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Impacts of the COVID-19 event on the NOx emissions of key polluting enterprises in China

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HIGHLIGHTS
- Real-time observations were used to analyze impact of COVID-19 on NOx emission.
- The impact in China is mainly concentrated in four industrial sectors.
- Operating vent numbers and emission concentration are effective indicators.
- COVID-19 significantly reduced the industrial NOx emissions of China.

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ABSTRACT
The unprecedented cessation of human activities during the COVID-19 pandemic has affected China’s industrial production and NOx emissions. Quantifying the changes in NOx emissions resulting from COVID-19 and associated governmental control measures is crucial to understanding its impacts on the environment. Here, we divided the research timeframe into three periods: the normal operation period (P1), the Spring Festival period (P2), and the epidemic period following the Spring Festival (P3). We then calculated the NOx operating vent numbers and emission concentrations of key polluting enterprises in 29 provinces and 20 industrial sectors and compared the data for the same periods in 2020 and 2019 to obtain the impacts of COVID-19 on industrial NOx emissions. We found that spatially, from P1 to P2 in 2020, the operating NOx vent numbers in North China changed the most, with a relative change rate of \(-33.84\%\). Comparing the operating vent numbers in P1 and P3, East China experienced the largest decrease, approximately \(-32.72\%\). Among all industrial sectors, the mining industry, manufacturing industry, power, heat, gas, and water production and supply industry, and the wholesale and retail industry, were the most heavily influenced. In general, the operating vent numbers of key polluting enterprises in China decreased by 24.68\%, and the standardized NOx ($w_{5-day}$) decreased by an average of \(-9.54 \pm 6.00\) due to the COVID-19 pandemic. The results suggest that COVID-19 significantly reduced the NOx emission levels of the key polluting enterprises in China.

1. Introduction

Coronavirus disease 2019 (COVID-19), which started at the end of 2019, has continued to spread and has not shown any obvious tipping point globally. On August 16, 2020, there were over 8.96 million confirmed COVID-19 cases and over 760,000 deaths \cite{1}. As the first country fighting COVID-19, the Chinese government launched the first level of measures in Wuhan and in other cities in Hubei Province in response to the major public health emergency on January 23rd and 24th, 2020, respectively, followed by other provinces \cite{2}. The government enacted measures including social distancing, stay-at-home orders, the closure of non-essential businesses, and regional lockdowns during the epidemic period \cite{3}. The significant reduction in human activities caused the slowing or even stagnation of industrial production, which
invariably led to a reduction in energy consumption [4], carbon emissions [5], and industrial pollution [6]. By using environmental monitoring data, the impacts of the COVID-19 epidemic on China’s economy [7], human mobility [8], income inequality [9], and secondary health risks [10] can be estimated. Moreover, stagnation provides a perfect sample of how industrial emissions will change if more effective policy intervention is taken to address future industrial emission reduction. However, an understanding of the environmental changes that have occurred during the COVID-19 epidemic is still needed.

Studies have investigated the correlation between epidemics and the atmospheric environment, including temperature [11], humidity [12], and others [13]. A few studies have focused on the impact of the epidemics on air quality. Zhang et al. [14] used the WRF-GC model, an online coupling of the Weather Research and Forecasting (WRF) mesoscale meteorological model and the GEOS-Chem atmospheric chemistry model, and tropospheric nitrogen dioxide (NO$_2$) column observations to estimate the top-down emission changes in nitrogen oxide (NOx) in eastern China from January 1, 2020, to March 12, 2020. They found that the average NOx emissions in East China decreased by 50% during the epidemic compared with the values before the pandemic. Meanwhile, they also found that NOx emissions in most provinces in East China began to recover after February 10 but did not return to the levels observed in early January. Wang et al. [15] analysed changes in PM$_{2.5}$ under different emission reduction cases in the North China Plain from January 1 to February 12, 2020, by using the Community Multiscale Air Quality Model (CMAQ). Their research indicated that the reduced anthropogenic activities after the COVID-19 outbreak did not mean that severe air pollution events were avoided. Concentration data for air pollutants obtained by remote sensing [16] and numerical weather prediction models [17] can reflect the real-time change in air quality during the COVID-19 epidemic period. Air quality changes are dynamic and can be affected by many factors, including meteorological conditions [18], human activity [8], and industrial production [19,20]. Therefore, using remote sensing data to analyse changes in air pollutant concentrations cannot help us understand changes in pollutants in different industrial sectors [21,22]. In addition, although a few studies have analysed the contributions of industrial sectors to atmospheric environmental change during epidemics [23,24], they have mainly combined industrial operations data to speculate on possible influencing factors, lacking real-time observation data as evidence.

NOx emission concentrations and operating vent numbers are effective indicators of industrial production [25]. NOx in the ambient atmosphere is mainly present in the form of nitric oxide (NO) and NO$_2$ [26], which are closely related to the combustion of energy fuels (i.e., coal, oil, and natural gas) for power generation [27] and heating [28], industrial processing [29], biomass burning [30], and other natural processes [31]. Its spatial agglomeration is related to the development of the regional social economy [32]. NOx is an important component of atmospheric particulate matter (PM$_{2.5}$) [33] and the precursor of ozone (O$_3$), a toxic air pollutant [34]. Understanding how the epidemic would affect industrial NOx emissions can also help constrain future NOx budgets and quantify human health impacts [35]. Initial estimates of NOx emissions changes based on a limited sample of power plants and the Tropospheric Monitoring Instrument (TROPOMI) have suggested that the tropospheric NOx concentrations dropped sharply after the Wuhan lockdown [36]. Therefore, the monitored NOx emissions and the operating vent numbers during the epidemic could be effective indicators to assess the real-time impact of COVID-19 on industrial sectors.

In this study, we attempt to reveal the impacts of COVID-19 on China’s NOx emissions for the first time at the spatiotemporal and industrial levels in China by using large-scale real-time monitoring data of key polluting enterprises. To accomplish this task, we first divided the NOx emissions data into three periods based on the dates for the Chinese New Year. Then, the number of operating vents and the emission concentrations of 20 industrial sectors compiled from 9169 key polluting enterprises in China were calculated for each period. On this basis, the natural breakpoint method was used to evaluate the spatial distribution of operating vent numbers and emission concentrations, and the relative change rate was used to estimate changes among the three periods in each sector. We also selected the typical sectors with the largest changes to show their change patterns. Finally, by comparing the changes in the NOx operating vent numbers and emission concentrations in the same period of 2020 and 2019, we estimated the changes in NOx emissions in all provinces and cities of China affected by the COVID-19 epidemic. Our study provides new insight into how the shutdown for COVID-19 affected industrial emissions and air quality, thus helping us propose more detailed suggestions to reduce the annual average NOx emissions of sectors or enterprises in China after the COVID-19 event. In addition, our study can provide a reference for assessing the social, economic, and environmental impacts (e.g., job and profit loss, carbon emission reduction, etc.) of COVID-19 and other natural and human-induced disturbances as the global epidemic situation continues to worsen.

2. Materials and methods

2.1. NOx emissions data

NOx online monitoring data of key polluting entities were collected and provided by Blue Map (http://www.ipe.org.cn/). Data included the daily average concentration of NOx emitted by all vents of the 9169 key polluting enterprises in China from January to February 2019 and from January to February 2020. These enterprises usually pose great environmental risks, such as a large number of toxic and harmful pollutants, and they are therefore screened by the environmental protection department of the local government based on the environmental carrying capacity, the environmental quality improvement requirements of their respective administrative areas and other specified conditions [37]. Spatially, polluting enterprises are unevenly distributed across China. The economically developed northern and eastern regions account for 27.81% and 36.90% of the total enterprises, respectively. In contrast, only 3.20% and 7.92% of polluting enterprises are located in the economically less advanced northwest and southwest regions, respectively. Specific information about the 9169 polluting enterprises can be found in Fig. 1 and SI Table S1.

2.2. Data analysis methods

2.2.1. Segment of time

Unlike the Western New Year beginning on January 1st at midnight, Chinese New Year takes place in either January or February and is based on the lunar calendar. The Chinese people celebrate the New Year according to the lunar calendar. Therefore, we divided all emissions data into three groups based on the date of the lunar calendar, including the normal operations period (pre-COVID-19 outbreak) (P1), the Spring Festival period (P2), a seven-day national holiday, and the epidemic period after the Spring Festival (P3). Generally, many enterprises begin to stop working approximately one week before the Spring Festival (P2). Therefore, we eliminated data from the week before the Spring Festival and took data from two and three weeks before the festival as the baseline data indicating the normal emissions of key enterprises. The data for P3 were used to analyse how enterprises were affected by COVID-19 after the Spring Festival, and it was defined according to the timing of the level 1 cancellations in all provinces and cities of China in response to the serious public health emergency (SI Table S2). The data from the same period in 2019 were taken as the control group, i.e., the NOx emissions of key enterprises in China without the impact of COVID-19. The specific dates for the three periods in 2019 and 2020 are shown in SI Table S3.

2.2.2. Industry classification

In this study, based on the national economic industry classification (GB/T4754-2017), enterprises were classified into 20 different
industrial sectors (SI Table S4) for statistical purposes.

2.2.3. Relative change rates

The number of vents in different regions is obtained by adding all the vents of key polluting enterprises in the region. The relative change rate ($r$) was used to indicate changes in the number of vents in different periods, as shown in Eq. (1).

$$r_p = \left( \frac{x_p - x_q}{x_p} \right) \times 100\%$$  \hspace{1cm} (1)

where $r_p$ is the relative change rate of the operating vent numbers or NOx emission concentration at time period $p$, and $x_p$ and $x_q$ are the numbers of vents or NOx emission concentration at time periods $p$ and $q$, respectively.

2.2.4. Data standardization and five-day moving average

To reduce the instability of NOx emission data over time, we first standardized it and then calculated the five-day moving average, as shown in Eqs. (2)–(3).

$$\omega_i = \frac{C_i}{C_0}$$  \hspace{1cm} (2)

$$\omega_{i,5\text{-day}} = \frac{\omega_{i-4} + \omega_{i-3} + \omega_{i-2} + \omega_{i-1} + \omega_i}{5}$$  \hspace{1cm} (3)

where $\omega_i$ is the value of the NOx emission concentration after standardization on the $i$th day, $C_i$ is the NOx emission concentration on the $i$th day, and $C_0$ is the NOx emission concentration on the last day of P1. ($\omega_{i,5\text{-day}}$) is the five-day moving average of the NOx emission concentration on the $i$th day, and $\omega_{i-4}$, $\omega_{i-3}$, $\omega_{i-2}$, $\omega_{i-1}$, $\omega_{i-1}$, and $\omega_i$ denote the value after standardization of the NOx emission concentration on the $(i - 4)$th, $(i - 3)$th, $(i - 2)$th, and $(i - 1)$th day, respectively.

2.2.5. NOx emissions affected by COVID-19

The recovering ratio ($R$) of operating vent numbers and NOx emission concentrations after the Spring Festival in 2019 and 2020 were calculated to show the recovery of enterprise production after the holiday. After the Spring Festival in 2019, enterprises recovered normally, while in 2020, the whole country was affected by COVID-19, and many enterprises did not resume operations. Therefore, we used the difference in the relative change rate in the same period in 2019 and 2020 to indicate the change in NOx emissions of the national key enterprises caused by COVID-19, as shown in Eqs. (4)–(6).

$$R_i = \left( \frac{x_i - \overline{x}_{P1}}{\overline{x}_{P1}} \right) \times 100\%$$  \hspace{1cm} (4)

where $R_i$ is the recovering ratio of operating vent numbers or NOx emission concentration on the $i$th day, $x_i$ is the number of vents or NOx emission concentration on the $i$th day, and $x_{P1}$ is the average number of vents or NOx emission concentration in P1.

$$\Delta R_i = (R_i)_{2020} - (R_i)_{2019}$$  \hspace{1cm} (5)

where $\Delta R_i$ is the difference between the recovery rates on the $i$th day in 2019 and 2020, and $(R_i)_{2020}$ and $(R_i)_{2019}$ denote the recovery rates on the $i$th day in 2019 and 2020, respectively.

$$\Delta x_i = \Delta R_i \times \left( \frac{x_i}{x_{P1}} \right)_{2020}$$  \hspace{1cm} (6)

Fig. 1. Spatial distribution of key polluting enterprises; red dots indicate the location of polluting enterprises. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
where $\triangle x_i$ is the change in operating vent numbers or NOx emission concentration on the $i$th day affected by COVID-19, and \( \bar{x}_{P1}^{2020} \) is the average number of vents or NOx emission concentration of $P1$ in 2020.

3. Results

3.1. Spatial distribution of NOx emissions

3.1.1. NOx operating vent numbers

The number of NOx vents shows spatial disparities in the study periods (Fig. 2). Shandong was the province with the most densely distributed NOx vents, with 2498–4195 operating vents in 2020 and 3460–4210 in 2019, followed by Hebei Province, with ranges of 1279–1781 and 704–1247 in 2020 and 2019, respectively. Compared with $P1$ (Fig. 2a and d) and $P2$ (Fig. 2b and e) in the same year, the number of operating vents for $P2$ in 2020 and 2019 was less than that of $P1$, which is consistent with the normal phenomenon of enterprise shutdowns during the Spring Festival. From $P2$ to $P3$ (Fig. 2c and f), the increase in the number of vents in 2019 was more than in 2020. This result shows that after the Spring Festival in 2019, the number of vents basically returned to the pre-Spring Festival level, while in the same period in 2020, the number has not yet recovered.

It can be seen from the relative change rate ($r$) of the number of vents in different periods (Fig. 3 and SI Table S5) that the national number of NOx vents in $P2$ was less than that in $P1$ by 27.91% in 2020. The areas seeing reductions were North China, East China, Southwest China, and Central China, with decreases of 33.84%, 33.50%, 16.29%, and 5.10%, respectively, while the number in the northwest and northeast regions increased by 7.11% and 26.55%, respectively. In the same period in 2019, the number of NOx vents in China decreased by 9.35%, and numbers in the southwest and northeast regions increased significantly by 1206.34% and 594.52%, respectively. We also calculated $r_{P2-P3}$ and found that in 2020, the number of NOx vents in East China, North China, Central China, Southwest China, and South China decreased by 32.72%, 23.82%, 18.33%, 13.33%, and 2.70%, respectively, while the numbers in Northwest China and Northeast China increased by 2.75% and 24.81%, respectively. This result shows that in the study period, the impact of COVID-19 was relatively low in the northwest and northeast regions. It is noteworthy that in East China and Northwest China, the number of NOx vents decreased and increased by 45.48% and 33.23%, respectively, compared with the numbers in the same period in 2019.

3.1.2. NOx emission concentration

Similar to the number of national NOx emission vents, the five-day moving average of the NOx emission concentration ($w_{5-day}$) in 2019 and 2020 experienced a process of initially decreasing from $P1$ to $P2$ and then increasing from $P2$ to $P3$ (Fig. 4). From $P1$ to $P2$ in 2020, except in Guangxi, Jilin, Ningxia, Guangdong, Liaoning, and Shaanxi, in which the $w_{5-day}$ increased by 0.15%, 2.18%, 6.73%, 18.50%, 41.18%, and 338.99%, respectively, the $w_{5-day}$ in the other regions showed a downward trend, from 94.57% (Zhejiang) to 13.13% (Sichuan). From $P2$ to $P3$, the $w_{5-day}$ of 21 provinces recovered or even exceeded the level of $P1$, and the relative change rate ranged from 1.46% (Qinghai) to 759.65% (Hebei) (SI Table S6). The $w_{5-day}$ of the other eight provinces continued to decline, with Hubei Province declining the most, reaching 27.72%. In 2019, the $w_{5-day}$ from $P1$ to $P2$ in Yunnan and Shanghai increased by 8.72% and 20.84%, respectively. However, the values in Zhejiang, Fujian, Jiangsu, Hubei, Hebei, Henan, Inner Mongolia, Jiangxi, Anhui, and Chongqing decreased by 44.64%, 1.25%, 154.43%,
41.66%, 191.35%, 484.94%, 60.42%, 21.87%, 354.17%, and 40.31%, respectively. Compared with the same period in 2019, the national recovery rate of (\(w_{5\text{day}}\)) in P3 vs P2 of 2020 decreased by 113.62%. These results show that although many enterprises started to resume production after the Spring Festival in 2020, they were seriously affected by the COVID-19 pandemic, and the recovery rate was lower than that for the same period in 2019.

The relative changes in the operating vent numbers in each region were different for the same periods of 2020 and 2019 (Fig. 5). In 2020, the (\(w_{5\text{day}}\)) in East, Central, North, Southwest, and Northwest China decreased significantly compared with that in P1, with decrease ratios of 76.75%, 61.32%, 44.42%, and 50.17%, respectively, and the (\(w_{5\text{day}}\)) in the same period in 2019 decreased by 97.00%, 121.53%, 37.63%, and 79.97%, respectively. The (\(w_{5\text{day}}\)) of P3 in Central China decreased by 18.04% compared with that in P2 in 2020, while it increased in other regions.

3.2. Industrial distribution of NOx emissions

3.2.1. Operating vent numbers

We comprehensively considered the industrial distribution of the number of vents and NOx emission concentrations and selected four industrial sectors characterized by more vents and higher concentrations as the representative sectors in this study: the mining industry (B), manufacturing industry (C), power, heat, gas and water production and supply industry (D), and wholesale and retail industry (F). Examining the daily trend in the number of NOx vents in the four sectors (Fig. 6), it can be seen that the number of vents in each sector was higher in 2020 than in 2019. The daily change trends in the number of NOx vents in sectors B, C, and D were similar in 2019 and 2020. The number of NOx vents began to decline around January 12 in 2020, reached the lowest point in P2, and then began to gradually increase. However, the number of NOx vents was affected by COVID-19, and thus the number increased.
by less than 10%. Specifically, in 2020, the average number of NOx vents in sectors B, D, and F from P2 to P3 increased by 2.67%, 1.64%, and 8.19%, respectively, while the number in sector C decreased by 0.48%. The average number of NOx vents in sectors B and F in P2 of 2020 exceeded the number in P2 of 2019 (Fig. 6a and d). The operating vent numbers of sectors C and D reached the same level they reached in 2019 after February 4, 2020 (Fig. 6b and c). It is worth noting that in 2019, the number of NOx operating vents in sectors C, D, and F returned to the pre-P2 level within 7 days, which is significantly different from the trend seen in the same period in 2020. Compared with the same period in 2019, in 2020, the recovery rate in the number of NOx vents in sectors B, C, D, and F decreased by 79.23%, 100.31%, 96.97%, and 104.24%, respectively. These results indicate that the operating vent numbers of these four typical sectors were seriously affected by the COVID-19

Fig. 5. Relative changes of the NOx (w)_5-day in different regions in the three periods of 2019 and 2020. The red and blue bars represent the relative changes in 2019 and 2020, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 6. Daily operating vent numbers (black and grey dots) in the representative sectors. The red and blue solid lines represent the daily operating vent numbers in 2019 and 2020, respectively, and the error bars represent the corresponding standard deviations of the data. Vertical black dashed lines represent the dates of the Wuhan lockdown, and the grey rectangle indicates the period of the Spring Festival. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
pandemic. Although the NOx operating vent numbers in all sectors gradually recovered after the Spring Festival, the recovery rate is far lower than that for the same period in 2019.

3.2.2. Daily NOx emission concentrations

Compared with P1, operating vent numbers in all sectors were significantly reduced in P2 and had a restricted recovery in P3, and the changes in \(\omega_{5\text{-day}}\) in sectors B, C, D, and F were more significant than those in the other sectors (Fig. 7a). The high values of the \(\omega_{5\text{-day}}\) are mainly distributed in sectors B, C, D, and F. The \(\omega_{5\text{-day}}\) in these four typical sectors decreased to the lowest point before the closure of Wuhan (Fig. 7b). The \(\omega_{5\text{-day}}\) of sector C increased sharply after the closure of Wuhan city, reaching a maximum value of 20.53 on February 2, 2020, and then fluctuated. The \(\omega_{5\text{-day}}\) in sector B began to increase rapidly during the Spring Festival, reaching its maximum on January 31, 2020, at 5.16, and then basically remained constant. However, after the \(\omega_{5\text{-day}}\) period in sector D and F reached their lowest values on January 17 and 18, 2020, these values remained in the ranges of 1.08-1.78 and 0.95-2.51, respectively. The above results show that although the \(\omega_{5\text{-day}}\) in the C sector was greatly affected by COVID-19, it quickly recovered to the pre-epidemic level after January 27, 2020. After the Spring Festival, the recovery of the \(\omega_{5\text{-day}}\) of sector B was not as fast as that of sector C, but it also recovered steadily. The \(\omega_{5\text{-day}}\) in sectors D and F remained approximately constant after the Spring Festival.

3.3. NOx vent and concentration change affected by COVID-19

The impact of COVID-19 on the change in operating vent numbers after the Spring Festival in 2020 varied by province (Fig. 8). The number of NOx vents of key enterprises in China decreased by \(-2694 \pm 324.83\) due to the impact of COVID-19. The NOx operating vent numbers of 17 provinces showed a negative change, of which the value decreased the most in Shandong Province (1823 \pm 80.59), followed by that in Jiangsu Province (420 \pm 142.95). In contrast, the average number of NOx vents in Hunan (1 \pm 1.24), Inner Mongolia (27 \pm 55.83), Hainan (45 \pm 8.15), Yunnan (66 \pm 54.79), and Shaanxi (143 \pm 48.36) showed a positive change during this period. This result shows that the epidemic had little impact on the number of NOx vents of key enterprises in these regions, which might be because there were smaller numbers of confirmed cases of COVID-19 found in these provinces. The reason NOx operating vent numbers in Guangxi, Hubei, Jiangxi, Liaoning, Ningxia, Qinghai, Shanghai, and Chongqing were unchanged is that the average number of NOx vents in these areas was 0 in P1 of 2019. This does not mean that the enterprises in these areas remained closed down after the Spring Festival in 2020.

After the Spring Festival, affected by the epidemic, although more provinces experienced increased NOx \(\omega_{5\text{-day}}\) than experienced decreased NOx \(\omega_{5\text{-day}}\), the NOx \(\omega_{5\text{-day}}\) of the whole country decreased by \(-9.54 \pm 6.00\) (Fig. 9). The NOx \(\omega_{5\text{-day}}\) of 13 provinces decreased compared with the same period in 2019, and the largest decline was in Anhui Province (\(-129.92 \pm 4.20\)). The NOx \(\omega_{5\text{-day}}\) in Fujian (\(-1.77 \pm 0.56\)), Jiangsu (\(-4.83 \pm 1.31\)), Jiangxi (\(-1.07 \pm 0.26\)), Shandong (\(-0.72 \pm 0.56\)), Shanxi (\(-0.55 \pm 0.25\)), Sichuan (\(-0.69 \pm 0.06\)), Xinjiang (\(-0.03 \pm 0.03\)), Yunnan (\(-26.57 \pm 16.81\)) and Zhejiang (\(-19.38 \pm 2.80\)) decreased gradually, which is similar to the changing trend for NOx operating vent numbers. This result shows that the impact of COVID-19 on these areas was gradually weakening. In Henan (\(-53.49 \pm 6.03\)) and Hubei (\(-2.64 \pm 0.46\)), even though the NOx \(\omega_{5\text{-day}}\) experienced negative changes, the rate of reduction was increasing with time, which may be related to the serious epidemic situation in these two provinces. In contrast, the NOx \(\omega_{5\text{-day}}\) in 16 provinces showed a positive change, with the largest increases in Inner Mongolia (3.99 \pm 1.37), Gansu (0.16 \pm 0.12), Guangxi (1.12 \pm 0.28), Hainan (0.55 \pm 0.19), Ningxia (0.68 \pm 0.05), Shanxi (0.55 \pm 0.25) and Shanxi (1.25 \pm 4.19), which observed a continuous increasing trend for NOx emission concentrations. This result is mainly because these areas were less affected by COVID-19, and when the epidemic was basically under control, enterprises there were able to restore production quickly. In Hunan (0.13 \pm 0.10), Jilin (0.23 \pm 0.16), and Shanghai (0.08 \pm 0.34), the NOx \(\omega_{5\text{-day}}\) had a positive change, but it declined gradually. This result is probably due to the high population density and floating population in these places, which could lead to the slow recovery of production in some enterprises.

4. Discussion

The NOx emission concentrations and NOx operating vent numbers showed significant spatial disparities in the three periods of 2020, which might be caused by different factors. During P1, North, East, and Central China had higher values of NOx emission concentrations and operating vent numbers. In P2 and P3, the most rapid decline in operating vent numbers also occurred in these three regions. In China, more than 70%
of enterprises are located in these regions, which means that most of China’s production capacity is concentrated there. Moreover, the governments in these areas are more open than those in West China [38,39], so they were able to more quickly respond to the emergency measures put forward by the state and work out effective measures to limit population flows and unnecessary business activities in a short time. Therefore, enterprises in these regions were more affected by the epidemic, resulting in more significant changes in NOx emissions. In contrast, because Northwest China is far from the outbreak’s epicentre, enterprises are scattered and numbers of confirmed COVID-19 cases are low, neither NOx emission concentrations nor operating vent numbers have a downward trend in P2 and P3 but instead show a slowly increasing trend. From the provincial differences, the provinces with a rapid and continuous decrease in operating vent numbers were mainly Hubei and its surrounding provinces and the eastern provinces (SI Fig. 3). This result may be caused by the relatively serious epidemic situation in these areas. Hubei, as the epicentre of the outbreak in China, maintained a low level of NOx vent numbers and emission concentrations in the P3 period. However, in Zhejiang, Shandong, and Shanghai, after the number of confirmed cases became relatively stable, local governments quickly took effective measures to resume production. As a result, the number of NOx vents and emission concentrations began to recover early.

Each sector plays a different role in the development of the social economy, resulting in industrial differences in NOx emissions. The manufacturing industry (C) is one of the pillar industrial sectors in China, and is largely composed of labour-intensive enterprises. Affected by the Spring Festival holiday and COVID-19, the NOx emission concentrations and operating vent numbers in the manufacturing industry in P3 of 2020 slightly increased after a short-term decline. This trend occurs because after the epidemic outbreak, some manufacturing enterprises had to resume production to supply emergency materials. The NOx operating vent numbers in the power, heat, gas, and water production and supply industry (D) are basically the same as those in 2019, while the emission concentration is approximately half of that in the same period in 2019. This result shows that in P3, the basic energy supply of the country was guaranteed, but its consumption intensity was effectively controlled. This result is in accordance with the conclusion of Hu et al. [35]. Moreover, although NOx operating vent numbers and emission concentrations in the wholesale and retail industry (F) declined rapidly during the Spring Festival, they increased rapidly in P3 and even exceeded the corresponding level in 2019. This result is due to China’s developed logistics system and convenient online shopping environment. The NOx operating vent numbers and emission concentrations in other sectors, such as the education, agriculture, financial, and real estate industries, experienced a slight decline after the epidemic outbreak. This decline occurred because, on the one hand, the NOx emissions generated by these sectors were limited and, on the other hand, the nature of enterprises in these sectors meant that they had a strong ability to resist the risk of this epidemic.

Based on the results of this study, it is feasible to propose targeted NOx emission reduction suggestions according to the characteristics of key enterprises in different regions and sectors. In places where key polluting enterprises are concentrated (Beijing-Tianjin-Hebei region and East China), the impact of the epidemic on the emission concentration of key polluting enterprises varies greatly. Therefore, when planning to reduce NOx emissions in such areas, enterprises with outdated clean technology should be eliminated, and the emissions of enterprises with an emission concentration exceeding the regional average level should be strictly controlled. However, regions with a small number of
polluting enterprises and a significant increase in NOx concentration during the epidemic period, such as western and northeast China, should pay more attention to improving regional clean technology on the premise of meeting the local market demand. Among the four typical sectors in this study, there are fewer NOx vents in sectors B and F than in the other two sectors, this number slightly decreased in P2, and the recovery after the epidemic was faster. However, the (w)5-day in sectors B and F decreased by approximately 60% and 80%, respectively, after the COVID-19 outbreak, and the (w)5-day data were scattered. This means that NOx emission concentrations emitted from a few enterprises in these two sectors are much higher than the average level. Therefore, when formulating NOx emission reduction measures for polluting enterprises in sectors B and F, more attention can be paid to the control of a few enterprises with high emission concentrations. In contrast, there are many key polluting enterprises in sectors C and D. After the COVID-19 outbreak, the number of NOx vents recovered slowly, but the (w)5-day recovered quickly. This shows that when controlling the NOx emissions of enterprises in these two sectors, more attention should be paid to reducing the number of enterprise emission outlets than to reducing the NOx emission concentration. Specifically, to reduce NOx emissions in sectors C and D, it may be more effective to focus on eliminating enterprises with outdated production capacity on the premise of ensuring the necessary regional supply than to improve the enterprise cleaning process on a large scale.

In this study, there are no NOx flow data; thus, the contributions of key polluting enterprises to the total emissions of NOx before and after the epidemic outbreak cannot be accurately calculated. However, we combined operating vent numbers with the concentrations of NOx emissions of these enterprises to analyse the spatial disparities of NOx emission changes in three periods, and the results are consistent with the spatial distribution of NOx emissions retrieved from satellite remote sensing data by Zhang et al. [14]. This result shows that the comprehensive analysis of operating vent numbers and emission concentrations of NOx can be used to reflect the impact of COVID-19 on the NOx emissions of enterprises. In addition, our results may have some deviations due to the increase or decrease in the NOx emission monitoring ports of enterprises. However, the automatic monitoring data of key polluting enterprises have clear quality requirements and standardized data auditing processes. Therefore, the error has little impact on these research results [40].

5. Conclusion

In 2020, the NOx operating vent numbers of key polluting enterprises in China during the Spring Festival (P2) and after the Spring Festival (P3) decreased by 27.91% and 25.02%, respectively, compared with the number before the Spring Festival (P1) and decreased by 18.55% and 24.68%, respectively, compared with the number in the same period in 2019. From P1 to P2 in 2020, the NOx operating vent numbers in North China changed the most (33.84%), while those in East China changed the most in P1 and P3 (32.72%). The NOx (w)5-day varied with the region. From P1 to P2 in 2020, the NOx (w)5-day in East, Central, and North China decreased by 76.75%, 61.32%, and 44.42%, respectively, and decreased by 97%, 121.53%, and 37.63% compared with the same period in 2019, respectively. In Zhejiang, Hubei, and Hebei, in particular, the NOx (w)5-day decreased by 94.57%, 79.60%, and 78.54%, respectively, compared with the number in the same period in 2019.

The NOx operating vent numbers and NOx (w)5-day of national key enterprises are mainly concentrated in four typical sectors: the mining
industry (B), the manufacturing industry (C), the power, heat, gas, and water production and supply industry (D), and the wholesale and retail industry (F). The number of NOx vents for sectors B and F exceeded the level for the same period in 2019 before the Spring Festival, while numbers in sectors C and D reached the level for the same period in 2019. The NOx concentrations of these four sectors decreased to their lowest point before the closure of Wuhan. The NOx (w5-day) of sector C began to increase sharply after the closure of Wuhan and reached its peak value (20.53) on February 2, 2020. The NOx of sector B increased steadily in P3, while the concentrations of sectors D and F remained low in P2 and P3, respectively.

After the Spring Festival in 2020, the number of NOx emission vents of key polluting enterprises in China decreased by an average of 2693 ± 324.83, and the NOx (w5-day) decreased by an average of −9.54 ± 6.00. There was a negative change in the number of NOx vents in 17 provinces caused by COVID-19, among which the number of vents in Shandong Province decreased the most (−1823 ± 80.59). After the Spring Festival, the (w5-day) also showed a trend similar to that of the vent numbers. In 13 provinces, the (w5-day) showed a negative trend, and the (w5-day) of Anhui Province changed the most (−129.92 ± 4.20). These results indicate that after the Spring Festival, COVID-19 significantly reduced the NOx emission levels of the key polluting enterprises in China.

The results show the regional and industrial characteristics of NOx emissions from key polluting enterprises during the epidemic period help formulate effective control measures. Western and northeast China could focus on improving the safety of enterprises to work out effective NOx reduction measures. The Beijing-Tianjin-Hebei region and East China should strictly control enterprises with high NOx emission concentrations and force enterprises with outdated production capacity to shut down. When formulating NOx emission reduction measures for polluting enterprises in sectors B and F, more attention can be paid to controlling a few enterprises with high emission concentrations. For sectors C and D, it may be more effective to focus on the elimination of enterprises with outdated production capacity.

CRedit authorship contribution statement

Chao He: Formal analysis, Writing - original draft, Writing - review & editing. Lu Yang: Formal analysis, Validation, Data curation, Writing - original draft. Bofeng Cai: Supervision, Resources, Writing - review & editing, Conceptualization. Qingyuan Ruan: Resources. Song Hong: Writing - review & editing. Zhen Wang: Supervision, Writing - review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2020.116042.

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