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Potential impacts of electric vehicles on air quality in Taiwan

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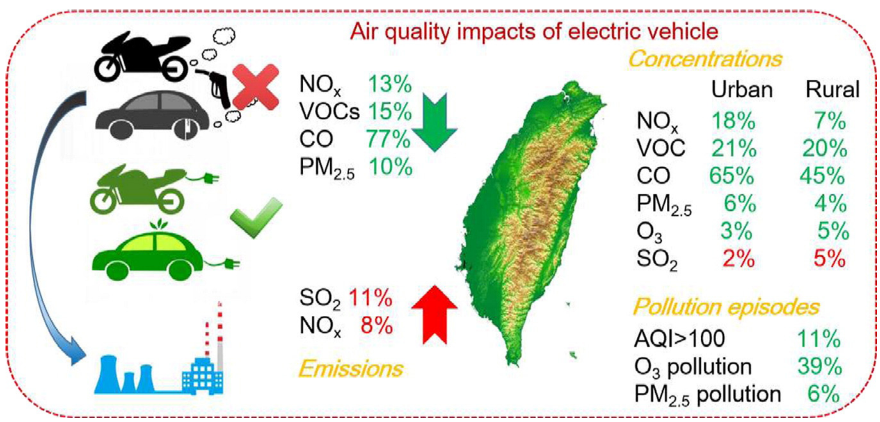
HIGHLIGHTS

- Air quality impact of EV is evaluated with WRF-CMAQ model under different scenarios.
- Net emissions of NO_x, VOCs, CO and $PM_{2.5}$ 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



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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, NO_x and $PM_{2.5}$ 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 NO_x and SO_2 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, NO_x and $PM_{2.5}$ by about 260, 11.3, 3.3 ppb and 2.1 μg m^{-3}, respectively, but to increase SO_2 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 O_3 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 O_3 pollution episodes by ~40% and $PM_{2.5}$ 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 NO_x 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 NO_x 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 NO_x 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 SO_2 and NO_x 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 SO_2 and NO_x 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 O_3 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 O_3 concentration would be reduced by 2–3 ppb on most days, but that O_3 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 O_3 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:

$$ED = \sum_i (VP_i \times VU_i \times VKT_i \times BE_i)/(TE \times CE_i) \quad (1)$$

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