



Supplement of

Emission inventory development for spatiotemporal release of vanadium from anthropogenic sources in China

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1 S1. Calculation procedure for vanadium emission pertinent to coal combustion

The development of vanadium emission inventories utilized collected raw data set from various resources, which were processed in streamlined procedure as illustrated in the following sections, and the raw data set have been provided in the data spreadsheet (denoted as SS-A\B\C\D\E\F\G\H), uploaded in the public repository (Zhang, 2024).

5 The coal combustion is common in many sectors, such as power plants, industrial productions, residential, and various other 6 processes. Both raw coal and coke contained vanadium contents (Lee et al., 2002). Combustion of raw coal usually involved 7 operation of various types of coal-fed boilers (Tian et al., 2010), from which vanadium bearing fly ashes went through the 8 downstream flue gas control device and were partially removed, and the remaining flue gas was emitted into the atmosphere 9 through the stacks (Tian et al., 2012). Coke was primarily used in coal-fired plants as secondary fuels, or steelmaking processes 10 (Visschedijk et al., 2013), inducing vanadium emission predominantly through air pathway (Moreno et al., 2010).

11 S1.1 Raw coal

Massive amount of raw coal was transported across province from production area to the consumption area, which led to great variability in properties and trace content between produced coal and consumed coal in the same province. The weighted average of V in consumed raw coal was obtained by combining the annual coal flow matrix among 31 China's province (Tian et al., 2011). The anthropogenic vanadium emission induced by coal consumption can be attained thorough the following method (Bai et al., 2021):

17

$$E(t) = \sum i \sum j[Aij(t) \times Cij(t) \times Ri \times (1 - \varphi i)]$$
(S1-1)

18 Where E(t) was the total amount of vanadium emission due to coal consumption at year t; A represented the yearly consumption 19 of coal type j (raw coal or coke) in province I; C was the vanadium content in coal type j in province I; R was the vanadium 20 fraction of released gas from combustion process; φ was the removal efficiency of flue gas vanadium in the treatment system. 21 V content was assumed to be consistent throughout 2015-2019. Supplementary spreadsheet SS-A1 provided the vanadium 22 content in raw coal produced in each coal producing province, which was calculated by associating the average vanadium 23 concentration with the coal transmission matrix (Wu et al., 2020), and the results were reported in previous work (Liu et al., 24 2018). SS-A2 provided the vanadium fraction of flue gas from four classic coal combustion boilers (i.e., pulverized coal fired 25 boiler, chain-grate boiler, fluidized bed combustion boiler, coking oven). SS-A3 provided the vanadium removal efficiencies 26 of typical air pollution control devices (APCDs) and the spatial variation in application rates of these treatment systems. For 27 electrostatic separator, baghouse filter, and wet method flue gas desulfurization, technology penetrate rates of these treatment systems in newly commissioned or upgraded coal combustion facility were calculated based on available data from China 28 29 Electricity Council (China Electricity Council, 2024). For old-fashion wet scrubber and cyclone separators, it was assumed

that their installation rates decreased. The application rates of these systems were extrapolated based on previously reported (Liu et al., 2011). We have adopted the application rates of APCDs during 2015-2019 in equation S1-1, assuming the technology penetration of APCDs remained unchanged during 2015-2019, given the short study period and variability of number of APCDs yearly installation. SS-A4 provided the calculation results of weighted average vanadium in raw coal consumed at provincial level. SS-A5 provided the yearly consumed volume of raw coal at provincial level, with data sourced from the Yearbook of Coal Industry of China 2015-2019 (National Bureau of Statistics of China, 2020a). The above datasets were utilized to calculate the vanadium emission inventory for raw coal and present them in **Table S1**.

37 S1.2 Coke

38 All consumed coke in Chinese province was presumably originated from raw coal.

39
$$C_j = [C_y M_y \times (1 - F)]/M_j$$
 (S1-2)

40 C_j was the V content (g/t) in consumed coke at provincial level; C_y was the vanadium content (g/t) in the raw coal for coke 41 production; M_y (t) was the amount of raw coal involved in coke production; M_j (t) was the total amount of coke production at 42 provincial level; F was the vanadium fraction in released gas from coke production (Helble et al., 1996; Chen et al., 2007; 43 Konieczyński et al., 2012; Lin et al., 2020). SS-A6 presented the provincial coke consumption level during 2015-2019, with 44 data provided by China Coal Industry Statistical Yearbook 1949-2021' (National Bureau of Statistics of China, 2024a). SS-A7 45 provided the average vanadium content in consumed coke at provincial level, which was obtained by applying formula 1-1 46 and 1-2. **Table S2** displayed the calculated result for vanadium emission inventory pertinent to coke consumption.

47 S2. Vanadium emission inventory for stationary oil combustion

48 Stationary combustion process involved burning of various types of petroleum-based products, including crude oil, gasoline, 49 diesel, fuel oil and kerosene. According to various studies, it was reasonable to assume that stationary oil combustion primarily 50 contributed to atmospheric emission (Pacyna et al., 2007; Schlesinger et al., 2017).

51
$$E(t) = \sum_{i} \sum_{j} [A_{ij}(t) \times EF_{ij}(t)] \quad (S2-1)$$

 A_{ij} typified the annual consumption activity level; EF_{ij} was the dynamic average emission factor for anthropogenic source j; To better reflect the dynamic impact of evolving technology on emission level (e.g., emission control technology, process technology), the following transformed normal distribution function was derived to estimate the variation in vanadium emission over years:

56
$$EF_P(t) = (EFa_p - EFb_p) e^{-(t-t0)2/2Sp2} + EFb_p$$
 (S2-2)

E(t) was the yearly amount of vanadium emission in province i as result of oil combustion; EFa_p was the non-controllable emission factor for combustion process p; EFb_p was the best emission factor for combustion process p; Sp was the shape parameter of the curve for process p. Both EFa_p and EFb_p were obtained by field measurement reported in other literature. S_p was also reported previously. SS-B1 provided the parameters for estimating the dynamic emission factors in different sectors along with literature reference. SS-B2 provided the calculated dynamic vanadium emission factor for consumed crude oil, coal oil, diesel and fuel oil from the corresponding transformed normal distribution functions. The obtained dynamic emission factors were applied for emission calculation for all provinces. Data results from China Energy Statistical Yearbook 1986-2023 was utilized (National Bureau of Statistics of China, 2024b), providing the yearly provincial consumption of oil products.

65 S2.1 Crude oil

SS-B3 provided the oil consumption at provincial level during 2015-2019. Table S3 presented the vanadium emission pertinent
 to crude oil combustion at provincial level during 2015-2019.

68 S2.2 Gasoline

SS-B4 provided the consumption volume of gasoline at provincial level. Table S4 displayed the calculated result for vanadium
 emission pertinent to gasoline consumption.

71 S2.3 Diesel

SS-B5 provided the consumption volume of diesel at provincial level. Table S5 provided the derived vanadium emission
 pertinent to diesel consumption.

74 S2.4 Kerosene

SS-B6 provided the consumption volume of kerosene at provincial level. Table S6 provided the derived vanadium emission
 pertinent to kerosene consumption.

77 S2.5 Fuel oil

- 78 SS-B7 provided the consumption volume of fuel oil at provincial level. Table S7 provided the derived vanadium emission
- 79 pertinent to fuel oil consumption.

80 S3. Vanadium emission inventory for industrial processes

- 81 Vanadium heavily involved in wide ranges of industrial processes such as steelmaking, glass production, mining activities,
- 82 which discharge vanadium bearing waste into the environment. The temporal dynamic emission factors for industrial processes
- 83 (steelmaking and glass production) obtained from transformed normal distribution function (2-2) were summarized in SS-B1,

along with reference source. SS-C2, C3, C4 and C5 provided the activity levels of each province in year 2015-2019 in sectors
of steelmaking, glass manufacturing, coal mining and oil extraction, respectively, with datasets sourced from statistical
yearbooks released by National Bureau of Statistics of China (National Bureau of Statistics of China, 2023a; National Bureau
of Statistics of China, 2024a; National Bureau of Statistics of China, 2024b; National Bureau of Statistics of China, 2024c).
The calculated results of vanadium emission inventories were obtained by applying formula 2-1 and displayed in Table S8 S12.

90 S3.1 Steelmaking

Vanadium was widely applied in the smelting furnace during steelmaking process to alter the physical properties of steel
 products (Lundkvist et al., 2013; Tian et al., 2015). Transformed normal distribution function was utilized to obtain the dynamic
 emission factor during 2015-2019 and displayed in SS-B1. Vanadium emission at provincial level was calculated in Table S8.

94 S3.2 Glass manufacturing

Vanadium was extensively used in the glass manufacturing process as colorant, and emitted in flue gas as result of melting
 process (Kuenen et al., 2016). Transformed normal distribution function was utilized to obtain the dynamic emission factor
 during 2015-2019 and displayed in SS-B1. Vanadium emission at provincial level was calculated in Table S9.

98 S3.3 Coal mining

99 Vanadium was mobilized and released during coal mining process (Schlesinger et al., 2017). Soil was the main receptor of 100 mining induced vanadium contamination as result of surface runoff, soil leaching and seepage and dust deposition (Bhuiyan 101 et al., 2010). The vanadium emission inventory was developed by firstly estimating the coal production activities at provincial 102 level published in China Coal Industry Statistical Yearbook 1949-2021 (National Bureau of Statistics of China, 2024a). 20 g/t 103 was adopted as the estimated average vanadium content in the extracted coal, while 0.51% was used as fraction of coal 104 subjecting to direct emission according to Pollution Source Survey (Beijing: Ministry of Ecology and Environment, 2017). 105 The provincial data for above parameters was lacking. The activity level at provincial level was provided in SS-C3. The 106 vanadium emission amount was estimated and provided in Table S10.

107 S3.4 Oil extraction

108 Oil exploration activities acted as another route for vanadium mobilization from earth crust, leading to soil pollution (Lashari 109 et al., 2023). The average vanadium content was estimated based on procedures introduced in previous study for heavy crude 110 oil. As a result, 28.9 mg/kg was adopted in our study (Pacyna et al., 2001). The release fraction was determined based on 111 Pollution Source Survey for oil extraction (Beijing: Ministry of Ecology and Environment, 2017). The activity level of crude

112 oil production was provided in SS-C5. Table S11 provided the calculated vanadium emission for petroleum production.

113 S3.5 Vanadium mining

114 The impact of vanadium mining was highlighted in this study due to the increasing demand in vanadium throughout various 115 industrial sectors, which caused significant level of soil pollution (Hao et al., 2021). The vanadium ore grades (vanadium 116 fraction) were obtained from provinces with major vanadium deposition (Ding et al., 2022). For the other province, default 117 value 0.15% was employed (ore grade < 0.1% was not eligible for mining) (Wang et al., 2023). The summarized ore grades 118 were displayed in SS-C6. Default value 0.51 % was adopted as fraction of vanadium ore subjected to direct release according 119 to Pollution Source Survey (Beijing: Ministry of Ecology and Environment, 2017). The activity level of vanadium mining was 120 provided in SS-C7, with data sourced from China Mining Sector Statistical Yearbook 2002-2019 (National Bureau of Statistics 121 of China, 2024d). Table S12 presented the vanadium emission for vanadium mining.

122 S4. Vanadium emission inventory for transportation

123 Vanadium emission could also be attributed to transportation sources, mainly including road vehicles and sea vessels, which 124 discharges vanadium bearing particulate into the atmospheric environment (Spada et al., 2018; Bai et al., 2021). Vanadium 125 based catalysts were also employed extensively to selectively reduce the nitrogen oxides from engine worldwide, leading to 126 vanadium release into atmosphere (Liu et al., 2015). According to Yearbook of Transportation and Automobile Industry 127 (National Bureau of Statistics of China, 2023b), the dramatic increase in numbers of car purchase, logistic flow, and operating 128 highway have led to increased consumption in different types of oil, which were the mobile source for vanadium emission. 129 The activity levels of oil consumption by transportation (gasoline, diesel, fuel oil) were summarized yearly in SS-D1. Here, 130 we applied the universal values to reflect the activity level due to lack of data collection from each province. We also made 131 assumption that gasoline, diesel oil and fuel oil was consumed in patterns similar to that in stationary source through 132 combustion, therefore, same emission factors were applied for calculating the vanadium emission inventory for mobile source. 133 All corresponded vanadium emission was calculated and displayed in Table S13.

134 S5. Vanadium emission inventory for waste disposal

Vanadium was abundantly detected in waste handling processes, including industrial solid waste, MSW incineration, MSW landfilling, municipal sludge disposal, and wastewater discharge (Mukherjee and Gupta, 1993; Bhatnagar et al., 2008; Pasko and Mochalova, 2014; Milik et al., 2017; Blokhina et al., 2018). Industrial solid waste, municipal solid waste, and sludges were disposed in waste heap or landfill, which was subjected to seepage process, leading to soil pollution (Schlesinger et al., 2018).

139 2017). Moreover, vanadium was also detected in surface water due to municipal wastewater discharge (Topal and Topal, 2023).

140 The following section offered the calculation procedures for developing vanadium emission inventory pertinent to waste 141 disposal.

S5.1 Industrial solid waste

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148

143 The volumes of generated industrial solid waste at provincial level were provided in SS-E1. 0.30 μ g/g was adopted to indicate 144 the average vanadium content in generated solid waste (Nriagu and Pacyna, 1988). Vanadium emissions were calculated at 145 provincial level during 2015-2019, and displayed in **Table S14**.

146 **S5.2 MSW incineration**

147 SS-E2 provided the dynamic vanadium emission factors applying the transformed normal distribution function of vanadium

149 Rural Construction Statistical Yearbook 2006-2022 (National Bureau of Statistics of China, 2023c); Table S15 displayed the

emission. SS-E3 provided the yearly volume of incinerated wastes throughout 2015-2019, with data provided by China Urban

150 calculated total amount of vanadium emission at provincial level.

151 **S5.3 MSW landfilling**

The default value 0.70 μg/g was used for universal emission factor (Nriagu and Pacyna, 1988). SS-E4 provided the amount of MSW admitted to landfill during 2015-2019, with data provided by China Urban Rural Construction Statistical Yearbook 2006-2022 (National Bureau of Statistics of China, 2023c). **Table S16** provided the calculated total amount of vanadium discharged into environment from landfill at provincial level.

156 **S5.4 Sludge disposal**

The provincial statistics of sludge generation was inadequate. Therefore, universal values were adopted for calculation of the vanadium emission pertinent to sludge disposal. The default value of emission factor 11.0 μg/g was obtained from literature (Nriagu and Pacyna, 1988). The total amount of sludge generation was calculated based on discharge fraction of hazardous waste (0.51%) according to Pollution Source Survey (Beijing: Ministry of Ecology and Environment, 2017), yielding the following results throughout 2015-2019 displayed in SS-E5. **Table S17** provided the total amount of vanadium emission pertinent to sludge generation throughout 2015-2019.

163 S5.5 Municipal wastewater

164 The default value 0.3 ng/L was obtained from literature (Nriagu and Pacyna, 1988). SS-E6 provided the provincial level

- 165 wastewater discharge during 2015-2019, with data provided by China Urban Rural Construction Statistical Yearbook 2006-
- 166 2022 (National Bureau of Statistics of China, 2023c). Based on the result, **Table S18** provided the total amount of vanadium
- 167 discharge into the water environment during 2015-2019.
- 168
- 169

Province	V emission from raw coal consumption (t)							
FIOVINCE	2015	2016	2017	2018	2019	Cumulative V		
Beijing	32.86	23.9	13.83	7.79	5.16	83.54		
Tianjin	135.36	126.15	115.58	114.31	112.32	603.72		
Hebei	1049.57	1019.2	994.23	1073.16	1042.15	5178.31		
Shanxi	1094.61	1050.55	1266.47	1443.36	1513.89	6368.88		
Inner	1044.2	1040 22	1104.16	1262 72	1402 84	5962 15		
Mongolia	1044.2	1049.22	1104.10	1202.75	1402.84	5805.15		
Liaoning	569.05	556.17	577.29	587.7	614.17	2904.38		
Jilin	405.96	389.88	387.3	354.12	361.47	1898.73		
Heilongjiang	539.97	564.15	581.62	537.47	568.5	2791.71		
Shanghai	135.45	132.51	131.14	126.64	121.42	647.16		
Jiangsu	695.94	717.4	680.88	649.86	636.93	3381.01		
Zhejiang	381.71	385.09	393.74	391.48	377.59	1929.61		
Anhui	428.08	429.65	439.37	455.45	456.18	2208.73		
Fujian	218.77	194.96	215.43	244.44	248.99	1122.59		
Jiangxi	441.52	436.89	445.13	451.81	458.59	2233.94		
Shandong	1554.11	1554.58	1449.22	1606.99	1637.88	7802.78		
Henan	1283.9	1257.2	1227.04	1208.82	1085.01	6061.97		
Hubei	558.68	554.88	559.21	527.07	558.8	2758.64		
Hunan	1439.79	1478.72	1602.9	1411.37	1377.99	7310.77		
Guangdong	533.67	519.13	552.49	549.12	541.6	2696.01		
Guangxi	330.35	356.08	361.3	400.99	438.26	1886.98		
Henan	32.92	31.18	33.76	35.7	34.71	168.27		
Chongqing	531.16	498.41	495.98	450.56	441.19	2417.3		
Sichuan	652.58	623.11	551.9	526.6	541.9	2896.09		
Guizhou	1373.59	1460.2	1435.26	1285.24	1306.23	6860.52		
Yunnan	959.26	927.96	896.87	920.64	936.85	4641.58		
Tibet	NA	NA	NA	NA	NA	NA		
Shaanxi	1112.5	1191.04	1215.19	1174.4	1304.75	5997.88		
Gansu	138.48	134.69	134.33	144.01	143.82	695.33		
Qinghai	36.93	48.06	42.78	40.15	37.76	205.68		
Ningxia	125.55	122.14	155.87	179.17	193.44	776.17		
Xinjiang	260.2	284.57	305.33	326.61	355.27	1531.98		
Hongkong	NA	NA	NA	NA	NA	NA		
Hainan	NA	NA	NA	NA	NA	NA		

 Table S1. Vanadium emission pertinent to raw coal combustion.

	V emission from coke consumption (t)						
Province	2015	2016	2017	2018	2019	Cumulative V	
Beijing	0.02	0.01	0.01	0	0	0.04	
Tianjin	43.77	42.35	39.12	41.67	43.59	210.5	
Hebei	327.02	256.34	277.84	309.58	317.21	1487.99	
Shanxi	51	51.4	49.74	58.18	62.89	273.21	
Inner Mongolia	70.05	47.34	47.2	60.8	67.65	293.04	
Liaoning	107.29	103.22	114.4	117.27	121.87	564.05	
Jilin	17.37	15.96	15.35	19.47	21.55	89.7	
Heilongjiang	7.94	7.46	8.85	13.39	15.34	52.98	
Shanghai	31.97	28.49	28.65	29.85	30.61	149.57	
Jiangsu	80	88.2	88.93	90.81	109.6	457.54	
Zhejiang	21.67	15.72	15.49	15.52	14.56	82.96	
Anhui	28.57	28.1	23.93	25.92	26.87	133.39	
Fujian	13.53	12.87	13.56	16.3	18.03	74.29	
Jiangxi	53.84	47.59	49.21	52.21	53.51	256.36	
Shandong	122	86.76	109.51	97.59	108.74	524.6	
Henan	120.27	129.04	106.25	63.97	66.2	485.73	
Hubei	47.76	48.99	46.15	49.89	48.82	241.61	
Hunan	161.54	132.59	132.81	135.02	137.19	699.15	
Guangdong	27.52	37.35	45.52	44.84	47.49	202.72	
Guangxi	51.6	60.53	63.06	54.41	56.97	286.57	
Hainan	0	0	0	0	0	0	
Chongqing	23.33	32.57	30.17	22.42	25.63	134.12	
Sichuan	126.44	115.48	116	82.28	91.94	532.14	
Guizhou	30.23	22.48	19.9	18.99	20.51	112.11	
Yunnan	106.97	107.17	114.83	126.82	134.33	590.12	
Tibet	0	0	0	0	0	0	
Shaanxi	72.27	62.65	63.38	58.04	57.01	313.35	
Gansu	12.18	10.73	10.18	9.47	10.51	53.07	
Qinghai	12.63	6.21	5.93	6.33	6.4	37.5	
Ningxia	6.7	5.89	7.36	7.84	8.65	36.44	
Xinjiang	14.51	15.93	19.62	19.58	19.93	89.57	

 Table S2. Vanadium emission pertinent to coke combustion.

Drovingo	V emission from crude oil consumption (t)					
Flovince -	2015	2016	2017	2018	2019	Cumulative V
Beijing	108.98	88.14	94.55	95.88	98.16	485.71
Tianjin	177.69	153.91	172.12	177.53	177.4	858.65
Hebei	183.19	189.16	163.36	179.24	228.12	943.07
Shanxi	0	0	0	0	0	0
Inner Mongolia	42.17	45.04	47.91	38.1	44.91	218.13
Liaoning	707.78	757.65	755.7	862.58	1036.57	4120.28
Jilin	105.55	112.87	108.89	98.41	108.48	534.2
Heilongjiang	233.43	237.31	201.84	163.27	160.79	996.64
Shanghai	277.63	265.64	264.06	242.83	272.09	1322.25
Jiangsu	420.19	439.33	409.53	427.78	431.75	2128.58
Zhejiang	312.88	286.37	321.89	291.28	363.77	1576.19
Anhui	75.9	57.89	79.62	76.59	69.03	359.03
Fujian	237.93	224.32	220.73	225.48	268.13	1176.59
Jiangxi	61.1	77.92	74.09	80.76	82.55	376.42
Shandong	945.96	1095.46	1216.85	1370.81	1428.14	6057.22
Henan	93.12	75.93	69.75	87.15	83.77	409.72
Hubei	142.77	133.09	151.37	149.4	158.87	735.5
Hunan	96.55	90.36	81.58	99.87	97.97	466.33
Guangdong	538.49	541.58	551.83	622.64	590.03	2844.57
Guangxi	157.03	143.91	165.57	168.19	171.58	806.28
Hainan	122.67	120.1	103.81	111.56	119.24	577.38
Chongqing	0	0	0	0	0	0
Sichuan	108.76	96.92	101.31	75.7	105.83	488.52
Guizhou	0	0	0	0	0	0
Yunnan	0	0	42.58	106.21	113.83	262.62
Tibet	0	0	0	0	0	0
Shaanxi	230.92	195.81	196.35	196.04	192.53	1011.65
Gansu	158.98	146.79	154.67	152.9	155.04	768.38
Qinghai	16.96	16.05	16.16	14.99	16.39	80.55
Ningxia	52.44	61.88	62.64	47.19	48.15	272.3
Xinjiang	273.61	263.34	268.22	252.86	248.97	1307

 Table S3. Vanadium emission pertinent to crude oil consumption.

Drovinco	V emission from gasoline consumption (t)					
Plovince –	2015	2016	2017	2018	2019	Cumulative V
Beijing	61.38	61.25	63.12	63.24	63.99	312.98
Tianjin	34.98	35.75	35.24	35.06	36.34	177.37
Hebei	63.05	64.44	63.58	62.76	54.06	307.89
Shanxi	27.65	29.73	33.21	30.14	31.63	152.36
Inner Mongolia	40.56	46	46.01	45.23	46.97	224.77
Liaoning	98.52	102.38	102.07	109.78	112.43	525.18
Jilin	23.61	23.27	26.54	26.22	23.34	122.98
Heilongjiang	45.38	41.17	48.77	50.37	54.97	240.66
Shanghai	80.61	83.06	85.39	63.29	63.09	375.44
Jiangsu	133.17	131.83	134.95	137.49	138.72	676.16
Zhejiang	100.02	103.78	110.69	110.47	100.82	525.78
Anhui	60.57	66.4	74.05	80.26	83.79	365.07
Fujian	61.69	64.43	68.54	70.19	71.85	336.7
Jiangxi	37.67	38.37	42.66	47.98	51.78	218.46
Shandong	96.31	96.28	104.26	88.42	90.32	475.59
Henan	89.76	91.19	87.52	97.6	98.33	464.4
Hubei	92.84	96.78	96.54	100.52	110.45	497.13
Hunan	68.27	74.98	82.73	92.11	104.74	422.83
Guangdong	163.04	195.65	197.14	199.25	199.41	954.49
Guangxi	38.59	49.36	50.55	42.81	32.79	214.1
Hainan	12.31	13.31	14.2	13.78	13.75	67.35
Chongqing	26.53	28.53	29.98	45.99	51.11	182.14
Sichuan	118.72	122.42	124.75	112	117.14	595.03
Guizhou	39	44.75	49.02	56.1	59.49	248.36
Yunnan	41.51	44.28	44.42	54.66	59.7	244.57
Tibet	0	0	0	0	0	0
Shaanxi	33.1	33.51	35.75	38.22	39.07	179.65
Gansu	20.99	25.95	26.97	25.94	26.67	126.52
Qinghai	5.96	7.29	7.74	7.95	8.53	37.47
Ningxia	4.79	3.78	4.03	2.4	2.51	17.51
Xinjiang	33.76	35.94	36.78	38.16	39.27	183.91

 Table S4. Vanadium emission pertinent to gasoline consumption.

Drovince	V emission from diesel consumption (t)					
Province -	2015	2016	2017	2018	2019	Cumulative V
Beijing	24.19	22.49	22.56	22.91	20.68	112.83
Tianjin	46.88	48.23	45.4	41.78	40.49	222.78
Hebei	99.38	109.86	92.94	56.63	59.34	418.15
Shanxi	68.61	69.81	72.22	62.69	63.9	337.23
Inner Mongolia	63.03	55.56	56.6	55.16	57.7	288.05
Liaoning	147.14	131.36	133.06	133.37	133.48	678.41
Jilin	46.05	44.76	46.36	46.72	44.22	228.11
Heilongjiang	67.65	43.02	42.59	45.24	50.1	248.6
Shanghai	74.53	73.21	70.92	56.31	57.4	332.37
Jiangsu	108.69	106.95	111.13	112.94	113.33	553.04
Zhejiang	128.45	114.85	107.21	97.63	93.32	541.46
Anhui	81.16	81.09	81.38	83.72	88.03	415.38
Fujian	59.07	55.94	55.89	56.23	57.94	285.07
Jiangxi	71.3	71.19	73.14	75.36	76.5	367.49
Shandong	177.12	178.25	199.02	163.2	170.66	888.25
Henan	110.8	105.22	119.47	127.33	128.71	591.53
Hubei	113.95	112.75	111.89	114.72	124.72	578.03
Hunan	91.08	92.85	81.97	83.19	85.92	435.01
Guangdong	210.63	218.27	215	214.29	213.62	1071.81
Guangxi	76.05	70.12	72.45	62.35	62.24	343.21
Hainan	15.5	14.1	14.2	11.54	11.21	66.55
Chongqing	65.16	66.96	69.88	52.71	52	306.71
Sichuan	108.08	104.3	105.32	115.58	116.62	549.9
Guizhou	60.22	63.91	61.97	73.17	74.53	333.8
Yunnan	77.32	78.33	78.29	80.55	86.02	400.51
Tibet	0	0	0	0	0	0
Shaanxi	61.78	53.34	48.17	51.32	48.17	262.78
Gansu	44.52	39.98	38.59	37.1	36	196.19
Qinghai	15.19	16.79	19.62	20.42	21.6	93.62
Ningxia	16.28	16.15	16.44	15.07	15.4	79.34
Xinjiang	84.52	84.79	83.47	74.02	75.6	402.4

 Table S5. Vanadium emission pertinent to diesel consumption.

Drovinco -	V emission from kerosene consumption (t)					
Flovince -	2015	2016	2017	2018	2019	Cumulative V
Beijing	380.06	413.04	446.47	478.42	482.77	2200.76
Tianjin	45.93	57.01	70.37	75.41	76.5	325.22
Hebei	5.75	20.48	19.11	19.14	22.26	86.74
Shanxi	18.51	18.74	22.39	25.1	31.61	116.35
Inner Mongolia	22.76	24.3	29.72	32.44	34.61	143.83
Liaoning	20.92	27.1	30.76	35.64	36.52	150.94
Jilin	1.33	14.19	12.07	22.56	23.3	73.45
Heilongjiang	47.8	54.6	60.7	44.32	48.27	255.69
Shanghai	357.07	407.17	452.23	485.77	521.43	2223.67
Jiangsu	59.24	62.96	73.05	78.39	91.91	365.55
Zhejiang	79.26	88.55	102.47	113.3	122.02	505.6
Anhui	9.73	11.11	10.77	10.72	11.48	53.81
Fujian	78.06	86.34	97.66	114.44	118.85	495.35
Jiangxi	1.48	1.72	1.96	12.41	13.37	30.94
Shandong	68.77	80.09	85.66	83.27	87.12	404.91
Henan	47.59	51.43	50.17	56.7	64.1	269.99
Hubei	48.78	65.78	67.67	80.49	88.88	351.6
Hunan	36.14	38.53	42.12	43.73	44.99	205.51
Guangdong	192.01	203.07	207.91	212.19	216.62	1031.8
Guangxi	39.35	43.45	35.32	36.14	32.07	186.33
Henan	59.83	73.51	79.51	88.73	90.66	392.24
Chongqing	46.52	56.28	57.85	65.72	70.67	297.04
Sichuan	194.21	214.63	218.54	145.02	148.19	920.59
Guizhou	21.99	26.86	33.67	39.24	40.9	162.66
Yunnan	63.11	71.56	78.91	84.85	88.31	386.74
Tibet	0	0	0	0	0	0
Shaanxi	24.07	20.87	34.66	53.97	63.04	196.61
Gansu	4.09	5.6	5.56	6.78	7.26	29.29
Qinghai	0.01	0.01	0.01	0.01	0.01	0.05
Ningxia	0.01	0.01	0.01	0.01	0.01	0.05
Xinjiang	19.53	19.59	52.66	45.9	42.51	180.19

 Table S6. Vanadium emission pertinent to kerosene consumption.

Drovince	V emission from fuel oil consumption (t)					
Province -	2015	2016	2017	2018	2019	Cumulative V
Beijing	3.43	3.22	1.95	1.07	0.33	10
Tianjin	65.72	31.51	28.2	32.53	34.59	192.55
Hebei	36.12	37.32	29.9	84.02	71.79	259.15
Shanxi	0.43	0.42	0.33	0.37	0.33	1.88
Inner Mongolia	7.4	2.27	2.59	1.76	0.86	14.88
Liaoning	217.3	212.03	211.44	150.15	152.98	943.9
Jilin	21.57	26.45	26.25	17.86	19.48	111.61
Heilongjiang	80.07	65.59	49.67	29.85	14.49	239.67
Shanghai	377.17	404.14	466.19	455.71	455.46	2158.67
Jiangsu	100.35	105.37	170.56	171.08	110.02	657.38
Zhejiang	227.78	265.01	276.15	210.52	210.18	1189.64
Anhui	9.38	14.74	15.81	15.33	14.87	70.13
Fujian	122.08	123.88	101.93	121.94	124.66	594.49
Jiangxi	12.28	10.46	8.28	8.13	8.48	47.63
Shandong	2266.94	3135.6	3249.01	1645.26	1450.33	11747.14
Henan	49.33	47.73	19.51	21.93	6.76	145.26
Hubei	103.85	94.61	90.23	89.61	102.97	481.27
Hunan	64.79	65.37	64.88	62.61	57.46	315.11
Guangdong	281.69	317.55	241.62	231.08	239.55	1311.49
Guangxi	16.83	7.33	7.24	11.27	12.45	55.12
Hainan	81.56	75.24	76.41	62.34	60.72	356.27
Chongqing	9.7	9.67	9.88	11.2	12.74	53.19
Sichuan	94.73	108.04	110.77	23.08	34.63	371.25
Guizhou	0.29	0.36	0.22	0.28	0.11	1.26
Yunnan	1.75	0.77	0.4	1.23	0.16	4.31
Tibet	0	0	0	0	0	0
Shaanxi	17.81	8.58	13.49	19.45	5.89	65.22
Gansu	3.47	2.31	1.99	2.66	2.4	12.83
Qinghai	0.02	0.07	0.15	0.12	0.14	0.5
Ningxia	35.49	57.1	60.57	55.72	97.58	306.46
Xinjiang	1.23	0.69	0.22	0.33	0.53	3

 Table S7. Vanadium emission pertinent to fuel oil consumption.

Duraninan	V emission from steel making process (t)					
Province –	2015	2016	2017	2018	2019	Cumulative V
Beijing	0.02	0.02	0	0	0	0.04
Tianjin	31.25	27.17	27.37	30.55	33.15	149.49
Hebei	284.44	290.88	288.78	358.27	364.83	1587.2
Shanxi	58.1	59.45	66.9	81.34	91.2	356.99
Inner Mongolia	26.21	27.38	29.96	34.85	40.08	158.48
Liaoning	89.02	91.23	97.03	103.81	111.11	492.2
Jilin	16.11	12.57	13.75	18.19	20.49	81.11
Heilongjiang	6.32	5.62	7.6	11.69	13.53	44.76
Shanghai	26.94	25.81	24.28	24.62	24.77	126.42
Jiangsu	166.06	167.35	157.48	157.4	181.48	829.77
Zhejiang	24.09	19.63	16.47	19.13	20.4	99.72
Anhui	37.85	41.25	42.8	46.88	48.67	217.45
Fujian	23.96	22.91	28.44	31.5	36.1	142.91
Jiangxi	33.39	33.85	36.44	37.74	38.12	179.54
Shandong	99.97	108.24	108.07	108.39	96	520.67
Henan	43.76	43.03	43.36	43.68	49.82	223.65
Hubei	44.1	44.21	43.42	46.39	54.29	232.41
Hunan	27.98	27.61	30.83	34.85	36.03	157.3
Guangdong	26.61	34.48	43.66	43.5	48.77	197.02
Guangxi	32.41	31.86	34.21	33.88	40.21	172.57
Hainan	0.36	0.42	0.01	0	0	0.79
Chongqing	10.41	5.54	6.21	9.64	12.77	44.57
Sichuan	29.42	30.32	30.6	36.26	41.28	167.88
Guizhou	7.05	7.79	6.64	6.32	6.68	34.48
Yunnan	21.42	21.41	22.92	29.07	32.54	127.36
Tibet	0	0	0	0	0	0
Shaanxi	15.52	13.97	17.89	19.8	21.61	88.79
Gansu	12.87	9.49	8.47	12.12	13.26	56.21
Qinghai	1.83	1.74	1.81	2.09	2.7	10.17
Ningxia	2.75	2.4	3.47	3.81	4.66	17.09
Xinjiang	11.87	13.13	16.77	17.45	18.68	77.9

 Table S8. Vanadium emission for steelmaking process.

Durani	V emission from glass production (t)							
Flovince –	2015	2016	2017	2018	2019	Cumulative V		
Beijing	0.05	0.05	0.05	0.05	0.05	0.25		
Tianjin	2.98	2.94	3.01	3.22	3.16	15.31		
Hebei	10.55	9.87	10.12	11.55	15.54	57.63		
Shanxi	1.33	1.57	1.62	2.02	1.75	8.29		
Inner Mongolia	0.96	0.95	0.94	0.99	0.94	4.78		
Liaoning	1.13	1.33	4.08	4.2	4.8	15.54		
Jilin	0.35	0.82	0.82	1.05	1.12	4.16		
Heilongjiang	0.37	0.38	0.38	0.37	0.38	1.88		
Shanghai	0	0	0	0	0	0		
Jiangsu	4.39	2.41	2.61	2.17	1.74	13.32		
Zhejiang	5.05	4.78	4.26	4.12	4.27	22.48		
Anhui	2.19	3.1	3.58	3.14	4.03	16.04		
Fujian	4.76	5.12	4.5	4.72	4.86	23.96		
Jiangxi	0.37	0.44	0.02	0.45	0.45	1.73		
Shandong	6.99	6.46	6.88	7.11	6.74	34.18		
Henan	1.12	1.06	1.92	1.88	1.82	7.8		
Hubei	8.42	8.28	8.34	8.98	9.77	43.79		
Hunan	2.04	2.54	2.43	2.36	3.14	12.51		
Guangdong	6.71	8.6	8.69	9.64	9.59	43.23		
Guangxi	0.59	0.49	0.27	0.44	1.13	2.92		
Hainan	0	0	0	0.68	0.49	1.17		
Chongqing	1.3	1.4	1.38	1.5	1.21	6.79		
Sichuan	3.98	5.1	5.13	5.79	5.71	25.71		
Guizhou	0.86	1.33	1.45	1.63	1.67	6.94		
Yunnan	0.6	0.37	0.31	1.14	1.66	4.08		
Tibet	0	0	0	0	0	0		
Shaanxi	1.73	1.95	2.05	2	1.94	9.67		
Gansu	0.12	0.58	0.49	0.51	0.53	2.23		
Qinghai	0.37	0.39	0.29	0.33	0.12	1.5		
Ningxia	0	0.05	0.27	0.39	0.4	1.11		
Xinjiang	1.05	0.66	0.7	0.76	0.74	3.91		

 Table S9. Vanadium emission pertinent to glass production.

Dec	V emission from coal mining (t)						
Province -	2015	2016	2017	2018	2019	Cumulative V	
Beijing	0.05	0.03	0.03	0.02	0	0.13	
Tianjin	0	0	0	0	0	0	
Hebei	0.52	0.57	0.61	0.66	0.76	3.12	
Shanxi	10.08	9.45	8.9	8.47	9.86	46.76	
Inner Mongolia	11.12	10.11	9.24	8.63	9.28	48.38	
Liaoning	0.34	0.35	0.37	0.43	0.48	1.97	
Jilin	0.13	0.17	0.17	0.17	0.27	0.91	
Heilongjiang	0.55	0.63	0.63	0.6	0.67	3.08	
Shanghai	0	0	0	0	0	0	
Jiangsu	0.11	0.13	0.13	0.14	0.2	0.71	
Zhejiang	0	0	0	0	0	0	
Anhui	1.12	1.16	1.2	1.25	1.37	6.1	
Fujian	0.09	0.1	0.12	0.14	0.16	0.61	
Jiangxi	0.05	0.06	0.1	0.16	0.23	0.6	
Shandong	1.22	1.28	1.34	1.31	1.45	6.6	
Henan	1.12	1.17	1.2	1.22	1.39	6.1	
Hubei	0	0.01	0.03	0.06	0.09	0.19	
Hunan	0.15	0.19	0.2	0.28	0.36	1.18	
Guangdong	0	0	0	0	0	0	
Guangxi	0.04	0.05	0.05	0.04	0.04	0.22	
Henan	0	0	0	0	0	0	
Chongqing	0.12	0.12	0.12	0.25	0.36	0.97	
Sichuan	0.35	0.38	0.49	0.63	0.65	2.5	
Guizhou	1.34	1.46	1.67	1.72	1.75	7.94	
Yunnan	0.56	0.47	0.48	0.47	0.53	2.51	
Tibet	0	0	0	0	0	0	
Shaanxi	6.49	6.42	5.82	5.26	5.36	29.35	
Gansu	0.38	0.37	0.38	0.43	0.45	2.01	
Qinghai	0.13	0.08	0.09	0.08	0.08	0.46	
Ningxia	0.76	0.8	0.78	0.72	0.81	3.87	
Xinjiang	2.46	2.18	1.81	1.64	1.55	9.64	

 Table S10. Vanadium emission pertinent to coal mining.

Dussiass	V emission from oil extraction (t)					
Province -	2015	2016	2017	2018	2019	Cumulative V
Beijing	0	0	0	0	0	0
Tianjin	5.15	4.83	4.57	4.55	4.59	23.69
Hebei	0.86	0.81	0.8	0.79	0.81	4.07
Shanxi	0	0	0	0	0	0
Inner Mongolia	0.07	0.07	0.02	0.02	0.02	0.2
Liaoning	1.53	1.5	1.54	1.53	1.55	7.65
Jilin	0.98	0.9	0.62	0.57	0.59	3.66
Heilongjiang	5.66	5.39	5.04	4.75	4.55	25.39
Shanghai	0.01	0.01	0.01	0.01	0.06	0.1
Jiangsu	0.28	0.25	0.23	0.23	0.23	1.22
Zhejiang	0	0	0	0	0	0
Anhui	0	0	0	0	0	0
Fujian	0	0	0	0	0	0
Jiangxi	0	0	0	0	0	0
Shandong	3.84	3.38	3.29	3.31	3.28	17.1
Henan	0.61	0.47	0.42	0.38	0.37	2.25
Hubei	0.11	0.09	0.08	0.08	0.08	0.44
Hunan	0	0	0	0	0	0
Guangdong	2.32	2.29	2.12	2.05	2.22	11
Guangxi	0.07	0.07	0.07	0.08	0.07	0.36
Hainan	0.04	0.04	0.04	0.05	0.05	0.22
Chongqing	0	0	0	0	0	0
Sichuan	0.02	0.02	0.01	0.01	0.01	0.07
Guizhou	0	0	0	0	0	0
Yunnan	0	0	0	0	0	0
Tibet	0	0	0	0	0	0
Shaanxi	5.51	5.16	5.14	5.19	3.98	24.98
Gansu	0.1	0.06	0.07	0.08	1.33	1.64
Qinghai	0.33	0.33	0.34	0.33	0.34	1.67
Ningxia	0.02	0.01	0	0	0	0.03
Xinjiang	4.12	3.78	3.82	3.9	4.11	19.73

 Table S11. Vanadium emission pertinent to oil extraction.

Dessin -	Yearly activity level of vanadium mining (t)					
Province -	2015	2016	2017	2018	2019	Cumulative
Beijing	0	0	0	0	0	0
Tianjin	0	0	0	0	0	0
Hebei	5.34	6	5.17	5.59	5.38	26.48
Shanxi	0	0	0	0	0	0
Inner	0.01	0.02	0.02	0.02	0.02	0.00
Mongolia	0.01	0.02	0.02	0.02	0.02	0.09
Liaoning	0	0	0	0	0	0
Jilin	0	0	0	0	0	0
Heilongjiang	0	0	0	0	0	0
Shanghai	0	0	0	0	0	0
Jiangsu	0.21	0.17	0.19	0.18	0.19	0.94
Zhejiang	0.05	0.04	0.05	0.05	0.04	0.23
Anhui	0.71	0.72	0.72	0.71	0.71	3.57
Fujian	0	0	0	0	0	0
Jiangxi	0.02	0.02	0.02	0.02	0.02	0.1
Shandong	0	0	0	0	0	0
Henan	0	0	0	0	0	0
Hubei	4.68	4.04	4.36	4.2	4.28	21.56
Hunan	2.8	2.9	2.8	2.8	2.9	14.2
Guangdong	0	0	0	0	0	0
Guangxi	0.01	0.01	0.01	0.01	0.01	0.05
Hainan	0	0	0	0	0	0
Chongqing	0	0	0	0	0	0
Sichuan	23.47	34.75	29.11	31.93	30.52	149.78
Guizhou	0	0	0	0	0	0
Yunnan	0.03	0.03	0.03	0.03	0.04	0.16
Tibet	0	0	0	0	0	0
Shaanxi	0.27	0.02	0.02	0.01	0.01	0.33
Gansu	0.03	2.24	2.23	2.23	2.22	8.95
Qinghai	0	0	0	0	0	0
Ningxia	0	0	0	0	0	0
Xinjiang	0.04	0.04	0.04	0.04	0.04	0.2

 Table S12. Vanadium emission pertinent to vanadium mining.

Process -	V emission from mobile source of oil consumption (t)						
	2015	2016	2017	2018	2019	Cumulative V	
Gasoline	691.05	731.01	779.43	870.65	961.28	4033.42	
Diesel	1453.67	1468.24	1528.3	1602.35	1518.87	7571.43	
Fuel gas	1000.5	1055.19	1246.1	1278.76	1469.49	6050.04	

 Table S13. Vanadium emission pertinent to transportation.

Drovince	V emission from industrial solid waste disposal (t)							
Province -	2015	2016	2017	2018	2019	Cumulative V		
Beijing	0.35	0.39	0.59	0.68	0.78	2.79		
Tianjin	0.07	0.07	0.14	0.07	0.08	0.43		
Hebei	44.19	19.84	14	14.41	15.12	107.56		
Shanxi	33.92	57.42	64.5	76.8	82.21	314.85		
Inner Mongolia	22.66	34.54	43.96	46.1	58.25	205.51		
Liaoning	24.2	14.38	18.1	16.28	25.53	98.49		
Jilin	4.71	4.03	4.78	5.42	4.68	23.62		
Heilongjiang	3.82	5.3	5.42	6.73	4.17	25.44		
Shanghai	0.22	0.23	0.32	0.5	0.45	1.72		
Jiangsu	1.22	3.97	3.57	3.62	2.98	15.36		
Zhejiang	0.62	1.81	1.61	1.35	1.01	6.4		
Anhui	3.15	3.65	2.18	3.53	4.72	17.23		
Fujian	3.47	3.29	4.82	5.31	5.53	22.42		
Jiangxi	0.82	4.69	3.83	3.66	4.17	17.17		
Shandong	2.21	3.97	4.95	5.17	6.9	23.2		
Henan	8.36	13.82	14.88	17.16	16.37	70.59		
Hubei	6.23	6.99	4.49	4.37	7.4	29.48		
Hunan	6.04	4.23	3.16	3.2	2.93	19.56		
Guangdong	1.32	1.88	2.11	2.66	2.78	10.75		
Guangxi	1.64	5.25	5.27	5.28	4.01	21.45		
Henan	0.13	0.12	0.68	0.64	0.6	2.17		
Chongqing	1.15	1.04	1.24	1.07	1.52	6.02		
Sichuan	12.53	9.29	4.8	5.21	6.69	38.52		
Guizhou	5.71	5.2	7.03	5.93	5.49	29.36		
Yunnan	12.49	22.75	26.6	29.22	22.23	113.29		
Tibet	0.12	0.28	0.15	0.52	0.67	1.74		
Shaanxi	5.93	8.07	18.34	21.53	20.12	73.99		
Gansu	6.78	5.09	4.43	4.18	5.47	25.95		
Qinghai	0.01	0.24	0.51	1.04	0.95	2.75		
Ningxia	2.79	5.73	8.1	9.83	8.91	35.36		
Xinjiang	2.27	8.16	8.39	8.42	8.37	35.61		

 Table S14. Vanadium emission pertinent to industrial solid waste disposal.

Dussians	V emission from MSW incineration (t)								
Province -	2015	2016	2017	2018	2019	Cumulative V			
Beijing	0.23	0.3	0.36	0.44	0.61	1.94			
Tianjin	0.13	0.15	0.15	0.15	0.21	0.79			
Hebei	0.24	0.32	0.31	0.38	0.42	1.67			
Shanxi	0.14	0.14	0.13	0.14	0.12	0.67			
Inner Mongolia	0.03	0.04	0.07	0.1	0.11	0.35			
Liaoning	0.08	0.07	0.07	0.07	0.16	0.45			
Jilin	0.13	0.14	0.18	0.15	0.22	0.82			
Heilongjiang	0.04	0.09	0.11	0.11	0.14	0.49			
Shanghai	0.28	0.3	0.4	0.43	0.54	1.95			
Jiangsu	1.16	1.23	1.42	1.47	1.54	6.82			
Zhejiang	0.86	0.92	0.91	1.08	1.23	5			
Anhui	0.22	0.31	0.37	0.46	0.51	1.87			
Fujian	0.41	0.47	0.54	0.65	0.69	2.76			
Jiangxi	0	0.03	0.06	0.13	0.21	0.43			
Shandong	0.62	0.78	0.99	1.23	1.43	5.05			
Henan	0.17	0.17	0.18	0.23	0.33	1.08			
Hubei	0.43	0.41	0.43	0.45	0.47	2.19			
Hunan	0.05	0.13	0.14	0.34	0.37	1.03			
Guangdong	0.79	0.87	1.01	1.37	1.91	5.95			
Guangxi	0.03	0.09	0.14	0.17	0.25	0.68			
Hainan	0.1	0.14	0.16	0.15	0.15	0.7			
Chongqing	0.16	0.22	0.24	0.28	0.34	1.24			
Sichuan	0.31	0.4	0.5	0.62	0.78	2.61			
Guizhou	0.03	0.04	0.08	0.14	0.18	0.47			
Yunnan	0.21	0.27	0.25	0.28	0.25	1.26			
Tibet	0	0	0	0.03	0.03	0.06			
Shaanxi	0	0.01	0	0	0.02	0.03			
Gansu	0	0.04	0.1	0.12	0.14	0.4			
Qinghai	0	0	0	0	0	0			
Ningxia	0	0.04	0.04	0.06	0.07	0.21			
Xinjiang	0	0.01	0.02	0.02	0.01	0.06			

 Table S15. Vanadium emission pertinent to MSW incineration.

Drovince	V emission from MSW landfilling (t)								
Province -	2015	2016	2017	2018	2019	Cumulative V			
Beijing	2.28	3.31	3.07	2.76	2.04	13.46			
Tianjin	0.76	0.79	1.07	0.99	0.56	4.17			
Hebei	2.69	2.86	2.74	2.7	2.71	13.7			
Shanxi	2.17	2.24	2.33	2.42	2.65	11.81			
Inner Mongolia	2.06	2.12	2.14	1.79	2.04	10.15			
Liaoning	5.45	5.29	5.1	5.14	5.71	26.69			
Jilin	2.03	2.09	1.36	1.89	1.57	8.94			
Heilongjiang	2.22	2.15	2.47	2.45	2.52	11.81			
Shanghai	2.3	2.31	2.59	2.76	1.51	11.47			
Jiangsu	2.85	3.16	2.91	2.44	2.48	13.84			
Zhejiang	3.84	4.19	4.19	3.18	2.43	17.83			
Anhui	2.01	1.81	1.87	1.26	1.1	8.05			
Fujian	1.66	1.44	1.89	1.78	2.11	8.88			
Jiangxi	2.18	2.44	2.71	2.35	2.44	12.12			
Shandong	5.25	4.94	4.59	3.5	2.8	21.08			
Henan	4.93	5.23	5.75	5.65	5.83	27.39			
Hubei	2.44	3.11	3.36	3.51	3.32	15.74			
Hunan	4.14	3.96	4.46	3.56	2.82	18.94			
Guangdong	9.72	10.34	11.38	12.18	10.82	54.44			
Guangxi	2.48	2.3	2.15	2.19	1.9	11.02			
Hainan	0.49	0.41	0.46	0.56	0.69	2.61			
Chongqing	2	2.1	2.17	2.05	1.58	9.9			
Sichuan	3.62	3.59	3.56	3.08	3.13	16.98			
Guizhou	1.58	1.66	1.64	1.29	1.25	7.42			
Yunnan	1.03	1.09	1.08	1.23	1.59	6.02			
Tibet	0	0.29	0.3	0.16	0.27	1.02			
Shaanxi	3.53	3.55	2.63	4.5	4.32	18.53			
Gansu	1.18	1.08	1.06	1.12	0.98	5.42			
Qinghai	0.5	0.55	0.51	0.63	0.63	2.82			
Ningxia	0.83	0.53	0.58	0.45	0.47	2.86			
Xinjiang	2.15	2.13	2.18	2.38	2.38	11.22			

 Table S16. Vanadium emission pertinent to MSW landfilling.

Ta	ble	S1	7.	Vanadium	emission	pertinent	to	sludge dispos	al.
						1		0 1	

Process	V emission from sludge disposal process (t)					
	2015	2016	2017	2018	2019	Cumulative V
Wastewater sludge	322.82	301.02	284.14	266.98	249.96	1424.92

 Table S18. Vanadium emission pertinent to wastewater discharge.

Process	yearly amount of wastewater discharge (kg)					
	2015	2016	2017	2018	2019	Cumulative V
wastewater discharge	16.05	17.13	17.67	18.24	18.87	87.96

Categories	Input parameters	Probability distribution	Range of uncertainties	
	raw coal consumption	Normal	(-2%, 2%)	
	coke consumption	Normal	(-3%, 3%)	
	V content in consumed coal	Lognormal	(-21%, 21%)	
	V content in consumed coke	Lognormal	(-20%, 19%)	
	V fraction in released gas	Normal	(00/00/)	
	(pulverized coal boiler)	INOFILIAL	(-9%, 9%)	
	V fraction in released gas	Normal	(560/ 560/)	
	(chain grate boiler)	INOFILIAL	(-30%, 30%)	
	V fraction in released gas	Na mu al	(40(- 40()	
	(fluidized bed combustion)	INOFINAI	(-4%, 4%)	
Coal	V fraction in released gas	t I: £	(1050/ 1080/)	
combustion	(coking oven)	Uniform	(-105%, 108%)	
	Application rate	Trionaular	(90/ 90/)	
	(Electrostatic dust collector)	Thangular	(-8%, 8%)	
	Application rate	Normal	(-6%, 6%)	
	(bag filter)	INOFILIAL		
	Application rate	Liniform	(100/ 100/)	
	(cyclone remover)	Uniform	(-10%, 10%)	
	Application rate	Na mu al		
	(wet method filter)	INOFINAI	(-1%, 1%)	
	Application rate	Normal		
	(desulfurizer)	INOFINAI	(-9%, 9%)	
	Crude oil consumption	Normal	(-5%, 5%)	
	Emission factor (crude oil)	Normal	(-1%, 3%)	
	Gasoline consumption	Normal	(-4%, 4%)	
0:11	Emission factor (gasoline)	Triangular	(-2%, 2%)	
Oil burning	Kerosene consumption	Normal	(-9%, 10%)	
(stationary	Emission factor (kerosene)	Normal	(-3%, 2%)	
source)	Diesel consumption	Normal	(-1%, 1%)	
	Emission factor (diesel)	Triangular	(-1%, 1%)	
	Fuel oil consumption	Normal	(-14%, 15%)	
	Emission factor (fuel oil)	Triangular	(-1%, 1%)	
	Gasoline consumption	Normal	(-5%, 5%)	
	Emission factor (gasoline)	Triangular	(-2%, 2%)	
Oil burning	Diesel consumption	Normal	(-3%, 4%)	
(transportation)	Emission factor (diesel)	Triangular	(-1%, 1%)	
	Fuel oil consumption	Normal	(-10%, 10%)	
	Emission factor (fuel oil)	Triangular	(-1%, 1%)	
	Steel production volume	Normal	(-7%, 7%)	

 Table S19. Uncertainties of the model input data.

Categories	Input parameters	Probability distribution	Range of uncertainties	
	Emission factor (steel	Normal	(40/ 40/)	
	production)	Normai	(-4%, 4%)	
	Glass production volume	Normal	(-7%, 7%)	
	Emission factor (glass	Normal	(50/ 40/)	
Industrial	production)	Normai	(-5%, 4%)	
process	Coal mining	Normal	(-3%, 3%)	
	Emission factor (coal mining)	Normal	(-5%, 5%)	
	Oil extraction	Normal	(-3%, 3%)	
	Emission factor (oil extraction)	Normal	(-1%, 1%)	
	Vanadium extraction	Normal	(-13%,12%)	
	Emission factor (vanadium	NI	(-10%, 9%)	
	extraction)	INOFINAI		
	Solid waste volume	Normal	(-15%, 15%)	
	Emission factor (solid waste)	Normal	(-20%, 20%)	
	MSW incineration volume	Normal	(-12%, 12%)	
	Emission factor (MSW	Normal	(00/ - 20/)	
	incineration)	Normai	(-2%, 3%)	
Waste disposal	MSW landfilling volume	Normal	(-2%, 2%)	
	Emission factor (landfilling)	Normal	(-3%, 3%)	
	Sludge generation volume	Normal	(-8%, 8%)	
	Emission factor (sludge)	Normal	(-2%, 2%)	
	Wastewater generation volume	Normal	(-5%, 4%)	
	Emission factor (wastewater)	Normal	(-2%, 2%)	

V emission source	Average	Median	Max	Min	Uncertainty range
Raw coal	32381.75	31981.56	8959.45	67745.41	(-24.34%, 24.96%)
Coke	3367	3330.99	573.03	6950.18	(-27.55%, 25.57%)
Crude oil	6218.44	6216.62	5516.51	6960.83	(6.47%, 6.39%)
Gasoline	1899.69	1899.26	1740.71	2069.03	(-4.79%, 4.79%)
Diesel	2416.18	2416.01	2007.62	2845.59	(-9.54%, 9.33%)
Kerosene	2325.48	2325.37	2253.16	2403.72	(-1.74%, 1.74%)
Fuel oil	4343.95	4343.65	3120.95	5631.6	(-5.93%, -5.52%)
Gasoline (mobile)	9.82	9.82	6.18	13.66	(-24.08%, 23.47%)
Diesel (mobile)	1313.89	1313.58	1141.55	1495.77	(-23.34%, 23.90%)
Fuel oil (mobile)	78.5	78.48	67.38	90.23	(-28.04%, 29.05%)
Steelmaking	37.24	37.24	34.53	39.92	(-3.92%, 3.87%)
Glass production	279	278.99	213.83	343.34	(-12.59%, 12.37%)
Coal mining	81.2	81.2	77	85.35	(-2.80%, -2.75%)
Oil extraction	39.46	39.46	32.38	46.45	(-9.68%, 9.50%)
Vanadium mining	29.1	29.1	26.99	31.19	(-3.92%, 3.85%)
Solid waste disposal	804.48	804.04	696.32	928.15	(-7.65%, 7.81%)
MSW incineration	1517.89	1517.35	1341.56	1727.03	(-6.68%, 6.77%)
MSW landfilling	1203.28	1203.14	962.72	1453.08	(-21.09%, 20.54%)
Wastewater sludge	284.31	284.3	240.28	327.77	(-45.3%, 44.02%)
Wastewater	0.0176	0.0175	0.0159	0.0192	(-5.50%, 4.43%)

 Table S20. Uncertainties of the vanadium emission for source subgroups.

Figure S1-S3



Figure S1. Decision tree for developing the emission inventory.



Figure S2. Cumulative vanadium emission pertinent to major categories and contribution fraction by subgroups under each category.



Figure S3. Province-resolute spatial variation in cumulative vanadium emission during2015-2019 for (a) all source categories, (b) coal combustion, (c) stationary oil burning,(d) industrial process, and (e) waste disposal.

Reference

Bhatnagar, A., Minocha, A., Pudasainee, D., Chung, H.: Vanadium removal from water by waste metal sludge and cement immobilization, Chem. Eng. J. 144, 197-204, 2008

Bai, X., Luo, L., Tian, H., Liu, S., Hao, Y., Zhao, S., Lin, S., Zhu, C., Guo, Z., Lv, Y.: Atmospheric Vanadium Emission Inventory from Both Anthropogenic and Natural Sources in China, Environ. Sci. & technol., 55, 11568-11578, 2021

Bhuiyan, B., Parvez, L., Islam, M., Dampare, S., Suzuki, S.: Heavy metal pollution of coal mine-affected agricultural soils in the northern part of Bangladesh. J. Hazard. Mat. 173, 384-392, 2010.

Blokhina, T., Karpenko, O.: Heavy metals pollution of a solid waste landfill, E3S Web of Conferences 116, 00010, 2019.

Bulletin on the second national general survey of pollution sources (in Chinese, fiscal year: 2017) [data set], National Bureau of Statistics of China, and Ministry of Agriculture and Rural Affairs of the People's Republic of China, www.gov.cn/xinwen/2020-06/10/content_5518391.htm.2020, 2020.

China Electricity Council (CEC), China Power Industry Annual Development Report in 2015-2019. https://www.cec.org.cn/. 2024.

Chen, Y., Liu, G., Gong, Y., Yang, J., Qi, C., Gao, L.: Release and enrichment of 44 elements during coal pyrolysis of Yima coal, China. J. Analyt. Appl. Pyrol., 80, 283-288, 2007.

Ding, J., Zhang, Y., Li, L., Ye, H., Li, H., Fu, X.: The characteristics and potential of vanadium resources in China, Geology in China, DOI:10.12029/gc20230526003, 2022.

Hao, L., Zhang, B., Feng, C., Zhang, Z., Lei, Z., Shimizu, K.: Human health risk of vanadium in farmland soils near various vanadium ore mining areas and bioremediation assessment, Chemosphere, 263, 128246, 2021.

Helble, J., Mojtahedi, W., Lyyränen, J., Jokiniemi, J., Kauppinen, E.: Trace element partitioning during coal gasification, Fuel, 75, 931-939, 1996.

Liu, F., Zhang, Q., Tong, D., Zheng, B., Li, M., Huo, H., and He, K. B.: High-resolution inventory of technologies, activities, and emissions of coal-fired power plants in China from 1990 to 2010, Atmos. Chem. Phys., 15, 13299–13317, https://doi.org/10.5194/acp-15-13299-2015, 2015.

Hope, B. K. A dynamic model for the global cycling of anthropogenic vanadium, Global Biogeochem. Cycles, 22, 1–16.(15), 2008.

Konieczyński, J., Zajusz-Zubek, E., Jabłońska, M.: The Release of Trace Elements in the Process of Coal Coking. Sci. World J., 294927, 2012.

Kuenen, J., van der Most, P., Rentz, O., Nunge, S., Trozzi, C., Pulles, T., Appelman, W.: EMEP/EEA air pollutant emission inventory guidebook 2016, European Environment Agency, 2016.

Lashari, A., Kazi, T., Afridi, H., Baig, J., Arain, M., Lashari, A., Kandhro, F.: Impact of oil well drilling activities on vanadium in soil, ground water, vegetables, fruits, and feed crops: a risk assessment, Int. J. Environ. Sci. Technol., 20, 11963-11972, 2023.

Lee, S., Wu, C.: Study of vanadium emission control in combustion systems by thermodynamic equilibrium analyses, Adv. Environ. Res., 7, 1-10, 2002.

Lin, K., Huang, W., Finkelman, R., Chen, J., Yi, S., Cui, X., Wang, Z.: Distribution, modes of occurrence, and main factors influencing lead enrichment in Chinese coals, Int. J. Coal Sci. & Technol. 7, 1-18, 2020. Liu, Z., Ottinger, N., Cremeens, C.: Vanadium and tungsten release from V-based selective catalytic reduction diesel aftertreatment, Atmos. Environ., 104, 154-161, 2015.

Lundkvist, K., Brämming, M., Larsson, M., Samuelsson, C.: System analysis of slag utilisation from vanadium recovery in an integrated steel plant, J. Clean. Prod., 47, 43-51, 2013.

Moreno, T., Querol, X., Alastuey, A., De la Rosa, J., Sánchez, AM, Minguillón, M., Pandolfi, M., González-Castanedo, Y., Monfort, E., Gibbons, W.: Variations in vanadium, nickel and lanthanoid element concentrations in urban air, Sci. Total Environ., 408(20):4569-4579, 2010.

Mukherjee, T., Gupta, C.: Extraction of Vanadium from an Industrial Waste., High Temperature Materials and Processes, 11, 1-4, 1993.

National Bureau of Statistics of China: China Steel Industry Statistical Yearbook 1985-2022 [Data set], https://www.shujuku.org/china-steel-industry-yearbook.html, 2023a.

National Bureau of Statistics of China: China Automobile Industry Yearbook 1986-2022 [Data set], https://www.shujuku.org/china-automobile-industry-yearbook.html, 2023b.

National Bureau of Statistics of China: China Urban Rural Construction Statistical Yearbook 2006-2022 [Data set], https://www.shujuku.org/china-urban-rural-construction-statistical-yearbook.html, 2023c. National Bureau of Statistics of China: China Coal Industry Statistical Yearbook 1949-2021 [Data set], https://www.shujuku.org/china-coal-industry-yearbook.html, 2024a.

National Bureau of Statistics of China: China Energy Statistical Yearbook 1986-2023 [Data set], https://www.shujuku.org/china-energy-statistical-yearbook.html, 2024b.

National Bureau of Statistics of China: China Light Industry Statistical Yearbook 1989-2022 [Data set], https://www.shujuku.org/china-light-industry-yearbook.html, 2024c.

National Bureau of Statistics of China: China Mining Sector Statistical Yearbook 2002-2019 [Data set], https://www.shujuku.org/mining-yearbook.html, 2024d.

Nriagu, J., Pacyna, J.: Quantitative assessment of worldwide contamination of air, water and soils by trace metals, Nature 333, 134-139, 1988.

Pacyna, J. M.; Pacyna, E. G.: An assessment of global and regional emissions of trace metals to the atmosphere from anthropogenic sources worldwide, Environ. Rev. 9, 269–298, 2001.

Pacyna, E., Pacyna, J., Fudala, J., Strzelecka-Jastrzab, E., Hlawiczka, S., Panasiuk, D., Nitter, S., Pregger,

T., Pfeiffer, H., Friedrich, R.: Current and future emissions of selected heavy metals to the atmosphere from anthropogenic sources in Europe, Atmos. Environ., 41, 8557-8566, 2007.

Pasko, O., Mochalova, T.: Toxicity Assessment of Contaminated Soils of Solid Domestic Waste Landfill, IOP Conf. Ser.: Earth Environ. Sci., 21 012044, 2014.

Schlesinger, W. H.; Klein, E. M.; Vengosh, A.: Global biogeochemical cycle of vanadium, Proc. Natl. Acad. Sci. U. S. A., 114, 11092–11100, 2017.

Spada, N., Cheng, X., White, W., Hyslop, N.: Decreasing Vanadium Footprint of Bunker Fuel Emissions, Environ. Sci. Technol. 52, 11528-11534, 2018.

Tian, H.Z., Wang, Y., Xue, Z.G., Cheng, K., Qu, Y.P., Chai, F.H., Hao, J.M.: Trend and characteristics of atmospheric emissions of Hg, As, and Se from coal combustion in China, 1980e2007, Atmos. Chem. and Phy, 10, 11905e11919, 2010.

Tian, H., Cheng, K., Wang, Y., Zhao, D., Long, L., Jia, W., Hao, J.: Temporal and spatial variation characteristics of atmospheric emissions of Cd, Cr, and Pb from coal in China, Atmos. Environ., 50, 157-163., 2012.

Tian, H., Zhu, C., Gao, J., Cheng, K., Hao, J., Wang, K., Hua, S., Wang, Y., Zhou, J.: Quantitative assessment of atmospheric emissions of toxic heavy metals from anthropogenic sources in China:

historical trend, spatial variation distribution, uncertainties and control policies, Atmos. Chem. Phys. Discuss., 15, 12107-12166, 2015.

Topal, M., Topal, E.: Investigation of Critical Raw Materials in Sludge of Municipal Wastewater Treatment Plant, Arabian J. for Sci. and Eng., 48, 107-115, 2023.

Visschedijk, A., Denier van der Gon, H., Hulskotte, J., Quass, U.: Anthropogenic Vanadium emissions to air and ambient air concentrations in North-West Europe, E3S Web of Conferences 1, 23 April 2013, 03004., 2013.

Wang, M., Cai, L., Wen, J., Li, W., Yang, X., and Yang, H.: The Prospect of Recovering Vanadium, Nickel, and Molybdenum from Stone Coal by Using Combined Beneficiation and Metallurgy Technology Based on Mineralogy Features, Minerals, 13, 21, https://doi.org/10.3390/min13010021, 2022.

Wu, B., Tian, H., Hao, Y., Liu, S., Sun, Y., Bai, X., Liu, W., Lin, S., Zhu, C., Hao, J., Luo, L., Zhao, S., and Guo, Z.: Refined assessment of size-fractioned particulate matter (PM2.5/PM10/PMtotal) emissions from coal-fired power plants in China, Science of The Total Environment, 706, 135735, https://doi.org/10.1016/j.scitotenv.2019.135735, 2020.

Yuan L. Vanadium in Coal Mining Area: Distribution, Modes of Occurrence, and Environmental Behavior. University of Science and Technology of China; Heifei, China: 2018.

Zhang, H.: Dataset for Emission Inventory Development for Spatiotemporal Release of Vanadium from Anthropogenic Sources in China [Data set]. Zenodo, https://doi.org/zenodo.14467726, 2024.