Assessments of the Emission Contributions from an Ultra-Supercritical Coal-Fired Power Plant to Ambient PM$_{2.5}$ in Taiwan

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Abstract

An ultra-supercritical (USC) coal-fired power plant was built to replace the old subcritical (SC) unit in the Linkou power plant (LPP) in northern Taiwan and has been in operation since 2016. Compared to the old SC power generator, the renovated unit (USC + emission control) can reduce SO\(_X\), NO\(_X\) and TSP emissions by 65%, 87% and 77%, respectively. Enhancing thermal efficiency can significantly reduce air pollutant emissions; however, its impact on ambient air pollutant concentrations under various meteorological conditions is rarely studied. To clarify the issue, we utilized the Community Multiscale Air Quality (CMAQ) model to estimate the contributions of the emissions from old and renovated LPP on the ambient PM\(_{2.5}\) concentrations in Taiwan. During the one-month study period, the LPP upgrade can reduce the PM\(_{2.5}\) concentrations to more than 10 \(\mu\)g/m\(^3\) for a severe PM\(_{2.5}\) episode when the weak wind persisted for several days. The reductions were most significant in northern Taiwan. Even with the substantial emission reductions through the advanced USC units, the LPP emissions contribute considerably to the PM\(_{2.5}\) concentrations, with a maximum reaching 5.1 \(\mu\)g m\(^{-3}\) (10.3%). This study quantitatively assesses the environmental burden that a USC coal-fired power plant places on the ambient PM\(_{2.5}\) concentrations.

Keywords: Ultra-supercritical coal-fired power plant; PM\(_{2.5}\); Emission contribution; Community Multiscale Air Quality Model (CMAQ); Weather condition
1 Introduction

With rapid economic development, the energy demand remains an increasing trend in Taiwan. According to the Bureau of Energy and the Ministry of Economic Affairs in Taiwan, in 2021 44.3%, 37.2%, and 1.83% of the electricity in Taiwan came from coal, natural gas, and fossil fuel-fired power plants, respectively, while 9.55% came from nuclear power plants, 6.0% from green energy, and 1.2% from hydroelectricity. Electricity generation in Taiwan mainly relies on coal combustion. Reportedly, the burning of coal can contribute to the fine particulate matter (PM$_{2.5}$) problem (Ma et al., 2017; McDuffie et al., 2021), which has become a significant public concern in Taiwan.

Power generation sectors have been a major target to be blamed for causing air pollution problems and have been requested by the government in Taiwan to reduce emissions. These approaches include replacing power generation units fueled by coal and oil with power generators fueled by liquefied natural gas (LNG), developing green energy, renovating coal-fueled power generators to include ultra-low emission control technology, and deploying air pollution emission control systems.

The Linkou power plant (LPP), located in northern Taiwan (Figure 1), has been in operation since 1968 and is run by the Taiwan Power Company (TPC), a government-owned electric power utility. Until 2013, the LPP remained in operation with two sub-critical (SC) coal-fired power units, each with a power generation capacity of 300 MW. Due to the pressing environmental concern and to improve the power supply capability, TPC decommissioned the two LPP power generators in 2014 and constructed three coal-fired units with 600°C high-efficiency ultra-supercritical (USC) boilers and turbines. Each unit has a power generation capacity of 800 MW. In 2016, the plant completed refurbishing the two old SC units and
commissioned one USC unit. The 2nd and 3rd USC units were in operation by March 2017 and
July 2019, respectively. Moreover, the NOx emission control system, selective catalyst reduction,
and particulate removal system were deployed along with the USC unit to further control the
emissions. Compared to the SC coal-fired unit, the USC unit operates at temperatures and
pressures above the critical point of water, which leads to higher thermal efficiencies, requires
less coal, and lowers air pollutant emissions (Zhang, 2013). Yue et al. (2021) developed a
framework to quantify the emission reductions of coal-fired plants. They indicated that
improving energy efficiency is more cost-effective than installing flue gas controls in China. In
particular, SC units with low pressures and temperatures have a lower energy efficiency;
moreover, they typically have less air pollution control implemented. The retirement of these SC
units can greatly improve emission reductions.

It is well known that enhanced thermal efficiency can reduce air pollutant emissions from
cal-fired power plants (Asif et al., 2022); however, its impact on ambient air pollutant
concentrations over receptor areas is rarely studied. The assessment is important because the
cal-fired power plant produces large amounts of emissions and has been blamed for causing air
pollution problems. Even with the upgrade to the USC power plant, many people still criticize
the emissions from the power plant and question its effectiveness in improving air quality. This
study applied Community Multiscale Air Quality (CMAQ) modeling (Byun and Ching, 1999;
Byun and Schere, 2006) to examine the impact of the coal-fired power plant, with the use of
advanced USC technology and emission control systems, on the environmental PM2.5
concentrations in Taiwan relative to the old SC coal-fired power generator. The one-month
simulation that occurred in February 2020 was conducted to assess the emission source
contributions from the LPP. Moreover, PM$_{2.5}$ sampling was conducted hourly in the LPP to investigate the characteristics of PM$_{2.5}$ compositions over northern Taiwan.

The goals of this study are outlined as follows: (1) examine the effectiveness of the PM$_{2.5}$ reductions by switching from the old power generator (SC power generator) to the renovated system (USC power generator + emissions control system); (2) quantify the emission source contributions from the renovated LPP to the ambient PM$_{2.5}$ concentrations; and (3) investigate the characteristics of the PM$_{2.5}$ compositions in the LPP. Section 2 describes the emission estimates from the old and renovated LPP power generators, the design of CMAQ numerical experiments, and the observational datasets. The characteristics of the meteorological and air quality conditions of the one-month study period are addressed in Section 3. The discussions of the emission source contributions from the LPP are given in Section 4. Conclusions are given in Section 5. To our knowledge, this is the first study conducted in Taiwan that evaluates the emission source contributions from USC coal-fired power generators.

2 Materials and methods

2.1 Estimations of LPP emissions

The emissions from the old and renovated LPP units are provided using the internal statistical data from TPC in 2013 and 2019, respectively. The capacity of power generation in 2013 and 2019 is shown in Table 1. The electricity production was about four times higher in 2019 than the 2013 production. It is unfair to assess the 2013 and 2019 emissions directly. As a result, the emissions from the old 2013 LPP units are adjusted to have the same electricity production capacity as the renovated 2019 units to fairly assess the emission contributions and
their subsequent influence on air quality between the old and new units. The adjusted emissions are estimated according to Eq. (1).

\[
E_{p,i}^{(\text{adjusted})} = E_{p,i} \times \frac{\text{Power generation (USC)}}{\text{Power generation (SC)}}
\]

(1)

where \(E_{p,i}\) is the emissions of pollutant \(p\) released by power generation unit \(i\).

Table 1. Electricity production from LPP power generator units in 2013 (SC) and 2019 (USC) (unit: MWh year\(^{-1}\)).

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<thead>
<tr>
<th>#1</th>
<th>#2</th>
<th>#3</th>
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</thead>
<tbody>
<tr>
<td>2013 SC units</td>
<td>1763598.3</td>
<td>2156638.7</td>
</tr>
<tr>
<td>2019 USC units</td>
<td>6527860.6</td>
<td>5208488.6</td>
</tr>
</tbody>
</table>

Table 2 shows the annual emissions estimated from individual LPP units in 2013 and 2019. The original and adjusted emissions in 2013 are both provided. There are significant reductions in the emissions between the old power generator and the renovated system; in particular, the NO\(_X\) emissions are significantly reduced due to the installation of the NO\(_X\) emission control facility. Compared to the old SC power generator, the renovated unit (USC + emission control) can reduce SO\(_X\) emissions by 65%, NO\(_X\) emissions by 87%, and total suspended particle (TSP) emissions by 77%.

Table 2. Annual emissions (tons year\(^{-1}\)) of each LPP power generator unit in 2013 (SC units) and 2019 (USC units).

<table>
<thead>
<tr>
<th></th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013 SC (original)</td>
<td>504.554</td>
<td>675.364</td>
<td>NA</td>
<td>1179.917</td>
</tr>
<tr>
<td>SO(_X) 2013 SC (adjusted)</td>
<td>1867.578</td>
<td>1631.069</td>
<td>NA</td>
<td>3498.647</td>
</tr>
<tr>
<td>2019 USC</td>
<td>647.771</td>
<td>417.906</td>
<td>169.580</td>
<td>1235.26</td>
</tr>
</tbody>
</table>
2.2 Atmospheric Chemical Transport Modeling

The Weather Research and Forecasting (WRF) meteorological model (Skamarock et al., 2008), version 3.8.1, was conducted and provided hourly meteorological fields to drive the chemical transport model. The initial and boundary conditions were taken from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 dataset (Hersbach et al., 2020) which has a grid resolution of 0.25 degree. The CMAQ model version 5.2 (Byun and Schere, 2006) was used to simulate the atmospheric physical and chemical processes and to investigate the emission source contributions from the LPP. The carbon bond (CB06) chemical mechanism (Yarwood et al., 2020) and aerosol module version six (AERO6) (Appel et al., 2017) were applied to simulate gaseous and aerosol phase chemical reactions. The WRF-CMAQ system was run offline and with two nested domains (Fig. 1). The coarse domain (D1) had a spatial resolution of 15 km and encompassed East Asia. The fine domain (D2) had a spatial resolution of 3 km and covered Taiwan and the surrounding oceans. The land use data, topographical height, and soil texture were updated in the area of Taiwan to better resolve the heterogeneous land surface distributions within the WRF model (Cheng et al., 2013; Lin and Cheng, 2016; Cheng and Chen, 2018; Cheng et al., 2022).
The anthropogenic emissions in D1 come from the 2010 Model Inter-Comparison Study for Asia (MICS-Asia) emissions inventory (Li et al., 2017), and the anthropogenic emissions in D2 are from the Taiwan Emission Data System (TEDS-10, 2019), for which the base year is 2016. The stationary emission sources in Taiwan are updated according to the 2019 emission data reported from industrial companies. The LPP emissions are replaced with the estimated emissions listed in Table 2. The biogenic emissions are from the Model Of Emissions Of Gases And Aerosols From Nature (MEGAN) (Guenther et al., 2012). The initial conditions for all domains come from the CMAQ output of the previous day, and the boundary conditions of D1 are based on the default background profile datasets, which are static and do not change with time. The boundary conditions for D2 are provided by the D1 output. Please refer to Cheng et al.
(2019, 2021) for the detailed setup of the physical and chemical configurations of the WRF and CMAQ models.

One-month CMAQ simulations for February 2020 were conducted to assess the emission source contributions. In winter, the Asia continental high-pressure system dominates the synoptic weather conditions in East Asia, which typically steers the northeasterly monsoonal (NEM) flow over Taiwan. In February, the strength of the NEM flow weakens compared to the previous month, and with reduced synoptic winds, air pollutants are likely to accumulate in the emission source regions, which leads to the occurrence of air pollution events. During the study period, two severe PM$_{2.5}$ events (with a maximum $> 100$ μg m$^{-3}$) occurred.

Three numerical simulations were conducted (Table 3). The first experiment, USC, used the TEDS-10 anthropogenic emission inventory, but the LPP emissions were replaced with the TPC internal data for 2019, which reports the emissions from the three renovated USC units (refer to Table 2, 2019 USC emissions). The second experiment, SC, is similar to the USC experiment, but the LPP emissions are replaced with the TPC internal data for 2013, which reports the emissions from the two old SC units (refer to Table 2, adjusted 2013 SC emissions). The third experiment, noLPP, used the same setup as the first experiment but removed the LPP emissions. A comparison between the first and the second experiment reveals the impact of the renovated units (USC power generator and emission control system) relative to the old SC power generator. A comparison between the first and the third experiments reveals the emission source contributions from the LPP that used the advanced USC coal-fired power generator.
Table 3. CMAQ experimental designs.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Name</th>
<th>Emissions of LPP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>USC</td>
<td>2019 TPC internal data</td>
</tr>
<tr>
<td>2</td>
<td>SC</td>
<td>2013 TPC internal data</td>
</tr>
<tr>
<td>3</td>
<td>noLPP</td>
<td>remove LPP emissions</td>
</tr>
</tbody>
</table>

3 Characterization of meteorological and air quality observations

The hourly wind fields and PM$_{2.5}$ concentrations from the 77 Taiwan Environmental Protection Agency (TWEPA) surface air quality monitoring stations were used to characterize the air quality conditions during the study period and to validate the model results (refer to Fig. 1 for site locations). Due to the distinct characteristics of the meteorology and air quality, the TWEPA has divided the nation into seven subregions, namely, northern Taiwan (NT), the Chu-Miao area (CM), central Taiwan (CT), the Yun-Chia-Nan area (YCN), the Kao-Ping area (KP), Yilan (YI) and the Hua-Dong area (HD) (Fig. 1). The following evaluation and analysis are organized based on the five subregions in western Taiwan to facilitate the discussion and understanding of this study. The air quality conditions in eastern Taiwan are typically good and are excluded from this discussion.

Spatiotemporal diagrams of the observed wind fields and PM$_{2.5}$ concentrations from the TWEPA surface stations in February 2020 are presented in Fig. 2. During the study period, several severe PM$_{2.5}$ events occurred, and most of the events were associated with stagnant wind fields. The two most serious events occurred on 12–13 and 24–25 February when the highest PM$_{2.5}$ concentration approached 100 μg m$^{-3}$. 
Figure 2. Distributions of the wind fields (upper panel), PM$_{2.5}$ concentration (μg m$^{-3}$) and wind vectors (bottom panel) in spatiotemporal diagrams based on observations from 77 TWEPA surface air quality monitoring stations. The horizontal axis indicates the time from February 1–29, 2020. From top to bottom, the vertical axis represents the individual stations sorted from north to south according to the order of their locations in the NT, CM, CT, YCN, and KP subregions. At the bottom of the figure, the colored bars identify the weather type for each individual day.
During the one-month study period, the synoptic weather pattern over Taiwan was mainly affected by the Asian continental anticyclone. According to the variations in the synoptic weather systems, three prevalent weather types were identified during the one-month study period, following Hsu and Cheng (2019). Fig. 3 presents the composite plot of the mean sea level pressure (MSLP) and surface wind fields from the 15 km WRF simulation results averaged for the days that occurred during each weather type. The corresponding distributions of the PM$_{2.5}$ concentrations and wind vectors from the TWEPA surface stations for each weather type are also shown in Fig. 3.

The first weather type is dominated by the strong NEM flow due to the intrusion of the Asian continental anticyclone system. With the eastward movement of the anticyclone, the prevailing wind over Taiwan is affected by the continental high-pressure peripheral circulation (i.e., the second type). The synoptic wind turns from a strong northerly flow into a weakened northeasterly to easterly flow. The Central Mountain Range runs from northern to southern Taiwan, with peaks as high as 3952 m. Northern Taiwan, which is affected by the synoptic weather system, exhibits stronger wind flows. In contrast, other regions of western Taiwan exhibit weaker wind fields due to mountain blocking of the prevailing wind. After the eastward passage of the continental anticyclone, the influence from the synoptic weather system weakens (i.e., weak synoptic weather, the third type), and the synoptic wind turns into easterly to southeasterly (i.e., the third type). Due to the mountain blocking of the prevailing wind, western Taiwan experiences a stagnant wind field and strong atmospheric stability. Among the 29 days during February 2020, 9, 10, and 10 days are subjectively classified into the first, second, and
third weather types based on the distributions of the MSLP. The weather types over the 29 days during February 2020 are also specified in Fig. 2.

**Figure 3.** (Left Panel) Composite plot of MSLP (hPa; shaded colors) and surface wind vector (m s$^{-1}$) averaged for the days occurring during the three weather types using the 15 km WRF simulation results. (Right Panel) Distributions of the PM$_{2.5}$ concentrations and wind vectors from the TWEPA surface stations averaged for the days during the three weather types.
For the first weather type, due to the strong NEM flow, the PM$_{2.5}$ concentrations from northern to central western Taiwan are lower than those over southwestern Taiwan. For the second weather type, the northeasterly winds are weaker and the PM$_{2.5}$ concentrations are higher than those during the first weather type. The highest PM$_{2.5}$ concentrations occurred during the third weather type. Due to the mountain blocking the prevailing easterly wind, low wind speeds and strong subsidence often occur over the leeside of the mountains, which leads to PM$_{2.5}$ accumulation and severe PM$_{2.5}$ events in western Taiwan.

Due to the distinct meteorological and PM$_{2.5}$ distributions during these three weather types, the subsequent discussions are separated according to the three weather types to examine the impact of LPP emissions on the surrounding environments under different weather conditions.

4 Results and discussion

4.1 Model Performance

To ensure the model reliability, the simulated temperature, wind and PM$_{2.5}$ concentrations are evaluated with the TWEPA surface stations (refer to Fig. 1 for site locations). The mean bias (MB) (Eq. 2) and root mean square error (RMSE) (Eq. 3) are calculated from the simulation outputs and the TWEPA observations during the one-month simulation period.

\[
MB = \frac{\sum_{i=1}^{n}(Model_i - OBS_i)}{n}
\]  

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Model_i - OBS_i)^2}{n}}
\]
where n is the number of TWEPA stations, Model_i is the hourly simulation results at the grid point nearest to the station from the 3 km simulation domain, and OBS_i denotes the hourly observation data.

Table 4 presents the results of the performance statistics averaged during the one-month period for daytime (07–18 local standard time, LST) and nighttime (19–06 LST) hours. The temperature presents a cold bias, while the wind speeds are overestimated; in particular, the northerly flow is too strong. The PM_{2.5} concentrations are underestimated during the day and overestimated during the night. These biases have been reported in several prior studies (Hsu et al., 2019; Cheng et al., 2022; Yang et al., 2022). Although model biases exist, the model captures the general PM_{2.5} variations well and with overall performance that is in reasonable agreement with the observation data.

Table 4. Performance statistics for WRF-simulated temperature, wind speed, U and V wind vectors and CMAQ (USC experiment)-simulated PM_{2.5} concentrations from February 2020.

<table>
<thead>
<tr>
<th></th>
<th>AVE</th>
<th>MB</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OBS</td>
<td>Model</td>
<td></td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daytime (07–18 LST)</td>
<td>20.62</td>
<td>20.23</td>
<td>-0.39</td>
</tr>
<tr>
<td>Nighttime (19–06 LST)</td>
<td>17.67</td>
<td>17.36</td>
<td>-0.31</td>
</tr>
<tr>
<td>Wind speed (m s(^{-1}))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daytime (07–18 LST)</td>
<td>2.24</td>
<td>3.21</td>
<td>0.97</td>
</tr>
<tr>
<td>Nighttime (19–06 LST)</td>
<td>1.60</td>
<td>2.38</td>
<td>0.78</td>
</tr>
<tr>
<td>U vector (m s(^{-1}))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daytime (07–18 LST)</td>
<td>-0.20</td>
<td>0.18</td>
<td>-0.02</td>
</tr>
<tr>
<td>Nighttime (19–06 LST)</td>
<td>-0.56</td>
<td>-0.80</td>
<td>-0.24</td>
</tr>
<tr>
<td>V vector (m s(^{-1}))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daytime (07–18 LST)</td>
<td>-1.24</td>
<td>-1.80</td>
<td>-0.56</td>
</tr>
<tr>
<td>Nighttime (19–06 LST)</td>
<td>-0.87</td>
<td>-1.24</td>
<td>-0.37</td>
</tr>
<tr>
<td>PM_{2.5} (μg m(^{-3}))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daytime (07–18 LST)</td>
<td>21.05</td>
<td>19.06</td>
<td>-1.99</td>
</tr>
<tr>
<td>Nighttime (19–06 LST)</td>
<td>22.53</td>
<td>23.51</td>
<td>0.98</td>
</tr>
</tbody>
</table>
In addition to the overall assessment of the model performance, as shown in Table 4, the time-series comparison of the PM$_{2.5}$ concentrations between the observations and USC CMAQ simulation at the Linkou air quality monitoring station is presented in Fig. 4. The station is in the southeast direction of the LPP. It is approximately 9-km from the LPP (refer to Fig. 1 for site location). The CMAQ model simulates the PM$_{2.5}$ temporal variations very well and is in good agreement with the observed features.

![Figure 4. Time series comparison of the observed (black) and simulated (red) PM$_{2.5}$ concentrations ($\mu g m^{-3}$) at the Linkou air quality monitoring station in February 2020.](image)

Additionally, PM$_{2.5}$ component sampling in the LPP was conducted to characterize the PM$_{2.5}$ compositions with inductively coupled plasma–mass spectrometry (ICP–MS). Details about the PM$_{2.5}$ sampling equipment can be found in Le et al. (2023) and Nguyen et al. (2023). Fig. 5 shows the temporal variability in sulfate (SO$_4^{2-}$), nitrate (NO$_3^-$), ammonium (NH$_4^+$), elemental carbon (EC), organic carbon (OC), and other particulate matter from 7–12 February in the LPP derived from observations and USC CMAQ simulations. The PM$_{2.5}$ concentrations were low on February 7 (< 10 $\mu g m^{-3}$) due to frontal precipitation and gradually increased to 20–25 $\mu g m^{-3}$ on February 9 and 10 due to the long-range transport of air pollutants from China via the
NEM flow. On February 9 and 10, the major PM$_{2.5}$ composition was sulfate. Previous studies (Chang et al., 2022) have also reported that sulfate is the major PM$_{2.5}$ component in northern Taiwan when the prevailing winds are dominated by NEM flow. When the Asian continental anticyclone was located farther away from Taiwan, the wind fields became weaker in western Taiwan on 11 and 12 February. The PM$_{2.5}$ concentrations increased from 25 to 40 $\mu$g m$^{-3}$, and nitrate was the major PM$_{2.5}$ component. According to Chuang et al. (2022), the nitrate concentration tends to increase with stagnant wind flow conditions in Taiwan. The characterization of the PM$_{2.5}$ sampling indicates that the emission compositions are complicated in the LPP, and the PM$_{2.5}$ problem in northern Taiwan is contributed by different emission sources, depending on the wind flow variations. The analysis also reveals that the power plant, area, traffic, other point sources, and even the transboundary emissions from other countries all contribute to the complex PM$_{2.5}$ problem in northern Taiwan, yet the tracking of the emission sources is not the focus of this study. Other than that, the CMAQ simulation captures the general variations in the PM$_{2.5}$ components well, such as the high portions of sulfate when the wind flow was northeasterly and high portions of nitrate when the wind flow was weak. The PM$_{2.5}$ concentrations were underestimated on 10 February 2020.
Figure 5. Time series of the SO$_4^{2-}$, NO$_3^-$, NH$_4^+$, EC, OC concentrations and other particulate matter from 7–12 February 2020 in LPP from observation (upper) and USC CMAQ simulation (bottom).

4.2 Impact of emissions from LPP

The emission contributions from LPP to the ambient PM$_{2.5}$ concentrations are estimated based on CMAQ simulation experiments and separated into three different weather types. First, three individual days representative of each weather type are selected to examine the emission source contributions. Fig. 6 presents the 3 km CMAQ-simulated PM$_{2.5}$ concentrations from the USC experiment, the PM$_{2.5}$ difference between the USC and SC experiments, and the PM$_{2.5}$ difference between the USC and noLPP experiments, averaged on February 5, 10 and 13. On February 5, the wind field was dominated by the NEM flow (type 1). With strong wind flow, the impact of LPP emissions on PM$_{2.5}$ concentrations is insignificant. By switching from SC to USC coal-fired units, the PM$_{2.5}$ reduction is less than 0.2 $\mu$g m$^{-3}$ (Fig. 6b). The LPP emission contributions to the ambient PM$_{2.5}$ concentrations are less than 0.1 $\mu$g m$^{-3}$ (Fig. 6c). These results
illustrate that with strong NEM flow, the impact of LPP emissions on the surrounding environment is trivial.

On February 10, with the eastward movement of the continental high-pressure system, the northeasterly to easterly wind prevailed over Taiwan (type 2). The areas affected mostly by the LPP emissions are the downwind regions (from central to southwestern Taiwan). By upgrading from SC to USC units, the PM$_{2.5}$ reductions can reach 0.7 μg m$^{-3}$ (Fig. 6e). The LPP emission contributions to the environmental PM$_{2.5}$ concentrations are insignificant and are less than 0.3 μg m$^{-3}$ (Fig. 6f).

On February 13, the synoptic wind flow was southeasterly, and the wind field over the LPP and northern Taiwan, the leeside region, was weak (type 3). The observed PM$_{2.5}$ concentrations were severe and approached 100 μg m$^{-3}$ in western Taiwan (refer to Fig. 2). The reduction in PM$_{2.5}$ as a result of switching from the SC to USC units was apparent, reaching 3.14 μg m$^{-3}$ (Fig. 6h). The contributions from LPP emissions to PM$_{2.5}$ concentrations reached 1.05 μg m$^{-3}$ (Fig. 6i). The PM$_{2.5}$ reduction reached above 10 μg m$^{-3}$ at 03 LST on February 13 (Fig. S1b). These results indicate that upgrading LPP from SC to USC power generators can effectively improve air quality conditions. PM$_{2.5}$ reduction is the most effective in the areas of northern Taiwan. As shown in Figure 2, the wind speed was weak and less than 2 m s$^{-1}$ between February 11 and 15 in northern Taiwan. With persistent weak wind, PM$_{2.5}$ continuously accumulated over the source region, and the impact of LPP emissions on the PM$_{2.5}$ concentrations became significant. The contribution from LPP emissions to the PM$_{2.5}$ concentration reached 3.29 μg m$^{-3}$ at 03 LST on February 13 (Fig. S1c).

On the other hand, the model simulations show the increases in PM$_{2.5}$ concentrations over central western Taiwan with the upgrade of LPP (Fig. 6h). The component analysis of the
simulated PM$_{2.5}$ indicates increases in the sulfate, nitrate, and organic carbon concentrations (Fig. S2). The atmospheric oxidants such as hydroxyl radical and hydrogen peroxide (Fig. S2) also increase, which can enhance atmospheric oxidation processes and increase PM$_{2.5}$ concentrations. The decrease in NO$_X$ concentration can degrade the photochemical reaction of NO$_X$ and VOCs. At the same time, the chemical oxidation of gaseous VOC into organic carbon is enhanced. The analysis revealed complex atmospheric chemical reactions in western Taiwan.
Figure 6. (a), (d), and (g) are the daily averaged PM$_{2.5}$ concentrations from surface observations (circle mark) and the USC experiment (shading color), and layered with the simulated wind vector. (b), (e) and (h) are differences in the PM$_{2.5}$ concentrations between the SC and USC experiments (negative values indicate PM$_{2.5}$ reductions due to the upgrade from SC to USC). (c), (f) and (i) are differences in the PM$_{2.5}$ concentrations between the USC and noLPP experiments.
(positive values indicate higher concentrations from the USC experiment). For the difference
plot, the maximum and minimum are provided. From top to the bottom are the results from the
individual days, on 5, 10, and 13 February 2020.

Furthermore, Fig. 7 presents the PM$_{2.5}$ contributions due to the LPP emissions in an
hourly time-series variation based on the difference between the USC and noLPP simulation
results. The classified three weather types are also specified in the figure. The evaluations are
assessed in the areas where the impact is the most significant. The grid location with the
maximum impact is selected, together with the surrounding 8 grids (approximately 81 square km
area), for the evaluation. Please note that the areas with the maximum impact are changeable due
to the variable wind fields. When the NE wind prevails in the area, the downwind locations from
central to southwestern Taiwan are likely to be affected. However, with stagnant wind flow, the
impact is the most significant in the LPP emission source region of northern Taiwan.

With strong NEM flow, the impact of the LPP emissions is insignificant; however, as the
wind transitions from northerly to easterly flow, the impact gradually increases to 0.5 μg m$^{-3}$.
When the Asian continental high-pressure system moved further away from Taiwan, the weak
wind and strong stability limited the ventilation capability of the air pollutants. The influence of
the LPP emissions increased, and the hourly contribution reached 5.1 μg m$^{-3}$ on February 12.
Within the one-month simulation, the impact is the most significant from February 11 to 15 due
to the persistent weak winds.
Figure 7. Hourly contributions from the USC coal-fired LPP emissions to the PM$_{2.5}$ concentrations for the areas where the impact is the most significant.

Finally, the LPP impact over the five air quality subregions in western Taiwan is quantified and averaged for the days in each weather type (Table 5). The estimation targets the areas where the impact is the most significant (9 grids) in each air quality subregion. Under the influence of strong NEM flow (type 1) and high-pressure peripheral circulation (type 2), the area most affected by LPP emissions is over the CT subregion, followed by the YCN subregion. The PM$_{2.5}$ reduction due to the upgrade from the SC to USC power units is approximately 0.43 and 0.81 μg m$^{-3}$, respectively, in type 1 and 2 weather conditions. The contribution from the LPP emissions is approximately 0.25 μg m$^{-3}$ (1.13%) in the CT region in weather type 2. With the weak influence of the synoptic weather system, western Taiwan exhibits stagnant and stable conditions that favor PM$_{2.5}$ accumulations (type 3), and the PM$_{2.5}$ reductions reached 2.04 μg m$^{-3}$ (8.02%) in the NT region. The contribution to the PM$_{2.5}$ concentration was approximately 0.95 μg m$^{-3}$ (4.06%). The impact is the most significant in the NT area, followed by the CM area.

Table 5. PM$_{2.5}$ reductions (μg m$^{-3}$) due to the upgrade from SC to USC units, and PM$_{2.5}$ contributions (μg/m$^{3}$) from the LPP emissions in five air quality subregions, averaged for the
days in three weather types. The relative proportions (%) are presented in parentheses. The grids (81 square km area) with the maximum impact are assessed. OBS and MODEL are the mean of the PM$_{2.5}$ concentrations averaged from the surface observation stations in each air quality subregion and the corresponding simulation result, respectively.

<table>
<thead>
<tr>
<th>NEM flow (type 1)</th>
<th>OBS (μg m$^{-3}$)</th>
<th>MODEL (μg m$^{-3}$)</th>
<th>PM$_{2.5}$ Reduction (μg m$^{-3}$)</th>
<th>PM$_{2.5}$ Contribution (μg m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NT</td>
<td>12.31</td>
<td>11.98</td>
<td>-0.13 (-1.07%)</td>
<td>0.08 (0.67%)</td>
</tr>
<tr>
<td>CM</td>
<td>11.71</td>
<td>10.24</td>
<td>-0.10 (-0.97%)</td>
<td>0.06 (0.59%)</td>
</tr>
<tr>
<td>CT</td>
<td>14.73</td>
<td>16.04</td>
<td>-0.43 (-2.61%)</td>
<td>0.16 (1.00%)</td>
</tr>
<tr>
<td>YCN</td>
<td>18.70</td>
<td>17.99</td>
<td>-0.32 (-1.75%)</td>
<td>0.13 (0.72%)</td>
</tr>
<tr>
<td>KP</td>
<td>23.50</td>
<td>16.10</td>
<td>-0.22 (-1.35%)</td>
<td>0.10 (0.62%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>High-pressure peripheral circulation (type 2)</th>
<th>OBS (μg m$^{-3}$)</th>
<th>MODEL (μg m$^{-3}$)</th>
<th>PM$_{2.5}$ Reduction (μg m$^{-3}$)</th>
<th>PM$_{2.5}$ Contribution (μg m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NT</td>
<td>13.18</td>
<td>8.10</td>
<td>-0.11 (-1.34%)</td>
<td>0.04 (0.49%)</td>
</tr>
<tr>
<td>CM</td>
<td>15.19</td>
<td>11.20</td>
<td>-0.24 (-2.10%)</td>
<td>0.09 (0.80%)</td>
</tr>
<tr>
<td>CT</td>
<td>21.72</td>
<td>22.08</td>
<td>-0.81 (-3.54%)</td>
<td>0.25 (1.13%)</td>
</tr>
<tr>
<td>YCN</td>
<td>25.80</td>
<td>22.61</td>
<td>-0.50 (-2.16%)</td>
<td>0.19 (0.84%)</td>
</tr>
<tr>
<td>KP</td>
<td>27.23</td>
<td>18.42</td>
<td>-0.35 (-1.86%)</td>
<td>0.12 (0.65%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weak synoptic weather (type 3)</th>
<th>OBS (μg m$^{-3}$)</th>
<th>MODEL (μg m$^{-3}$)</th>
<th>PM$_{2.5}$ Reduction (μg m$^{-3}$)</th>
<th>PM$_{2.5}$ Contribution (μg m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NT</td>
<td>21.48</td>
<td>23.39</td>
<td>-2.04 (-8.02%)</td>
<td>0.95 (4.06%)</td>
</tr>
<tr>
<td>CM</td>
<td>24.24</td>
<td>24.16</td>
<td>-1.02 (-4.05%)</td>
<td>0.32 (1.32%)</td>
</tr>
<tr>
<td>CT</td>
<td>31.08</td>
<td>26.87</td>
<td>-0.72 (-2.61%)</td>
<td>0.18 (0.67%)</td>
</tr>
<tr>
<td>YCN</td>
<td>33.33</td>
<td>24.38</td>
<td>-0.44 (-1.77%)</td>
<td>0.13 (0.53%)</td>
</tr>
<tr>
<td>KP</td>
<td>22.61</td>
<td>14.89</td>
<td>-0.22 (-1.46%)</td>
<td>0.07 (0.47%)</td>
</tr>
</tbody>
</table>

These analyses demonstrate that the impact of LPP emissions on the ambient PM$_{2.5}$ concentrations is strongly affected by the synoptic weather pattern. Under the influence of strong NEM flow, the contributions from LPP emissions to the PM$_{2.5}$ concentrations are trivial and negligible. When the synoptic wind flow transitions from the strong NEM wind into the continental peripheral circulation, the impact of the LPP emissions slightly increases. With persistent weak winds, locally emitted air pollutants can continuously accumulate in emission source regions, and emissions from advanced USC units can make substantial PM$_{2.5}$ contributions.
5 Conclusions

The emissions released from coal-fired power plants have been a major concern due to
the adverse effects they have on air quality conditions and the dangers they pose to the human
body. The LPP was built with SC coal-fired power generators before 2013 and was renovated
with USC coal-fired units, which began operation in 2016. Moreover, advanced protection
facilities were constructed to control and reduce air pollutant emissions. Enhancing thermal
efficiency can greatly reduce air pollutant emissions; however, its impact on ambient air
pollutant concentrations under various meteorological conditions is rarely examined. It is
important to quantify the PM$_{2.5}$ contributions from the LPP emissions even with advanced USC
units, particularly when meteorological conditions are unfavorable for air pollutant dispersion.
This study applied the CMAQ model to assess the emission source contributions from LPP to the
PM$_{2.5}$ concentrations.

The numerical simulation results demonstrate that the impact of LPP emissions on
ambient PM$_{2.5}$ concentrations is strongly affected by the synoptic weather pattern. Under the
influence of strong NEM flow, the contributions from LPP emissions to PM$_{2.5}$ concentrations are
trivial and negligible. The impact of the LPP emissions slightly increased when the synoptic
wind field transitioned from NEM flow (type 1) to continental high-pressure peripheral
circulation (type 2). The areas affected by the LPP emissions were mainly over downwind
regions (central to southwestern Taiwan). When the wind flow became weak, the impact of the
LPP emissions on the PM$_{2.5}$ concentrations was enhanced, with the highest impact over the areas
surrounding the LPP and over northern Taiwan. Although the power plant emits vast amounts of
air pollutants, with upgrades and enhanced control facilities, air pollution can be improved.
However, the LPP emissions still contribute to environmental degradation. The contributions are noticeable, significant, and cannot be ignored particularly when the wind flow becomes stagnant. Notably, LPP only contributes a certain amount to PM$_{2.5}$ concentrations. In contrast, many other sources, such as traffic, area, other point sources, and even transboundary emissions, all contribute substantially to the PM$_{2.5}$ problems in Taiwan. Reductions in power plant emissions are needed, while other critical emissions, such as traffic and area sources, need to be regulated to further improve the air quality in Taiwan. The analysis of the PM$_{2.5}$ sampled from the LPP revealed that sulfate is a major portion of the air pollutants when a strong NEM flow prevails over Taiwan, while the major PM$_{2.5}$ component is nitrate when the wind flow becomes stagnant. Although the CMAQ model presents certain biases, it can simulate the general PM$_{2.5}$ compositions of the observed features.

This study clarifies the contributions of LPP emissions to PM$_{2.5}$ concentrations through a series of numerical air quality experiments. Regarding air pollution risks from the power plant, this information is important for future energy planning and environmental management. Energy planning should put the environmental sustainability as the top concern. Although coal-fired electricity generation will decline in the future, it remains an important energy source for decades. The results are not only applicable in Taiwan but also serve as a reference for other countries that encounter serious air pollution problems.

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