

1           **Atmospheric emission characteristics and control policies of**  
2           **anthropogenic VOCs from industrial sources in Yangtze River Delta**  
3                           **region, China**

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5           **Chenghang Zheng, Jiali Shen, Yongxin Zhang, Xinbo Zhu, Xuecheng Wu,**  
6                           **Linghong Chen, Xiang Gao\***

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8           State Key Laboratory of Clean Energy Utilization, State Environmental Protection Engineering  
9                           Center for Coal-Fired Air Pollution Control,  
10                          Zhejiang University, Hangzhou, 310027, China

11   **Abstract**

12  
13           A bottom-up inventory of atmospheric emissions of industrial MNVOCs in Yangtze River  
14   Delta (YRD) region was established for the period of 2010–2012. Results indicated that the total  
15   emissions of industrial VOCs increased from 3.34 Tg in 2010 to 3.99 Tg in 2012 at an annual  
16   average rate of 9.3%. Furniture manufacturing, machinery equipment manufacturing,  
17   architectural ornament, and petroleum refining were estimated to be the key sources, which  
18   contributed 58.6% of the total emissions in 2012. Based on the population database, the emission  
19   inventory was gridded into 1 km ×1 km grid cells with ArcGIS, which indicated that VOC  
20   emissions exhibited remarkable spatial and temporal characteristics. The most polluted areas  
21   were mainly centered in Shanghai, Nanjing, Ningbo, Hefei, and the Hangzhou and Taihu lake  
22   basin, which were the most developed and industrialized regions in the YRD. VOC emissions  
23   from specified anthropogenic sources under three different control scenarios for the different  
24   emission targets in 2030 were projected. The estimated average removal efficiency of the control  
25   technologies for each anthropogenic source should improve by 68.1% (scenario 2030B) and 79.0%  
26   (scenario 2030C). An entire process-control management scheme needs to be established based  
27   on the investigation of industrial processes, and the proportion of the application should be  
28   improved in the future.

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30   **Keywords:** control technologies, emission inventory, industrial VOCs, Yangtze River Delta region

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\* Corresponding author. Tel: (+86-571) 87951335  
E-mail address: xgao1@zju.edu.cn

## 32 INTRODUCTION

33

34 Over the past three decades, China experienced rapid economic development, as well as  
35 dramatic growth of energy consumption, extensive industries, a0000nd number of motor vehicles,  
36 accompanied by increased emission of ozone precursors and aerosols (Li et al., 2016); these  
37 factors cause frequent regional air pollution episodes, such as haze, photochemical smog, and  
38 high ozone concentration. The Yangtze River Delta (YRD) region is one of most developed and  
39 heavily-polluted regions in China. Located in the eastern part of the country, the YRD region  
40 contributes approximately 2.19% of the total territory area and more than 21.0% of the national  
41 gross domestic product (GDP) (region, 2013; Sun, 2013). The data from long-term  
42 meteorological monitoring sites in the YRD region indicate high concentrations of fine particles  
43 and ozone (Gao et al., 2011; Xiao et al., 2011). People with long-term exposure to air pollution  
44 are more susceptible to acute or chronic respiratory, cardiovascular, and neurological diseases  
45 (Zhou et al., 2011; Zhu and Liu, 2014).

46 Volatile organic compounds (VOCs) are crucial precursors to secondary organic aerosol  
47 (SOA). An analysis of the influencing factors of VOCs indicates that a significant portion of SOA  
48 accounts for the oxidation of VOCs, which contribute 80%–90% to organic particulate matter  
49 (Liu et al., 2012; Huang et al., 2014; EPA, 2016). Studies have revealed that VOCs are also  
50 involved in the photochemical formation of ozone, the reactions of alkoxy radicals and the  
51 mechanisms of the gas-phase reactions of O<sub>3</sub> with alkenes explained it (Atkinson, 2000).

52 VOCs are numerous, varied and ubiquitous, which are emitted from various sources,  
53 including motor vehicles, industries, and natural (biogenic) sources (mainly trees)(EPA, 2015).  
54 Some studies (Kesselmeier and Staudt, 1999; Baudic et al., 2016; Cappellin et al., 2017; Sobanski  
55 et al., 2017) have investigated the biogenic VOC emissions of different areas such as the paris  
56 megacity, south-west Germany and so on, and analyzed the significant role they played in the  
57 photochemical reactions. For the anthropogenic VOCs, several VOC emission inventories were  
58 established in recent years, which provide information on emission sources and characteristics  
59 (Chen et al., 2014). Basing on the emission inventory of China, a previous study determined that  
60 industrial and domestic solvent use contributed 28.6% to the total NMVOC (are identical to  
61 VOCs, but with methane excluded) emission in China (Wei et al., 2008), and Shandong, Jiangsu,  
62 Guangdong, and Zhejiang were the provinces with the highest VOC emissions (Qiu et al., 2014a;  
63 Wu et al., 2015). The inventory of VOCs in the YRD for 2007 also illustrated that industrial  
64 sources, including fuel combustion facilities and non-combustion processes, contribute roughly  
65 69% of the total VOC emissions (Huang et al., 2011). Although significant progress was achieved  
66 in estimating VOC emissions and characterizing the spatiotemporal variations over the YRD  
67 region, some limitations persist. For example, integrated and detailed investigations of the VOC  
68 emission characteristics in atmosphere are hard to make, and the corresponding policies  
69 concerned with VOC control in the YRD region are difficult to implement. Till now, the control  
70 strategies to reduce emissions have been mentioned by only few researchers (Cheng et al., 2015).

71 In this paper, a bottom-up emission inventory from anthropogenic sources of high spatial  
72 resolution was established for 22 cities in the YRD region in 2010–2012. Population

73 density-based Geographic Information System (GIS) was used to present the distribution of the  
74 VOC emissions in the YRD region. With the great practical significance regarding the aim of air  
75 quality pointed out in the government scheme, a scenario analysis of the expected reduction of  
76 VOC emissions in the target year 2030 was proposed, and the potential reduction of the key  
77 emission sources in the YRD region was calculated.

78

## 79 **DATA AND METHODOLOGY**

80

### 81 *Methodology*

82 In this study, the atmospheric emissions of industrial VOCs were calculated by applying a  
83 bottom-up methodology (Townsend-Small et al., 2015) with a refined activity database and an  
84 upgraded specific emission factor database.

85

$$86 \quad E = \sum_j \sum_k A_{j,k} EF_{j,k} (1 - \eta_{j,k}), \quad (1)$$

87

88 where  $j$  represents the province,  $k$  represents a specific sector,  $E$  represents annual total  
89 emission of VOCs,  $A$  represents the activity data,  $EF$  represents the emission factor, and  $\eta$   
90 represents the removal efficiency.

91 In this study, the domain covered 22 cities, including Shanghai, Hangzhou, Ningbo, Jinhua,  
92 Shaoxing, Zhoushan, Jiaxing, Huzhou, Quzhou, Taizhou, Nanjing, Suzhou, Wuxi, Changzhou,

93 Nantong, Yangzhou, Yancheng, Zhenjiang, Huaian, Taizhou, Hefei, and Maanshan, which all  
94 became members of the YRD Economic Coordination Association in 2010.

95 The source categorization listed in Table 1 is based on the concept of source-tracing (Wang et  
96 al., 2012; Ying Chen et al., 2012; Zhao et al., 2012), which includes all types of sources from four  
97 major links: production of VOCs, storage and transport, industrial processes using VOCs as raw  
98 materials, and use of VOC-containing products. After reviewing the types of available activity  
99 data in the various cities, the industrial VOC source categorization considered in this study are  
100 aggregated into 78 particular industrial sources by relating city-specific activity data to VOC  
101 sources associated with these activities, which effectively demonstrate the present situation of  
102 VOC emission around the YRD region.

### 103 *Compilation of activity data*

104 Table 1 presents the types of urban activity data, which represent the activities associated with  
105 each source. Most of the data were obtained from the yearbooks of the cities in 2010–2012,  
106 which were developed by the local government. These data included product output and fuel  
107 consumption ((NBS), 2010-2012d, b, a, c). In some cases such as the annual output of ethylene,  
108 benzene, synthesis, and other are adopted from official statistical records and available sources,  
109 such as data from the Urban Bureau of Statistics of China and Industry Association. In other  
110 cases, the data were obtained through estimation. For example, when the amount of the adhesives  
111 and the ratio for various purposes are available, the distributions of different sources were  
112 calculated.

### 113 *Determination of emission factors*

114 Emission factors describe the amount of emissions associated with one unit of a particular  
115 statistic, which is the foundation of an accurate emission inventory. In this study, we identified  
116 the emission factors of different sources. We consider the local measurement results first,  
117 followed by Chinese emission factors. However, when the local results and Chinese emission  
118 data were not available, the emission factors of other countries (e.g., USEPA (United States  
119 Environmental protection Agency) and EEA (European Environment Agency)) or regions (where  
120 the emission standards and the production process are the same in the domestic condition) were  
121 adopted.

122

## 123 **RESULTS AND DISCUSSION**

124

### 125 *Emissions and source contributions in 2012*

126 The total industrial VOC emissions were 3.99 Tg in 2012. The top 10 sources are listed in  
127 Table 2. Use of VOC-containing products was the major contributor of the four links, which  
128 accounted for 68.8% of the total emissions in 2012. Industrial processes using VOCs as raw  
129 materials, the production of VOCs, and storage and transport contributed 15.7%, 10.3%, and  
130 5.3%, respectively. The different rates of the four links in 22 cities are shown in Fig. 1.

131 Furniture manufacturing, architectural ornament, and machinery equipment manufacturing  
132 respectively contributed 36.0%, 17.7%, and 16.9% to the use of VOCs-containing products,

133 which were the largest emitters. About 33.7% of the VOCs in use of VOCs-containing products  
134 were emitted by Shanghai, the largest city in the YRD region, and with the most developed  
135 industry.

136 Chemical pesticide and synthetic fiber were the key sources of industrial processes that use  
137 VOCs as raw materials, contributing 35.0% and 25.8% of the link, respectively. Fig. 2a presents  
138 the cities with high emissions, which indicates the various industrial structures in different cities.

139 Table 3 lists the VOC emissions of the four links for 22 cities in 2012. Shanghai generated the  
140 most VOCs in the YRD region (115.8 kt), which accounted for 29.2% of the total emissions.  
141 Most emissions in Shanghai were from furniture manufacturing, machinery equipment  
142 manufacturing, and architectural ornaments, which produced 41.1, 19.3, and 18.9 kt VOCs,  
143 respectively. Ningbo (35.7 kt), Nanjing (33.3 kt), Hangzhou (28.8 kt), Suzhou (28.7 kt), and  
144 Shaoxing (22.7 kt) also contributed high amounts of VOC emissions, which accounted for 29.2%,  
145 9.0%, 8.4%, 7.2%, 7.1%, and 5.7% of the total industrial VOC emissions in the YRD region.

#### 146 ***Temporal-spatial distribution of VOC emissions in YRD region***

147 Table 4 lists the VOC emissions during 2010–2012, which indicates that the total emissions of  
148 industrial VOCs increased from 3.34 Tg in 2010 to 3.99 Tg in 2012 at an annual average rate of  
149 9.3%. Emissions from the production of VOCs, storage and transport, industrial processes using  
150 VOCs as raw materials, and use of VOC-containing products increased by 9.5%, 5.9%, 33.0%,  
151 and 19.4%, respectively, compared with that in 2010. Fig. 3 shows that furniture manufacturing,  
152 machinery equipment manufacturing, architectural ornament, petroleum refining, printing,  
153 synthetic leather, storage and transport, chemical pesticide, and synthetic fiber were the key

154 sources of VOCs, which contributed 82.5% of the total industrial VOC emissions in 2010 and  
155 increased by 84.8% in 2012.

156 The spatial distribution characteristics of YRD are shown in Fig. 4. Based on the population  
157 database, the emission inventory was gridded into 1 km ×1 km grids using ArcGIS. Fig. 4  
158 illustrates that the VOC emissions exhibited remarkable spatial and temporal characteristics. The  
159 most polluted areas were mainly centered in Shanghai, Nanjing, Ningbo, Hefei, and the  
160 Hangzhou and Taihu lake basin, which are the most developed and industrialized regions in the  
161 YRD. These areas generated approximately 76.1% of the total industrial VOC emissions in three  
162 years although these areas cover 40.2% of the territory. Hangzhou (second), Nanjing (third), and  
163 Ningbo (fifth) account for 68.7% of the total gross economic production of the YRD region.

164 Fig 4 indicates that the Hongkou (36,014 people per km<sup>2</sup>) and Xuhui (20,292 people per km<sup>2</sup>)  
165 districts had the highest emission densities with the largest population density in Shanghai. The  
166 highly polluted areas expanded from the coastal to the inland regions, particularly for the  
167 Hangzhou and Taihu lake basin.

### 168 *Uncertainty analysis*

169 Compared with estimates of other air pollutants, those of VOC emissions from anthropogenic  
170 sources are uncertain because the activity data vary spatially and temporally. Monte Carlo  
171 simulation is employed to quantify the uncertainties of VOC emissions for different sectors and  
172 variable activity data (Zhao et al., 2011). For example, uncertainties of the activity data and  
173 emission factors in 2012 may be fitted with lognormal distributions (Wei et al., 2011). Thus, the  
174 uncertainties for the total emissions in 2012 was [-16.4%, 65.6%] at the 95% confidence interval



175 in the YRD region. Table 5 shows the uncertainties of the different sectors and the uncertainties  
176 of the use of VOC-containing products. The uncertainty is relatively high, particularly in  
177 synthetic leather, shoemaking, architectural ornament, and machinery equipment manufacturing,  
178 because of the inadequate source information and the limited field-test data of emission factors.

179 The uncertainty and VOC emission estimated in the YRD region and China from different  
180 studies are presented in Table 6. Our findings were lower than those reported by Fu et al. (2010),  
181 Wu et al. (2015), and Wu et al. (2016) but larger than those reported by Huang et al. (2011). The  
182 results vary because of the different source classifications and areas covered in these studies.

183 The differences of inventory uncertainty at 95% confidence interval were mainly due to the  
184 different industrial source classifications, emission factors, and activity data. Therefore, various  
185 manufacturing processes for each sector should be investigated thoroughly, and field tests for  
186 each process should be conducted to obtain accurate emission inventory estimates.

187

### 188 *Scenario projection and proposals for technology applications*

189 According to the collected information on activity data, GDP, urbanization, and population (Li  
190 Xuefeng, 2013) (Lei et al., 2005; Haiyong Zhang, 2012) for 2005–2012, the increasing rates of  
191 relevant activities were specified, and three scenarios (2030A, 2030B, and 2030C) were set to  
192 project the industrial VOC emissions in the YRD region. The activity data of the 2030A scenario  
193 were compiled based on the annual growth rate in 2005–2012, which was characterized by  
194 unchanged control technologies based on the level in 2010. For scenario 2030B, we assume that  
195 the VOC emissions of each anthropogenic source category in 2030 are equal to those in 2010.

196 According to a previous report (Jiming Hao, 2014), scenario 2030C indicates the VOC emission  
197 of every anthropogenic source in 2030 decreased by 36% compared with that in 2010. The bars in  
198 Fig. 5 indicate the emission of VOCs for three scenarios, and the lines show the removal  
199 efficiency of the seven key anthropogenic source categories to meet the different scenario targets.

200 To reach the emission target, the average removal efficiency of VOC emissions from  
201 anthropogenic sources should be improved by approximately 68.1% (scenario 2030B) and 79.0%  
202 (scenario 2030B). In scenarios 2030B and 2030C, the removal efficiency of control technologies  
203 from machinery equipment manufacturing, furniture manufacturing, and synthetic leather should  
204 improve by 79.4%, 76.6%, 75.8%, and 86.8%, 85.04%, and 81.8%, respectively. To improve  
205 removal efficiency, advanced control technologies should be adopted for different anthropogenic  
206 sources. Traditional industries may combine different control technologies to reduce VOC  
207 emissions.

208 Condensing, adsorption, and absorption are traditional technologies to recycle VOCs.  
209 Membrane separation was recently developed. Thermal incineration, catalytic combustion,  
210 biodegradable, photocatalytic degradation, and plasma technologies control VOCs by  
211 decomposing VOCs. These technologies are widely applied in different anthropogenic sources.  
212 However, technologies such as adsorption and catalytic combustion must be hyphenated.

213 For example, the process of spraying is the main source of VOC emission in the furniture  
214 manufacturing industry. According to an earlier investigation, the most widely applied control  
215 technologies are activated carbon adsorption and solution adsorption. The average removal  
216 efficiency of activated carbon adsorption is 50% (Luo Chao, 2012). However, the field test shows

217 that the removal efficiency of solution adsorption (solvent: water) is roughly 14.7% (Haixia,  
218 2013), which is lower than the laboratory data. To achieve the emission target in scenario 2030B,  
219 the average removal efficiency of VOC emissions from furniture manufacturing should be  
220 improved by 76.6%, which is higher than that of the control technologies applied. Technologies  
221 must be **hyphenated** and developed. For example, the **hyphenation** of activated carbon adsorption  
222 and solution adsorption can improve the removal efficiency by 79% (Luo Chao, 2012) and the  
223 **hyphenation** of activated carbon adsorption and environment-friendly materials can increase  
224 removal efficiency by 85% (Lixian, 2012).

225 In summary, combining technologies is the prospect of innovative VOC control technologies to  
226 achieve the target removal efficiency for petroleum refining, machinery equipment manufacturing,  
227 architectural ornament, printing, and synthetic leather industries. An entire process-controlled  
228 management system must be established, which includes selecting the optimum control  
229 technologies, maintaining the control system, **reinforcing law implement**, and regulation.

230

## 231 **CONCLUSIONS**

232

233 In this study, an inventory of industrial sector-based sources of VOC emissions was conducted  
234 for 2010–2012 in the YRD region using the most recent EFs and activity data at the city level  
235 based on the emission factor method. The estimated total industrial VOC emission in YRD  
236 increased from 33.4 Tg in 2010 to 39.9 Tg in 2012 at an annual average rate of 9.3%. The use of

237 VOC-containing products is the major contributor of the four links, which account for 68.8% of  
238 the total emissions in 2012. Industrial processes using VOCs as raw materials, production of  
239 VOCs, and storage and transport contributed 15.7%, 10.3%, and 5.3%, respectively. Furniture  
240 manufacturing, machinery equipment manufacturing, architectural ornament, petroleum refining,  
241 printing, synthetic leather, storage and transport, chemical pesticide, and synthetic fiber were the  
242 key sources, which contribute 84.8% of the total industrial VOC emissions in 2012. Shanghai,  
243 Ningbo, Nanjing, Hangzhou, Suzhou, and Shaoxing generated the highest emissions in 2012,  
244 contributing 29.2%, 9.0%, 8.4%, 7.2%, 7.1%, and 5.7% of the total emissions. VOC emissions  
245 exhibited remarkable spatial and temporal characteristics in the YRD region. Shanghai, Nanjing,  
246 Ningbo, Hefei, and the Hangzhou bay area and Taihu lake basin are the most polluted areas,  
247 which generated roughly 76% of the total industrial VOC emissions.

248 The uncertainty for the total emissions in 2012 was -16.4% to 65.6% at the 95% confidence  
249 interval in the YRD region, which ranged from 6.5 Tg to 26.2 Tg for VOC estimates. Therefore,  
250 conducting further investigation on local industrial sources and additional field tests for emission  
251 factors on each sector in this region is crucial.

252 The projection of three scenarios indicates that the average removal efficiency of VOC  
253 emissions from anthropogenic sources should be improved by 68.1% (scenario 2030B) and 79.0%  
254 (scenario 2030B) based on the data in 2012. The top seven anthropogenic sources were chosen  
255 and investigated according to the VOC emissions inventory. Activated carbon adsorption and  
256 solution adsorption are the main control technologies adopted by furniture manufacturing  
257 enterprises. The removal efficiency of applied control technologies is lower than laboratory data

258 because of the lack of effective management and maintenance. Combining technologies is key to  
259 improve removal efficiency, and an entire process control management system must be  
260 established. For the fugitive sources such as manufacturing industries of furniture, chinery  
261 equipment, and transportation equipment, which commonly use a large amount of  
262 VOCs-containing products in the process of painting, we have to improve the process of  
263 production, reduce the exposure duration of VOCs-containing products, and adopt suitable  
264 control technologies to collect and treat the exhaust gas.

265

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267

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397 **Table 1.** Source categorization and activity data of industrial VOCs emission inventory

Links	Emission sources	Activity data
Production of VOCs	Crude oil/natural gas exploration	Crude oil/Natural gas exploration
	Petroleum refining	Tank/Transport/Leakage loss
		Volatile refining wastewater
	Basic chemical raw materials manufacturing	Ethylene
		Methyl alcohol
Benzene		
	Synthesis ammonia	
Storage and transport	Storage and transportation of crude oil/gasoline/other oil	Production/Import/Export
	Storage and transportation of solvent	Production/Import/Export
Industrial processes using VOCs as raw materials	Manufacture of paint	
	Manufacture of printing	
	Primary form of plastic	Polyethylene/PVC/ABS/Other resins
	Synthetic rubber/fiber	Polyester/Chinlon/Acrylic/Vinylon/Spandex/Cellulose/Acetate /Other fibers
	Manufacture of adhesive	Water-based/Other adhesive
	Manufacture of food and drink	Vegetable oil/Sugar refining
		Fermentation alcohol/Wine
	Beer	
	Chemical raw materials	/

	Chemical pesticide/ Tire	/
	Manufacture of commodity	Manufacture of commodity
	Textile dyeing	Textile dyeing
	Synthetic leather	PU size
	Shoemaking industry	Shoe adhesive
	Printing industry	Planographic/Gravure/Relief/Porous/Other printing
		Packaging/Binding/Wood adhesive
	Wood processing	
	Furniture manufacturing	Wood paintings (furniture manufacturing)
	Chinery equipment manufacturing	Other paintings
		Assembling adhesive
	Transportation equipment manufacturing	Transport equipment manufacturing adhesive
Use of VOC-containing products	Architectural ornament	Coating for interior walls/other building
		Wood paintings (architecture decoration)
		Assembling adhesive
	Dry cleaning of clothing	Tetrachloroethylene
	Electronic component manufacturing	Diode/Transistor
		Printed circuit board (PCB)
		Copper clad laminate
	Coke production	Coke
	Paper production	Pulp/Paper products
	Garbage pollution treatment	Sanitary landfill/Composting/MSW incineration
	Thermal power/Heat supply	Coal/Fuel Oil/Liquefied petroleum gas/Natural gas
	Industrial consumption	Coal/Fuel Oil/Coal

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400 **Table 2.** Industrial VOC emissions of major sources

Number	Emission source	Emission, Tg	Share in total, %
1	Furniture manufacturing	98.02	24.28
3	Machinery equipment manufacturing	51.83	12.84
2	Architectural ornament	48.36	11.98
4	Petroleum refining	38.93	9.65
5	Synthetic leather	24.97	6.18
6	Printing industry	24.91	6.17
8	Chemical pesticide	20.71	5.13
7	Storage and transport	19.87	4.92
9	Synthetic fiber	14.84	3.68
10	Textile dyeing	7.66	1.89
11	Others	49.8	13.28

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413 **Table 3.** VOC emission inventory of 22 cities in YRD region in 2012 (kt)

	Production of VOCs	Storage and transport	Industrial processes using VOCs as raw materials	Use of VOC-containing products
Shanghai	11.56	7.14	5.12	92.05
Hangzhou	0.38	0.93	7.19	20.30
Jinhua	0.01	0.09	1.11	7.77
Ningbo	12.86	4.96	1.40	16.56
Shaoxing	0.05	0.32	4.68	17.64
Zhoushan	1.99	0.69	0.10	1.74
Jiaxing	0.00	0.46	3.84	8.52
Huzhou	0.00	0.07	1.54	4.30
Quzhou	0.17	0.09	0.05	2.91
Taizhou	0.00	0.17	1.05	6.88
Zhejiang Province	15.46	7.78	20.96	86.62
Nanjing	10.71	4.02	8.01	10.53
Suzhou	0.34	1.23	7.75	19.45
Wuxi	0.27	0.33	3.02	11.40
Changzhou	0.00	0.10	5.69	7.40
Nantong	0.06	0.06	3.71	11.29
Yangzhou	0.32	0.11	1.24	5.99
Yancheng	0.20	0.02	2.20	5.46
Huaian	0.56	0.19	0.52	3.20

Zhenjiang	0.00	0.06	2.32	4.18
Jiangsu Province	14.11	6.19	35.14	85.27
Hefei	0.00	0.00	1.22	6.21
Taizhou	1.65	0.07	0.68	6.37
Maanshan	19.02	0.01	0.15	2.35
Anhui province	19.02	0.01	1.37	8.26

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432 **Table 4.** VOC emission inventory of 22 cities in YRD region in 2010–2012

Links	Sectors	Year (t)		
		2010	2011	2012
Production of VOCs	Crude oil and natural gas exploration	1214.8	1200.6	1182.0
	Petroleum refining	352788	379143	389340.5
	Basic chemical raw materials manufacturing	21079.1	22061.6	20869.6
Storage and transport	Storage and transport	199364.6	171807	211169.7
Industrial processes using VOCs as raw materials	Manufacture of paint	41107.2	50681.1	51975.8
	Manufacture of printing	11104.7	10566	11484.5
	Primary form of plastic	37522.3	51072.5	55290.3
	Synthetic rubber	5990.6	7976.1	9510.4
	Synthetic fiber	121983	147357.1	148355.2
	Manufacture of adhesive	3264.3	3454.2	3781.7
	Manufacture of food and drink	40764.1	49452.3	37389.4
	Chemical raw materials	41071.4	35543.2	44316.7
	Chemical pesticide	113829.5	123935.1	201036.8
	Manufacture of commodity	15.85003	24.831	14.20635
	Tire	60324.6	65824.5	62779.5
Use of VOC-containing products	Textile dyeing	82598.9	50712.9	74961.3
	Synthetic leather	185894.8	197622	249704.9
	Shoemaking industry	37101.8	40334.3	17563.7
	Printing industry	288851.8	184721.5	249091.2

	Wood processing	38166.8	40092.1	45589.7
	Furniture manufacturing	765548.7	875408.7	980218.9
	Machinery equipment manufacturing	359595.4	522330.1	460363.8
	Transportation equipment manufacturing	48001.7	49542.9	53808.6
	Architectural ornament	373054	378669.7	483627.1
	Dry cleaning of clothing	15024.5	6869.1	5287.1
	Electronic component manufacturing	19405.6	8439.3	7656.4
	Coke production	30842.8	26433.3	32297.2
	Paper production	1971.1	1151.6	869.0
	Garbage pollution treatment	14120.4	16108.6	18783.9
	Thermal power	29426.8	26087.6	41477.1
	Heating	9884.9	10512.0	10560.9
	Industrial consumption	1425.1	1063.4	1068.1
	Total emissions (Tg)	3.34	3.57	3.99

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450 **Table 5.** Uncertainty in emission inventories of each sector in YRD region, 2012

Links	Sectors	95% confidence interval
Production of VOCs	Crude oil and natural gas exploration	[-7% 10%]
	Petroleum refining	[-18% 26%]
	Basic chemical raw material manufacturing	[-4% 10%]
Storage and transport	Storage and transportation of code oil	[-86% 26%]
	Storage and transportation of gasoline	[-6% 13%]
	Storage and transportation of other oil	[50% 243%]
	Storage and transportation of solvent	[-6% 39%]
Industrial processes using VOCs as raw materials	Manufacture of paint	[-9% 10%]
	Manufacture of printing	[-65% 121%]
	Primary form of plastic	[-9% 11%]
	Synthetic rubber	[-10% -11%]
	Synthetic fiber	[-9% 10%]
	Manufacture of adhesive	[-78% 156%]
	Manufacture of food and drink	[-32% 72%]
Chemical raw materials	[-16% -2%]	



	Chemical pesticide	[-46% -34%]
	Manufacture of commodity	[-43% 75%]
	Tire	[-9% 10%]
Use of VOC-containing products	Textile dyeing	[-46% 71%]
	Synthetic leather	[-45% 259%]
	Shoemaking industry	[140% 453%]
	Printing industry	[-24% 125%]
	Wood processing	[-80% 214%]
	Furniture manufacturing	[-84% 144%]
	Chinery equipment manufacturing	[-79% 242%]
	Transportation equipment manufacturing	[-74% 221%]
	Architectural ornament	[-55% 168%]
	Electronic Component Manufacturing	[-14% 5%]
	Coke production	[9% 11%]
	Paper production	[-5 % 6%]
	Garbage pollution treatment	[-6% 6%]
	Thermal power	[240% 313%]
	Heating	[-143% 128%]
Industrial consumption	[-48% 154%]	

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470 **Table 6.** Comparison of results with those of other studies

Reference	Year	Domain	Emission source	VOCs emissions, Tg	Inventory uncertainty 95% confidence interval
Bo et al., 2008 (Bo et al., 2008)	2005	China	Total source	16.49	/
Huang et al., 2011 (Huang et al., 2011)	2007	Yangtze River Delta (YRD) region	Total source	2.77	[-133.4%, 133.4%]
Fu et al., 2013 (Fu et al., 2013)	2010	Yangtze River Delta (YRD) region	Total source	3.82	[-52%, 105%]
Qiu et al., 2014 (Qiu et al., 2014a)	2010	China	Industrial source	13.356	/
Yin et al., 2015 (Yin et al., 2015)	2010	Pearl River Delta Region	Total source	1.17	/
Qiu et al., 2013 (Qiu et al., 2014b)	2010	Central Plain Urban Agglomeration (CPUA) region	Total source	4.66	[-22%, 20%]
Li et al., 2013 (Han et al., 2013)	2011	Sichuan province	Major source	4.82	/

al., 2013)			including		
Wu et al., 2015(Wu et al., 2015)	2011	China for Yangtze River Delta (YRD) region	Industrial source	3.89	[-42%, 71%]
Wu et al., 2016(Wu et al., 2016)	2012	China for YRD region	Total source	5.18	[-40%, 101%]
This study	2010, 2011, 2012	YRD region	Industrial source	3.34, 3.57, 3.99	[-16.4%, 65.6%]

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### Figure Captions

476 **Fig 1.** Rate of industrial VOC emission of four links in YRD region for 2012

477 **Fig. 2.** Urban industrial VOCs emission of link in YRD region for 2012 (a) using

478 VOC-containing products; (b) for industrial processes utilizing VOCs as raw materials

479 **Fig. 3.** Industrial VOC emission of sources in YRD region for 2010–2012

480 **Fig. 4.** Spatial distribution of VOC emissions in YRD region at a grid of 1 km ×1 km in 2010–

481 2012

482 **Fig. 5.** Projection of industrial VOC emissions from specified anthropogenic sources

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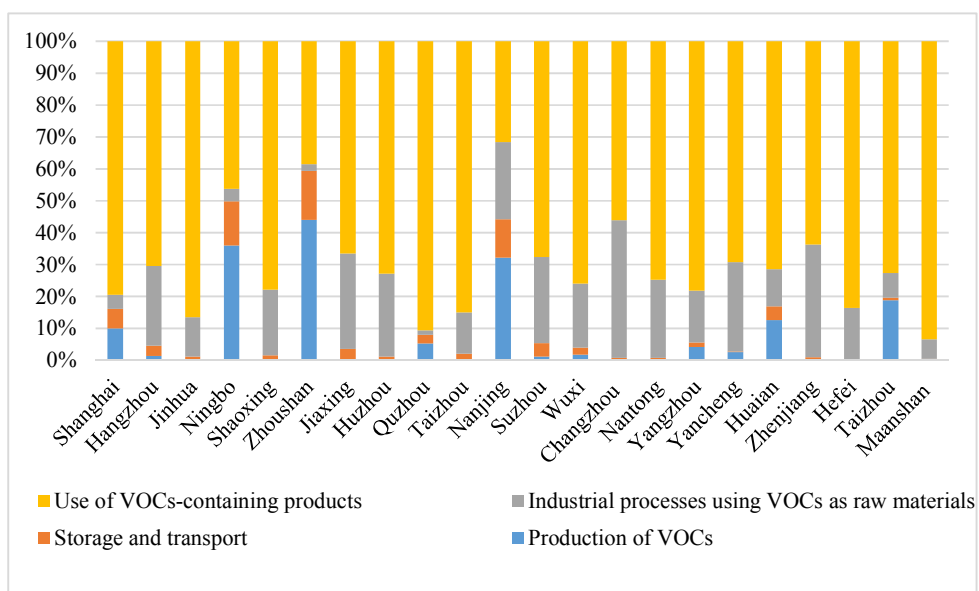
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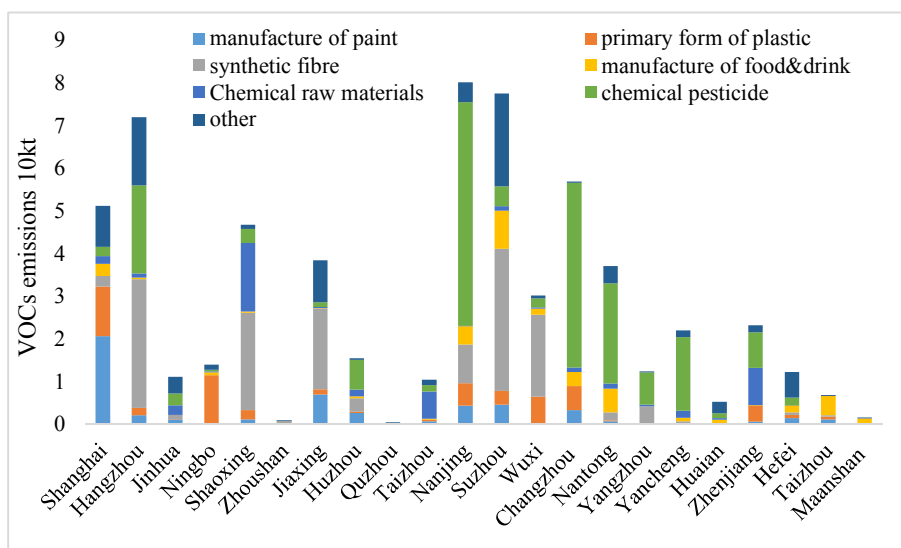
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**Fig 1.** Rate of industrial VOC emission of four links in YRD region for 2012

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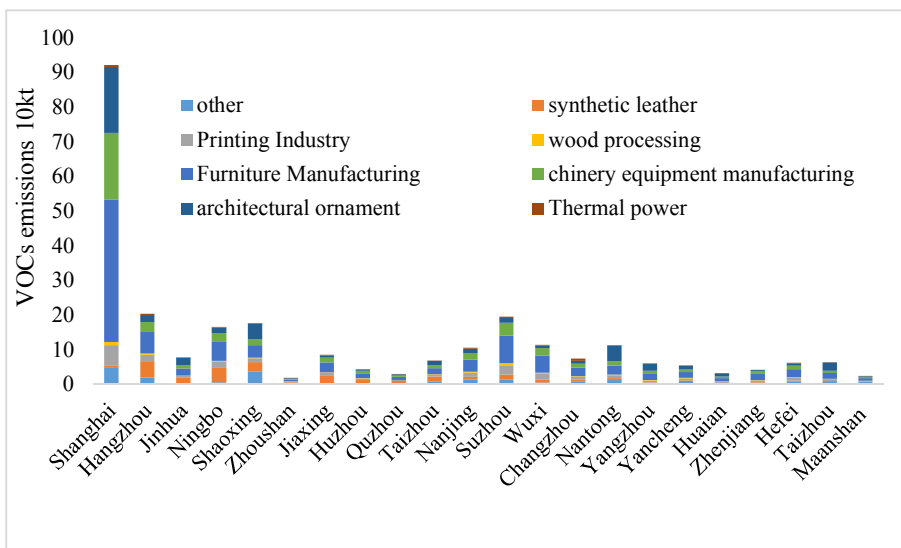


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**Fig. 2.** Urban industrial VOCs emission of link in YRD region for 2012 (a) using VOC-containing products; (b) for industrial processes utilizing VOCs as raw materials

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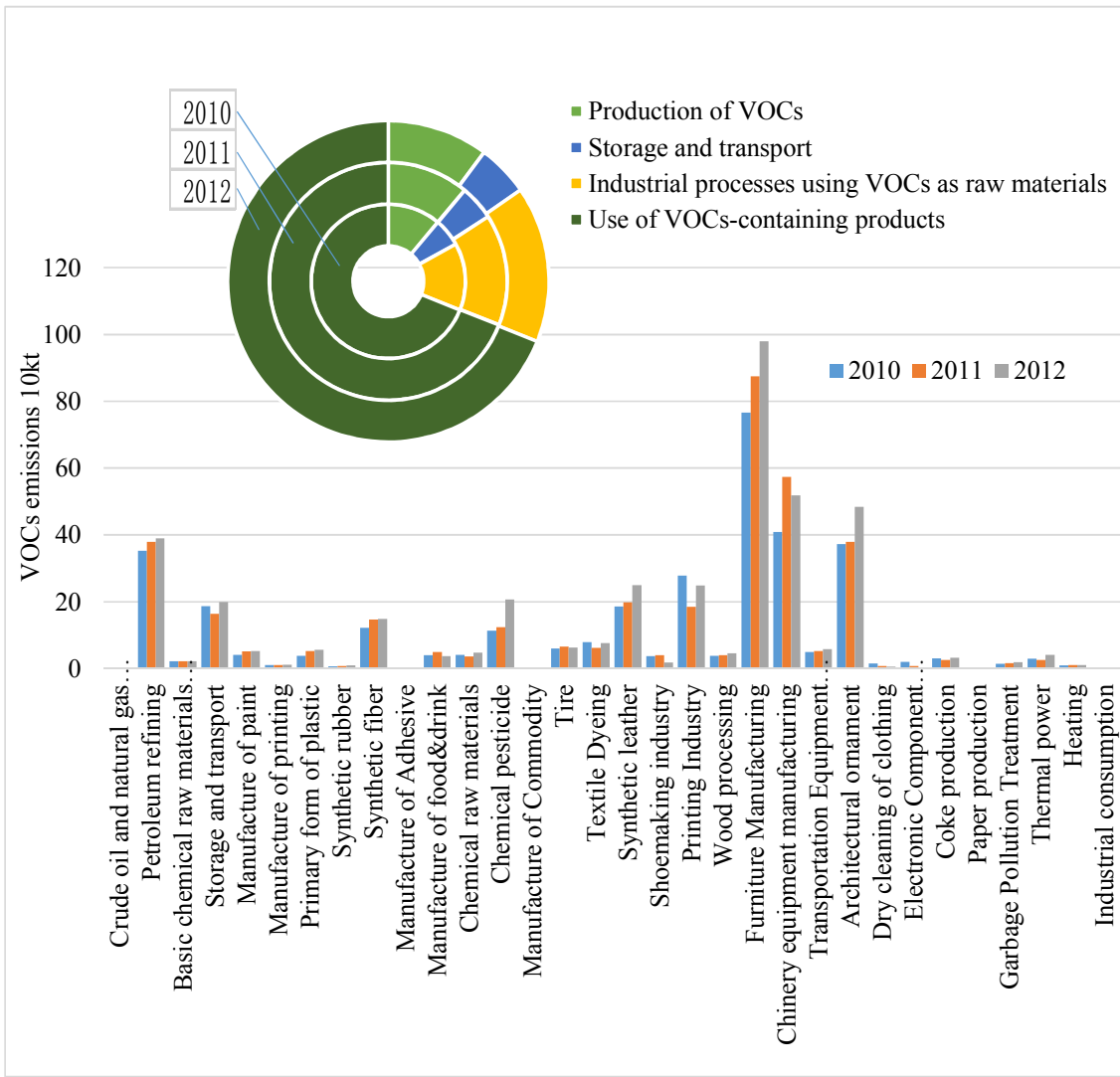
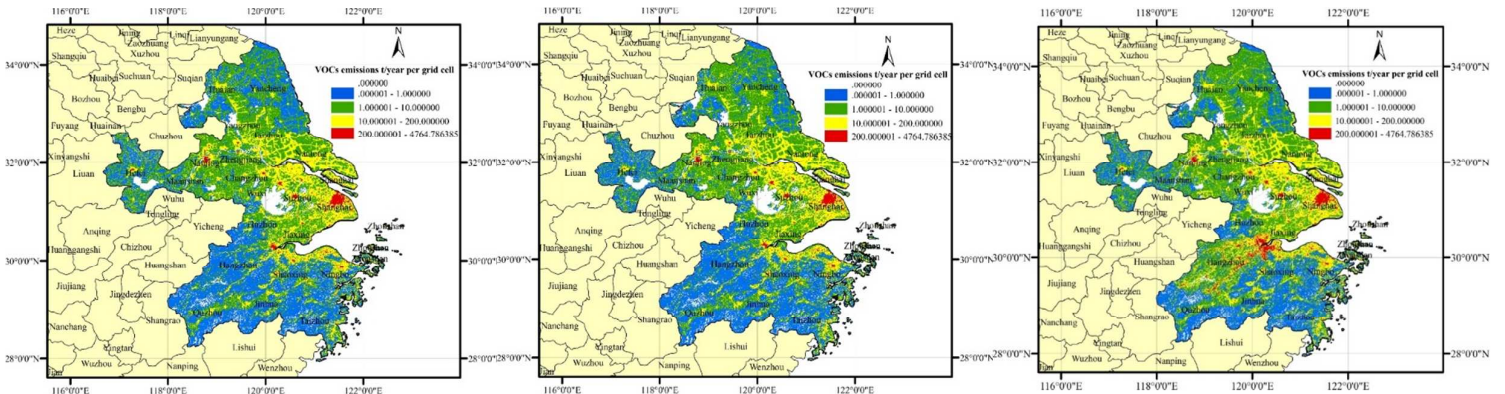


Fig. 3. Industrial VOC emission of sources in YRD region for 2010–2012



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**Fig. 4.** Spatial distribution of VOC emissions in YRD region at a grid of 1 km ×1 km in 2010–

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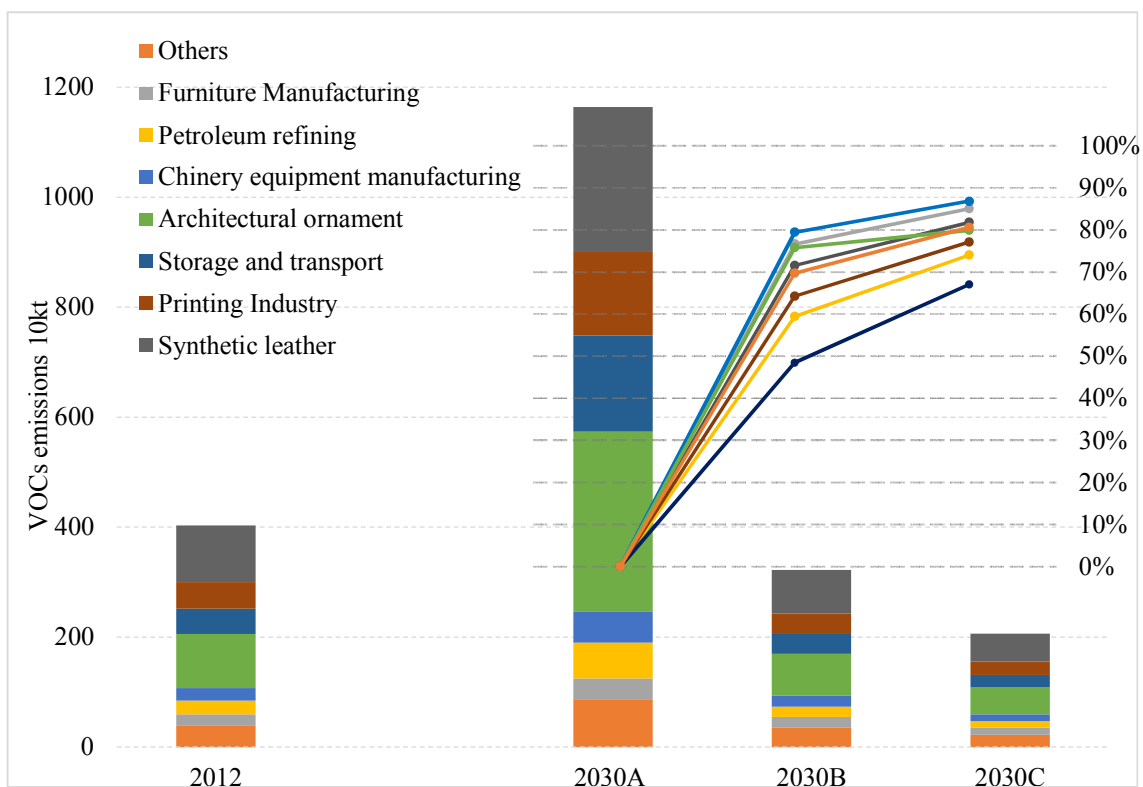
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540 **Fig. 5.** Projection of industrial VOC emissions from specified anthropogenic sources  
 541 ( The bars indicate the emission of VOCs for three scenarios, and the lines show the removal  
 542 efficiency of the seven key anthropogenic source categories to meet the different scenario  
 543 targets. )



Table S1 The control technologies and removal efficiency for sources.

Sources	Control technologies	Removal efficiency
Petroleum refining	Thermal combustion	60%-95%
Storage and transport	Oil and gas recovering system	80%-95%
Furniture Manufacturing	Rotary adsorption-concentration and combustion	73%-89%
Chinery equipment manufacturing	Catalytic combustion	72%-85%
Transportation Equipment Manufacturing	Catalytic combustion	75%-85%
Architectural ornament	Environmentally friendly materials	55%-70% <sup>a</sup>
Coke production	Condensation separation/Catalytic combustion	70%-85%
Chemical raw materials	Adsorption/condensation separation/ catalytic combustion	70%-90%
Chemical pesticide	Adsorption/condensation separation/ catalytic combustion	70%-90%
Textile Dyeing	Adsorption concentration and catalytic combustion	70%-85%
Printing Industry	Adsorption separation/ catalytic combustion/ Environmentally friendly materials	75%-85%/70% <sup>a</sup>
Dry cleaning of clothing	Condensation separation	70%-85%

Basic chemical raw materials manufacturing	Thermal combustion / Adsorption separation /RTO	70%-98%
Manufacture of food & drink	Adsorption / biological	70%-85%
Synthetic leather	Activated carbons adsorption/ catalytic combustion	70%-85%
Shoemaking industry	Adsorption concentration and catalytic combustion	70%-85%
Synthetic fiber	Activated carbons adsorption	55-60%
Tire	Adsorption concentration and catalytic combustion	65-70%
Wood processing	Environmentally friendly materials	70% <sup>a</sup>

<sup>a</sup> represents the equivalent efficiency of using environmentally friendly materials

Table S 2 Emission factors and activity data of different sources

Sources	Emission factors	Units	References
Crude oil exploration	0.6	kg/t	(Wei et al., 2008)
Natural gas exploration	0.5	kg/t	
Tank loss	0.5	kg/t turnover	(Ning, 2010)
Transport loss	1.5	kg/t ( production raw material average turnover )	
Leakage loss(odors)	2.4	kg/t the processing of crude oil	
Leakage loss(normal)	0.8	kg/t the processing of crude oil	

Volatile refining wastewater	0.12	kg/t the processing of crude oil	
Ethylene	0.5	kg/t Product	((Taiwan), 2012; Chen Yin, 2012)
Methyl alcohol	5.75	kg/t Product	((Taiwan), 2012; Yang, 2012; Ying Chen et al., 2012)
Benzene	0.55	kg/t Product	((Taiwan), 2012; Ying Chen et al., 2012)
Synthesis ammonia	4.72	kg/t Product	((Taiwan), 2012; Ying Chen et al., 2012)
Storage & transportation of Crude oil-Made in China	0.54	kg/t Product	(Yang, 2012)
Storage & transportation of Crude oil-Import	0.88	kg/t Product	
Storage & transportation of Crude oil-Export	0.51	kg/t Product	
Storage & transportation of gasoline-Made in China	4.54	kg/t Product	
Storage & transportation of gasoline-Import	4.49	kg/t Product	
Storage &	4.22	kg/t Product	

transportation of gasoline-Export			
Storage & transportation of other oil-Made in China	2.46	kg/t Product	
Storage & transportation of other oil-Import	3.06	kg/t Product	
Storage & transportation of other oil-Export	1.84	kg/t Product	
Storage & transportation of solvent-Made in China	3.1	kg/t Product	
Storage & transportation of solvent-Import	3.6	kg/t Product	
Storage & transportation of solvent-Export	3.2	kg/t Product	
Manufacture of paint	15	kg/t Product	(Huang et al., 2011; Wei, 2009; Yang, 2012; Ying Chen et al., 2012)
Manufacture of printing	60	kg/t Product	(Yang, 2012; Ying Chen et al., 2012)
Polyethylene resin	8	kg/t Product	(USEPA, AP-42)
PVC resins	8.5	kg/t Product	
ABS resins	1.4	kg/t Product	(EEA)

Other resins	2.2	kg/t Product	
Synthetic rubber	7.39	kg/t Product	(Yang, 2012; Ying Chen et al., 2012)
Polyester	0.6	kg/t Product	((Taiwan), 2012)
Chinlon	3.75	kg/t Product	
Acrylic fibers	125.1	kg/t Product	
Vinylon	7.7	kg/t Product	
Spandex	40	kg/t Product	
Cellulose acetate fiber	145.2	kg/t Product	
Other fiber	5.1	kg/t Product	
Other adhesive	8	kg/t Product	(Ying Chen et al., 2012)
Water-based adhesive	0.5	kg/t Product	
Vegetable oil refining	2.45	kg/t Product	(Cheng et al., 2012; Ying Chen et al., 2012)
Sugar refining	0.6	kg/t Product	(Ying Chen et al., 2012)
Fermentation alcohol	32.1	kg/kL alcohol	((Taiwan), 2012)
Wine	16.26	kg/kL Wine	(Ying Chen et al., 2012)
Beer	0.43	kg/kL beer	
Chemical raw materials	114.14	kg/t Product	((Taiwan), 2012)
Chemical pesticide	146	kg/t Product	
Manufacture of Commodity	0.025	kg/t Product	(Ying Chen et al., 2012)
Tyre	0.28	kg/tyre	(Cheng et al., 2012; Klimont et al., 2002; Ying Chen et al., 2012)
Textile Dyeing	98	kg/t Product	((Taiwan), 2012)

PU size	245	kg/t Product	(Ying Chen et al., 2012)
Shoe adhesive	670	kg/t Product	(Ying Chen et al., 2012)
Planographic printing	216	kg/t Product	(Yang, 2012)
Gravure printing	620	kg/t Product	
Relief printing	100	kg/t Product	
Porous printing	683	kg/t Product	
Other printing	750	kg/t Product	
Packaging adhesive	1385	kg/t Product	(Ying Chen et al., 2012)
Binding adhesive	89	kg/t Product	(Yang, 2012)
Wood adhesive	89	kg/t Solvent consumption	(Ying Chen et al., 2012)
Wood paintings (furniture manufacturing)	640	kg/t Solvent consumption	(Wei et al., 2008)
Coiled material paintings	455	kg/t Solvent consumption	(Ying Chen et al., 2012)
Anti-corrosive paintings	440	kg/t Solvent consumption	
Ship paintings	442	kg/t Solvent consumption	
Other paintings	750	kg/t Solvent consumption	
Assembling adhesive	89	kg/t Solvent consumption	(Ying Chen et al., 2012)
Transport equipment manufacturing paintings	470	kg/t Solvent consumption	(Wei et al., 2008)
Transport equipment manufacturing adhesive	89	kg/t Solvent consumption	(Ying Chen et al., 2012)

Coating for Exterior Walls	180	kg/t Solvent consumption	(Wei, 2009)
Coating for other building	590	kg/t Solvent consumption	
Wood paintings (architecture decoration)	640	kg/t Solvent consumption	
Assembling adhesive	62	kg/t Solvent consumption	(Ying Chen et al., 2012)
Tetrachloroethylene	1000	kg/t Solvent consumption	((Taiwan), 2012; USEPA, AP-42; Ying Chen et al., 2012)
Diode / Transistor	0.155	kg/thousands	((Taiwan), 2012)
Printed circuit board (PCB)	0.026	kg/m <sup>2</sup>	
Copper clad laminate	0.1	kg/m <sup>2</sup> Product	(Yang, 2012)
Coke	1.25	kg/t Product	(China, 1990)
Pulp	0.25	kg/t Pulp	
Paper products	0.1	kg/t Product	
Sanitary landfill	0.23	kg/t Rubbish	(EEA; Wei et al., 2008)
Composting	0.74	kg/t Rubbish	
MSW incineration	0.74	kg/t Rubbish	
Coal for thermal power	0.15	kg/t Fuel	(Cheng et al., 2012; Ying Chen et al., 2012)
Fuel Oil for thermal power	0.13	kg/t Fuel	
Liquefied petroleum gas for thermal power	66	g/m <sup>3</sup> Fuel	
Natural gas for thermal	0.18	g/m <sup>3</sup> Fuel	

power			
Coal for heat supply	0.19	kg/t Fuel	
Fuel Oil for heat supply	66	kg/t Fuel	
Liquefied petroleum gas	0.18	g/m <sup>3</sup> Fuel	
Natural gas for heat supply	0.18	g/m <sup>3</sup> Fuel	
Coal for industrial consumption	0.18	kg/t Fuel	(Wei et al., 2008)
Fuel Oil for industrial consumption	0.15	kg/t Fuel	(Yang, 2012)
Coal gas for industrial consumption	0.00044	g/m <sup>3</sup> Fuel	
Liquefied petroleum gas for industrial consumption	66	g/m <sup>3</sup> Fuel	
Natural gas for industrial consumption	0.18	g/m <sup>3</sup> Fuel	