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# Episodic air quality impacts of plug-in electric vehicles

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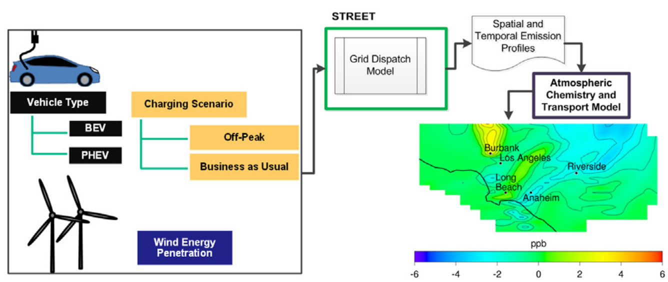
## HIGHLIGHTS

- Dispatch and air quality impact of generators are modeled for future cases.
- PEVs will generally have a positive impact on urban air quality.
- Area-wide ozone and $PM_{2.5}$ averages decrease with integration of PEV and wind.
- Charging profile's impact on air quality is very small.
- Localized increase in 8-h average ozone is observed in some cases.

## GRAPHICAL ABSTRACT

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## ABSTRACT

In this paper, the Spatially and Temporally Resolved Energy and Environment Tool (STREET) is used in conjunction with University of California Irvine – California Institute of Technology (UCI-CIT) atmospheric chemistry and transport model to assess the impact of deploying plug-in electric vehicles and integrating wind energy into the electricity grid on urban air quality. STREET is used to generate emissions profiles associated with transportation and power generation sectors for different future cases. These profiles are then used as inputs to UCI-CIT to assess the impact of each case on urban air quality.

The results show an overall improvement in 8-h averaged ozone and 24-h averaged particulate matter concentrations in the South Coast Air Basin (SoCAB) with localized increases in some cases. The most significant reductions occur northeast of the region where baseline concentrations are highest (up to 6 ppb decrease in 8-h-averaged ozone and 6 μg/m$^3$ decrease in 24-h-averaged $PM_{2.5}$). The results also indicate that, without integration of wind energy into the electricity grid, the temporal vehicle charging profile has very little to no effect on urban air quality. With the addition of wind energy to the grid mix, improvement in air quality is observed while charging at off-peak hours compared to the business as usual scenario.



## 1. Introduction

Environmental concerns such as air quality and global climate change, along with political concerns, have given rise to elevated interests in alternative transportation. Plug-in electric vehicles (PEVs) are considered as a viable option by many researchers (Electric Power Research Institute, 2001; McKinney et al., 2011; U.S. Department of Energy, 2006; Zhang et al., 2011), and also by the U.S.

*Abbreviations:* BEV, Battery Electric Vehicle; PEV, Plug-in Electric Vehicle; PHEV, Plug-in Hybrid Electric Vehicle; SCAQMD, South Coast Air Quality Management District; SoCAB, South Coast Air Basin; STREET, Spatially and Temporally Resolved Energy and Environment Tool; UCI-CIT, University of California Irvine – California Institute of Technology; VMT, Vehicle Miles Traveled.

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government (U.S. Department of Energy, 2009) to replace conventional vehicles. These vehicles include plug-in hybrid electric vehicles (PHEVs) as well as purely battery electric vehicles (BEVs). Since these vehicles are directly connected to the electricity grid, their interaction with the grid is of utmost importance in assessing their overall environmental and economic impacts, especially when deployment numbers become significant (Electric Power Research Institute, 2007; Parks et al., 2007; Peng et al., 2012). Studies that have investigated the impacts of deploying PEVs (Electric Power Research Institute, 2001, 2007; Jansen et al., 2010; Kintner-Meyer et al., 2007; Razeghi et al., 2011, 2014; Samaras and Meisterling, 2008; Sioshansi and Denholm, 2009a, 2009b; Sioshansi and Miller, 2011; Stephan and Sullivan, 2008; Valentine et al., 2011) suggest that PEVs, when considering both the emissions from the vehicles and the electricity required to charge the vehicles have a net emission advantage over conventional vehicles (Jansen et al., 2010; Razeghi et al., 2011; Samaras and Meisterling, 2008; Sioshansi and Denholm, 2009a, 2009b; Sioshansi and Miller, 2011; Stephan and Sullivan, 2008; Valentine et al., 2011). The majority of these studies use an average grid mix (Kintner-Meyer et al., 2007) or the marginal generation technology to determine the amount of annual emissions increased from the electric power generation sector due to PEVs (Electric Power Research Institute, 2007). Jansen et al (Jansen et al., 2010). developed a more sophisticated temporal dispatch strategy which used historical data and dispatch order of various resources to determine the electricity generated from each resource at each hour. These results showed that, although the addition of PHEVs to the light-duty fleet might result in an increase in the intensity of emissions ($lbMWh^{-1}$) from electricity generating sector at specific hours, the overall impact is favorable (i.e. the net impact of deploying these vehicles is decreased emissions from the transportation and electricity generation sectors).

While most of the previous studies suggest that the deployment of PEVs results in an overall decrease in criteria pollutant emissions, analyzing the impact on air quality requires 1) a spatially and temporally resolved generator dispatch model, and 2) a sophisticated atmospheric chemistry and transport model. The majority of previous studies focusing on the dispatch strategies are not both spatially and temporally resolved, and those that are, lack the air quality modeling (Sioshansi and Denholm, 2009b; Sioshansi and Miller, 2011). In addition, the studies focusing on air quality use a simple dispatch methodology that does not capture the details of the grid operations (Tammy et al., 2011). In this paper, a detailed grid dispatch model is used along with an atmospheric chemistry and transport model.

For this purpose, a detailed grid dispatch model has been developed which solves the emissions both spatially and temporally for South Coast Air Basin (SoCAB) of California (Razeghi et al., 2011). Even though the area under study is relatively small, the SoCAB includes one of the largest metropolitan areas in the United States, with more than 16 million inhabitants. In addition, it is of particular interest since the basin is among the worst areas in terms of air quality in the United States. The SoCAB exceeded the 24-h $PM_{2.5}$ standard 15–30 days per year in the last 5 years (California Air Resources Board, 2013). Other reasons for choosing SoCAB are:

- The SoCAB grid mix is relatively clean,
- The SoCAB has historically been a hub for new technologies, and
- The SoCAB is subject to stringent policies like AB32 and AB118 which encourage both manufacturers and consumers to move toward alternative and low to non-carbon options.

This grid dispatch model is a part of the Spatially and Temporally Resolved Energy and Environment Tool (STREET). STREET is a comprehensive planning methodology developed at University of California, Irvine (UCI) to assess environmental and economic impacts of transportation and grid mix options. For example, STREET has been previously used to study the air quality impacts of fuel cell electric vehicles in the SoCAB (Stephens-Romero et al., 2009), and also in developing roll-out strategies associated with hydrogen fueling stations (Stephens-Romero et al., 2011).

In this paper, various transportation and electricity generation scenarios are developed for the year 2050. Using the grid dispatch model, temporally and spatially resolved emissions associated with each scenario are developed and then used as inputs to the University of California Irvine – California Institute of Technology (UCI-CIT) atmospheric chemistry and transport model (Ensberg et al., 2010; Vutukuru et al., 2006) to analyze the air quality impacts of PEVs.

## 2. Methodology

### 2.1. Grid dispatch model

With the introduction of PEVs into the light-duty fleet, the tail-pipe emissions of criteria pollutants will partially be transferred to the electricity grid. To fully grasp the impacts of electric vehicle charging on grid operations, emissions, and urban air quality, a dispatch model with both temporal and spatial resolution has been developed for the U.S. Western electrical grid serving the SoCAB (Razeghi et al., 2011). This model is capable of determining individual power plant generation profiles for a given electricity demand for the region in a future year.

The electricity demand of the SoCAB is calculated in two parts. First, the base electricity demand is forecasted based on historical data, population growth, and census data, and it is verified by projections made by the California Energy Commission (Kavalec and Gorin, 2009). The second part is the electricity demand of PEVs which depends on the type of the vehicle, charging profiles, and penetration in the light-duty fleet. Two types of vehicles are selected for this study: BEVs with a 100 mile (160 km) range, and PHEVs with a 40 mile (64 km) all-electric range. In the state of California 70% of drives have a daily vehicle miles traveled (VMT) of 40 miles or less, and 95% of drivers have a daily VMT of 100 miles or less (California Department of Transportation, 2012; U.S. Department of Transportation Federal Highway Administration), and thus the vehicles selected here, can be used by the majority of drivers for their everyday use. PHEVs have the characteristic of Chevrolet Volt and the BEVs have characteristics of a typical BEV (0.31 kWh/mi (DC) consumption and 0.85 charging efficiency).

The size of the fleet and emissions factors associated with conventional vehicles (including hybrid electric vehicles) for a future year are determined using the California Air Resource Board's Emission Factor (EMFAC) model (California Air Resources Board, 2007) which takes into account the improvements in the conventional vehicles' efficiency and tail-pipe emissions. In the base case, the penetration of PEVs is insignificant (less than 0.1%, equal to 2010 penetration), in all other cases PEVs comprise 40% of the light-duty fleet by replacing same amount of conventional vehicles. The conventional vehicles replaced by PEVs have emission factors equal to the average emission factors of *conventional* vehicles in the fleet. This penetration of PEVs in light-duty fleet is consistent with year 2050 southern California deployment penetrations studied elsewhere (McKinney et al., 2011; Ogden and Ramage, 2010; Santimi, 2007; Schremp et al., 2011).

Two particular charging scenarios are considered—"business-as-usual" and "off-peak" charging which have been used in previous studies (Jansen et al., 2010; Razeghi et al., 2011). In the business-as-usual charging profile, the vehicles are plugged in without any restrictions and both work place and home charging are allowed. This results in concentrated charging in the morning when the majority of users get to work and plug-in their vehicles, in addition to another charging peak in the afternoon when the drivers return home from work. In all cases, home charging and 50% of work charging is at Level 1, and the other 50% of work charging is at Level 2.

The total electricity demand for the year 2050 is calculated by adding the extra vehicle demand to the projected 2050 base demand. The new generation required to serve the load and the locations of these new generating facilities are determined based on the land use (SCAG- Southern California Area Governmets), and footprint required (see (Razeghi et al., 2011)). These new generating units include natural gas combined cycle power plants (as load-following units) and gas turbines (as peaking units). In order to examine scenarios with maximum in-basin emissions that might result in an air quality episode, it is assumed that all the new electricity generation is installed inside the SoCAB boundaries. This is also done to ensure that possible benefits observed in various cases are not due to transferring emissions and negative impacts to outside of the basin. Furthermore, there are several obstacles (including securing environmental permits and rights-of way, securing regulatory approval for publicly-owned utilities and federal agencies, and local opposition due to visual and environmental impacts) that hinder building transmission infrastructure.

The dispatch model takes into account minimum and maximum capacity factors, ramp rates, minimum on/off time for the generators and also takes into account retirement of old generators and replaces them with new generators of higher efficiency and lower emissions.

For cases including wind energy, the normalized daily wind profile is determined based on measured data and wind speed from the Tehachapi wind farm (U.S. Department of Energy, 2007). The amount of electricity generated by wind (in kWh) is then calculated according to the year of the scenario and projected penetration: Wind penetration is defined as the electricity generated by wind (in kWh) in a year to the total electricity generation (kWh) in that year, thus with the demand projection one can calculate the annual wind generation during a year, and using the normalized wind profiles, one can find the wind profile for any day in that year.

In the model, the wind energy is dispatched after the base-loading units, but before any of the load following generators. Base-loading units are dispatched first because reducing their outputs or operating them in lower capacity factors is not economic and they are usually cheaper units. The renewable resources are dispatched next to take advantage of zero-carbon resources. This is consistent with current operations of the grid. In some cases with high penetration of wind, the grid cannot handle the intermittencies of the wind without integration of additional complementary technologies. In these cases, the extra wind is curtailed in order not to violate the constraints of the grid. A detailed description of the dispatch strategy is given in Razeghi et al. (Razeghi et al., 2011).

### 2.2. Air quality model

The UCI-CIT atmospheric chemistry and transport model is a three-dimensional Eulerian urban photochemical model designed to study the dynamics of pollutant transformation and transport in the atmosphere. The model uses a horizontal 80 × 30 rectangular grid which encompasses the SoCAB which includes Orange County and part of Los Angeles, Ventura, San Bernardino and Riverside counties (Fig. 1) and is physically bounded by mountain ranges in the north and east, limiting transport from and to regions outside the basin. Each grid cell corresponds to a 5 km × 5 km region

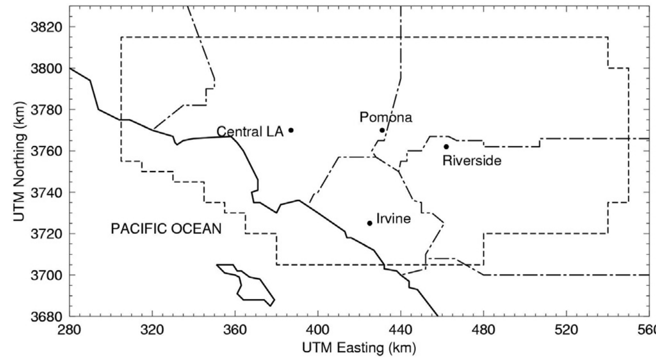



**Fig. 1.** UCI-CIT Airshed modeling domain of the South Coast Air Basin of California.

extending 1100 m in height. Additionally the vertical resolution is described through 5 vertical layers with the following dimensions from ground level up: 1) 0 m–39 m, 2) 39 m–154 m, 3) 154 m–308 m, 4) 308 m–671 m, and 5) 671 m–1100 m. Note that the mixing height during the episode studied, was always less than 1100 m, so the effect of adding additional layers on top of the modeling domain is expected to have little effect on ground level observations.

The model includes the CalTech Atmospheric Chemistry Mechanism (CACM) (Griffin et al., 2002a, 2002b) which is based on the work of Stockwell et al. (Stockwell et al., 1997), Jenkin et al. (Jenkin et al., 1997), SAPRC-97 and SAPRC-99 (Available from W.P.L. Carter), and includes $O_3$ chemistry and a mechanism of the gas phase precursors of secondary organic aerosol (SOA). The full mechanism consists of 361 chemical reactions and 191 gas-phase species, which describe a comprehensive treatment of volatile organic compounds (VOC) oxidation.

The inorganic aerosol formation is calculated using the Simulating Composition of Atmospheric Particles at Equilibrium 2 (SCAPE2) model (Meng et al., 1995). SCAPE2 has been modified to account for the interaction between organic ions present in the aqueous phase and the inorganic aerosol components.

The model used to determine the partitioning of secondary organic compounds is the Model to Predict the Multiphase Partitioning of Organics (MPMPO) (Griffin et al., 2002a, 2003). MPMPO allows for the simultaneous formation of SOA in a hydrophobic organic phase and a hydrophilic aqueous phase. The module consists of 37 size-resolved aerosol-phase species, in 8 different size bins ranging from 0.04 to 10 μm. The integrated module allows particulate matter to undergo advection, turbulent diffusion, condensation/evaporation, nucleation, emissions and dry deposition processes.

The simulations consist of a typical three-day summer period where there is a high ozone forming potential. Results are based on the third day of simulation as the first two days are used to dissipate the effect of initial conditions, as suggested earlier (Carrera-Sospedra et al., 2006). The discussion of an episode with high ozone formation is to determine whether attainment of ozone standard may be hindered by a particular scenario. The ozone standard is defined as the 4th highest value in a consecutive 3-year period of maximum 8-h average ozone, a value that should be lower than 75 parts-per-billion. Hence, for the analysis of ozone, it is reasonable to analyze high ozone forming potential episode, and not include low ozone episodes.

The episode chosen corresponds to a South Coast Air Quality Management District (SCAQMD) episode, in August 27–29, 1987 which has been studied extensively and used as benchmark in ozone modeling and ozone attainment demonstrations in the past (Griffin et al., 2002a, 2002b; Knipping and Dabdub, 2002; Meng

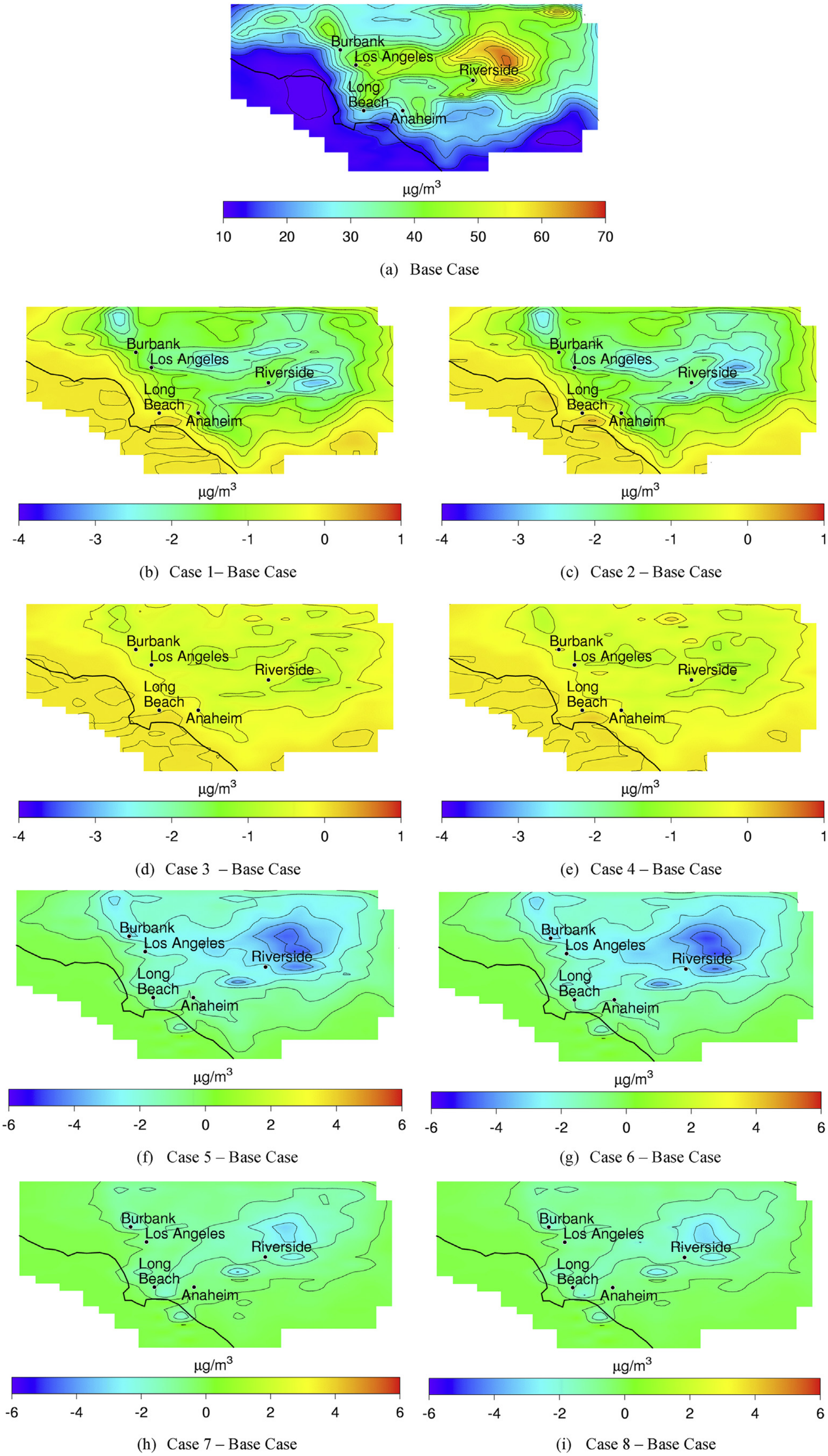
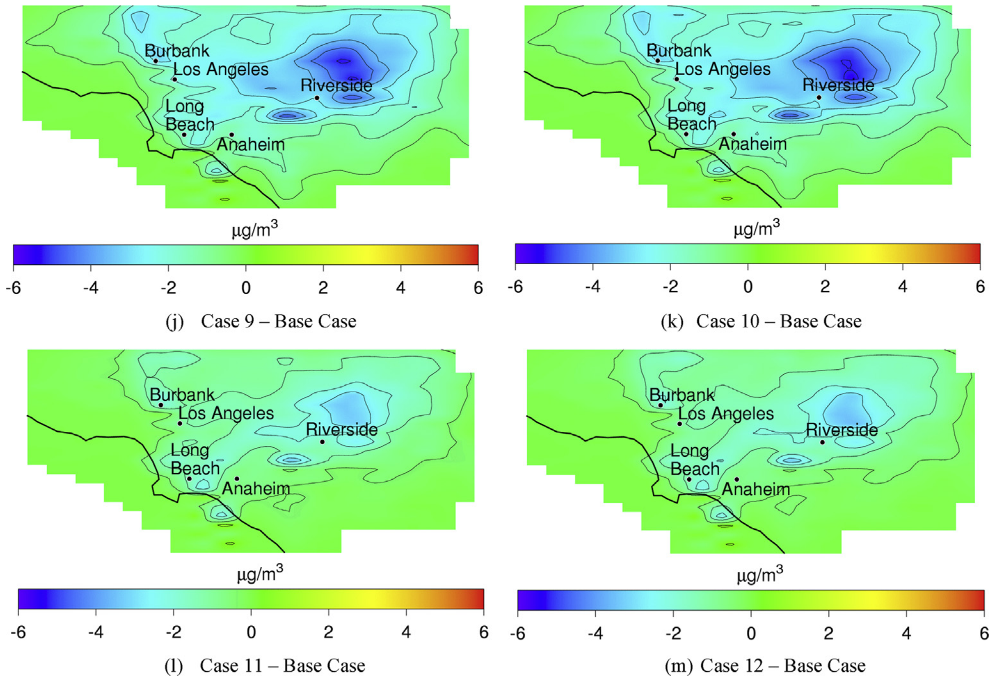



**Fig. 2.** (a) Predicted 24-h average $PM_{2.5}$ concentration for Base Case 2050. (b)-(m) Predicted change in 24-h average $PM_{2.5}$ concentration in each case from the Base Case.




(j) Case 9 – Base Case (k) Case 10 – Base Case

(l) Case 11 – Base Case (m) Case 12 – Base Case

**Fig. 2.** *Continued*

et al., 1998; Moya et al., 2002; SCAQMD, 1997, 2003). Based on a statistical analysis, the episode represents conditions for the top 10% peak ozone concentration conditions (Zeldin et al., 1990). In other words, the episode is representative of conditions for days with the 36 highest concentrations. It should be noted that this is not an extreme case, but rather a *typical high ozone* case which could occur 30–40 days a year.

This type of analysis does not provide a full spectrum of air quality impacts, because it bases the analysis in one day as opposed to seasonal modeling. However, being a *representative high-ozone* episode, this analysis illustrates the potential impacts that are higher than the average impacts for *typical* (average) days. Moreover, the use of a representative short episode allows for an analysis of numerous emission scenarios, which provide a wide spectrum of possible impacts due to emissions, while keeping meteorology the same. The use of longer or more moderate smog-forming episodes would span the range of potential impacts, probably showing lower overall impacts on air pollutant concentrations. Even though the range of air quality impacts is limited to the specific meteorological episode, this approach provides a reference for assessing the relative impacts among different emissions scenario. Hence, one should interpret the results not based on absolute air quality values, but in the differences among scenarios and relative changed (%) compared to the base case.

Baseline emissions are taken from the emissions inventory developed by the SCAQMD for the 2007 Air Quality Management Plan (SCAQMD, 2007) to show attainment of the ozone standard by the year 2023. Hence, baseline emissions assume drastic emission reductions of nitrogen oxides and VOC from current emissions levels. Additionally, emissions of automobile sources in each grid cell, are scaled using the change in number of vehicles, VMT, and tail-pipe emissions factors for conventional vehicles in future years projected by the California emissions model EMFAC (California Air Resources Board, 2007) from year 2023–2050. Sources except transportation and power generation are maintained constant beyond 2023.

In the following section, the impacts of various cases on the $PM_{2.5}$ and ozone will be studied.

## 3. Results and discussion

In order to study a high emission scenario, a peak demand day in summer was selected. The high electricity demand, and thus high emissions from the power generation units, along with high temperatures and meteorological inputs selected, result in a poor air quality episode. It is important to study a scenario resulting in a possible air quality episode to demonstrate the attainment for the area (i.e. whether the air quality goals set by the Environmental Protection Agency (EPA) in National Ambient Air Quality Standards (NAAQS) are met (Environmental Protection Agency)); or, in the case of nonattainment, assess strategies to avoid such episodes.

In the present paper, thirteen cases (including a Base Case) were studied. The description of each case is provided in Table 1. Fig. 2 shows 24-h average $PM_{2.5}$ concentration for the Base Case, and the *change* in 24-h average $PM_{2.5}$ concentration between the Base Case and each of the other 12 cases. In order to depict the changes in concentration with high contrast, the scale is different between the first 4 cases and the final 8 cases. Likewise, Fig. 3 shows 8-h average ozone concentration for the Base Case, and the difference in 8-h average ozone concentration between each of the other 12 cases and the Base Case. Similarly, the scale of the plots changes between the first 4 cases and the final 8 cases to provide high contrast.

Figs. 2 and 3 indicate that overall addition of PEVs to the light-duty fleet results in an improvement in overall air quality of the area with the most significant reductions occurring where baseline concentration are highest. Results also show localized increases in ozone and $PM_{2.5}$ in regions with low baseline concentrations. For example, Case 6 and Case 10 differ only in the higher portion of wind power utilized for Case 10. As expected, average ozone concentration is generally lower for Case 10, particularly in the most problematic areas of the northeast SoCAB due to the use of more renewable power, and consequently less in-basin fossil-fueled power generation. However, average ozone concentration is unexpectedly higher toward the western side of the SoCAB, particularly near Burbank where a localized increase is observed. To further understand the change in 8-h average ozone concentrations in

**Table 1**
Description of various cases studied.

| Case number | Type of electric vehicle | Penetration of electric vehicles in light-duty fleet | Electric vehicle charging scenario | Wind energy penetration |
|---|---|---|---|---|
| Base case | None | Negligible | Not applicable | Baseline (7%) |
| 1 | BEV | 40% | Business as usual | Baseline (7%) |
| 2 | BEV | 40% | Off-peak | Baseline (7%) |
| 3 | PHEV | 40% | Business as usual | Baseline (7%) |
| 4 | PHEV | 40% | Off-peak | Baseline (7%) |
| 5 | BEV | 40% | Business as usual | 33% |
| 6 | BEV | 40% | Off-peak | 33% |
| 7 | PHEV | 40% | Business as usual | 33% |
| 8 | PHEV | 40% | Off-peak | 33% |
| 9 | BEV | 40% | Business as usual | 50% |
| 10 | BEV | 40% | Off-peak | 50% |
| 11 | PHEV | 40% | Business as usual | 50% |
| 12 | PHEV | 40% | Off-peak | 50% |

various cases, the differences in $NO_x$ emissions are presented in Fig. 4 for several cases.

Cases 1 through 4 result in a significant reduction of emissions from automobiles combined with localized increases in emissions, ozone, and $PM_{2.5}$ due to the addition of fossil-fuel-based power generation to support vehicle charging. Conversely, Cases 5 through 12 result in a net decrease in emissions throughout the entire basin, due to both vehicle emissions reductions, and power generation emissions reductions due to increased use of renewable power. This overall difference between Cases 1–4 and Cases 5–12 results in two differentiated responses in ozone concentrations. For instance, comparing Cases 2 and 6, where vehicle penetration and vehicle type is the same, one can see the differences in ozone concentration due to in-basin fossil-based power generation (Case 2) and out-of-basin renewable power generation (Case 6). The difference in emissions between Cases 2 and 6 corresponds only to the additional emissions from fossil-based power generation in Case 2. The effect of Case 2 is a reduction in ozone concentration of up to 4 ppb and localized increase near Los Angeles and Burbank due to increased emissions from power plants. The effect due to Case 6 is a larger reduction in ozone in the eastern portion of the domain, up to 6 ppb, and a localized increase in ozone concentration near the power plants in Los Angeles and Burbank. This increase in ozone concentration is due to the decrease in $NO_x$ emissions in an area where $NO_x$ concentrations tend to be high. This localized reduction in $NO_x$ emissions reduces the extent of ozone termination reactions, resulting in an unexpected increase in ozone in an area with relatively low ozone concentrations. In Cases 1–4, the increase in emissions due to the addition of in-basin fossil-fuel-based power generation leads to localized increases in $PM_{2.5}$ near the plants in Long Beach. The increases are smaller than 1 $\mu g/m^3$, and are due to both direct emissions of particulates, and indirect formation of nitrates from $NO_x$ emissions. However, decreases in emissions from vehicles cause overall decreases in $PM_{2.5}$ concentrations in large areas in the center and eastern portions of the domain. Reduction in $PM_{2.5}$ in Cases 1 and 2 are up to 3 $\mu g/m^3$, and are larger reductions than in Cases 3 and 4, because the adoption of BEV in Cases 1 and 2 result in higher emission reductions than the ones achieved by PHEV in Cases 3 and 4. Area-wide average $PM_{2.5}$ concentrations in Cases 5–12 consistently drop with respect to the Base Case because of the reduction of emissions from both vehicles and power generation.

### 3.1. PHEV vs. BEV

The results indicate that when charged in a relatively clean grid, PEVs have a lower net emission per mile compared to conventional internal combustion vehicles. Although BEVs have considerably higher electricity demand compared to PHEVs in all cases, deployment of these vehicles results in a more significant improvement in area-wide average air quality and greater maximum reduction in ozone and $PM_{2.5}$ compared to PHEVs. The difference is especially evident in the northeast part of the region. However, comparing Case 1 with 3 and Case 2 with 4, it is observed that the BEVs in these cases result in greater localized increase in ozone near Los Angeles and Burbank compared to PHEVs. This is due to higher emissions from power plants serving BEVs greater charging demand which can be concluded by comparing Fig. 4b and c. With integration of wind energy, however, BEVs result in better overall air quality and lower localized increases in ozone.

These results further emphasize the important role of the transportation and power generation sectors and careful planning in urban air quality.

### 3.2. Impact of charging profile

Two electric vehicle charging scenarios are considered in this paper. The "business-as-usual" charging scenario assumes that charging stations are available at both work and home. Additionally, it is assumed that drivers plug in their vehicles when they get home and the charging starts immediately. The charging of the vehicles in this scenario coincides unfavorably with the afternoon peak electricity demand. The second electric vehicle charging scenario is "off-peak" charging. In this scenario, the majority of the vehicle home-charging occurs late at night or early in the morning. In all cases studied, the "off-peak" charging scenario results in lower ozone and $PM_{2.5}$ average concentrations, especially in the northeast part of the region. The effect of charging profile on urban air quality is small but becomes more evident as wind energy is added to the grid mix. This is due to the fact that the wind energy peak does not coincide with peak demand. When vehicle charging is moved to off-peak hours, the electricity required is provided by wind energy that would otherwise be curtailed. It must be noted that with the current renewable penetrations curtailment does not occur and renewable resources are taken as must-take resources. However, as the renewable penetration increases, curtailment occurs due to various constraints of the electric grid such as generator ramp rates and the amount of baseloading generators.

### 3.3. Impact of wind energy penetration

Comparing the ozone and $PM_{2.5}$ average concentrations for cases with zero, 33 and 50 percent wind energy penetrations indicates that an increase in wind penetration usually helps improve air quality. However, the impact is not as significant as expected. The most significant improvement occurs in the northeast part of

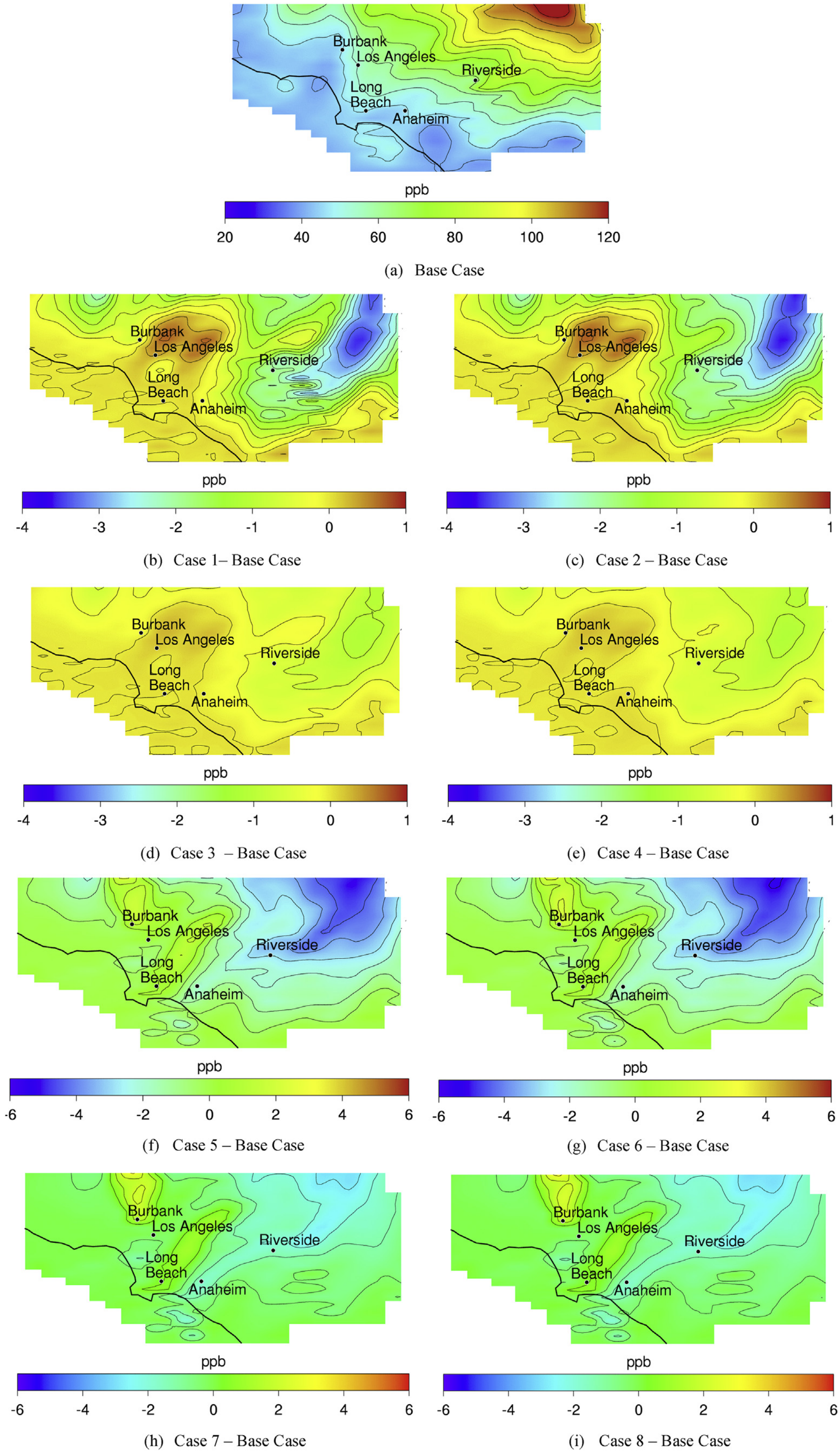



**Fig. 3.** (a) Predicted 8-h average ozone concentration for Base Case 2050. (b)-(m) Predicted change in 8-h average ozone concentration in each case from the Base Case.

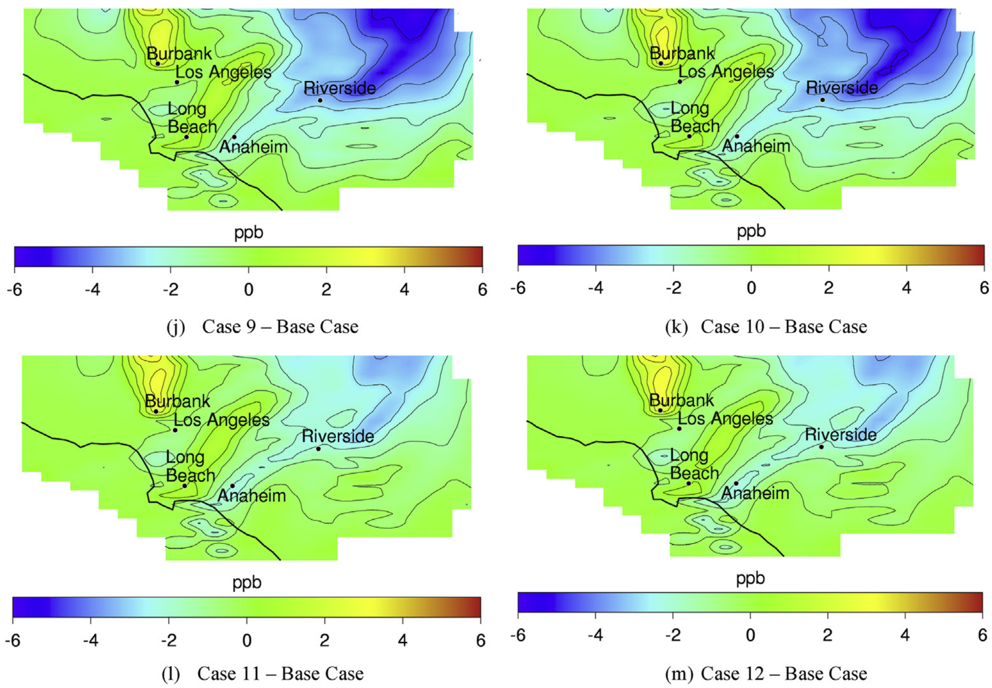



**Fig. 3.** *Continued*

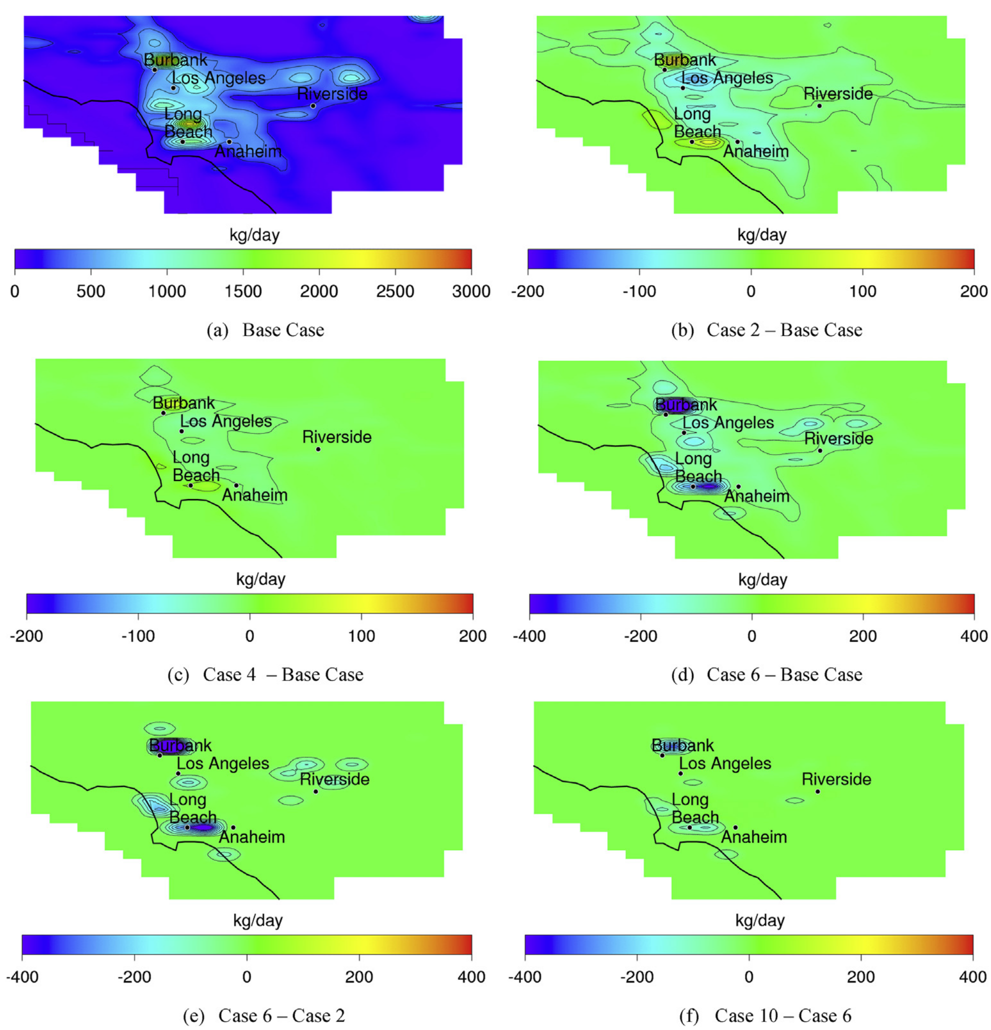



**Fig. 4.** (a) Base Case $NO_x$ emissions. (b)-(f) Differences in $NO_x$ emissions as labeled.

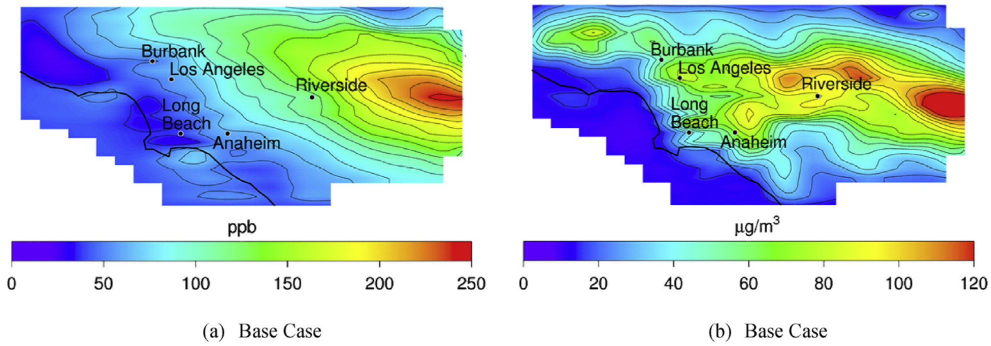



**Fig. 5.** Pollutant concentrations for the Base Case 2050 using September 8–9 meteorology: (a) 8-h peak average O3 concentration, (b) 24-h average PM2.5 concentration.

the region which has been proven to be the most sensitive to changes in cases.

With an increase in wind penetration, a small increase in 8-h average ozone concentration can be seen (compare Cases 6 and 10, for example). This localized increase is due to decrease in $NO_x$ as discussed previously.

### 3.4. Sensitivity to meteorology

The UCI-CIT model requires meteorological information as an input. Based on the meteorology chosen, the results are different from one another showing that the results are indeed dependent on the meteorological conditions provided to the air quality model. So far in this paper, a *typical high ozone* episode was simulated. In this section, additional simulations are performed in order to determine model sensitivity to meteorological conditions. The additional meteorological conditions correspond to a high-ozone forming potential episode in September 08–09, 1993. This episode was previously evaluated by Griffin et al (Griffin et al., 2002a). to demonstrate the use of the CACM mechanism. The episode leads to *extremely* high concentrations of ozone and particulate matter as shown in Fig. 5, due to stagnant conditions and high temperatures, up to 4 °C higher than in the August 27–29 episode which is shown in Fig. 6. As a result, this episode is unlikely to occur.

Despite the differences in the absolute values of pollutant concentrations between the two episodes, the air quality trends are similar in both cases. Namely, peak ozone and particulate matter concentrations occur in the eastern part of the domain, downwind from Los Angeles. In addition, future cases cause the highest reductions in ozone and PM concentrations in areas where the peak concentrations typically occur.

Due to higher temperatures and high stagnation, the impacts in absolute terms of future cases using the Sep 8–9 episode (shown in Fig. 7) are amplified with respect to the Aug 27–29 (Fig. 8). In particular, the decreases in ozone concentration in the September episode are up to 15 ppb, and decreases in $PM_{2.5}$ are up to 15 μg/m$^3$, compared to decreases in the August episode of 6 ppb and 6 μg/m$^3$in ozone and $PM_{2.5}$, respectively. However, the impacts in relation to Base Case concentrations are similar in both cases. Reductions in ozone concentrations with respect to the basin-wide peak are 5 percent and 6 percent in the August and September episodes, respectively, whereas reductions in $PM_{2.5}$ concentrations are 9 percent and 12 percent. Localized increases in ozone concentration are also amplified in Sep 8–9 episode compared to the Aug 27–29. These occur at locations with low baseline concentrations, but possible negative impacts on these communities should be take into account.

Overall, higher temperatures and stronger stagnation lead to higher pollutant concentrations, and higher sensitivity of air quality to changes in emissions in absolute values; however, the changes in concentrations relative to baseline concentrations are similar in the different meteorological episodes.

## 4. Summary and conclusions

In this study, a detailed dispatch model was applied to the U.S. Western Grid and the spatially and temporally resolved emission outputs of this model were then used as inputs to a detailed atmospheric chemistry and transport model to assess an air quality episode. The goal was to assess the impacts of deploying PEVs and remote wind power on urban air quality in a future year when PEVs would likely comprise a significant portion of the light-duty vehicle fleet.

The conclusions of the study are:

- Area-wide averages of ozone (8-h average) and $PM_{2.5}$ (24-h average) concentrations decrease in all cases when compared to

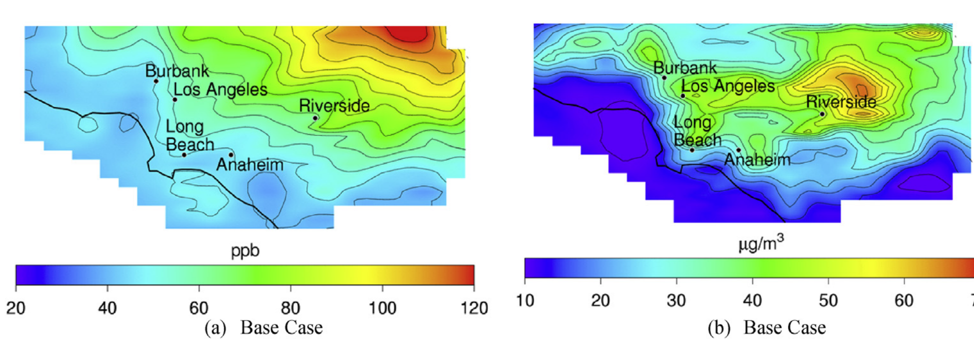



**Fig. 6.** Pollutant concentrations for the Base Case 2050 using August 27–29 meteorology: (a) 8-h peak average $O_3$ concentration, (b) 24-h average $PM_{2.5}$ concentration.

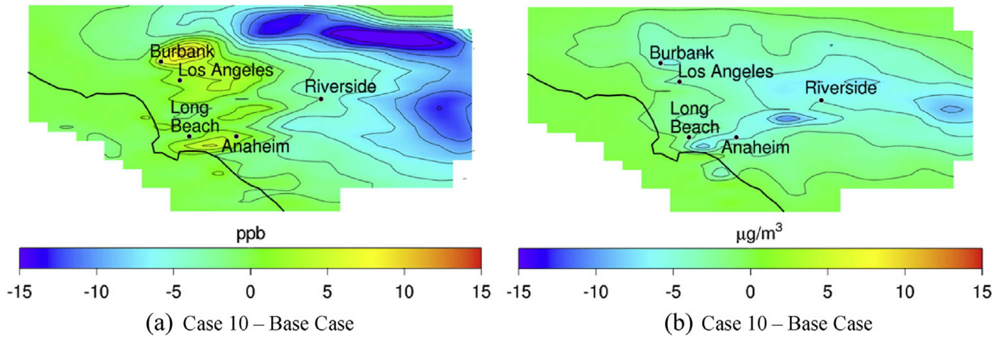



**Fig. 7.** Predicted change in pollutant concentrations in Case 10 with respect to the Base Case 2050 using September 8–9 meteorology: (a) 8-h peak average O3 concentration, (b) 24-h average PM2.5 concentration.

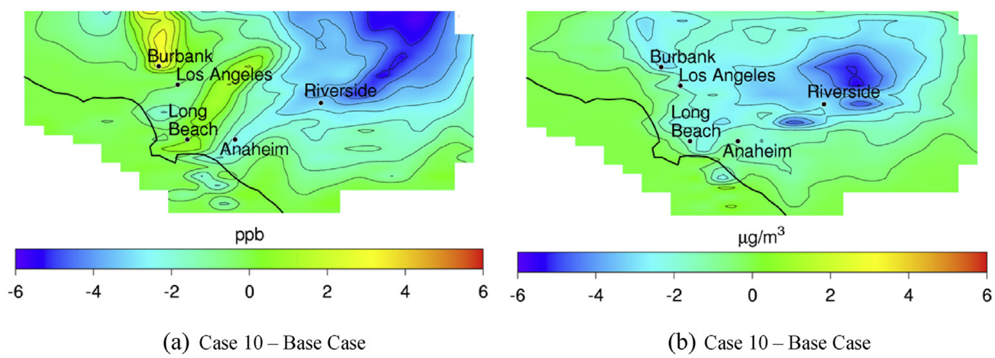



**Fig. 8.** Predicted change in pollutant concentrations in Case 10 with respect to the Base Case 2050 using August 27–29 meteorology: (a) 8-h peak average $O_3$ concentration, (b) 24-h average $PM_{2.5}$ concentration.

the Base Case. The most significant reduction is observed in northeast of the region where baseline concentrations are highest. The U.S. Western Grid has a relatively clean grid mix and powering vehicles using electricity leads, as a result, to a reduction of emissions per vehicle mile and consequently lower area-wide concentrations of ozone and PM.

- Localized increases in ozone and PM are observed in some cases in regions with low baseline concentrations (northwest of the region). In some cases, the increase is due to increase in emissions from power plants to serve PEVs charging demand. In other cases, decrease in $NO_x$ emissions leads to increases in ozone in a small number of areas having low baseline ozone concentrations due to the absence of ozone scavenging reactions.
- With the integration of wind energy into the electricity grid, the area-wide ozone and PM average concentrations decrease further. As the wind penetration is increased, the general ozone and PM concentrations decrease further, but the improvement is not linear.
- The vehicle charging profile have very little impact on air quality. The advantage of “off-peak” charging becomes evident in cases with high wind penetration. In these cases, the vehicles are charged using wind energy and thus the overall reduction in emissions is even greater.

Overall, this research demonstrates that in the area studied, PEVs will generally have a positive impact on overall urban air quality with localized increases in some cases. Although these increases occur in regions with low baseline concentrations, it is necessary to assess the possible negative impacts on these communities. Thus, in order to further increase these benefits, and reduce and mitigate negative impacts, careful planning in transportation and power generation sectors is required, along with adding greater communication capabilities between vehicles and the grid to incentivize charging when electricity demand is low and wind energy available.

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