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Environmental implications of reduced electricity consumption in Wuhan during COVID-19 outbreak: A brief study

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ABSTRACT

Due to the COVID-19 outbreak, Wuhan was locked down from 23 January 2020 to 8 April 2020, a total of 76 days. It is well known that the electricity consumption is a direct reflection of human activity. During the lockdown of Wuhan, most of human activities were forbidden. The reduction in human activity would inevitably lead to a reduction in electricity consumption. At the same time, anthropogenic emissions of air pollutants would also be reduced with the reduction of human activity. In this study, the correlation between electricity consumption and air pollutants during lockdown was discussed in detail. The result showed that the drop in pollutants concentrations in January should be attributed to the washout effect of rainfall rather than the lockdown. The decrease of electricity consumption in the secondary industry might play a significant role on the decrease of PM 2.5 and NO 2 concentrations in Wuhan in February 2020. The decrease in NO 2 concentration in March should be attributed to the reduction of pollutants emissions from the tertiary industry, which means that more attention should be paid to the control of NO 2 emission in the tertiary industry. Due to reduced emissions from local sources, the role of long-range transport sources might be more significant during the lockdown of Wuhan. By PSCF analysis, southeast of Wuhan could be the major potential emission sources of PM 2.5, especially in the northern part of Jiangxi province. It was suggested that stricter regulation of pollutants emissions should be implemented in this area.

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1. Introduction

In past few years, the air pollution problem was plaguing many cities in China (Chan and Yao, 2008; Zhou et al., 2018). Poor air quality not only has a negative impact on people’s daily life, but also does harm to human health (Ostro et al., 2009; Yu et al., 2019). High levels of air pollutants exposure might lead to an increase in mortality (Weitekamp et al., 2020). Among the air pollutants, NO 2, PM 2.5, SO 2 and O 3 etc. were the major monitored species in China’s air pollutants emission control standards (Wu et al., 2016; Li et al., 2017). In recent years, the concentration of SO 2 had been effectively controlled and reduced under the strict supervision of the national emission control policies (Zhang et al., 2015). The
concentration level of SO\textsubscript{2} was consistent with other countries over the world (Meraz et al., 2015; Sicard et al., 2021). Compared with the reduction of SO\textsubscript{2}, although the concentrations of NO\textsubscript{2} and PM\textsubscript{2.5} had also been greatly reduced, they still failed to meet the national air quality standard (40 \(\mu\text{g m}^{-3}\) for NO\textsubscript{2} and 35 \(\mu\text{g m}^{-3}\) for PM\textsubscript{2.5}, GB 3095-2012) and were higher than other developed countries (Sicard et al., 2021). While O\textsubscript{3} pollution had not been well controlled, which had become more serious in recent years (Zhao et al., 2018b, 2021).

The year 2020 was a special time for people all over the world. The COVID-19 broke out in Wuhan, Hubei province, China, in December 2019 and quickly spread around the world in 2020 (Lin et al., 2020). In order to reduce the health risk caused by COVID-19, national governments around the world were actively taking measures to prevent further spread of epidemic situation. Among them, the actions and performance of China were particularly impressive. After the outbreak, President Xi Jinping ordered that people’s lives and health should be put first (People’s Daily, 2020a). In order to avoid more serious losses of people’s health and property, Chinese government decided to temporarily lock down the city of Wuhan. Wuhan went into lockdown from 23 January 2020 and was not lifted until that the COVID-19 was effectively controlled from 8 April 2020, a total of 76 days. The decisive intervention of the Chinese government effectively slowed the spread of COVID-19, which bought valuable time for the rest of the world to fight the epidemic. During the 76 days, most of human activities were stopped in Wuhan, except for parts of the livelihood guarantee industries. The strict lockdown policy made energy consumption fluctuate in Wuhan in first half of 2020.

The COVID-19 outbreak not only significantly reduced the local energy consumption in Wuhan, but also had a certain impact on the development of the economy in the entire Asia (Abiad et al., 2020). While the lockdown had a serious negative impact on social activities and the local economy, the positive impact on the reduction in pollutants and greenhouse gases was also widely discussed (Quéré et al., 2020; Higham et al., 2020; Liu et al., 2020; Global Energy Review, 2020). The concentration of NO\textsubscript{2} across the USA during the COVID-19 outbreak has declined 25.5\%, and even up to a similar 30\% in the urban northeastern United States (Blumberg, 2020; Berman and Ebisu, 2020). The decrease of NO\textsubscript{2} concentration was also observed in many European cities, and even dropped more (European Environmental Agency, 2020; Muhammad et al., 2020). A 10–30\% reduction in NO\textsubscript{2} was also observed during early 2020 in China (Patel, 2020). This epidemic outbreak made pollutants changes including PM\textsubscript{2.5}, PM\textsubscript{10}, NO\textsubscript{2}, CO, CO\textsubscript{2}, SO\textsubscript{2}, O\textsubscript{3} and etc. during the COVID-19 pandemic become a topic of common concern to scholars all over the world (Sharma et al., 2020; Zhang et al., 2021; He et al., 2020; Bekbulat et al., 2021). It is well known that human activities are an important cause of air pollution (Ramanathan and Feng, 2009). The electricity consumption is an important reflection of human activities (Hsu et al., 2011). Reduced human activity and reduced power consumption were closely linked during COVID-19 pandemic, which also affected the pollutants emissions (Travaglio et al., 2021; Magné et al., 2020). Therefore, it was significative to discuss the environmental implications of energy consumption fluctuation during the lockdown of Wuhan.

During the lockdown of Wuhan, the reduction in human activities was bound to lead a decrease in electricity consumption. And the decrease in electricity consumption would lead to a chain reaction in air quality such as the emission reduction of industrial pollutants (Alam et al., 2012; Shabbaz et al., 2014). In this study, the impact of COVID-19 outbreak on the electricity consumption of three industries in Hubei province was discussed in detail. Moreover, the relationship between the decreased concentrations of pollutants and the decreased electricity consumption was also analyzed. The main reasons caused the decline in pollutants concentrations in Wuhan from January to march were detailedly expounded. Due to the decrease of local source emissions during lockdown, long-range transport of pollutants might become one of the important factors caused the air pollution in Wuhan. Therefore, the potential emission sources were identified with the potential source contribution function (PSCF) analysis in this study.

2. Experimental method

2.1. Geographical location

As the capital city of Hubei province, Wuhan is located in the central economic zone of China (shown in Fig. 1). According to the Wuhan Statistical Bulletin (WSB, 2019), the gross domestic product (GDP) of Wuhan reached 235 billion dollars in 2019. And its annual electricity consumption was 61.5 billions kWh. The population of Wuhan reached more than 11 millions, in which there were more than one million college students. It means that there was a large floating population in Wuhan. Because of the large population in Wuhan, the COVID-19 was very easy to spread quickly here if there was not a strict control measure. According to the Wuhan Environmental Status Bulletin (WSB, 2019), the annual mean concentration of PM\textsubscript{2.5} was 45 \(\mu\text{g m}^{-3}\) in Wuhan in 2019, which decreased by 2.2\% compared with 2018. The annual mean concentrations of SO\textsubscript{2}, NO\textsubscript{2}, and O\textsubscript{3} were 9, 44, and 183 \(\mu\text{g m}^{-3}\), increased by 12.5\%, 2.3\%, and 21.2\%, respectively. Among the four air pollutants, the concentration of O\textsubscript{3} increased the most.

2.2. Data acquisition

In this study, the concentration data of air pollutants was obtained from the National Air Quality Monitoring Network. The electricity consumption data was from the Hubei Provincial Bureau of Statistics (HPBS, 2020) and National Bureau of Statistics (NBS, 2020). Global meteorological reanalysis data was from the National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP and NCAR, 2020). The weather condition data was obtained from the Weather Enquiry Service website (WES, 2019-2020). Due to the impact of the COVID-19 epidemic, most of the data was obtained from the real-time monitoring system and the website of government statistics department. All of the data had been double-checked and verified before these data were used.
2.3. Cluster analysis

To investigate the effect of air mass transport, the backward trajectories were calculated for 72 h with GDAS1 data. Cluster analysis was carried out for the backward trajectories. The HYSPLIT-4 model was used as the calculation tool of backward trajectories, which was developed by the National Oceanic and Atmospheric Administration (NOAA), USA. The resolution of backward trajectories was $1^\circ \times 1^\circ$ in this study. The location of simulated receptor was located in the center of Wuhan (114.31° E, 30.59° N). The starting vertical height was set at 100 m. The trajectory simulation was run every 8 h. After calculating, a GIS-based plug-in of TrajStat was used for cluster analysis of the trajectories (Wang et al., 2009).

2.4. PSCF analysis

PSCF analysis was a common analysis method to determine the contribution of potential emission sources (Hopke et al., 1995). As a semi-quantitative analysis tool, PSCF assigned concentrations values of pollutants to each backward trajectory. Its theoretical basis was based on the conditional that the air mass should be responsible for the concentrations of pollutants which were higher than a threshold value when the air mass reached the simulated receptor area (Xu et al., 2018a). The PSCF values could be used to express the possibility of each grid as a potential emission source (Xu et al., 2021). The PSCF value was calculated using the following equation:

$$\text{PSCF}_{ij} = \frac{m_{ij}}{n_{ij}}$$

where $n_{ij}$ was endpoint number of trajectories fallen in the $ij$th cell; $m_{ij}$ was the endpoint number of high pollution trajectories in the $ij$th cell.

In this study, the threshold value of PM$_{2.5}$ concentration was set at 75 $\mu$g m$^{-3}$ which was equivalent to the level II of the National Air Quality Standard (GB3095-2012). The values of PM$_{2.5}$ hourly concentrations were assigned to each hourly trajectory. The range of 105–130°E, 20–45°N were rasterized into 15625 cells. Furthermore, a weight function $W_{ij}$ was applied to avoid the interfering caused by some small values of $n_{ij}$ in this study (Polissar et al., 2001).

$$W_{ij} = \begin{cases} 1.00 & n_{ij} > 3n_{Ave} \\ 0.70 & 3n_{Ave} \geq n_{ij} > 1.5n_{Ave} \\ 0.42 & 1.5n_{Ave} \geq n_{ij} > n_{Ave} \\ 0.17 & n_{Ave} \geq n_{ij} > 0 \end{cases}$$

3. Results and discussion

3.1. Overview of air pollutants

To better understand the impact of lockdown on air quality, the temporal variations of pollutants concentrations were compared simultaneously in Wuhan in 2019 and 2020. As shown in Fig. 2, NO$_2$ and PM$_{2.5}$ concentrations decreased significantly during lockdown compared with 2019. The concentration of SO$_2$ barely changed compared with the same period in 2019. And O$_3$ concentration was up slightly from the same period last year. Table 1 shows the concentration
Table 1
Concentrations of pollutants during lockdown (23 Jan. to 8 Apr. 2020).

| Year | NO₂  | PM₂.₅ | SO₂  | O₃   |
|------|------|-------|------|------|
|      | Max  | Min   | Mean | Max  | Min   | Mean | Max  | Min   | Mean |
| 2019 | 88   | 13    | 47   | 148  | 16    | 59   | 17   | 5     | 9    |
| 2020 | 54   | 10    | 22   | 97   | 8     | 38   | 17   | 5     | 8    |

Fig. 2. Pollutants concentrations in 2019 and 2020.

statistics of pollutants in the same period in 2019 and 2020. Compared with 2019, the mean concentration of NO₂ went down by 25 µg/m³ during the lockdown, and PM₂.₅ decreased by 21 µg/m³. SO₂ was almost unchanged. While O₃ went up by 17 µg/m³. As the main product of industry and transportation emissions, more than 62% of PM₂.₅ came from the sources of industry and transportation in Wuhan in winter (Huang et al., 2019). The reduction of PM₂.₅ concentration should be attributed to the industrial closures and traffic restrictions during the lockdown in Wuhan. Same as PM₂.₅, NO₂ mainly come from the combustion of energy fuels (Huang et al., 2012; Filonchyk and Hurynovich, 2020). The reduced concentration of NO₂ should also be associated with the reduced energy combustion during the lockdown (Filonchyk et al., 2020). The concentration of SO₂ did not change significantly, which mainly due to SO₂ had been well controlled under the strict monitoring system at sources in China (Xu, 2011). The increase of O₃ concentration could be related to a combination of factors including the reduction of reductive components, solar radiation, and photochemical reactions etc. (Yang et al., 2019; Lian et al., 2020). Under the combined action of factors, O₃ became the major pollutant on the first polluted day in Wuhan in winter in 2020 (Lian et al., 2020).

3.2. Electricity consumption and air pollution

In order to prevent further spread of the COVID-19 epidemic, the Chinese government decided to temporarily close down the city of Wuhan from 23 Jan. 2020. During the lockdown, all productions were prohibited except for some necessary subsistence security. Not only the city of Wuhan, but also Hubei province and even the whole of China had been badly affected. There had been a significant drop in electricity consumption in Hubei province during the lockdown, especially the electricity consumption in the secondary industry. Fig. 3 shows the decline values statistics of the monthly electricity consumption. Compared with 2019, the electricity consumption of primary industry had barely been affected by
the COVID-19. It might be because the primary industries mainly include agriculture, forestry, fishing, animal husbandry, and some of the other primitive industries (HPBS, 2020). These primitive industries used less electricity, and its peak value of electricity consumption was mostly concentrated in summer and autumn (NBS, 2020). The electricity consumption in the secondary industry fell sharply in February 2020. The secondary industries mainly include manufacture, energy supply, construction, and others (HPBS, 2020). Most of the secondary industries were closed throughout February because of the COVID-19 epidemic. While the electricity consumption in the tertiary industry had a significant decrease in March 2020. The tertiary industries were mainly in the services industries including transportation, catering, accommodation, finance, and other public services (HPBS, 2020). Due to the impact of COVID-19 epidemic was a long-term process, its influence on the tertiary industries showed a hysteresis effect.

Besides of the electricity consumption, Fig. 3 also showed the dropped values of PM$_{2.5}$ and NO$_2$ monthly concentrations. During the lockdown in Wuhan, both PM$_{2.5}$ and NO$_2$ monthly concentrations showed an obvious decrease. Compared with 2019, the maximum reduction of PM$_{2.5}$ concentration was in January 2020. NO$_2$ concentration also showed a significant reduction in the same period. But the lockdown of Wuhan was began from 23 January. A week lockdown should not have such a significant effect on the monthly concentrations of PM$_{2.5}$ and NO$_2$. Moreover, the electricity consumption in January did not change as much as its pollutants concentrations. We suggested that there should be other more important factors led to the decrease of PM$_{2.5}$ and NO$_2$ concentrations in January besides of the lockdown. By analyzing the weather factors, the long-term rainfall might be one of the important reasons for the decrease of PM$_{2.5}$ and NO$_2$ concentrations in January. In many previous studies, the washout effects of rainfall on air pollutants was considered to be an important factor to improving air quality. (Bhattarai et al., 2021; Guo et al., 2016; Halfon et al., 2009; Zhao et al., 2018a). As shown in Fig. 4, the total rainfall duration was 12.3 days in January 2020, which was far exceeding the 4.3 days in January 2019. Therefore, the prolonged rainfall might have contributed to the wet deposition of air pollutants in Wuhan in January. Compared with 2019, although the duration of rainfall decreased in February in 2020, the concentrations of PM$_{2.5}$ and NO$_2$ still dropped significantly. It should be mainly attributed to the emission reduction of pollutants caused by industrial closures. In March, the concentration of PM$_{2.5}$ was basically at the same pollution level as 2019. But the concentration of NO$_2$ was still significantly lower than that in 2019. It might be related to China’s policies of resuming production. On 4 March 2020, the Chinese government stressed the need to promote orderly resumption of work and production at different levels according to epidemic situation (People’s Daily, 2020b). Although Wuhan was still under lockdown, the industrial production had begun to resume gradually in elsewhere from 4 March 2020. The electricity consumption in the secondary industry had also been picking up in Hubei province since March 2020 (shown in Table 2). Due to the hysteresis of the impact of epidemic on the tertiary industry, the electricity consumption in the tertiary industry fell to its valley value in March. Therefore, the low concentration of NO$_2$ in March might be closely related to the reduction of electricity consumption in the tertiary industry. It means that NO$_2$ emitted from the tertiary industry should be paid enough attention in the further control of air pollutants, especially from the transportation industry.

![Fig. 3. Dropped values of electricity consumption and pollutants concentrations during Wuhan lockdown.](image)

|                        | Jan. | Feb. | Mar. | Apr. | May | Jun. | Jul. | Aug. |
|------------------------|------|------|------|------|-----|------|------|------|
| Primary industry       | 0.13 | 0.14 | 0.11 | 0.14 | 0.17| 0.22 | 0.23 | 0.25 |
| Secondary industry     | 10.91| 1.97 | 6.59 | 9.85 | 12.06| 12.72| 12.71| 16.55|
| Tertiary industry      | 3.76 | 2.98 | 1.59 | 1.98 | 2.33| 3.10 | 3.63 | 4.26 |
3.3. Backward trajectories and cluster analysis

The long-range transport of pollutants was one of the important factors affecting regional air quality (Wang et al., 2006; Han et al., 2015; Xu et al., 2018b). In order to investigate the contribution of air mass transport, 72 h backward trajectories were simulated using the HYSPLIT-4 model in this study. Based on the simulated results, the trajectory cluster was calculated using a GIS-based plug-in of TrajStat. As shown in Fig. 5, most of the air mass came from northeast (56.99%) and northwest (22.58%) of Wuhan in January 2019. North of Wuhan belongs to the North China Plain (NCP) where usually had a heavier air pollution than south China in winter (Hu et al., 2014; Wang et al., 2015a; Xu et al., 2016). Compared with 2019, only 34.41% of air mass was long-range transported from the NCP region. The reduction of air masses from highly polluted areas might have contributed to the decrease in pollutants concentrations in January 2020. In February 2020, 73.56% of air mass were regional transport, which enhanced the regional accumulation of air pollutants. Even so, the monthly concentration of air pollutants was lower than that in February 2019. It should be attributed to the reduction of industrial emissions caused by the COVID-19 epidemic. In March, 62.37% of air mass came from the highly polluted NCP region. Furthermore, 32.26% of air mass was regional transport from south of Wuhan. The unfavorable weather conditions that pollutant transport and pollutant accumulation coexist promoted the increase of PM$_{2.5}$ concentration. Coupled with the impact of the resumption of industrial production, multiple factors conspired to cause PM$_{2.5}$ concentrations to return to its historical levels.

3.4. PM$_{2.5}$ Potential regional sources

Potential regional source analysis was an important method to determine regional emission contribution of pollutants (Hopke et al., 1995). As a semi-quantitative analysis tool, the PSCF had been widely used in many studies of air pollutant transport (Kong et al., 2020; Liao et al., 2017; Wang et al., 2015b). By calculating, Wang et al. (2015b) suggested that about 35.5% (32.8 µg/m$^3$) of PM$_{2.5}$ in Beijing was from long-range transportation between 2005 and 2010. In the Ordos region of Inner Mongolia with less local pollution sources, the long-range transport contribution of PM$_{2.5}$ reached approximately 77% (59.32 µg/m$^3$) which was much higher than the local sources contribution of 23% (17.41 µg/m$^3$) (Khuzestani et al., 2017). Considering the serious impact of long-range transportation, the potential regional sources were identified with PSCF analysis in this study. On account of the reduction of local pollutant emission caused by industrial closure, the contribution of long-range transport sources might be more significant during the lockdown of Wuhan. In this study, the simulated calculation of PSCF was performed from 23 January 2020 to 8 April 2020. As shown in Fig. 6, the emission sources of PM$_{2.5}$ were mainly distributed in southeast of Wuhan, especially in the northern part of Jiangxi province. It might be related to the developed economy and dense population in the northern Jiangxi along the Yangtze River. This region had been identified as a high emission source of pollutants in many studies (Hui et al., 2019; Liao et al., 2019). The PM$_{2.5}$ emitted from this area also have an important transport impact on the PM$_{2.5}$ pollution in Wuhan during COVID-19 outbreak.

4. Conclusions

This study mainly expounded the influence of COVID-19 on air quality in Wuhan. The relationship between electricity consumption and air pollutants was detailedly analyzed during the lockdown of Wuhan. The COVID-19 had a great impact
on the secondary industry in Wuhan, which resulted in a significant decrease in PM$_{2.5}$ and NO$_2$ concentrations in February. The improvement in air quality in January should be mainly attributed to the washout effect of rainfall rather than the impact of Wuhan lockdown caused by COVID-19. According to the results of pollutants analysis in March, the pollutants emissions from tertiary industry might have an important contribution to NO$_2$ concentration in Wuhan. Therefore, NO$_2$ emitted from the tertiary industry should be paid more attention in the further control of NO$_2$ emission in China. Aiming to ascertain the spatial distribution of potential regional sources, the PSCF analysis was used to identify the potential regional source contribution of PM$_{2.5}$. The result showed that the northern Jiangxi province might be the main potential source of PM$_{2.5}$ pollution in Wuhan during the lockdown. The emission regulation of fine particles in this region should be strengthened in the next step of pollution control work.

CRediT authorship contribution statement

Xianmang Xu: Conceptualization, Methodology, Writing - original draft, Writing - review & editing. Wen Zhang: Writing - review & editing, Formal analysis, Visualization. Yanchao Yin: Validation, Investigation. Yuezhen Dong: Data curation. Deliang Yang: Visualization. Jialiang Lv: Supervision. Wenpeng Yuan: Supervision.

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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