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A novel dataset of emission abatement sector extended input-output table for environmental policy analysis

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Abstract: Environmentally extended input-output table (EEIOT), a balanced matrix of industrial commodity and environmental resources, is widely used to evaluate environmental policy impacts. However, the existing EEIOTs contain energy consumption and pollution emission but neglect emission abatement cost and benefit. In this study, a novel Chinese emission abatement sector extended input-output table (EAS-IOT) is developed through introducing abatement cost, emission charge and abatement benefit into the conventional input-output table. Furthermore, this new EAS-IOT is applied to estimate the environmental efficiency and assess the effects of environmental policies on economy and environment. Results show that the new framework of EAS-IOT has advantage on solving the problem of biased efficiency estimation related to the conventional input-output table.

Keywords: Data on emission abatement cost and benefit; extended input-output table; emission abatement sector; environmental policy

Introduction

The rapid economic growth in China is based on the sacrifice of environmental quality. Multiple air emissions in China all come to top around the world, including but not limited to air pollution such as carbon dioxide (CO_2), sulfur dioxide (SO_2), oxides of nitrogen (NO_x) and soot and dust (SD) [1-3]. Besides, the problem of water pollution is receiving increasing attention in China, especially chemical oxygen demand (COD), ammonia nitrogen (AN) and heavy metal pollutions [4, 5]. Because air and water pollutions have severe environmental and health impacts [6], the Chinese government has realized the seriousness of its environmental

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problem, and has issued a series of environmental laws and regulations in recent two decades [7, 8].

Considering the trade-offs between economy and environment, environmental policy will have impacts not only on environment, but also on economy [9-12]. To be specific, emission and abatement condition under the influences of environmental policy will impact production strategies directly or indirectly. Besides, environmental benefit arising from high intensity abatement activities will lead to abatement cost and economic loss. In fact, from the enterprise or sector perspective, strategies of production, abatement and emission are mutually restrictive. Moreover, the production scale of one sector is influenced by other sectors.

In order to support the trade-offs analysis between economy and environment and the cost-benefit analysis of environmental policy at sector level, a novel dataset of extended input-output table is proposed in this study. Input-output table gives quantitative description of intersectoral relationships in an economic structure [13]. The conventional input-output table is improved by introducing various emission abatement sectors. Thus, the emission abatement sector extended input-output table (EAS-IOT) is constructed. The emission load and abatement cost, as well as abatement benefit of each production sector can be monetarily evaluated through emission abatement sectors in the extended input-output dataset. Additionally, a case study of Beijing is provided. Firstly, we compare the environmental efficiencies based on the new framework and the conventional method. It is indicated that the new framework reduces the biased estimation related to the conventional IOT. Secondly, we assess the effects of different environmental policies on economy and emission. It can be noted that raising environmental tax rate has positive effects on environmental efficiency and emission intensity.

The dataset of EAS-IOT has insights into the following aspects: a) It integrates production and abatement activities at input-output database level; b) It quantifies cost and benefit monetarily associated with abatement activities; c) It depicts the value flows among internal production sectors, internal emission abatement sectors, and interactional production and abatement sectors; d) It could be extended by multiple pollutions if associate data are available (such as air pollution, water pollution, solid waste pollution); e) It is capable of supporting policy analysis at different levels such as national level, provincial level, and regional level.

The EAS-IOT can be applied in many fields: a) the assessment of the impacts of environmental policy both on economy and on environment, b) the estimation of environmental efficiency and abatement welfare by combining with optimization model, c) the evaluation of efficiency and productivity changes of an economy's production and abatement activities.

Literature review: environmentally extended input-output analysis and input-output table

Environmentally extended input-output analysis

There are massive studies for analyzing the impacts of environmental policy on economy and environment with various methods. For instance, Igos et al. predicted the environmental effects of energy policies using a hybrid analysis combined life cycle analysis (LCA) and input-output model [14]. Sommer et al. used the econometric input-output Dynamic New Keynesian (DYNK) model to analyze private consumption and distributional impacts on different household income quintiles in Austria [15]. Mardones and Munoz analyzed the impact of environmental taxation on reducing greenhouse gases emission in Chile with an environmental extension of the Leontief price model [16]. Wang et al. proposed a modified data envelopment analysis (DEA) method combined with materials balance principle to estimate the effects of pollution taxes on thermal power industry in China [3].

However, there are certain limitations of the above studies, since they examined impacts (trade-offs or cost-benefit) of environmental policy on economy and environment separately. Therefore, results of the assessment of policy effects are likely biased estimated. Environmentally extended input-output analysis (EEIOA) is one of the solutions. On the one hand, it promotes analysis of the impacts of environmental policy by quantifying energy consumption and emission of pollutions in addition to commodity flow [17]. On the other hand, the relationship between economy and environment is treated completely closed [18]. Therefore, EEIOA is widely applied in many areas. For instance, through using EEIOA, Shmelev assessed the sustainability of investment in different economic sectors in UK [19]; Reynolds et al. evaluated the environmental impact of food consumption in Australia [20]; Aydın examined the economic and environmental effects of coal share in electricity generation in Turkey [21]; Dias et al. evaluated the environmental impacts of products consumption of households living in a city of Portugal [22]; Sherwood et al. analyzed the energy intensities in America [23]; Kerkhof et al. depicted the relationships between household expenditures and environmental impacts in Netherlands [24]. Besides, EEIOA is also a commonly used tool for assessing the impacts of environmental policy in China [25]. For example, Li et al. estimated the embodied mercury emissions derived from fossil energy consumption in Beijing [26]. Hubacek and Sun evaluated the effect of widely perceived changes on future land use at China's regional level [27]. Guan et al. assessed the driving forces of CO_2 emissions from 1980 to 2030 in China [28].

Environmentally extended input-output table

The environmentally extended input-output table (EEIOT) is the data base of EEIOA, which is an improvement of the input-output table (IOT) taken into account the environmental impact. The official Chinese IOTs are issued every five years, covering the input-output data both at the national level and at its provincial level. The conventional IOTs provide the material flow relationships measured by monetary value among different production sectors.

The extension of IOT is various and depends on the objectives of the researches. One common extension is adding energy consumption and energy usage or energy flow into the conventional IOT. Rocco and Colombo set up a novel bioeconomic input-output model and applied it to the estimation of energy embodied in commodity produced and primary energy requirements in Italy [29]. Mayer depicted the hybrid energetic input-output table in Germany in two ways: one is to disaggregate energy producers and users, and the other one is integrating energy flows into IOT [30]. Kim used energy input-output table to estimate energy efficiency of Korea [31]. Guevara and Domingos introduced energy flows to the conventional input-output model and established a multi-factor energy input-output model [32]. Nakano and Asakura introduced energy inputs and CO_2 emissions to the conventional IOT and calculated CO_2 emissions of new power generation technology in Japan [33]. Zhang et al. proposed a coal physical IOT which contained the complete coal flow of production to assess resource issues such as material recycling and coal reduction effect in China [34].

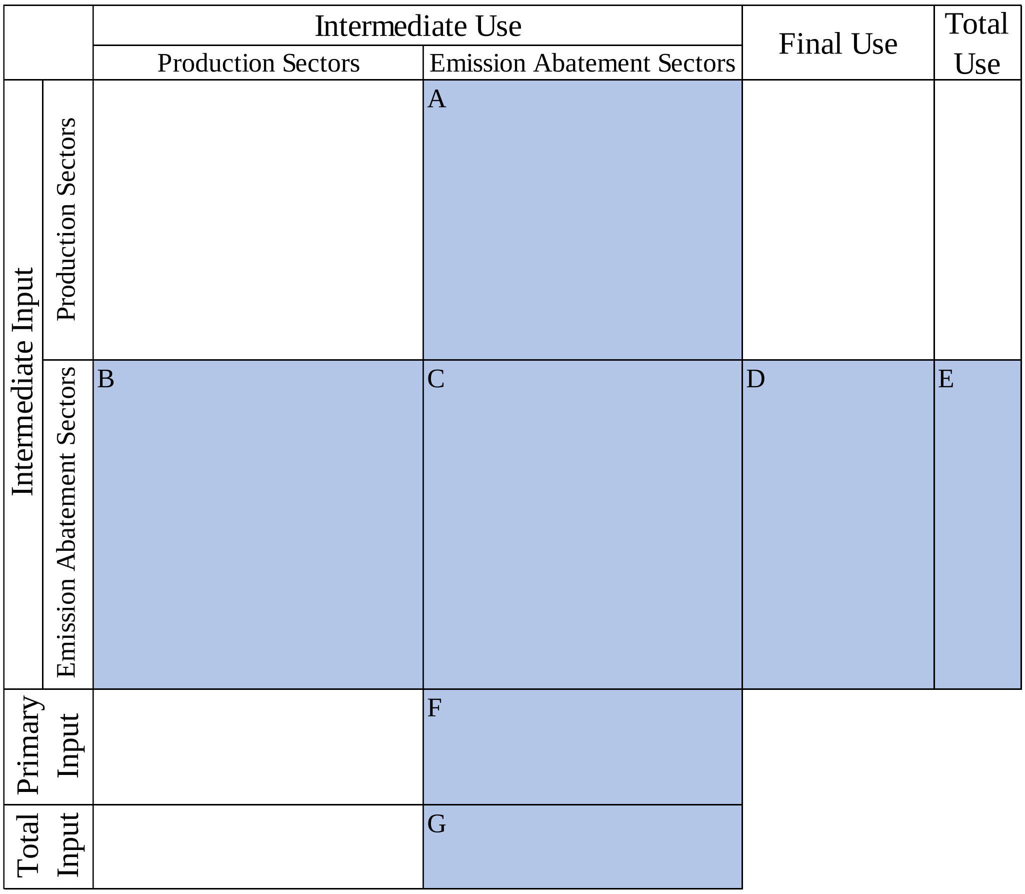
Another common extension of IOT is introducing resources (such as wind and water) inputs and emissions to the conventional IOT. Huppes et al. added a number of environmental sectors into the IOT to specify the environment impacts of household consumption in EU [35]. Tukker et al. presented the setup procedure of EEIOT, providing powerful support for analysis of total environmental impacts and external costs assessment [36]. Nagashima et al. developed a new extended input-output table by adding wind turbine production data and examined the environmental and economical impacts of a wind power generation system in Japan [37]. Deng et al. improved the conventional IOT through adding water consumption in primary industry and water usage in other industries of a county in Gansu province of China [38]. Chong and Ng constructed Hong Kong's IOT and multi-regional IOT to measure its resources consumption and carbon emissions [39]. Lutter et al. extended multi-regional input-output table with water consumption and captured water distribution footprints embodied in European countries [40]. Yang et al. provided the United States EEIOT which was mixed with data of land, energy, mineral, emission, nutrients and toxics and evaluated the environmental performance of an average hospital [41]. Similarly, Stadler et al. presented a time series of multi-regional EEIOTs during 1995 and 2011 of 44 countries, including energy, emission, water, material, land, waste and labor accounts [42]. Nevertheless, the current environmental extensions of IOT underline the environmental impacts of economic activities but put less emphasis on the inputs and outputs of emission abatement activities. For the purpose of quantizing cost and benefit of emission abatement activities, we provide a new dataset of emission abatement sector extended input-output table (EAS-IOT).

The emission abatement sector extended input-output table (EAS-IOT)

In view of the trade-offs between economy and environment, we extend the conventional Chinese IOTs with environmental part. Besides, in order to monetarily quantify the material flow between production sectors and emission abatement sectors, and to extract the costs and benefits associated with emission abatement activities, we introduce various emission abatement sectors into the conventional Chinese IOTs as the environmental part. This section gives description of the extension procedure and data sources, as well as the calculation method of EAS-IOT.

Establishment procedure of EAS-IOT

Taking Mahlberg and Luptacik as a reference [43], the EAS-IOT can be established based on Chinese IOT and emission abatement data. The main input and output variables related to emission abatement activities are *abatement cost*, *emission charge* and *abatement benefit*. All these variables need to be quantified monetarily in keeping with the production sectors. The description of the structure is presented in Fig. 1.

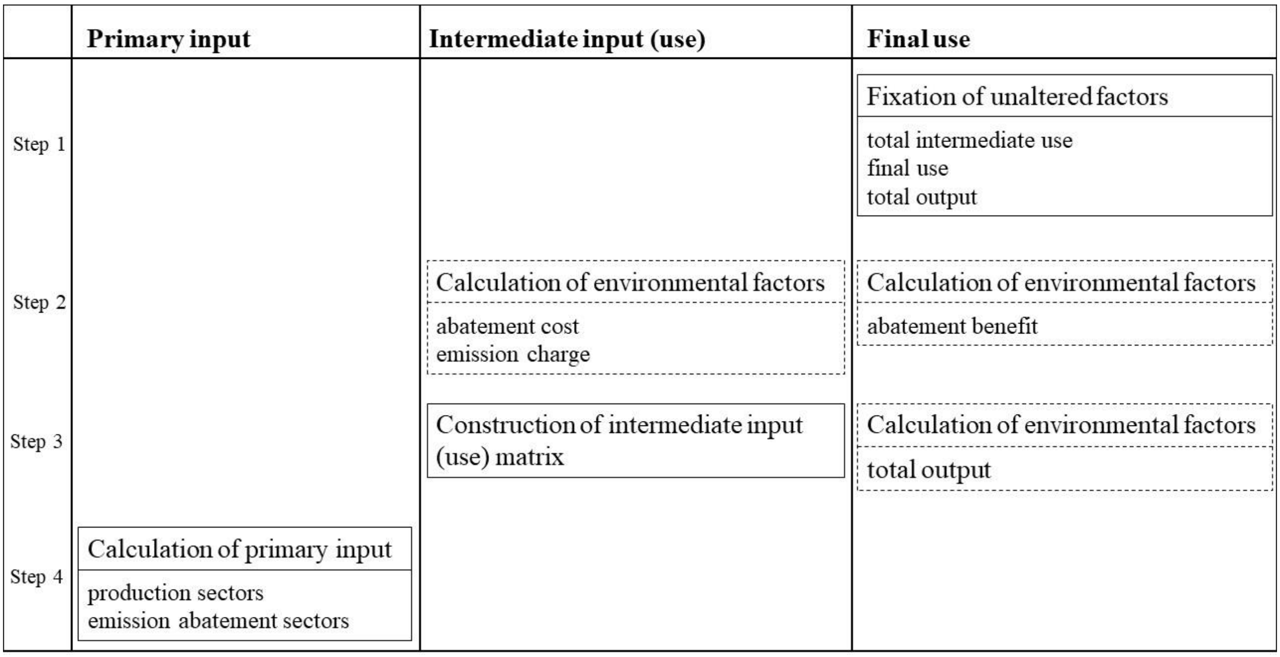


		Intermediate Use		Final Use	Total Use
		Production Sectors	Emission Abatement Sectors		
Intermediate Input	Production Sectors		A		
	Emission Abatement Sectors	B	C	D	E
Primary Input			F		
Total Input			G		

Fig. 1. Schematic diagram of EAS-IOT

According to 错误!未找到引用源。, variables can be interpreted as follow: A) *abatement cost* is the annual expenditure of emission treatment facilities, representing the intermediate inputs from production sectors to emission abatement sectors. B) *Emission charge of production sectors* is the environmental tax due to emission, representing the intermediate inputs from emission abatement sectors to production sectors. Emission charge can also be regarded as a kind of emission right. Production sectors are supposed to pay for environmental loss due to the emission. C) *Emission charge of emission abatement sectors* is the environmental tax of emission abatement sectors. In this study, we suppose that there is no emission produced by emission abatement sectors. Thus, C is a zero matrix. D) *Abatement benefit* is the avoided environmental loss due to abatement activity, representing the final use of emission abatement sectors. The excessive emission causes a series of environmental problems, and lead to severe health cost as well. Consequently, emission abatement activities will avoid health cost through emission reduction. According to World Bank, health cost can be interpreted as the percentage of GDP associated with the damages of pollution or willingness to pay for emission abatement [6]. Lots of the existing studies used the value of willingness-to-pay or Value of Statistical Life (VSL) to measure health benefits or health effects monetarily [44-46]. In view of this effect, we use the avoided health cost to measure abatement benefit. E) *Environmental value* contains the lost environmental value due to emissions and the protected environmental value due to abatement activities, representing total output of emission abatement sectors. F) *Primary input* of emission abatement sectors. G) *Total input* of emission abatement sectors. E, F, G are calculated through the balance relationships of IOT.

The extension procedure is presented as Fig. 2 step by step.



	Primary input	Intermediate input (use)	Final use
Step 1			Fixation of unaltered factors total intermediate use final use total output
Step 2		Calculation of environmental factors abatement cost emission charge	Calculation of environmental factors abatement benefit
Step 3		Construction of intermediate input (use) matrix	Calculation of environmental factors total output
Step 4	Calculation of primary input production sectors emission abatement sectors		

Fig. 2. Construction procedure of EAS-IOT. *Note:* The process fragment with solid box and dashed box respectively denotes step of production sectors and step of emission abatement sectors.

3.1.1 Fixation of unaltered factors

In consideration of that the existing production scale is not affected by the quantification of emission charge and abatement cost, as well as abatement benefit, environmental extension will have no effect on production capacity. In other words, the current production capacity is decided by productive technology, productive scale and other productive factors; there is no difference of whether being connected with environmental part and being introduced of several emission abatement sectors. Therefore, the unaltered factors of production should be fixed at first. To be specific, total intermediate use of production sector is fixed in intermediate input (use) matrix; final use, import, error and total output of production sectors are fixed in final use matrix.

3.1.2 Calculation of environmental variables associated with emission abatement

As mentioned above, *abatement cost*, *emission charge* and *abatement benefit* are calculated from externality data. Annual expenditure of industrial pollution treatment facilities distributed by emission proportion of each pollution is served as *abatement cost* of each pollution in production sectors. For purpose of monetary measurement of emission, environmental tax rate is chosen as the coefficient to transform emission load from physical quantity to economic quantity. Thus, environmental tax, the product of emission load and environmental tax rate, is served as *emission charge* (also known as the lost environmental value). Besides, considering different pollutions have different negative effects on environment, all emission variables are measured by equivalent-kg other than physical quantity unit (kg). In addition, the avoided environmental loss (also known as the protected environmental value) served as *abatement benefit*, is calculated by the product of the emission reduction compared to 2010 level and the health costs per unit of emission. Specifically, it has been pointed out from World Band that total health costs of air pollution and water pollution in China is 3.8 percent (using Value of Statistical Life, VSL) of GDP and 2.0 percent of GDP, respectively [6]. So far, intermediate input, intermediate use and final use of emission abatement sectors are determined. Meanwhile, total output of emission abatement sector is also confirmed through the balance between intermediate use and final use of emission abatement sectors.

3.1.3 Construction of intermediate input (use) matrix of production sectors

Supposing that the intermediate input proportion of each production sector over all production sectors is unchanged, intermediate input (use) matrix of production sectors can be constructed through the difference between total intermediate use and abatement cost of production sectors.

3.1.4 Calculation of primary input matrix

Assuming that the primary input proportion of each primary input in each production sector is constant in the original IOT and the extended IOT, primary input matrix of production sectors can be constructed. Besides, emission abatement is related to all production sectors during their productive processes. Given that the primary input proportion of each emission abatement sector is unavailable, it is assumed to be the same with that of total production sectors. Thus, the primary input matrix of emission abatement sectors can be calculated.

Data sources

The main datasets of this study are the Chinese national IOT and provincial IOT. The national and provincial IOTs are available from Department of National Economic Accounting, National Bureau of Statistics of China. Environmental datasets include emission loads of various pollutions, environmental tax rates, abatement costs, health costs and emission abatement target, which can be obtained through Liang et al. [47], network resources (see Appendix Table 2), Department of Industry Statistics of National Bureau of Statistics of China, Word Bank and government work report, respectively.

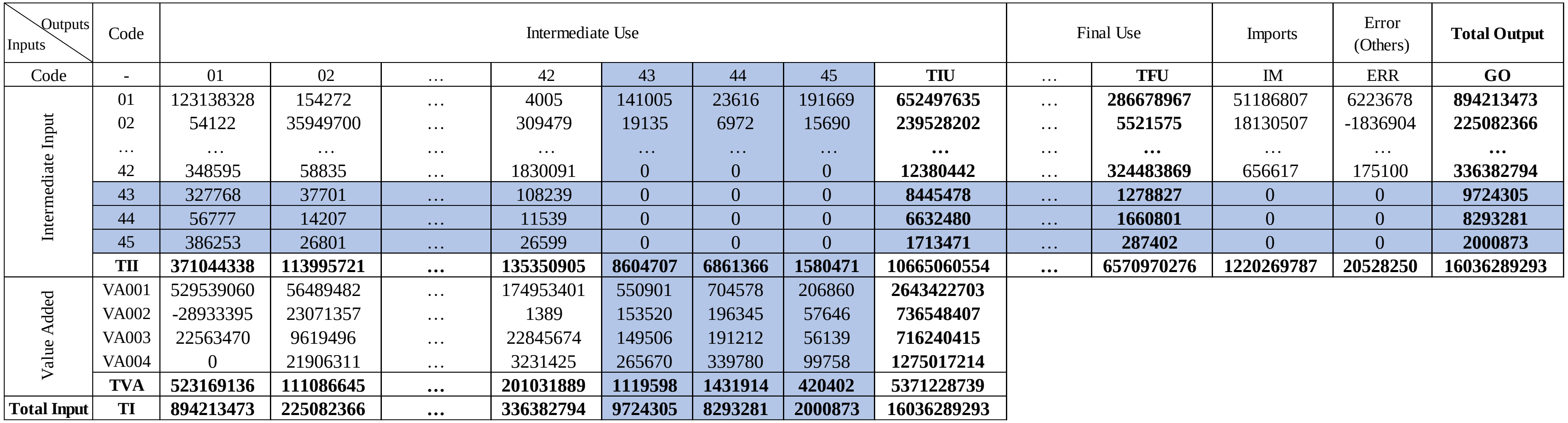
Samples of EAS-IOT

Given that EAS-IOT is based on conventional IOT, it shows good flexibility in many ways. Specifically, it can not only be extended at nation level or provincial level, but also be extended with multiple pollutions. We develop the three pollutions EAS-IOT at national level and sixteen pollutions EAS-IOT at provincial level as samples. The 42 sectors in 2012 IOT are adopted as sector category standard. Production sectors and emission abatement sectors together with the corresponding codes are represented in Appendix Table 1. The pollutions contained in EAS-IOTs are listed as Table 1. The diagram sample of three pollutions Chinese EAS-IOT in 2012 and sixteen pollutions Beijing's EAS-IOT in 2012 is represented in Fig. 3 and4, respectively. And more detailed datasets are attached in Supporting Material.

Table 1 List of pollutions contained in EAS-IOTs

EAS-IOT	**Pollutions**
National level	***Air pollutions***: sulfur dioxide (SO_2), oxides of nitrogen (NO_x), soot and dust (SD)
Provincial level	***Air pollutions***: sulfur dioxide (SO_2), oxides of nitrogen (NO_x), soot and dust (SD) ***Water pollutions***: chemical oxygen demand (COD), ammonia nitrogen (AN), phosphorus (P), petroleum pollutants (PP), volatile phenol (VP), Cyanide (Cy), aquatic Hg (Hg), aquatic Cd (Cd), aquatic Cr (Cr), aquatic Pb (Pb), aquatic As (As), aquatic Cu (Cu), aquatic Zn (Zn)

From Fig. 3 we can see that, the official 42 sectors Chinese IOT in 2012 is extended to 45 sectors EAS-IOT by adding three emission abatement sectors, which are SO_2, NO_x, and SD abatement sectors. In primary input matrix, the last 3 columns of value added are primary inputs of each emission abatement sector. In intermediate input (use) matrix, the first 42 rows of last 3 columns are abatement costs of each production sector for each pollution, the last 3 rows of first 42 columns are emission charges of each production sector for each pollution, while the last 3 rows of last 3 columns are abatement costs (or emission charges) of each emission abatement sector for each pollution. Similarly, in final use matrix, the last 3 rows of total final use are abatement benefits of each emission abatement sector, while the last 3 rows of total output are environmental values of each emission abatement sector (the same to the last 3 columns of total input). Similarly, the 45 sectors EAS-IOT is further extended to 58 sectors at provincial level by additionally introducing thirteen water emission abatement sectors (see Fig. 4), including COD, AN, P, PP, VP, Cy, Hg, Cd, Cr, Pb, As, Cu, and Zn abatement sectors.



Outputs Inputs	Code	Intermediate Use								Final Use		Imports	Error (Others)	**Total Output**
Code	-	01	02	…	42	43	44	45	**TIU**	…	**TFU**	IM	ERR	**GO**
Intermediate Input	01	123138328	154272	…	4005	141005	23616	191669	**652497635**	…	**286678967**	51186807	6223678	**894213473**
	02	54122	35949700	…	309479	19135	6972	15690	**239528202**	…	**5521575**	18130507	-1836904	**225082366**
	…	…	…	…	…	…	…	…	**…**	…	**…**	…	…	**…**
	42	348595	58835	…	1830091	0	0	0	**12380442**	…	**324483869**	656617	175100	**336382794**
	43	327768	37701	…	108239	0	0	0	**8445478**	…	**1278827**	0	0	**9724305**
	44	56777	14207	…	11539	0	0	0	**6632480**	…	**1660801**	0	0	**8293281**
	45	386253	26801	…	26599	0	0	0	**1713471**	…	**287402**	0	0	**2000873**
	TII	**371044338**	**113995721**	**…**	**135350905**	**8604707**	**6861366**	**1580471**	**10665060554**	**…**	**6570970276**	**1220269787**	**20528250**	**16036289293**
Value Added	VA001	529539060	56489482	…	174953401	550901	704578	206860	**2643422703**					
	VA002	-28933395	23071357	…	1389	153520	196345	57646	**736548407**					
	VA003	22563470	9619496	…	22845674	149506	191212	56139	**716240415**					
	VA004	0	21906311	…	3231425	265670	339780	99758	**1275017214**					
	TVA	**523169136**	**111086645**	**…**	**201031889**	**1119598**	**1431914**	**420402**	**5371228739**					
Total Input	**TI**	**894213473**	**225082366**	**…**	**336382794**	**9724305**	**8293281**	**2000873**	**16036289293**					

Fig. 3. Diagram of EAS-IOT of China in 2012

Outputs Inputs	Code	Intermediate Use									Final Use		Imports	Infow	Error (Others)	**Total Output**
Code	-	01	02	…	42	43	44	…	58	**TIU**	…	**TFU**	IM	IF	ERR	**GO**
Intermediate Input	01	799922	445	…	0	2284	382	…	3	**5617936**	…	**12392178**	8081148	5971466	0	**3957500**
	02	25598	8277410	…	10848	342	125	…	0	**9576000**	…	**32907204**	3272875	29491390	0	**9718938**
	…	…	…	…	…	…	…	…	…	**…**	…	**…**	…	…	…	**…**
	42	14928	48	…	10592	0	0	…	0	**539943**	…	**15117847**	525769	336422	0	**14795599**
	43	22208	2823	…	7334	0	0	…	0	**572706**	…	**23168**	0	0	0	**595874**
	44	3719	1029	…	756	0	0	…	0	**434771**	…	**36615**	0	0	0	**471386**
	…	…	…	…	…	…	…	…	…	**…**	…	**…**	…	…	…	**…**
	58	150	0	…	0	0	0	…	0	**150**	…	**0**	0	0	0	**150**
	TII	**2837228**	**9180116**	**…**	**9183445**	**139431**	**111173**	**…**	**3**	348576511	**…**	**898796687**	**247564903**	**472366740**	**0**	527441552
Value Added	VA001	766655	170756	…	4960290	230351	181788	…	74	**90968111**						
	VA002	8135	154348	…	43799	74824	59049	…	24	**29362196**						
	VA003	180602	11047	…	607380	58478	46150	…	19	**22045760**						
	VA004	164879	202671	…	685	92789	73227	…	30	**36488981**						
	TVA	**1120272**	**538822**	**…**	**5612154**	**456442**	**360214**	**…**	**146**	178865048						
Total Input	**TI**	**3957500**	**9718938**	**…**	**14795599**	**595874**	**471386**	**…**	**150**	527441552						

Fig. 4. Diagram of EAS-IOT of Beijing in 2012

Case study: environmental efficiency evaluation and environmental policy analysis for Beijing

In this section, we use the EAS-IOT and frontier based environmentally extended input-output model to estimate environmental efficiency and assess effects of environmental policy for Beijing in 2012 for demonstration purposes.

Methodology

Given that values of emission abatement cost and emission fee or tax are embodied in the economic flow of industrial sectors in the conventional IOT, intermediate input contains not only products provided to other sectors but also products used to emission abatement. Therefore, environmental efficiency based on conventional IOT is likely to be biased estimated. Model (1) measures the conventional environmental efficiency based on conventional IOT.

$$
\begin{aligned}
&\max_{x,e,\delta}\ \delta \\
&s.t. \\
&x - A\cdot x + IM^0 + IF^0 - ERR^0 \geq (1+\delta)TFU^0 \\
&e - EI\cdot x \geq (1+\delta)AT^0 \\
&B\cdot x \leq (1-\delta)z^0 \\
&x,\ e,\ \delta \geq 0
\end{aligned}
\tag{1}
$$

Notations in model (1) are illustrated as follows: δ is the environmental inefficiency score, showing the improved potential of the whole economic system. A is the 42×42 intermediate input coefficient matrix, EI is the 16×42 emission coefficient matrix, while B is the 4×42 primary input coefficient matrix. TFU^0, IM^0, IF^0 and ERR^0 is the total final use vector, imports vector, inflow vector and error vector of 42 industrial sectors respectively. AT^0 is the abatement target vector, measured by the product of emission load in 2012 and emission abatement percentile target of the "12th Five-Year Plan". Z^0 is the social available vector of the 4 primary inputs, calculated by the observed value and the available but not used percentage. x and e is the variable of total output vector and the variable of total produced pollution vector, respectively.

The first constraint means that for each industrial sector, the optimal total output deducted with intermediate use should no less than the observed total final use. The second constraint represents that for each pollutant, the optimal total produced pollution deducted with emission load should satisfy the abatement target. While the third constraint gives the upper bound of each primary input. Moreover, each variable (x, e, δ) should be positive.

Furthermore, in order to capture the value of environmental management, we take the reference of [47] and estimate modified environmental efficiency based on EAS-IOT in model (2). The most important difference between model (1) and model (2) is that whether the intermediate input for production and the intermediate input for emission abatement are distinguished appropriately.

$$
\begin{aligned}
&\max_{x_1,x_2,\delta}\ \delta \\
&s.t. \\
&x_1 - A_{11}\cdot x_1 - A_{12}\cdot x_2 + IM^0 + IF^0 - ERR^0 \geq (1+\delta)TFU_1^0 \\
&x_2 - A_{21}\cdot x_1 - A_{22}\cdot x_2 \geq (1+\delta)TFU_2^0 \\
&B_1\cdot x_1 + B_2\cdot x_2 \leq (1-\delta)z^0 \\
&x_1,\, x_2,\ \delta \geq 0
\end{aligned}
\tag{2}
$$

In model (2), because of the disaggregation of emission abatement sector and the extension of environmental portion, values of pollution and abatement can be quantified through the EAS-IOT. Hence, notations of production in conventional IOT and notations of emission in exogenetic environmental account in model (1) are replaced by notations of production and emission which are both derived from EAS-IOT. Notations with subscript 1 and 2 stands for values of industrial sectors and emission abatement sectors respectively. Specifically, A_{11} is the 42×42 production-production intermediate input coefficient matrix. A_{12} is the 42×16 production-abatement intermediate input coefficient matrix, representing the *abatement cost* per unit of total output. A_{21} is the 16×42 abatement-production intermediate input coefficient matrix, donating the *emission charge* per unit of total output. A_{22} is the 16×16 abatement-abatement intermediate input coefficient matrix, showing the *abatement cost* (*emission charge*) per unit of total output. Besides, it is striking to note that the second constraint is the most significant diversity compared with model (1). The second constraint is quantified in physical value in model (1), while it is quantified in monetary value in model (2). The second constraint of model (2) means that for each pollutant, the optimal total *environmental value* deducted with *emission charge* should greater than *abatement benefit*.

Environmental efficiency evaluation

In 2012, the environmental taxation policy in China is executed through collecting pollution discharge fees. Discharge fees of air pollutions and water pollutions are levied on the top three air emissions and the top three water emissions, at the value of 0.6 and 0.7 Yuan per unit of equivalent-kg, respectively. As a consequence, we take pollution discharge fees as environmental tax rates to estimate *emission charge* of Beijing in model (2).

Model (1) is based on the conventional IOT and model (2) is based on EAS-IOT. Environmental inefficiency score of model (1) is greater than that of model (2), valued 0.0017 and 0.0011, respectively, which means environmental efficiency based on conventional IOT is underestimated. Meanwhile, results of model (1) and model (2) are shown in Table 2. According to the third row and the fourth row, improved potential of GDP and total output is overestimated. Moreover, emission is influenced by production. In other words, more products will lead to more emission. Thus, compared with observed value, emission of optimal value raises due to the increased GDP and total output. And the optimal emission based on the conventional IOT is overestimated. Turning to the last row of Table 2, emission intensity, representing the emission per unit of total output, is also overestimated.

Table 2 Optimal values and improved potentials of economic indicators and environmental indicators of model (1) and model (2)

Indicator	**Observed value**	**Optimal value**		**Improved potential**	
		model (1)	model (2)	model (1)	model (2)
Economic indicator					
GDP (billion Yuan)	1,788	1,803	1,800	15	12
Total output (billion Yuan)	5,251	5,307	5,287	56	36
Environmental indicator					
Emission (million equivalent-kg)	1,747	1,802	1,782	55	35
Emission intensity (equivalent-kg/thousand Yuan)	3.3263	3.3957	3.3705	0.0693	0.0441

To figure out the biased degree, we transform values of environmental inefficiency score and emission intensity, as well as improved potential of GDP, total output, and emission into their corresponding indexes (see Fig. 5). Results of model (2) serve as the standard index, which equal to 1. Indexes of model (1) are measured through dividing results of model (1) by results of model (2), respectively. We can notice that the biased degrees of environmental inefficiency score, total output, and emission rank top (1.58), which are followed by the biased degree of GDP (1.21). Biased degree of emission intensity is tiny, which has a slight distinction from the standard index of EAS-IOT.

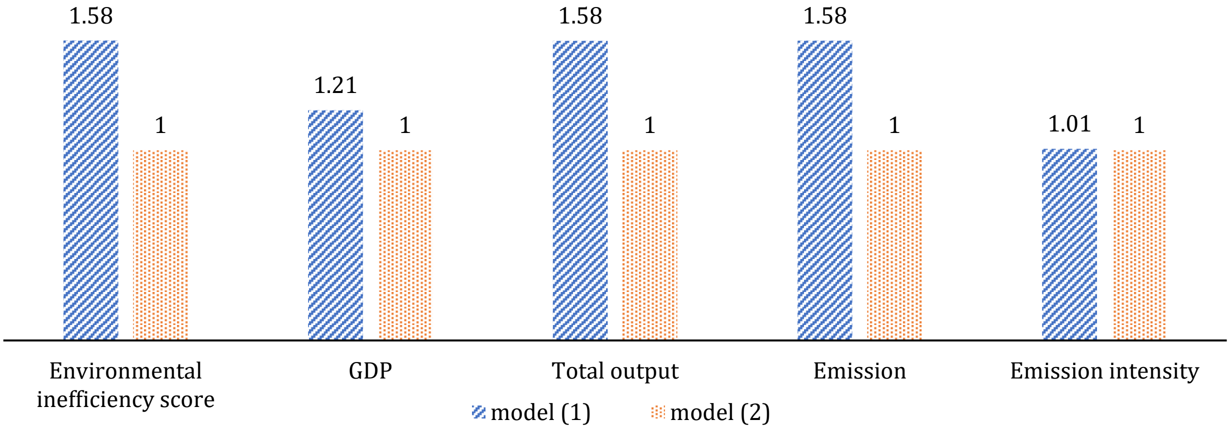


Fig. 5 Indexes of economic indicators and environmental indicators of model (1) and model (2)

Environmental policy analysis

Starting in the beginning of 2018, environmental taxation has been levied in China. From then on, pollution discharge fees have been replaced by environmental taxation. Each province has issued its own tax rate standard. Under the great abatement pressure, environmental taxation of each pollutant is levied at the upper bound in Beijing, which is 12 Yuan/equivalent-kg for air pollution and 14 Yuan/equivalent-kg for water pollution.

For purpose of simulating the effects of environmental taxation policy, we conduct two experiments with EAS-IOT based model (2), which are taking pollution discharge fees and environmental taxation ceteris paribus to calculate the *emission charge* respectively. Results are compared in Table 3. The second column denotes the existing environmental policy (discharge fees) in 2012, while the third column stands for the new issued environmental policy (environmental tax) in 2018. The last column shows the change rate of each indicator from the first policy to the second policy.

Table 3 Economic indicators and environmental indicators under different environmental policies

Indicator	Pollution discharge fees	Environmental tax rates	Change rate
Environmental tax rate (Yuan/equivalent-kg)	0.6 (air pollution) 0.7 (water pollution)	12 (air pollution) 14 (water pollution)	1900% 1900%
Environmental inefficiency score	0.0011	0.0010	-6.68%
Economic indicator			
GDP (billion Yuan)	1800	1778	-1.25%
Total output (billion Yuan)	5287	5284	-0.04%
Environmental indicator			
Emission (million equivalent-kg)	1782	1780	-0.12%
Emission intensity (equivalent-kg/thousand Yuan)	3.3705	3.3678	-0.08%

From Table 3 we can see that, the new environmental policy raises the environmental tax rate substantially, representing an increased emission punishment and an environment-oriented production strategy. Changing environmental policy from pollution discharge fees to the environmental tax, environmental efficiency becomes more efficient. Environmental inefficiency score decreases from 0.0011 to 0.0010, at the change rate of -6.68%. Besides, emission reduces from 1782 million equivalent-kg to 1780 million equivalent-kg. However, because of the trade-offs between economy and environment, environmental improvement will cause economic loss. Hence, GDP and total output drops by 1.25% and 0.04%, respectively. Furthermore, taking economy and environment into an integrated indicator, emission intensity tends to decrease by 0.08%, which represents raising environmental tax rates will cut down the emission load per unit of total output.

Conclusion

In this study, we introduce a novel framework about the input-output table (IOT) extension at dataset level. The framework provides a solution to researches on trade-offs analysis and cost-benefit analysis of economy and environment. The conventional IOT and environmentally extended input-output table (EEIOT) cannot take emission abatement into consideration. Emission abatement sector extended input-output table (EAS-IOT) plays a key role in filling this gap. The EAS-IOT, compared to conventional IOT, has a detailed representation of abatement cost, emission charge, and abatement benefit associated with emission abatement sectors. By this means, value flows of production sectors and emission abatement sectors can be connected in the same dimension. Furthermore, we provide a case study of environmental efficiency evaluation and environmental policy analysis for Beijing. Results show that: 1) environmental efficiency measured with EAS-IOT is more accurate and solves the problem of biased efficiency measure derived from the conventional IOT; 2) raising environmental tax rates will increase environmental efficiency and decrease emission intensity in Beijing.

The new framework can be applied in many fields. Firstly, it is essential for analyzing the impacts of environmental policies. There exists a relationship chain between abatement and production. Environmental policies will impact emission abatement intensity directly, and impact production strategy indirectly at the same time. Since stricter environmental policies may lead to higher intensity abatement cost, lower emission load, higher abatement benefit, and lower production value simultaneously. EAS-IOT provides a fundamental dataset for trade-offs analysis or cost-benefit analysis of environmental policies. Secondly, combined with optimization model, EAS-IOT can be used as an optimal measurement of environmental efficiency. The conventional optimization model of environmental efficiency or ecological efficiency measurements usually treats emissions as undesirable outputs and energy consumptions as environmental inputs [49, 50], but neglects emission abatement costs and benefits, which lead to an incomplete efficiency analysis to some extent. The new framework improves the ability for comprehensive efficiency measurement on production, emission and abatement. Thirdly, the framework makes it possible for time series analysis, since it is extended from the every-five-years-updated IOTs. Moreover, the calculation methods in our study are general linear programming models based on frontier analysis. Environmental data were indirectly calculated based on public data from Statistical Yearbooks or obtained directly from Statistical Bureau. Thus, the framework can be expanded to other countries to analysis their local issues related to air pollution, water pollution, solid waste pollution, or noise pollution, as long as the environmental data are available. And given that the frequent global trade and the significant regional heterogeneity, multiregional input-output analysis involved with emission abatement can be developed in further research.

Nevertheless, there are several limitations of the framework. There is little or no harmonized data across different sectors associated with emission abatement. Therefore, we have to estimate some environmental variables of each sector based on hypothesis, which may lead to inaccurate data. In addition, along with the more investment in environmental protection, the overall scale of environmental protection industry expands rapidly and the structure is gradually more complete in China. But there is still no large scale statistics of the emission abatement cost and emission abatement benefit in environmental protection industrial and production industrials. Besides, the sector of environmental protection industry is not separated as an independent sector in official Chinese IOTs. Therefore, further research work should try to avoid using estimated data and construct a more accurate EAS-IOT if the environmental data are available.

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Appendix

Appendix Table 1 Sector category and corresponding code

Sector	Code	Sector	Code
Production sectors			
Agriculture	01	Other manufacturing	22
Coal mining	02	Scrap and waste	23
Petroleum and gas	03	Repair service of metal products, machinery and equipment	24
Metal mining	04	Electricity and heat production and supply	25
Nonmetal mining	05	Gas production and supply	26
Food processing and tobaccos	06	Water production and supply	27
Textile	07	Construction	28
Clothing, leather, fur, etc.	08	Wholesale and retailing	29
Wood processing and furnishing	09	Transport, storage and post	30
Paper making, printing, stationery, etc.	10	Hotel and restaurant	31
Petroleum refining, coking, etc.	11	Information transmission, software and information technology	32
Chemical industry	12	Financial intermediation	33
Nonmetal products	13	Real estate	34
Metallurgy	14	Leasing and commercial services	35
Metal products	15	Scientific research and technical services	36
General machinery	16	Management of water conservancy,	37
Specialist machinery	17	Service to households, repair and other services	38
Transport equipment	18	Education	39
Electrical equipment	19	Health and social service	40
Electronic equipment	20	Culture, sports and entertainment	41
Instrument and meter	21	Public management, social security and social organization	42
Emission abatement sectors			
SO_2	43	Cy	51
NO_x	44	Hg	52
SD	45	Cd	53
COD	46	Cr	54
AN	47	Pb	55
P	48	As	56
PP	49	Cu	57
VP	50	Zn	58

Appendix Table 2 Environmental tax rates **(Yuan/equivalent-kg)** of 16 pollutants in 30 provinces

	SO_2	NO_x	SD	COD	AN	P	PP	VP	Cy	Hg	Cd	Cr	Pb	As	Cu	Zn
Beijing	12	12	12	14	14	14	14	14	14	14	14	14	14	14	14	14
Tianjin	6	8	6	7.5	7.5	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Hebei	6	6	6	7	7	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6
Shanxi	1.8	1.8	1.8	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
Inner Mongolia	1.8	1.8	1.8	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
Liaoning	1.2	1.2	1.2	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Jilin	1.2	1.2	1.2	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Heilongjiang	1.2	1.2	1.2	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Shanghai	6.65	7.6	1.2	5	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Jiangsu	4.8	4.8	4.8	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6
Zhejiang	1.2	1.2	1.2	1.4	1.4	1.4	1.4	1.4	1.4	1.8	1.8	1.8	1.8	1.8	1.4	1.4
Anhui	1.2	1.2	1.2	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Fujian	1.2	1.2	1.2	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Jiangxi	1.2	1.2	1.2	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Shandong	6	6	1.2	3	3	1.4	1.4	1.4	1.4	3	3	3	3	3	1.4	1.4
Henan	4.8	4.8	4.8	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6
Hubei	2.4	2.4	1.2	2.8	2.8	1.4	1.4	1.4	1.4	2.8	2.8	2.8	2.8	2.8	1.4	1.4
Hunan	2.4	2.4	2.4	3	3	3	3	3	3	3	3	3	3	3	3	3
Guangdong	1.8	1.8	1.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Guangxi	1.8	1.8	1.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Hainan	2.4	2.4	2.	2.8	2.	2.	2.	2.	2.	2.	2.	2.	2.	2.	2.	2.

			4		8	8	8	8	8	8	8	8	8	8	8	8
Chongqing	3.5	3.5	3.5	3	3	3	3	3	3	3	3	3	3	3	3	3
Sichuan	3.9	3.9	3.9	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Guizhou	2.4	2.4	2.4	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Yunnan	1.2	1.2	1.2	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Shaanxi	1.2	1.2	1.2	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Gansu	1.2	1.2	1.2	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Qinghai	1.2	1.2	1.2	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Ningxia	1.2	1.2	1.2	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Xinjiang	1.2	1.2	1.2	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4

Notes: 1) For data available, environmental tax rates of 30 provinces or cities in China are included, excluding Hong Kong, Macau, Taiwan and Tibet. 2) Environmental tax rates of Inner Mongolia, Heilongjiang, Anhui and Qinghai are not accessible. Values of those provinces are supposed to be equaled to that of neighboring areas. 3) Data sources are listed as follows: http://app.myzaker.com/news/article.php?pk=5a2612481bc8e07f4700000a; http://huanbao.bjx.com.cn/news/20180112/873697.shtml; https://baijiahao.baidu.com/s?id=1586809125063001379&wfr=spider&for=pc.