Supplement information for:

# Emission Characteristics, OFPs, and Mitigation Perspectives of VOCs from Refining Industry in China's Petrochemical Bases

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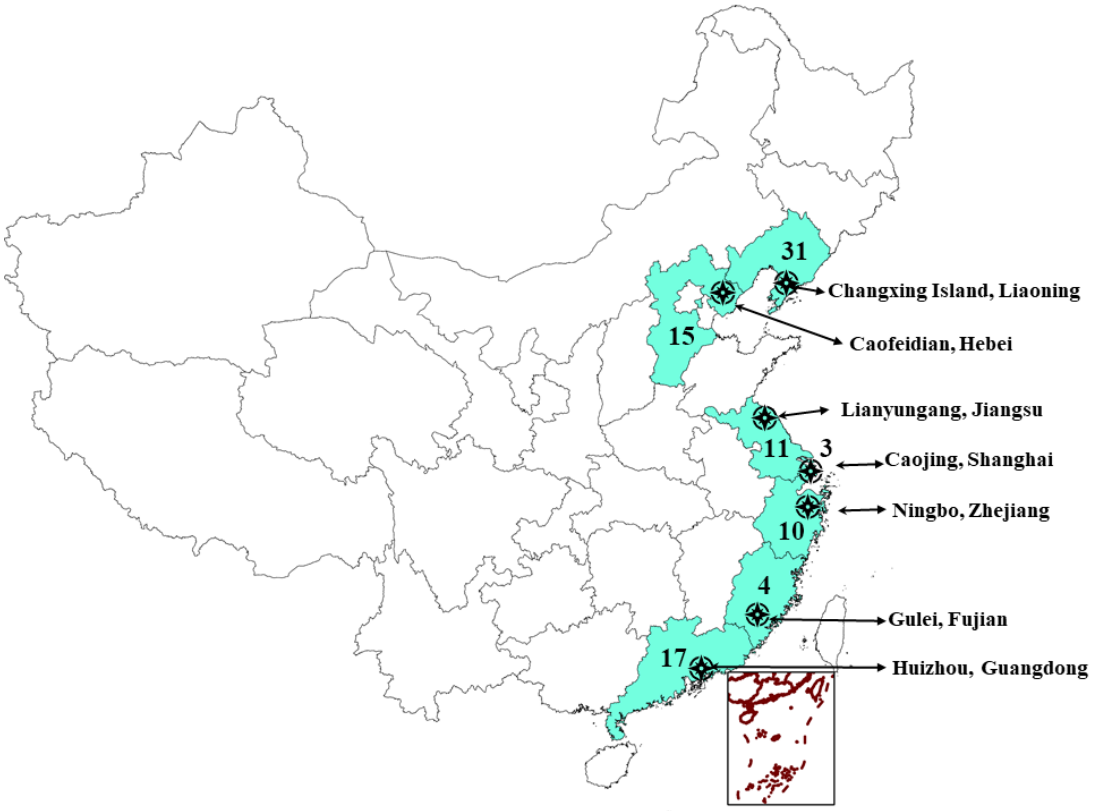


**Fig. S1.** the location of petrochemical bases in seven provinces of China and the total number of refineries (digits in the figure) in each province in 2019.

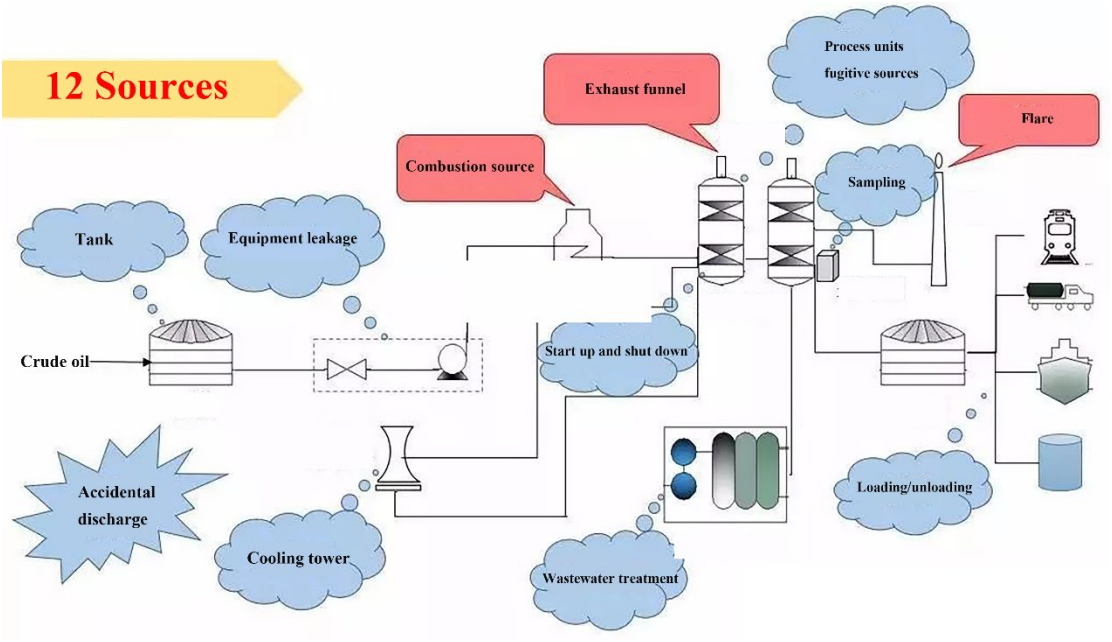


Fig. S1 VOCs emission sources in refinery industry

**Text S1**

**(1) Fugitive emission source**, including leakage from dynamic and static sealing points of equipment, emission from cooling tower and circulating water cooling system, emissions from start-up, shutdown and maintenance processes, fugitive emissions from the non-hermetic process under normal conditions, sampling pipeline emissions, emissions due to accidents; **(2) Tank emission Source**, including static breathing loss and working loss of fixed roof tanks and floating roof tanks, loading-unloading processes, and packaging processes; **(3) End-of-pipe emission source**, including the organized discharge of production process, flare system discharge, emissions from combustion processes of boilers, heating furnaces, internal combustion engines, and gas turbines; **(4) Wastewater treatment source**, including wastewater collection, storage, and treatment process. VOC emission from refining was calculated, analyzed, and discussed based on above mentioned four source categories.

**Table S1.** VOCs emission control technologies and their removal efficiency for the different sectors in refinery

| Sector | Control option | Efficiency (%) |
|---|---|---|
| Tanks | Internal floating covers and secondary seals | 85 |
| | Vapor recovery units - single/double stage systems | 95/99 |
| | Vapor balancing on tankers and loading facilities | 78 |
| Wastewater | Covers on oil/water separators | 90 |
| | Two-stage oil separation and two-stage flotation technology for oily wastewater treatment | 90 |
| Process Leakage | Quarterly, monthly inspection and maintenance programs | 60/70 |
| End-of-pipe | Flaring / Incineration | 98/99 |
| | absorption, adsorption, photocatalytic/thermocatalytic combustion | 90-97 |

**Text S2**

In order to investigate the changes in crude oil processing capacity in refineries and the penetration rate of VOCs control technologies, this study selected several refineries of Sinopec, PetroChina and local refineries in Shanghai, Yingkou city in Liaoning, Anqing city in Anhui, and Shijiazhuang city in Hebei for investigation and consultation.

For better explain the changes of refining capacity of refineries and provinces, the Anqing branch of Sinopec was selected to investigate due to there is only this one refinery in Anhui Province. The survey results show that the crude oil processing capacity of Anqing branch from 2004 to 2012 is in the ranged of 4.14 Tg to 4.20 Tg. After 2012, it has been approved by the state to expand its scale, and processing capacity during 2014-2018 was raged of 7.27 Tg to 7.48 Tg. Besides, the processing capacity of Shijiazhuang branch since 2013 was in the range of 6.55 Tg to 6.89 Tg. Thus, we can assume that the refining capacity of other existing refineries will be little change or not change, because the maximum refining capacity of a refinery is fixed and the refinery cannot change its refining capacity without the approval of the government in China, and above survey data support our hypothesis

For the application rate of the control technologies, this study selected a local refinery and one branch of PetroChina in Liaoning and one branch of SINOPEC in Shanghai, and conducted the inquiry on the application rate of control technologies.

According to the survey, the scale of local refineries is smaller, and the penetration rate of control measures is very low in local refineries. The state-owned refineries which belongs to Sinopec and PetroChina are larger in scale, and they use the same management system in all regions, so the penetration rate of control measures is higher than local refineries and almost the same in each region, especially in the key pollution regions, such as Pearl River Delta, Yangtze River Delta, and Beijing-Tianjin-Hebei region. In addition, there were no requirements to control of VOCs in refineries in China before 2017, and the "Petroleum Refining Industry Pollutant Emission Standards (GB31570—2015)" were implemented after 2017. Therefore, the penetration rate of control technologies in refineries was very low until 2018. In the other word, the refineries in key regions have applied the end-of-pipe control technologies, and most of refineries have not applied any control measures yet. The six provinces in this study are located in key regions or around the key regions, thus the highest penetration rate (50%) of end-of-pipe control technologies was assumed for this study.

**Text S3**

The most important factors affecting the penetration rate of control technology are the implementation of control policies and the installation and operation price of control technology. Thus, the implementation of different control technologies for different sources was assumed as described in the policy scenario in the manuscript. For example, the LDAR system is almost not used in refineries before 2018, and it requires large financial investment and human sources to operate the LDAR on a regular basis. Therefore, its penetration rate was assumed 20% and 30% for 2025 and 2030, respectively, in the BAU scenario, and it will be run by quarterly. In the AC and the HC scenarios, the penetration rate of LDAR will be higher than BAU and will be operated monthly. Due to most of the refineries already using end-of-pipe control technologies in those seven provinces, the penetration rate of technologies in end-of-pipe was much higher than other control technologies.

**Table S2** Sector-based key emission control measures and scenario analysis in this study

| Scenario | Measures | Policies | Assumptions |
|---|---|---|---|
| **Scenario 1: BAU** | Internal floating covers and secondary seals; Vapor recovery units - single/double stage systems; Vapor balancing on tankers and loading facilities. Covers on oil/water separators; Two-stage oil separation and two-stage flotation technology. Quarterly, monthly inspection and maintenance programs. Flaring / Incineration, absorption, adsorption, photocatalytic combustion | It will remain the tendency until the year 2030, which implements the general and special emission standards in the GB37822-2019 in 2025 and 2030. Wastewater liquid surface control general and special requirements in the GB37822-2019 will be implemented in 2025 and 2030, respectively. LDAR technology will be implemented quarterly in general equipment, valves, and connectors as in GB37822-2019. The general and special emission standards in the GB31570-2015 will be implemented for end-of-pipe in 2025 and 2030. | The ratio of fixed: External floating: Internal floating roof tanks in refineries will be 3:4:3; 30% of tanks will use secondary seals in 2030; penetration of vapor recovery and balancing will be 15% in 2025 and 30% in 2030. The penetration ratios of cover on oil/water separators will be 20% and 40%, and the penetration of two-stage oil separation and two-stage flotation technology will be 15% and 30%, respectively, in 2025 and 2030. Quarterly inspection will be assumed for 2025 and 2030; Leak thresholds will be 5000 and 2500 ppm for 2025 and 2030. The end-of-pipe control technology application rate will be estimated to be 60% and 80% for 2025 and 2030. |
| **Scenario 2: NPC** | Internal floating covers and secondary seals; Vapor recovery units - single/double stage systems; Vapor balancing on tankers and loading facilities. Covers on oil/water separators; Two-stage oil separation and two-stage flotation technology. Quarterly, monthly inspection and maintenance programs. Flaring / Incineration, absorption, adsorption, photocatalytic combustion | The special emission standards for tanks in the GB37822-2019 will be implemented since 2025. Wastewater liquid surface control special. requirements in the GB37822-2019 will be implemented since 2025. LDAR technology will be implemented quarterly and monthly in general equipment, valves, and connectors as in GB37822-2019. The special emission standards in the GB31570-2015 will be implemented for end-of-pipe since 2025 | The ratio of different roof tank will be changed to 2:4:4; 30% and 60% of tanks will use secondary seals in 2025 and 2030; penetration of vapor recovery and balancing will be 30% in 2025 and 60% in 2030. The penetration ratios of cover on oil/water separators will be 40% and 60%, the penetration of two-stage oil separation and two-stage flotation technology will be 30% and 50%, respectively, in 2025 and 2030. Quarterly and monthly LDAR will be assumed for both 2025 and 2030; Leak threshold will be 2500 and 1500 ppm for 2025 and 2030, respectively. The end-of-pipe control technology application rate will be estimated to be 80% and 90% for 2025 and 2030. |

| Scenario | Measures | Policies | Assumptions |
|---|---|---|---|
| **Scenario 3：HC** | Internal floating covers and secondary seals; Vapor recovery units - single/double stage systems; Vapor balancing on tankers and loading facilities. Covers on oil/water separators; Two-stage oil separation and two-stage flotation technology. Quarterly, monthly inspection and maintenance programs. Flaring / Incineration, absorption, adsorption, photocatalytic combustion. | The special emission standards for tanks in the GB37822-2019 will be implemented since 2020. Wastewater liquid surface control special requirements in the GB37822-2019 will be implemented since 2020. LDAR technology will be implemented monthly in general equipment, valves, and connectors as in GB37822-2019. The special emission standards in the GB31570-2015 will be implemented for end-of-pipe since 2020 | The ratio of different roof tanks will be changed to 1:5:4; penetration of vapor recovery and balancing, and the secondary seals will be 60% in 2025 and 80% in 2030. And the application rate of double-stage vapor recovery units will be more than 50% in 2030. The penetration ratios of cover on oil/water separators will be 80% and 90%, and the penetration of two-stage oil separation and two-stage flotation technology will be 60% and 80%, respectively, in 2025 and 2030. monthly LDAR will be assumed since 2020; the Leak threshold will be 1500 and 1000 ppm for 2025 and 2030. The end-of-pipe control technology application rate will be estimated to be 90% and 100% for 2025 and 2030. |

Taking into consideration technological development, policy implications, and advanced management, the penetration of technology will gradually increase. The assumptions of the penetration rate of different control technologies for different periods and scenarios were described in Text S3.