Supplement of

Emission Inventory Development for Spatiotemporal Release of Vanadium from Anthropogenic Sources in China

Han Zhang et al.

Correspondence to: Baogang Zhang (baogangzhang@cugb.edu.cn) & Yi Xing (xingyi@ustb.edu.cn)

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), uploaded in the public repository (Zhang, 2023).

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

The anthropogenic vanadium emission induced by coal consumption can be attained thorough the following method (Bai et al., 2021):

$$E(t) = \sum i \sum j[Aij\,(\mathrm{t}) \times Cij(\mathrm{t}) \times Ri \times (1 - \varphi i)] \qquad \text{(S1-1)}$$

Where E(t) was the total amount of vanadium emission due to coal consumption at year t; A represented the yearly consumption 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 fraction of released gas from combustion process; φ was the removal efficiency of flue gas vanadium in the treatment system. Supplementary spreadsheet SS-A1 provided the vanadium content in raw coal produced in each province. SS-A2 provided the vanadium fraction of flue gas from four classic coal combustion boilers. SS-A3 provided the vanadium removal efficiency of typical flue gas treatment system.

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). V content was assumed to be consistent throughout 2015-2019, SS-A4 provided the weighted average vanadium in raw coal consumed at provincial level. SS-A5 provided the yearly consumed volume of raw coal at provincial level. The above datasets were utilized to calculate the vanadium emission inventory for raw coal and present them in **Table S1**.

S1.2 Coke

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

$$C_j = [C_y M_y \times (1 - F)]/M_j \qquad \text{(S1-2)}$$

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 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 provincial level; F was the vanadium fraction in released gas from coke production (Helble et al., 1996; Chen et al., 2007; Konieczyński et al., 2012; Lin et al., 2020). SS-A6 provided the coke consumption at provincial level during 2015-2019. SS-A7 provided the average vanadium content in consumed coke at provincial level, which was obtained by applying formula 1-1 and 1-2. **Table S2** displayed the calculated result for vanadium emission inventory pertinent to coke consumption.

S2. Vanadium emission inventory for stationary oil combustion

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

$$E(t) = \sum i \sum j [A_{ij}(t) \times EF_{ij}(t)] \qquad \text{(S2-1)}$$

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:

$$EF_P(t) = (EFa_p - EFb_p)\, e^{-(t-t0)2/2Sp2} + EFb_p \qquad \text{(S2-2)}$$

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.

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.

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.

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.

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.

S2.5 Fuel oil

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

S3. Vanadium emission inventory for industrial processes

Vanadium heavily involved in wide ranges of industrial processes such as steelmaking, glass production, mining activities, which discharge vanadium bearing waste into the environment. The temporal dynamic emission factors for industrial processes (steelmaking and glass production) obtained from transformed normal distribution function (2-2) were summarized in SS-B1. 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. The calculated results of vanadium emission inventories were obtained by applying formula 2-1 and displayed in **Table S8 - S12**.

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**.

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**.

S3.3 Coal mining

Vanadium was mobilized and released during coal mining process (Schlesinger et al., 2017). Soil was the main receptor of mining induced vanadium contamination as result of surface runoff, soil leaching and seepage and dust deposition (Bhuiyan et al., 2010). The vanadium emission inventory was developed by firstly estimating the coal production activities at provincial level published in China Coal Sector Statistic Yearbook (2015-2019). 20 g/t was adopted as the estimated average vanadium content in the extracted coal, while 0.51% was used as fraction of coal subjecting to direct emission according to Pollution Source Survey (Beijing: Ministry of Ecology and Environment, 2017). The provincial data for above parameters was lacking. The activity level at provincial level was provided in SS-C3. The vanadium emission amount was estimated and provided in **Table S10**.

S3.4 Oil extraction

Oil exploration activities acted as another route for vanadium mobilization from earth crust, leading to soil pollution (Lashari et al., 2023). The average vanadium content was estimated based on procedures introduced in previous study for heavy crude oil. As a result, 28.9 mg/kg was adopted in our study (Pacyna et al., 2001). The release fraction was determined based on Pollution Source Survey for oil extraction (Beijing: Ministry of Ecology and Environment, 2017). The activity level of crude oil production was provided in SS-C5. **Table S11** provided the calculated vanadium emission for petroleum production.

S3.5 Vanadium mining

The impact of vanadium mining was highlighted in this study due to the increasing demand in vanadium throughout various industrial sectors, which caused significant level of soil pollution (Hao et al., 2021). The vanadium ore grades (vanadium fraction) were obtained from provinces with major vanadium deposition. For the other province, default value 0.15% was employed (ore grade < 0.1% was not eligible for mining). The summarized ore grades were displayed in SS-C6. Default value 0.51 % was adopted as fraction of vanadium ore subjected to direct release according to Pollution Source Survey (Beijing: Ministry of Ecology and Environment, 2017). The activity level of vanadium mining was provided in SS-C7. **Table S12** presented the vanadium emission for vanadium mining.

S4. Vanadium emission inventory for transportation

Vanadium emission could also be attributed to transportation sources, mainly including road vehicles and sea vessels, which discharges vanadium bearing particulate into the atmospheric environment (Spada et al., 2018; Bai et al., 2021). Vanadium based catalysts were also employed extensively to selectively reduce the nitrogen oxides from engine worldwide, leading to vanadium release into atmosphere (Liu et al., 2015). According to Yearbook of Transportation and Automobile Industry (National Bureau of Statistics of China, 2020), the dramatic increase in numbers of car purchase, logistic flow, and operating highway have led to increased consumption in different types of oil, which were the mobile source for vanadium emission. The activity levels of oil consumption by transportation (gasoline, diesel, fuel oil) were summarized yearly in SS-D1. Here, we applied the universal values to reflect the activity level due to lack of data collection from each province. We also made assumption that gasoline, diesel oil and fuel oil was consumed in patterns similar to that in stationary source through combustion, therefore, same emission factors were applied for calculating the vanadium emission inventory for mobile source. All corresponded vanadium emission was calculated and displayed in **Table S13**.

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., 2017). Moreover, vanadium was also detected in surface water due to municipal wastewater discharge (Topal and Topal, 2023). The following section offered the calculation procedures for developing vanadium emission inventory pertinent to waste disposal.

S5.1 Industrial solid waste

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

S5.2 MSW incineration

SS-E2 provided the dynamic vanadium emission factors applying the transformed normal distribution function of vanadium emission. SS-E3 provided the yearly volume of incinerated wastes throughout 2015-2019; **Table S15** displayed the calculated total amount of vanadium emission at provincial level.

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. **Table S16** provided the total amount of vanadium discharged into environment from landfill at provincial level.

S5.4 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.

S5.5 Municipal wastewater

The default value 0.3 ng/L was obtained from literature (Nriagu and Pacyna, 1988). SS-E6 provided the provincial level wastewater discharge during 2015-2019. Based on the result, **Table S18** provided the total amount of vanadium discharge into the water environment during 2015-2019.

Table S1. Vanadium emission pertinent to raw coal combustion.

Province	V emission from raw coal consumption (t)					
	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 Mongolia	1044.2	1049.22	1104.16	1262.73	1402.84	5863.15
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 S2. Vanadium emission pertinent to coke combustion.

Province	V emission from coke consumption (t)					
	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 S3. Vanadium emission pertinent to crude oil consumption.

Province	V emission from crude oil consumption (t)					
	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 S4. Vanadium emission pertinent to gasoline consumption.

Province	V emission from gasoline consumption (t)					
	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 S5. Vanadium emission pertinent to diesel consumption.

Province	V emission from diesel consumption (t)					
	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 S6. Vanadium emission pertinent to kerosene consumption.

Province	V emission from kerosene consumption (t)					
	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 S7. Vanadium emission pertinent to fuel oil consumption.

Province	V emission from fuel oil consumption (t)					
	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 S8. Vanadium emission for steelmaking process.

Province	V emission from steel making process (t)					
	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 S9. Vanadium emission pertinent to glass production.

Province	V emission from glass production (t)					
	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 S10. Vanadium emission pertinent to coal mining.

Province	V emission from coal mining (t)					
	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 S11. Vanadium emission pertinent to oil extraction.

Province	V emission from oil extraction (t)					
	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 S12. Vanadium emission pertinent to vanadium mining.

Province	Yearly activity level of vanadium mining (t)					
	2015	2016	2017	2018	2019	Cumulative
Beijing	0	0	0	0	0	0
Tianjin	0	0	0	0	0	0
Hebei	4.34	6	5.17	5.59	5.38	26.48
Shanxi	0	0	0	0	0	0
Inner 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 S13. Vanadium emission pertinent to transportation.

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 S14. Vanadium emission pertinent to industrial solid waste disposal.

Province	V emission from industrial solid waste disposal (t)					
	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 S15. Vanadium emission pertinent to MSW incineration.

Province	V emission from MSW incineration (t)					
	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 S16. Vanadium emission pertinent to MSW landfilling.

Province	V emission from MSW landfilling (t)					
	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 S17. Vanadium emission pertinent to sludge disposal.

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

Table S19. Uncertainties of the model input data.

Categories	Input parameters	Probability distribution	Range of uncertainties
Coal combustion	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 (pulverized coal boiler)	Normal	(-9%, 9%)
	V fraction in released gas (chain grate boiler)	Normal	(-56%, 56%)
	V fraction in released gas (fluidized bed combustion)	Normal	(-4%, 4%)
	V fraction in released gas (coking oven)	Uniform	(-105%, 108%)
	Removal efficiency (Electrostatic dust collector)	Triangular	(-12%, 13%)
	Removal efficiency (bag filter)	Uniform	(-33%, 32%)
	Removal efficiency (cyclone remover)	Normal	(-15%, 14%)
	Removal efficiency (wet method filter)	Triangular	(-20%, 20%)
	Removal efficiency (desulfurizer)	Normal	(-37%，38%)
Oil burning (stationary source)	Crude oil consumption	Normal	(-5%, 5%)
	Emission factor (crude oil)	Normal	(-1%, 3%)
	Gasoline consumption	Normal	(-4%, 4%)
	Emission factor (gasoline)	Triangular	(-2%, 2%)
	Kerosene consumption	Normal	(-9%, 10%)
	Emission factor (kerosene)	Normal	(-3%, 2%)
	Diesel consumption	Normal	(-1%, 1%)
	Emission factor (diesel)	Triangular	(-1%, 1%)
	Fuel oil consumption	Normal	(-14%, 15%)
	Emission factor (fuel oil)	Triangular	(-1%, 1%)
Oil burning (transportation)	Gasoline consumption	Normal	(-5%, 5%)
	Emission factor (gasoline)	Triangular	(-2%, 2%)
	Diesel consumption	Normal	(-3%, 4%)
	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%)

Categories	Input parameters	Probability distribution	Range of uncertainties
Industrial process	Emission factor (steel production)	Normal	(-4%, 4%)
	Glass production volume	Normal	(-7%, 7%)
	Emission factor (glass production)	Normal	(-5%, 4%)
	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 extraction)	Normal	(-10%, 9%)
Waste disposal	Solid waste volume	Normal	(-15%, 15%)
	Emission factor (solid waste)	Normal	(-20%, 20%)
	MSW incineration volume	Normal	(-12%, 12%)
	Emission factor (MSW incineration)	Normal	(-2%, 3%)
	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%)

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

V emission source	Average	Standard deviation	Median	Max	Min	2.50%	97.50%	Uncertainty range
Raw coal	32381.75	87322.22	31981.56	8959.45	67745.41	16986.05	49762.68	(-47.54%, 53.68%)
Coke	3367	895.62	3330.99	573.03	6950.18	1769.41	5160.73	(-47.45%, 53.27%)
Crude oil	6218.44	202.44	6216.62	5516.51	6960.83	5816.29	6616.03	(6.47%, 6.39%)
Gasoline	1899.69	46.1	1899.26	1740.71	2069.03	1808.74	1990.62	(-4.79%, 4.79%)
Diesel	2416.18	116.02	2416.01	2007.62	2845.59	2185.59	2641.49	(-9.54%, 9.33%)
Kerosene	2325.48	20.62	2325.37	2253.16	2403.72	2285.12	2365.98	(-1.74%, 1.74%)
Fuel oil	4343.95	347.46	4343.65	3120.95	5631.6	3652.13	5018.09	(-15.93%, -15.52%)
Gasoline (mobile)	9.82	1.04	9.82	6.18	13.66	7.75	11.83	(-21.08%, 20.47%)
Diesel (mobile)	1313.89	48.99	1313.58	1141.55	1495.77	1216.19	1408.42	(-7.44, 7.19%)
Fuel oil (mobile)	78.5	3.16	78.48	67.38	90.23	72.19	84.6	(-8.04%, 7.77%)
Steelmaking	37.24	0.74	37.24	34.53	39.92	35.78	38.68	(-3.92%, 3.87%)
Glass production	279	17.63	278.99	213.83	343.34	243.86	313.51	(-12.59%, 12.37%)
Coal mining	81.2	1.14	81.2	77	85.35	78.93	83.43	(-2.80%, -2.75%)
Oil extraction	39.46	1.92	39.46	32.38	46.45	35.64	43.21	(-9.68%, 9.50%)
Vanadium mining	29.1	0.57	29.1	26.99	31.19	27.96	30.22	(-3.92%, 3.85%)
Solid waste disposal	804.48	31.7	804.04	696.32	928.15	742.97	867.34	(-7.65%, 7.81%)
MSW incineration	1517.89	52.21	1517.35	1341.56	1727.03	1416.42	1620.63	(-6.68%, 6.77%)
MSW landfilling	1203.28	68.5	1203.14	962.72	1453.08	1066.24	1338.54	(-11.39%, 11.24%)
Wastewater sludge	284.31	11.91	284.3	240.28	327.77	260.57	307.62	(-8.35%, 8.20%)
Wastewater discharge	0.0176	0.0004	0.0175	0.0159	0.0192	0.0167	0.0185	(-5.50%, 4.43%)

Figure S1-S3

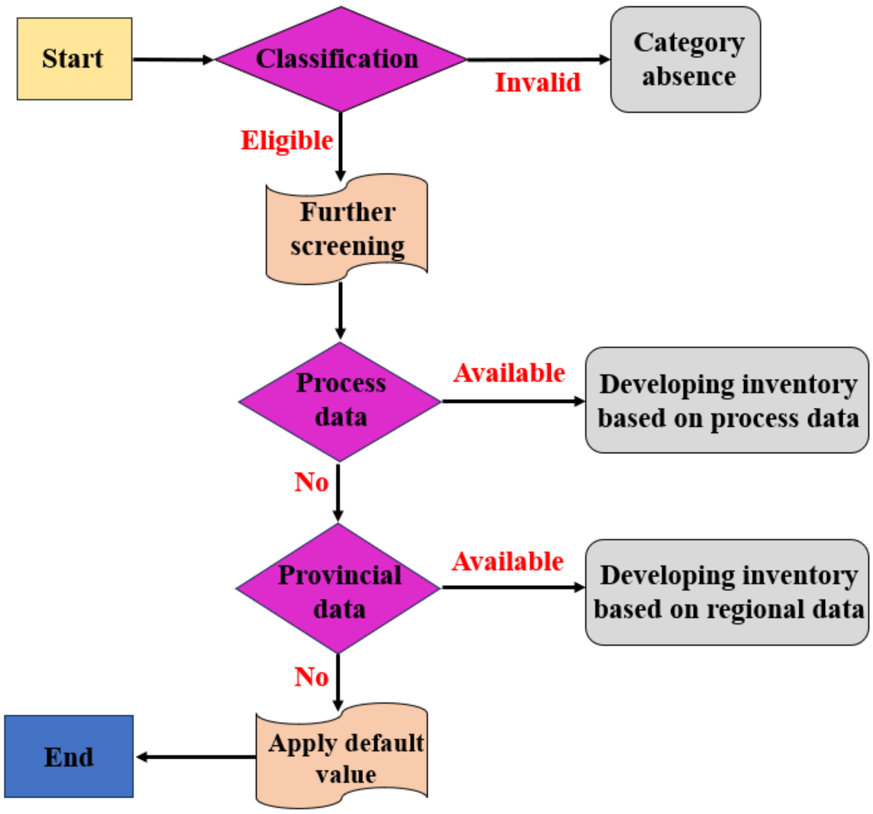

Figure S1. Decision tree for developing the emission inventory.

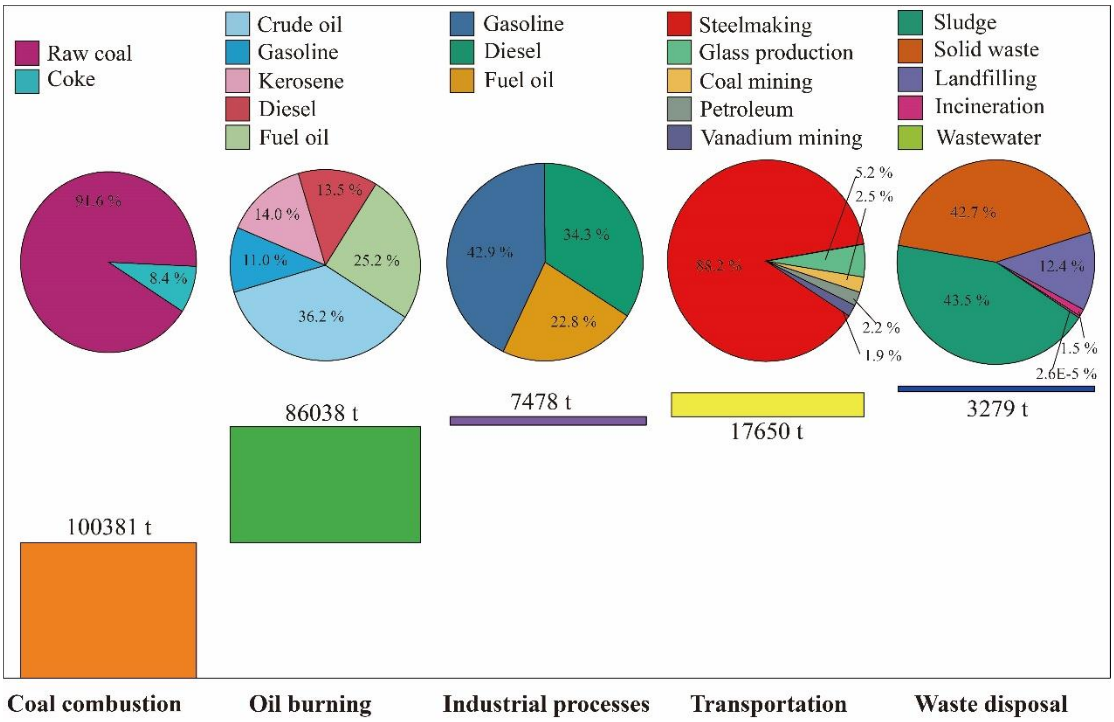

Figure S2. Cumulative vanadium emission pertinent to major categories and contribution fraction by subgroups under each category.

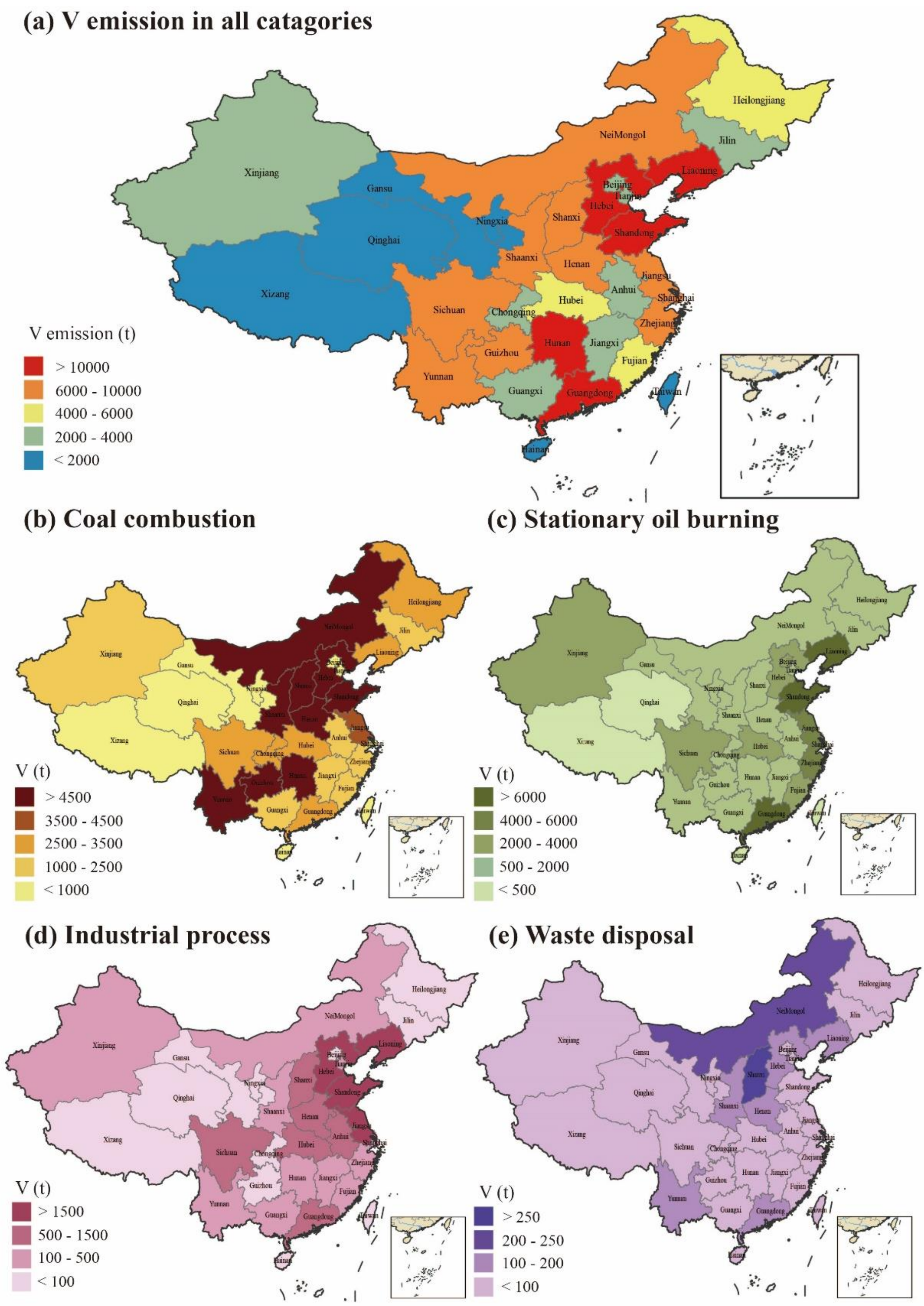

Figure S3. Province-resolute spatial variation in cumulative vanadium emission during 2015-2019 for (a) all source categories, (b) coal combustion, (c) stationary oil burning, (d) industrial process, and (e) waste disposal.

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