Potential impacts of electric vehicles on air quality in Taiwan

Nan Li a, Jen-Ping Chen a,⁎, I-Chun Tsai b, Qingyang He a, Szu-Yu Chi a, Yi-Chiu Lin c, Tzung-May Fu d

a Department of Atmospheric Sciences, National Taiwan University, Taipei, Taiwan
b Research Center of Environmental Changes, Academia Sinica, Taipei, Taiwan
c Taiwan Typhoon and Flood Research Institute, Taipei, Taiwan
d Department of Atmospheric and Oceanic Sciences and Laboratory for Climate and Ocean-Atmosphere Studies, Peking University, Beijing, China

HIGHLIGHTS
• Air quality impact of EV is evaluated with WRF-CMAQ model under different scenarios.
• Net emissions of NOx, VOCs, CO and PM2.5 would be reduced by introducing EV to Taiwan.
• EV penetration would reduce pollution episodes in Taiwan’s major cities by up to 60%.

GRAPHICAL ABSTRACT

ABSTRACT

The prospective impacts of electric vehicle (EV) penetration on the air quality in Taiwan were evaluated using an air quality model with the assumption of an ambitious replacement of current light-duty vehicles under different power generation scenarios. With full EV penetration (i.e., the replacement of all light-duty vehicles), CO, VOCs, NOx and PM2.5 emissions in Taiwan from a fleet of 20.6 million vehicles would be reduced by 1500, 165, 33.9 and 7.2 Gg yr−1, respectively, while electric sector NOx and SO2 emissions would be increased by up to 20.3 and 12.9 Gg yr−1, respectively, if the electricity to power EVs were provided by thermal power plants. The net impacts of these emission changes would be to reduce the annual mean surface concentrations of CO, VOCs, NOx and PM2.5 by about 260, 11.3, 3.3 ppb and 2.1 μg m−3, respectively, but to increase SO2 by 0.1 ppb. Larger reductions tend to occur at time and place of higher ambient concentrations and during high pollution events. Greater benefits would clearly be attained if clean energy sources were fully encouraged. EV penetration would also reduce the mean peak-time surface O3 concentrations by up to 7 ppb across Taiwan with the exception of the center of metropolitan Taipei where the concentration increased by ~2 ppb. Furthermore, full EV penetration would reduce annual days of O3 pollution episodes by ~40% and PM2.5 pollution episodes by 6–10%. Our findings offer important insights into the air quality impacts of EV and can provide useful information for potential mitigation actions.

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1. Introduction

The rapid growth of transportation via automobiles is raising worldwide concerns about the associated fossil energy crisis and environmental pollution. Taiwan is one of the most high-traffic places in the world with vehicle ownership (including motorcycles) having reached ~900 vehicles/1000 people in the year 2010. To drive these vehicles, about 9.7 billion liter gasoline and 4.4 billion liter diesel are consumed each year. Additionally, large amounts of exhaust gases are emitted into the atmosphere. According to the Taiwan Environmental Protection Administration, 50% of NOx emissions in Taiwan were caused by a fleet of 21.7 million vehicles (EURO IV) in 2010 (MTC, 2010a; TWEPA, 2015), and the situation was even worse in large cities such as the Taipei metropolis, where 85% of NOx were emitted by on-road traffic (TWEPA, 2015). To address these issues, the electric vehicle (EV) is being considered as a potential option for both energy saving and pollution mitigation (e.g., Brinkman et al. 2010; Helmers and Marx, 2012; Tessum et al. 2014). Compared with conventional vehicles, EVs are more energy efficient and have zero exhaust emissions in street canyons. However, generating electricity to power these vehicles would engender additional emissions from power plants.

Current studies have predicted a wide range of emission changes from the introduction of EVs, depending on assumptions about EV penetration percentage and charging scenarios as well as local emission characteristics (Sioshansi and Denholm 2009; Huo et al. 2010, 2013; Wu et al. 2012; Lang et al. 2013; Nichols et al. 2015). Sioshansi and Denholm (2009) assumed a low penetration (<15%) of plug-in hybrid electric vehicles (PHEVs) and the flexible charging of vehicles under smart grid controls in Texas, USA. They suggested that a PHEV fleet could actually reduce electric sector NOx emissions during the ozone season, despite the additional charging load. In contrast, Huo et al. (2010) pointed out that EV penetration in China would increase SO2 and NOx emissions per vehicle-kilometer by two- to tenfold if the electricity were sourced from the current grid. Lang et al. (2013) agreed that net emission would increase in China, and suggested that increments in SO2 and NOx emissions would result from the high proportion of coal-fired energy generation.

Beyond estimating emission changes, only a limited number of studies have focused on the impacts of EVs on air quality levels, even though this topic is in need of much further detailed analysis in areas including chemistry and transport modeling (Thompson et al. 2009; Brinkman et al. 2010; Soret et al. 2014; Tessum et al. 2014). Brinkman et al. (2010) used an air quality model to explore the potential impacts of PHEVs on O3 concentration in Denver, USA, in the summer of 2006, by considering different PHEV penetration levels and charging scenarios. They estimated that, under 100% PHEV penetration, peak 8-h average O3 concentration would be reduced by 2–3 ppb on most days, but that O3 would increase in specific areas near central Denver. Thompson et al. (2009) assumed that PHEVs replaced 20% of the gasoline vehicles in the northeastern USA and were all charged at night. Their simulated peak 8-h average O3 concentrations decreased by 2–6 ppb across urban areas under this scenario, but increased by up to 8 ppb in highly localized areas. Tessum et al. (2014) analyzed environmental health impacts of EVs across the entire USA by assuming a replacement of 10% of the vehicle fleet in 2020 under different powering scenarios. They found that powering EVs using electricity from corn ethanol or coal would increase environmental health impacts by ~80%, while using low-emitting electricity from natural gas or renewable energy would reduce the impacts by 50% or more.

The purpose of this study is to explore the potential impacts of switching conventional vehicles to EVs on air quality in Taiwan. We used a regional chemical model to simulate gaseous and particulate pollutants in Taiwan in the year 2010, and compared the results with the hourly surface chemical measurements from a network of 69 monitoring sites. We discussed detailed environmental impacts of EVs based on assumptions about ambitious vehicle replacements and different electricity supply scenarios.

2. Methods and data

2.1. Electric vehicle scenarios

To understand the prospective impact of EV penetration on air quality in Taiwan, we assumed that light-duty vehicles (motorcycles and light-duty passenger cars, which account for 95% of the total vehicles in Taiwan) were 100% replaced by EVs, and that the additional demand for electricity was leveled on power plants as they existed in 2010. Although this ambitious full penetration of EV is not realistic in the short term and the characteristics of both vehicle and power plant fleet would change over time, this hypothetical case provided an insight into the maximum potential benefits from vehicle replacement. Replacements of buses and trucks were not considered in this study, partly due to their minor numbers and partly due to the high uncertainties in estimating their battery efficiency rate. Although some hybrid electric buses are already on the streets, heavy trucks powered by electricity currently remain at the concept stage.

The electricity to power EVs was calculated as follows:

\[ ED = \sum_{i} (VP_i \times VU_i \times VKT_i \times BE_i)/(TE \times CE_i) \] (1)

where \( ED \) is the total electricity demand (kWh) by EVs; \( i \) is the vehicle type; \( VP \) is the vehicle population; \( VU \) is the vehicle usage rate (%); \( VKT \) is the annual mean vehicle kilometers traveled (km); \( BE \) is the average battery efficiency rate (kWh km\(^{-1}\)); \( TE \) is the electricity transmission efficiency (%); and \( CE \) is the electric vehicle charging efficiency (%). \( VP \) and \( VU \) were sourced from the monthly statistics of transportation and communications in Taiwan (MTC, 2010a). \( VKT \) was obtained from the annual reports of motorcycles, private and business light-duty passenger cars in Taiwan (MTC, 2010b, 2011a,b). \( BE \) was the average value for typical electric vehicles obtained from the yearbook of energy-saving and new energy vehicles (EBYENEV, 2011). \( TE \) was set to 96% following the Taiwan energy statistical yearbook (BEMEA, 2010), and \( CE \) was set to 91% following Shi et al. (2013). These details are summarized in Table 1.

EV penetration generally would shift emissions from vehicle exhausts to electric generating units. The resulting additional electricity demand was estimated at 58.1 billion kWh. Providing power plants to meet the electricity demand is hence an important parameter for evaluating the consequent air quality impacts. Table S1 summarizes power generations from different sources in Taiwan 2010. Thermal power (mainly coal-fired) accounts for 80% of the total electricity generation, whereas “clean” powers (nuclear, hydro, geothermal, solar photovoltaic and wind energy) provided the remaining 20%. To better evaluate the prospective impacts of EV, we conducted three scenario simulations in this study: (1) base case (BASE), (2) EV powered by thermal power (EVTP), and (3) EV powered by clean power (EVCP). The first scenario provided a baseline representing 2010 pollutant emissions and air quality levels in Taiwan. The other two scenarios considered the hypothetical adaptation of EV and assumed that the required electricity would be completely sourced from thermal power plants (EVTP) or from clean power sources (EVCP). Comparing these latter two scenarios with the BASE case allowed an evaluation of the degree of environmental impacts under different power generation modes at a high EV penetration level.

2.2. Air quality model

The Community Multi-scale Air Quality model (CMAQ) version 4.7.1 (Binkowski and Roselle 2003; Byun and Schere 2006) was used to simulate gaseous pollutants and aerosols in Taiwan. Meteorological fields to drive CMAQ were obtained using the Weather Research and Forecasting model (WRF) version 3.5.1 (Skamarock et al. 2008). We applied three nested domains (Fig. 1a) with horizontal resolutions of 27, 9 and...
The simulation was conducted for a period of one year, from January to December 2010.

SAPRC-99 (Carter 2000; Carlton et al. 2010) was used to represent gas-phase chemical mechanisms. Photolysis rates were estimated by simulated clear-sky photolysis ratio, and then corrected for cloud cover (Byun and Schere 2006). We also simulated Asian and local dust as per Chen et al. (2004) and Lin et al. (2015). Removal of gases and aerosols was implemented with both wet and dry deposition mechanisms following Byun and Schere (2006). In addition, secondary organic aerosol (SOA) formation via the irreversible uptake of dicarbonyls (glyoxal and methylglyoxal) by wet aerosols and cloud droplets was included following Fu et al. (2008). This formation pathway was implemented into CMAQ by Li et al. (2013), and might constitute an important source of SOA in Taiwan (Tsai et al. 2015).

2.3. Emission inventories

This study considered emissions of SO$_2$, NO$_x$, VOCs, CO, NH$_3$, and PM$_{2.5}$ from power plants, transportation and other source sectors. Table 2 summarizes the annual emissions in Taiwan during 2010 in the BASE case and the changes associated with the EV scenarios. Domestic emissions from power plants, transportation and other anthropogenic source sectors (including industry, residential, agriculture and open biomass burning) for the year 2010 were obtained from Taiwan Emission Data System (TEDS) version 8.1 (TWEPA, 2015). This emission inventory has a spatial resolution of 1 x 1 km. We applied diurnal and seasonal variations to the emissions based on activity statistics and surface measurements. Emissions from anthropogenic sources for the rest of Asia were taken from the inventories developed by Li et al. (2015) and Wiedinmyer et al. (2011). Emissions from biogenic sources for both Taiwan and the rest of the model domain were calculated using the MEGAN algorithm (Guenther et al. 2006), driven by meteorological fields simulated by WRF, and land cover and vegetation data from MODIS. Total annual emissions in Taiwan were estimated as follows: 120 Gg SO$_2$, 263 Gg NO$_x$, 1110 Gg VOCs, 1940 Gg CO, 188 Gg NH$_3$ and 72.8 Gg PM$_{2.5}$. Power generation was an important contributor of SO$_2$ (37%) and NO$_x$ (27%) emissions, but played a minor role for other pollutants (<5%). Transportation sources dominated CO emissions (91%) and also contributed 19–48% to NO$_x$, VOCs and PM$_{2.5}$ emissions. Fig. 2 shows the spatial distributions of total emissions and emissions from light-duty vehicles in Taiwan. Light-duty vehicles strongly contributed to emissions mostly in major cities (Fig. 2b), such as Taipei (northern Taiwan), Taichung (central Taiwan) and Kaohsiung (southern Taiwan); however rural areas also showed significant emissions, due to the dense network of county routes and express ways systems around these regions. Major thermal power plants in Taiwan are located in the coastal areas (Fig. S1) because electricity generation requires a large quantity of cooling water. The plant located in Taichung (TC, 120.46°E, 24.19°N) is currently the largest coal-fired power plant in the world, contributing 35% to electric sector SO$_2$ and NO$_x$ emissions in Taiwan. Details of each thermal power plant are summarized in Table S2.

![Fig. 1. The simulation domain and locations of the eight selected surface observation sites in Taiwan, including four urban sites (circles) and four rural sites (triangles). The yellow indicates conventional observations of SO$_2$, NO$_x$, O$_3$, CO and PM$_{2.5}$ concentrations, and the blue indicates photochemical observations of VOCs concentrations.](image-url)
Introducing EV significantly changed the emissions. Emissions from light-duty vehicles were completely removed in both EV scenarios, while emissions from power plants were increased by 25% in EVTP and 0% in EVCP. In the EVTP scenario, NOx emissions from transportation were reduced by 33.9 Gg yr\(^{-1}\) (27% of transportation NOx emissions), but 20.3 Gg yr\(^{-1}\) were added from power plants. CO, VOCs and PM\(_{2.5}\) emissions from transportation were estimated to be 1500 Gg yr\(^{-1}\) (85%), 165 Gg yr\(^{-1}\) (79%) and 7.2 Gg yr\(^{-1}\) (27%) lower than those in the BASE case, respectively, while the additional power demands from thermal power plants caused <1% increases in these emissions. The percentage reductions in VOCs and CO emissions were significantly larger than those in other pollutants, because light-duty vehicles had larger contributions to these categories than to other pollutants. The change in SO\(_2\) emissions stood out in that it was the only pollutant that increased (by 12.7 Gg yr\(^{-1}\) or 11%). This was because conventional vehicles contributed very little to SO\(_2\), but coal-fired power plants were big emitters of SO\(_2\). The change in NH\(_3\) emissions was <1% because neither transportation nor power plants were significant contributors.

### 3. Results

#### 3.1. Model evaluation

To better evaluate model performance, we selected eight surface stations (Fig. 1b) from a network of 69 available monitoring sites operated by the Taiwan Environmental Protection Administration to provide hourly surface concentrations of SO\(_2\), NO\(_x\), CO, VOCs, O\(_3\) and PM\(_{2.5}\) from January to December 2010 (http://taqm.epa.gov.tw/taqm/tw/default.aspx). The eight representative stations include four urban sites (BQ, DL, QT and WH) and four rural sites (GY, SY, TX and WL), with site details given in Table S3. As shown in Fig. S2, our model reproduced the annual mean SO\(_2\), NO\(_x\), CO and VOC concentrations at most sites well, with normalized mean biases (NMB) below ±16%. The simulated annual mean VOCs and PM\(_{2.5}\) agreed well with the measurements at rural sites (biases below ±11%), but were overestimated at urban sites (biases up to ±41%). Seasonal and diurnal patterns are discussed in supplement section S1.

Fig. 3 summarizes the model performance by statistical comparisons between the measured and simulated monthly diurnal concentrations at the eight sites. All pollutants showed high correlations (r = 0.72–0.86) between simulation and observation, indicating that our model did fairly well in reproducing the diurnal and seasonal variations at these sites. The regression slopes of SO\(_2\), NO\(_x\), O\(_3\) and CO were within the range of 0.91–1.06; however, our model overestimated the VOCs and PM\(_{2.5}\) concentrations, with regression slopes of 1.41 and 1.30, respectively. In general, although not without biases, our model showed a reasonable agreement with the surface observations in Taiwan, which allowed a decent evaluation of EV effects.

#### 3.2. Impacts of EV on surface pollutant concentrations

As stated earlier, replacing current vehicles with EVs would yield substantial reductions in gaseous and particulate pollutant emissions (up to 77%), with the exception of SO\(_2\). In this section, we analyze the consequent impacts on surface pollutant concentrations.

##### 3.2.1. SO\(_2\), NO\(_x\), VOCs, CO and PM\(_{2.5}\)

Fig. 4 shows the spatial distributions of the simulated annual mean surface concentrations of SO\(_2\), NO\(_x\), CO, VOCs and PM\(_{2.5}\) in the BASE case, as well as their changes in the EVTP and EVCP scenarios. Surface SO\(_2\) concentrations evidently increased near the thermal power plants in the EVTP scenario, with the largest changes (up to 3 ppb) occurring near the Talin (TL) power plant in southern Taiwan. The annual mean changes due to EVTP is to increase SO\(_2\) concentration by about 0.1–0.2 ppb across Taiwan (Table 3). It is worth noting that the largest change did not occur at the largest thermal power plant (TC). This is because the chimneys of TL (130 m) are much lower than those of other power plants. An-
For CO and VOCs, we found substantial reductions over large cities, with surface concentrations decreased by up to 850 ppb for CO and 35 ppb for VOCs. Reductions in CO and VOCs were unchanged for different electricity supply modes, since electric generating units emitted low quantities of these pollutants. The reduction of CO concentration was the most prominent effect among pollutants, as light-duty vehicles are the dominant sources (77%) of CO emissions in Taiwan. The spatial distribution of PM$_{2.5}$ changes was similar to those of CO and VOCs, but appeared to cover a wider area, likely due to the time required for secondary aerosol formations and thus further dispersion. The degree of PM$_{2.5}$ reduction was somewhat smaller in the EVTP scenario (up to 6 μg m$^{-3}$) compared to that in the EVCP scenario (up to 7 μg m$^{-3}$). The smaller changes were due to be offset by increased emissions of SO$_2$ and NO$_x$, which can convert into sulfate and nitrate aerosols, from the electrical sector.

Fig. 5 shows the annual mean diurnal pattern of changes in surface pollutant concentrations associated with EV penetration. Full EV penetration reduced the surface concentrations of NO$_x$, CO, VOCs and PM$_{2.5}$.
around the clock, and reductions were more substantial in urban than in rural sites. Concentration reductions were particularly prominent during the morning and evening rush hours, synchronized with the peaks in the baseline case. Combined with the spatial patterns discussed above, our results suggest that large reductions in NOx, CO, VOCs and PM2.5 concentrations tend to occur at times and places with high pollutant concentrations. The SO2 concentration behaved rather differently, showing diurnally flat increases for both urban and rural sites in the EVTP scenario, but changing little in the EVCP scenario. Note that the diurnal patterns of the concentration changes showed little seasonal differences in most sites (see Figs. S16–S21).

Table 3 summarizes the air quality impacts of EV penetration averaged for all 69 sites (46 urban and 23 rural sites). Replacement with EV could markedly reduce annual mean concentrations of NOx (7–21%), CO (45–65%), VOCs (20–21%) and PM2.5 (4–8%) in both EVTP and EVCP scenarios, with more substantial effects in urban than in rural areas. SO2 generally increased by 2–5% due to the extra burden of electric power generation in the EVTP scenario.

Fig. 4. Spatial distributions of simulated annual mean surface concentrations of SO2, NOx, CO, VOCs and PM2.5 in Taiwan 2010 for the BASE case (a1–a5), overlaid with observed annual mean concentrations at the urban (circles) and rural (triangles) sites. Also shown are the changes in concentrations for the EVTP (b1–b5) and EVCP (c1–c5) scenarios.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>BASE (ppb)</th>
<th>EVTP (ppb)</th>
<th>EVCP (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO2</td>
<td>4.6</td>
<td>5.2</td>
<td>-0.1 (+2%)</td>
</tr>
<tr>
<td>NOx</td>
<td>26.9</td>
<td>24.7</td>
<td>-2.1 (-18%)</td>
</tr>
<tr>
<td>CO</td>
<td>541</td>
<td>506</td>
<td>-328 (-65%)</td>
</tr>
<tr>
<td>VOCs</td>
<td>39.8</td>
<td>68.7</td>
<td>-141 (-21%)</td>
</tr>
<tr>
<td>O3</td>
<td>31.9</td>
<td>39.3</td>
<td>-2.5 (-6%)</td>
</tr>
<tr>
<td>PM2.5</td>
<td>19.7</td>
<td>28.7</td>
<td>-1.0 (-5%)</td>
</tr>
<tr>
<td>O3 (ppb)</td>
<td>24.6</td>
<td>31.0</td>
<td>+0.8 (+3%)</td>
</tr>
<tr>
<td>Peak time</td>
<td>45.7</td>
<td>48.7</td>
<td>-1.7 (-3%)</td>
</tr>
<tr>
<td>Rush hours</td>
<td>23.8</td>
<td>28.5</td>
<td>+1.4 (+5%)</td>
</tr>
</tbody>
</table>

* For VOC observation, the values are averaged for 5 urban photochemical sites and 3 rural photochemical sites, respectively.

b O3 peak time: 12:00–14:00 local time.

Rush hours: 6:00–9:00 and 17:00–20:00 local time.
3.2.2. Ozone

O₃ is a secondary pollutant formed through nonlinear reactions of NOₓ and VOCs in the presence of sunlight. O₃ production is most efficient when there is sufficient solar radiation. At night, however, the titration effect of freshly emitted NO dominates and the O₃ concentration tends to drop to a lower level. Fig. 6 shows the spatial distributions of the simulated annual mean concentrations of surface O₃. During O₃ peak time (12:00–14:00 local time), simulated surface O₃ concentrations were higher in western and central Taiwan, consistent with the observations in the same time (NMB = 2%). Replacement with EV could evidently reduce peak O₃ concentrations by up to 7 ppb over all of Taiwan, except for a slight increase (~2 ppb) over downtown Taipei. It should be noted that O₃ production regime varies depending on the ratio of ambient VOCs and NOₓ (Stockwell and Goliff 2004). For the NOₓ-sensitive regime, O₃ concentration tends to decrease in response to reductions in on-road NOₓ emissions; however, in the high NOₓ emission areas, O₃ concentration reacts in the opposite direction of NOₓ emission change.

The inverse response of O₃ concentration to NOₓ emission (i.e., the titration effect) is even more obvious during rush hours and at night. Figures 6b3 and 6c3 show that, during the morning and evening rush hours, surface O₃ concentration increased over a much broader area around the Taipei metropolis (up to 6 ppb) and downwind of prevailing winds, as well as over a small portion of Taichung city. For Kaohsiung city, however, there were no significant O₃ increases in the EVTP scenario because the on-road NOₓ reduction was offset by the increased emissions from nearby power plants. Daily O₃ concentration was determined by values somewhere between those during the O₃ peak time and rush hours. Fig. 5 suggests that the diurnal patterns of O₃ changes due to the EV effect were negatively correlated with the ambient NOₓ concentrations. In the urban areas, reduced NOₓ emissions caused O₃ to increase (especially near rush hours), except around noon when O₃ photochemical production is the strongest. Across the rural areas, O₃ concentrations reduced during daytime and stayed the same during nighttime. Overall, EV penetration reduced the averaged O₃ peak value by 1.3–2.2 ppb in both scenarios. The magnitudes of these changes are summarized in Table 3.

3.3. Impacts of EV on pollution episodes

Compared with the impacts on the annual scale, we found that EV penetration would produce even higher benefits in pollution episode mitigation than in mean concentrations. We applied the Air Quality Index (AQI) to define the days of pollution episodes (AQI > 100), and evaluated the influences caused by EV. As shown in Fig. 7, the simulated annual number of days with AQI > 100 was 62 (averaged for the regions with at least one day of AQI > 100; this criterion was used for all further evaluations), which is consistent with the observations (see Table S4). All pollution episodes (simulated and observed) in Taiwan were caused by PM₂.₅ and O₃. A total of 52 annual pollution episode days were caused by excessive PM₂.₅ (24-h average PM₂.₅ concentration exceeded 35 μg m⁻³) (USEPA, 2012), and a total of 18 days were caused by excessive O₃ (peak 8-hour average O₃ concentration exceeded 70 ppb) (USEPA, 2012). Western and southwestern Taiwan are the most seriously polluted areas; for example, Taichung and Kaohsiung stand out with over 150 d yr⁻¹ of episode incidence.

Under EV penetration, O₃ episode days were significantly reduced by as much as 7 d yr⁻¹ (39%), averaged for the polluted areas. The largest reductions (up to 35 d yr⁻¹) occurred around the most O₃-polluted areas (i.e., cities of Taichung and Kaohsiung; cf. Fig. 7). Compared with O₃ pollution mitigation, EV penetration had a smaller mitigation effect on PM₂.₅ pollution, reducing annual PM₂.₅ episode days by 3–5 d yr⁻¹ (6–10%). The spatial distributions of reductions in PM₂.₅ episode days (Fig. 7) were similar to the patterns of PM₂.₅ concentration changes (Fig. 4). For episodes with AQI > 100 in general, annual mitigation was estimated to be 7–9 d yr⁻¹ (population). The mitigation effect was much more prominent over urban areas, because air pollutions in urban areas are mostly caused by transportation sources. Our results suggest that EV penetration could considerably reduce pollution episodes by up to 34 d yr⁻¹ (62%) and 44 d yr⁻¹ (66%) in the cities of Taipei and Taichung, respectively. However, the improvements over Kaohsiung city (the other most polluted area) would be less significant because the area is influenced strongly by heavy industry and thus would benefit less from EV penetration.

4. Discussion

It should be noted that in addition to uncertainties pertaining to the emission inventory data and the simulations of meteorological fields, some uncertainties also remain with regard to the assumptions used in this study. Firstly, we assumed that the additional electricity to power EVs were proportionately provided by power plants according to their original diurnal patterns. However, previous studies have suggested that charging EVs under smart grid controls (using efficient units and during low electricity demand periods) might significantly reduce the additional emissions from power plants (Stioshansi and Denholm 2009; Thompson et al. 2009). Secondly, we did not consider...
the manufacturing process of EV batteries, which would produce considerable emissions of \( \text{SO}_2 \), \( \text{NO}_x \), and \( \text{PM}_{2.5} \) (Tessum et al. 2014). Thirdly, the limitations of the current chemical model (e.g., imperfect understanding of the precursors and formation pathways of SOA) are also likely to have introduced uncertainties into our results.

Our study is the first attempt to explore the potential impacts of EV on air quality in Taiwan. The findings are generally comparable to results from other similar studies. For example, Thompson et al. (2009) found that with PHEVs replacing 20% of the gasoline vehicles and charged overnight could lead to reductions in peak 8-h \( \text{O}_3 \) concentrations by 2–6 ppb across the northeastern USA, except around Newark and Philadelphia where significant \( \text{O}_3 \) increase may occur in certain summer days. Brinkman et al. (2010) estimated that, under the 100% PHEV penetration condition, peak 8-h \( \text{O}_3 \) concentration in Denver would be reduced by 2–3 ppb on most days during summer, except for a small area near central Denver that experienced elevated \( \text{O}_3 \). In comparison, our results showed decreases in peak 8-h \( \text{O}_3 \) concentrations by 1.3 to 2.2 ppb annually across Taiwan. Exceptions (elevated \( \text{O}_3 \)) near urban centers also occurred in our simulation but only in the Taipei City. Brinkman et al. (2010) further calculated the associated changes in the frequency of \( \text{O}_3 \) pollution episode associated with EV penetration, and they fund that the number of 8-h \( \text{O}_3 \) exceeding the 75 ppb standard would reduce by 20.5% and 17.1% for all-day charging and night charging scenarios, respectively. Our results showed a general improvement in \( \text{O}_3 \) episode days by 11–15% across Taiwan; the improvement is more significant over the cities, with over 60% reduction in episode days in the cities of Taipei and Taichung. Instead of changes in episode days, Thompson et al. (2009) calculated the changes in
population exposure, showing decreases by 5% and 9%, respectively, in maximum population exposure under the 75 ppb and 85 ppb standards. Such calculations are more pertinent to public health impact assessment, but require high-resolution data on the temporal and spatial distribution of the population which are not available for the studied area. Note that this study assumed full EV penetration, and the associated power demand is evenly distributed among existing power plants; the mitigation benefit could be higher if a smart grid control scheme was implemented. Compared with those studies, our analysis covered a longer period (one-year) to show the patterns in different seasons, and employed a higher spatial resolution (3 km) to compare the characteristic in different regions.

5. Conclusion

Electric vehicles have been identified as a potential option for reducing air pollution, especially over urban areas. In this study, we used a regional air quality model to simulate gaseous and particulate pollutants in Taiwan, aiming at evaluating the prospective impacts of EV penetration on air quality. The simulations were parameterized using the best
The burden of electricity supply (~58.1 billion kWh) was shifted to either coal-fired power plants or clean energy sources. With this ambitious EV penetration, CO, VOCs, NOx and PM2.5 emissions in Taiwan from on-road sources would be reduced by 1500 (85%), 165 (79%), 33.9 (27%) and 7.2 (27%) Gg yr⁻¹, respectively. On the other hand, electric sector NOx and SO2 emissions would be increased by up to 20.3 (29%) and 12.9 (29%) Gg yr⁻¹ if all electricity were provided by thermal power plants. Overall, total emissions of most pollutants except for SO2 (which increased by 11%) would be considerably reduced by EV penetration.

We further analyzed the consequent impacts of EV on the level of air quality. Replacement with EV would be effective in reducing annual mean surface concentrations of CO (by 260 ppb), VOCs (by 11.3 ppb), NOx (by 3.3 ppb) and PM2.5 (by 2.1 μg m⁻³), while SO2 would increase slightly (by 0.1 ppb). The large reductions tended to occur at times and places with high ambient concentrations. Greater benefits would clearly be attained if clean energy sources were fully encouraged. EV penetration would cause widespread reductions in annual average O3 peak values (up to 7 ppb) across Taiwan, except for a slight increase (<2 ppb) in downtown Taipei. Further analysis suggests that EV penetration would tend to be of significant benefit to the mitigation of high pollution episodes. Calculated regional mean pollution episode days (AQI > 100) in Taiwan would be reduced by 7–9 d yr⁻¹ (11–15%), and the local reductions may reach 44 d yr⁻¹ in highly-polluted Taichung city. We found O3 and PM2.5 to be the main causes of air pollution, and attributed at least 70% of the improvements to O3 reduction. Our findings are important for understanding the potential effects of EV on air quality, and can provide useful information to local governments for use in air pollution strategies.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2016.05.105.

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