomposition of embodied exergy in industrial sectors

Country	Exergy （GJ）	Anergy (GJ)	Anergy %	U exergy* (GJ)	Output （Billion $）	Unit exergy （GJ/Billion$）
EU	5660.87	5.72	0.001	5655.15	6626.65	0.85
China	19966.2	7.95	0.03	19954.48	7146.90	2.79
Japan	2397.97	0.79	0.0003	2397.18	2814.71	0.85

Note: U exergy= useful exergy

Source: Energy data from IEA; Output data from UNIDO 2012.

As is shown in Table 2, both EU-27 and Japan have comparatively lower input of exergy with less anergy emitted than China. From Table 3, we may find that the exported products from China have higher contents of exergy than the imports under the same BEC codes. The plausible explanations for this could be either caused by energy-intensive production or inefficient technological and managerial operations.

4.2. A balance account of embodied exergy flow in manufactured products trade

The study shows, in the conditions that all the available exergy are put to use in production, the aggregated useful embodied exergy in the industrial sectors of EU, China and Japan totals about 975.18 GJ per billion dollars of trade value. The total exergy losses are approximately 15.25GJ per billion dollars. When we set up a balance account of embodied exergy flow in manufactured products between the three trade partners, we can find that EU enjoys a surplus of embodied exergy consumption, while China and Japan both suffer from a deficit of embodied exergy export, as these two countries actually burden the negative environmental and social effects resulting from exergy losses (Table 4).

Table 3 The embodied useful chemical exergy in manufactured products traded between EU and China，Japan in 2009

（Trade: Billion $; Exergy:GJ / Billion $）

	Item (BEC code)	EU-27 Export			EU-27 Export			China Export			Japan Export		
		China			Japan			EU			EU		
		Trade	Exergy	%	Trade	Exergy	%	Trade	Exergy	%	Trade	Exergy	%
Intermediate Goods	Food & beverages, primary, mainly for industry（111）	0.11	0.09	0.09	0.14	0.11	0.29	0.35	0.99	0.12	0.003	0.003	0.004
	Food & beverages, processed, for industry（121）	0.29	0.25	0.25	0.41	0.35	0.84	0.04	0.12	0.01	0.02	0.02	0.03
	Industrial supplies nes（2）	31.99	27.19	28.4	13.03	11.08	26.6	45.02	125.61	15.06	14.32	12.17	18.55
	Fuels & lubricants, primary（31）	0.004	0.004	0.004	0.01	0.01	0.02	0.01	0.04	0.004	0	0	0
	Fuels & lubricants, processed (without motor spirit)（322）	0.24	0.21	0.21	0.02	0.02	0.04	0.19	0.53	0.06	0.07	0.06	0.091
	Parts & accessories of capital goods (without transport equipment)（42）	21.61	18.37	19.2	4.00	3.40	8.2	40.51	113.04	13.56	16.19	13.76	20.97
	Parts & accessories of transport equipment（53）	9.20	7.82	8.2	3.00	2.55	6.14	7.08	19.74	2.37	8.73	7.42	11.31
	Sub-total	**63.45**	**53.93**	**56.35**	**20.61**	**17.52**	**42.17**	**93.21**	**260.06**	**31.19**	**39.33**	**33.43**	**50.95**
Final Goods	Food & beverages, processed, household consumption（112）	0.13	0.11	0.12	0.20	0.17	0.41	1.33	3.71	0.44	0.03	0.03	0.39
	Food and beverages, processed, household consumption（122）	1.58	1.34	1.40	3.47	2.95	7.10	2.87	8.02	0.96	0.12	0.10	0.16
	Capital goods (except transport equipment)（41）	25.76	21.90	22.88	6.38	5.42	13.01	80.23	223.85	25.69	15.07	12.81	19.52
	Transport equipment, passenger motor car（51）	7.64	6.49	6.78	3.73	3.17	7.63	0.49	1.36	0.16	11.29	9.60	14.62
	Transport equipment, other, industrial（521）	4.82	4.10	4.28	0.41	0.35	0.84	4.70	13.10	1.57	1.22	1.04	1.58
	Transport equipment, other, non-industrial（522）	0.04	0.03	0.04	0.14	0.12	0.29	0.87	2.42	0.29	1.96	1.67	2.54
	Consumption goods nes, durable（61）	1.13	0.96	1.00	1.59	1.36	3.25	23.87	66.61	7.99	3.97	3.38	5.14
	Consumption goods nes, semi-durable（62）	1.40	1.19	1.24	3.79	3.22	7.76	76.78	214.22	25.55	1.61	1.37	2.09
	Consumption goods nes, non-durable（63）	3.16	2.69	2.81	7.31	6.21	14.96	12.59	35.12	4.21	1.57	1.34	2.03
	Goods nes（7）	3.51	2.98	3.12	1.24	1.05	2.54	1.94	5.42	0.65	1.03	0.88	1.33
	Sub-Total	**49.15**	**41.78**	**43.65**	**28.26**	**24.02**	**57.83**	**205.67**	**573.83**	**68.81**	**37.87**	**32.21**	**49.05**
	Total	**112.60**	**95.71**	**100**	**48.87**	**41.54**	**100**	**300.56**	**833.89**	**100**	**77.20**	**65.64**	**100**

Note: 1.nes.: not elsewhere specified; 2. Capital goods: machinery, such as electrical generators and computers, and other manufactured goods.

Source：UNcometrade

Table 4   A balance account of embodied exergy flow in manufactured products

Unit: GJ/Billion$

Exergy flow	EU	China	Japan
Import	899.53	95.71	41.54
Export	137.25	833.89	65.64
Balance	+762.28	-738.18	-24.1

However, according to the studies carried out by Saxena from Asian Productivity Organization (2009) and European Commission (2009), there exists universally 20-30% more onsite exergy losses in manufacturing processes as a result of technological barriers. Since there is no available data for specific sectors, we can just assume that the estimated exergy losses (anergy) in Table 2 is the sunk loss decided by the properties of different fuels, while there is an extra loss resulting from low technological and management efficiencies. That is, we need to deduct 20-30% more of exergy from the nominal embodied useful exergy in products.

Another important discovery is that by comparing the two major intermediate products trade data, as Figure 1 shows, both China and Japan have surpluses for the intermediate food and beverage products under BEC items 111 and 121.

Fig.1. China's intermediate products export-import ratio with EU

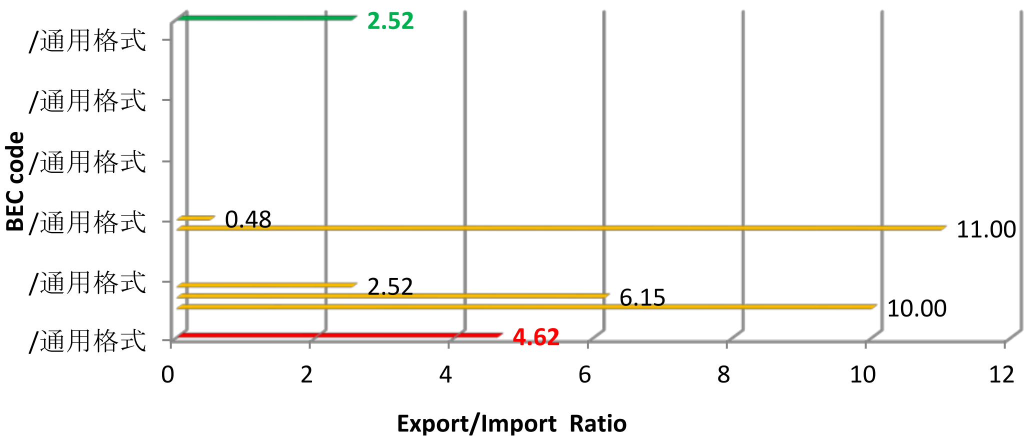


Fig. 2 Japan's intermediate products export-import ratio with EU

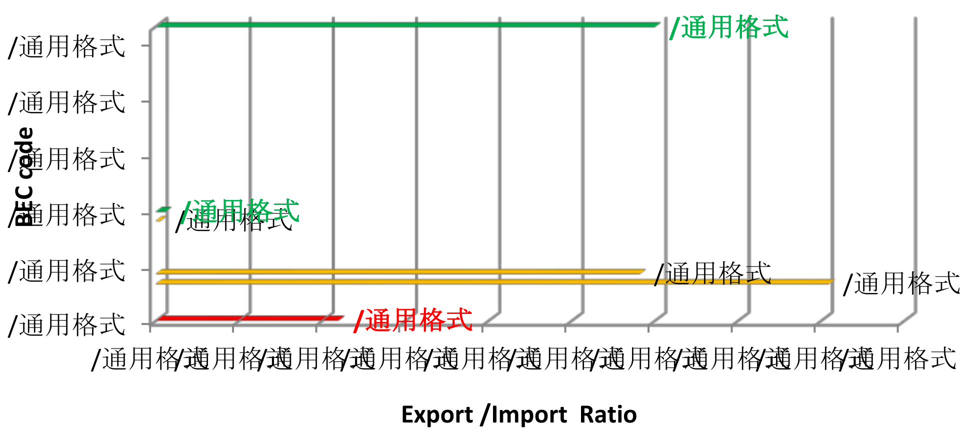
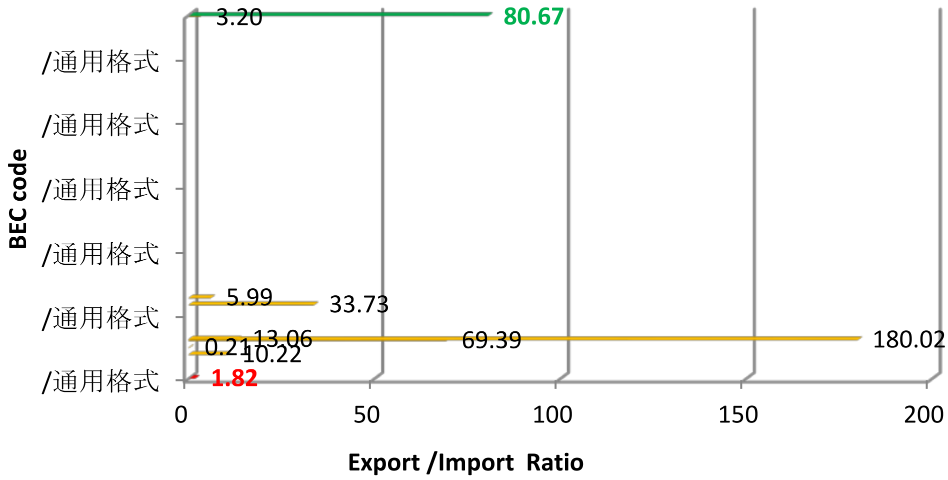
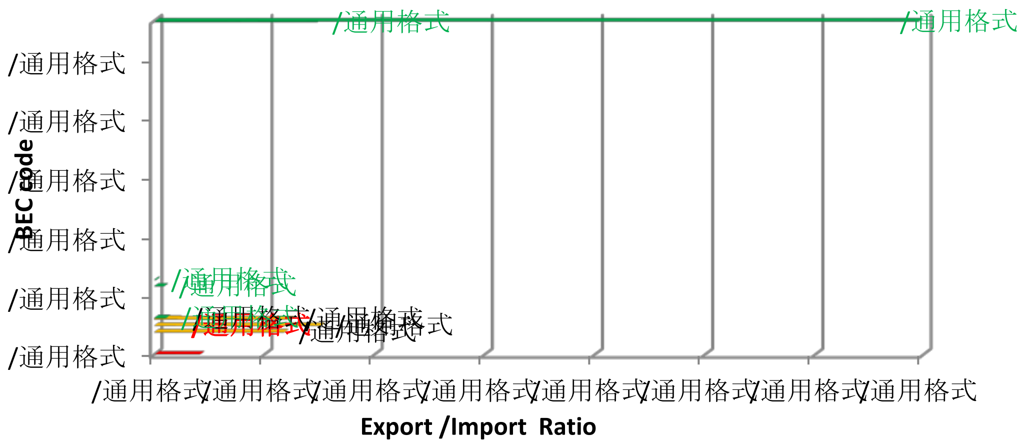


Fig.3 China's embodied exergy in final manufactured products trade with EU



For the embodied exergy in final products, China has a surplus for transport equipment under BEC 51 with EU (Fig.3), and Japan has surpluses for altogether five items with EU(Fig.4).

Fig.4 Japan's embodied exergy in final manufactured products trade with EU



5. Simulations on GTAP-E v.8

The questions raised from the above analysis could be further testified by comparing the distributional effects of energy-based carbon tax versus anergy-based carbon tax on China, Japan and EU-27. By integrating a proposed carbon tax rate into import tax (rtms) in GTAP-E v8, we simulate the effects of different tax shocks and compare the welfare decomposition results. The rationale is that anergy-based carbon tax should be set as the baseline for manufactured products, while the energy-based carbon tax should be set as the ceiling rate. The margin between the two could be treated as "negative value-added", because this is the cost incurred for carbon mitigation efforts.

5.1. Negative value-added in the Social Accounting Matrix (SAM)

The concept of negative value-added in this context is to identify, in a general equilibrium framework, the types of production loss due to domestic carbon mitigation costs. This can be illustrated by constructing the production data in the SAM for China, Japan and EU-27 (Table 5). This general equilibrium analysis has two distinct advantages: first, it shows why “value subtraction necessarily implies that some factors will carry negative shadow prices”(Bhagwati,1978),and second, it illustrates clearly the sources that the negative value-added include both factor inputs and intermediate inputs. A negative amount of value added is generated when the producers have to reimburse the environment costs out of their value added. As a measure of carbon emission costs, the negative value-added may be associated with changes of technical structure of production and terms of trade. The practical importance of negative value-added is to internalize the economic externality and to provide a justification for both subsidy and taxation initiatives.

5.2.Carbon tax and shocks design

Considering that the carbon tax to be levied on traded products is an added tariff to the import and export products, we therefore adjust the default import tax rate by source (rTMS) with calculated carbon tax rate. Based on our study, the carbon tax is designed to be levied on the quantities of anergy at the cost of carbon capture at default technological parameters. To do this, we take the following steps:

(1) The import tax rate by source to be shocked is adjusted by adding carbon tax expressed as:

$$TMc = rTMS + TMSag \qquad (8)$$

where TMc is compound import tax with both import tax rTMS and carbon tax TMSag.

(2) TMSag is the result estimated by total anergy per unit $E^{x}_{a,i}$ of energy input in products multiplied by the cost of carbon capture per unit of anergy. Here, we adopt McKinsey’s projection for the cost of carbon capture technology at around \$84 per CO_2 per ton（Beinhocker, et al,2008）. Based on the calculations in Table 2, we can calculate anergy intensity and carbon tax rates for both energy input and anergy in Table 6.

Table 6 Two different carbon tax bases for industrial sectors

EU-27	Export to China%	Export to Japan%
Energy	2.22	2.22
Anergy	0.002	0.002
EU-27	Import from China%	Import from Japan%
Energy	18.30	2.44
Anergy	0.007	0

(3) We choose variables of tax on imports (tms) to shock for energy intensive industry (En_Int_ind) and other industry sector (Oth_ind_ser) of China, Japan and EU-27 respectively as shown in Table 7. The update anergy data is calculated under perfect technological

conditions.

Table 7 Exogenous Variable Adjustment

	Base Rate	Update Rate(Energy)	Update data(Anergy)
Import tax			
rtms("En_Int_ind","CHN","EU-27")	3.1	21.4	3.107
rtms("En_Int_ind","JPN","EU-27")	2.7	5.1	2.7
rtms("En_Int_ind","EU-27","CHN")	41.8	44	41.802
rtms("En_Int_ind","EU-27","JPN")	1.4	3.6	1.402
rtms("Oth_ind_ser","CHN","EU-27")	3.6	21.9	3.607
rtms("Oth_ind_ser","JPN","EU-27")	3.3	5.7	3.3
rtms("Oth_ind_ser","EU-27","CHN")	5.6	7.8	5.602
rtms("Oth_ind_ser","EU-27","JPN")	2.1	4.3	2.102
(negative value=subsidy)			

Source: GTAP-E v.8

5.3.Experiment results analysis

By comparing the results of two shocks in Table 8, and percentage changes of anergy-based tax to energy-based tax, we can observe the following results:

First, under the default conditions of production factors, parameters, exogenous and endogenous variables, both energy-based and anergy-based tax mechanisms will not affect the output quantity, producer price and inputs of intermediate goods. However there are significant variances between the two for welfare changes.

Second，the big differences of the energy-based and anergy-based taxes on the effects of resource allocation, terms of trade and investment-savings justify that a negative value-added zone existed between anergy-based tax line as the bottom rate and energy-based tax line as the ceiling rate.

Third, the negative effects for China and Japan and the postive effect for EU-27 with energy-based tax simulation correspond to the balance account of embodied exergy flow in Table 4. It raises a question about the equity of levying energy-based carbon taxes on producers, since obviously when the import countries enjoy an embodied exergy suplus, the partner export county like China is facing worsening situations throughout.

This simulation also leaves us two more questions : what are the effects if different technological parameters for different countires are taken into consideration ? and what are the effects when different foreign exchange rates are counted ?

Table 4. Production Inputs of Energy intensive industries and other industrial sectors of China, Japan and EU-27 ($ U.S.Billions)

	China Activities		Japan Activities		EU-27 Activities			
SAM entry	En_Int_ind	Oth_ind_ser	En_Int_ind	Oth_ind_ser	En_Int_ind	Oth_ind_ser	Definition	
Commodities-total	1215967	3894835	423010	3278050	1412603	13039058	Intermediate inputs	
En_Int_ind-imports	168939.2	135241.1	77003.9	40239.6	391617.9	670200.3		
Oth_ind_ser-imports	32427.4	400681.3	5258.2	220005.3	103393.5	2075329		
En_Int_ind-domestic	679308.8	901484.8	186740	333187.8	354165.6	752831.6		
Oth_ind_ser-domestic	335291.8	2457428	154007.9	2684617	563425.6	9540697		
Factor-total	382669.4	2137927	150602.5	3307938	646295.1	11091278	Factor payment	(Value-added)-(negative value-added)
Land	0	0	0	0	0	0		
Labor	173952.3	1079567	76336.6	1869507	329605.9	5549093		
Capital	200595.4	1058360	73519.5	1438432	311028.7	5542185		
NatRes	8121.7	0	746.4	0	5660.5	0		
Factor use taxes-total	0	0	16468.5	391233.2	132127.1	2175924	Factor use taxes	
Land	0	0	0	0	0	0		
Labor	0	0	14108.8	345529.1	126439.2	2063871		
Capital	0	0	2336	45704.1	5580.1	112052.9		
NatRes	0	0	23.7	0	107.8	0		
Carbon tax-total	1215967	3328642	423009.9	3278050	1412603	13039057	Carbon tax	
En_Int_ind-imports	168939.2	135241.1	77003.9	40239.6	391618	670200.3		
Oth_ind_ser-imports	32427.4	400681.3	5258.2	220005.3	103393.5	2075329		
En_Int_ind-domestic	679308.8	335291.8	186739.9	333187.8	354165.6	752831.6		
Oth_ind_ser-domestic	335291.8	2457428	154007.9	2684617	563425.6	9540696		
Total	2814604	9361403	1013091	10255271	3603628	39345316	Gross value of output	

Source: GTAP –E v.8.0 database

Table 5 Simulation results: % changes and variances of output quantity, producer prices, intermediate goods inputs and welfare decomposition changes between two shocks

output quantity (Billion Dollars)

CHINA	qo ("En_Int_ind","CHN")	qo ("Oth_ind_ser","CHN")	JAPAN	qo ("En_Int_ind","JPN")	qo ("Oth_ind_ser","JPN")	EU-27	qo ("En_Int_ind","EU-27")	qo ("Oth_ind_ser","EU-27")
Energy	1838.08	6535.52	Energy	710.21	7363.88	Energy	2559.80	28074.83
Anergy	1857.50	6565.13	Anergy	709.79	7365.20	Anergy	2562.80	28061.76
Change%	1.06	0.45	Change%	-0.06	0.02	Change%	0.1	-0.05

Producer price(Change rate%)

CHINA	ps ("En_Int_ind","CHN")	ps ("Oth_ind_ser","CHN")	JAPAN	ps ("En_Int_ind","JPN")	ps ("Oth_ind_ser","JPN")	EU-27	ps ("En_Int_ind","EU-27")	ps ("Oth_ind_ser","EU-27")
Energy	-1.97	-2.23	Energy	-0.22	-0.34	Energy	0.58	0.59
Anergy	0	0	Anergy	0	0	Anergy	0	0
Variance %	1.97	2.23	Variance %	0.22	0.34	Variance %	-0.58	-0.59

As Intermediate goods(Billion Dollars)

CHINA	VIFM ("En_Int_ind","CHN")	VIFM ("Oth_ind_ser","CHN")	JAPAN	VIFM ("En_Int_ind","JPN")	VIFM ("Oth_ind_ser","JPN")	EU-27	VIFM ("En_Int_ind","EU-27")	VIFM ("Oth_ind_ser","EU-27")
Energy	300.28	523.31	Energy	117.96	291.76	Energy	1092.17	2812.80
Anergy	316.23	553.16	Anergy	118.87	293.98	Anergy	1088.03	2812.82
Change%	5.31	5.70	Change%	0.77	0.76	Change%	-0.38	0

Welfare Decomposition(Billion Dollars)

CHINA	alloc	tot	IS	JAPAN	alloc	tot	IS	EU-27	alloc	tot	IS
Energy	-12.81	-28.46	-4.26	Energy	-0.56	-0.79	-0.12	Energy	-18.32	15.55	-0.90
Anergy	-0.03	-0.07	0.009	Anergy	-0.002	0.004	0	Anergy	-0.008	0.04	-0.002
Variance %	99.77	99.75	100.10	Variance %	99.64	100.51	100.00	Variance %	99.96	-99.74	99.78

Source : GTAP-E v.8

6. The policy implications for embodied exergy flow analysis

The embodied exergy analysis has provided us some new foci to reconsider the international governance theory for energy-saving and GHG emission mitigation drives.

6.1. The new trade pattern and a balance account of embodied exergy flow

The world trade pattern is now undergoing a structural change driven by global economic integration. At the front the manufacture industries, typically electronic, automobiles and apparel and footwear have their production increasingly segmented across regions. The intermediate goods trade or foreign value-added products have increasingly become a major trade pattern. In 2009, trade in intermediate goods accounts for 50 per cent more of non-fuel world merchandise trade. The analysis of embodied exergy flows in industrial products between EU and China, Japan demonstrates that energy issue can no longer be treated separately from its product carrier, as the global production value chain has segregated both of its economic and environmental benefits and costs from producers and consumers.

According to the statistics, the production and export of intermediate inputs have been mainly concentrated in Europe and Asia, each accounting for 41% and 35% in total world exports of intermediate goods, while the interregional import flows of intermediate goods between Europe and Asia topped US$ 384 billion (IDE-JETRO and World Trade Organization,2011). In Europe, about two thirds of European imports are of intermediate goods and raw materials, especially a large part of which are processed for re-export (De Gucht,2012). This study has demonstrated that EU has enjoyed an overall surplus of intermediate products trade with both China and Japan, although the overall trade balance of goods was negative during the period of 2009. One of the positive impacts is on the total factor productivity of industries (Miroudot, Lanz, Ragoussis,2009). This is not only the attraction of those more productive foreign technology embodied, more importantly it is that by the setup of cross-region production value chain, a country may choose to import comparatively environmental friendly intermediate goods or final products, leaving the comparatively polluted processing section in other countries. The aftermath is some countries, especially those underdeveloped countries will suffer not only the depletion of non-renewable resources, also the environmental degradation and thus incurred public health costs.

If we look at this issue not merely from the concern of short-term economic returns, but from a concern of a long-term sustainable development, we should redefine the “joint but different responsibility” as “joint production and shared responsibility”.

6.2. Embodied useful exergy flow, ecological cost and carbon evasion

If it is not too rash to say that all the debates on energy related pollution tax in economics overlook the chain effects of energy consumption embodied in products, we can thus conclude that the exergy losses and negative environmental impacts induced by heat generation in the process of work can be adequately measured with thermodynamic tools and its cost can be monetized. As what is discussed in the above, if all the useful exergy is fully utilized, only a very small portion of waste exergy will emit into the environment, and this would not do harm to the environment. The harm comes mainly from the underutilized useful exergy, since 20-30% more of the exergy losses are the results of low operation efficiencies. If we can precisely measure out those losses caused by inefficient management mechanism, and monetize the cost thus incurred, rather than put claim on total energy consumption, we may have more incentive policy instruments to mitigate the emissions. This is perhaps why by far it sees no real progress for an effective carbon tax mechanism.

What we propose here is, by measuring the ecological costs based on exergy efficiency, and designing a tax mechanism on “negative VAT” to compensate producers for investing in green technology, it will direct the public attention away from “the quantity of energy used” to “quality of energy using” and cultivating a new social consensus about carbon civilization to deter carbon evasion behavior.

Concluding remarks

The green utilization of energy resources cannot be effectively implemented unless we treat energy as both a public and private goods with joint production and shared responsibility. It will not help if we still cling to the transaction value of energy without distinguishing the positive value from negative value of energy use. Joint production and shared environment require us to step out of the confines of national boundaries and to renovate our knowledge about energy resources to the tempo of globalization.

This is only a preliminary study on the concept of embodied exergy and its decomposition method. It might be more interesting if we can differentiate the three trading partners by using specified parameters for each. For example, we may go deeper to compare the energy mix in each partner’s industrial sector, the productivity as well as its value-added capacity, in order to get a more thorough understanding about its causes and effects.

The issues raised here require further study, namely, the specific ecological costing methods when estimating both the value of exergy loss and a tax base. Second, the value added feature in the embodied exergy flow should be an important aspect if we want to use it as a metric to determine the location of production. Exergy analysis is found to provide the most correct and insightful assessment of thermodynamic features of any process and to offer a clear quantitative indication of both the irreversibility and the degree of matching between the used resources and the end-use material or energy flows. However, if it is applied in economic analysis still requires more work on it.

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