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Title

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Permalink

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Journal

Atmospheric Environment, 44(26)

ISSN

1352-2310

Authors

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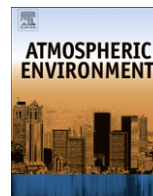Vutukuru, Satish
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Publication Date

2010-08-01

DOI

10.1016/j.atmosenv.2010.05.017

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Peer reviewed

Central power generation versus distributed generation – An air quality assessment in the South Coast Air Basin of California

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ARTICLE INFO

ABSTRACT

This study assesses the air quality impacts of central power generation and compares them with the impacts of distributed generation (DG). The central power plant emissions factors used are from a newly installed combined cycle gas turbine system. Because location of power plants is a key parameter affecting air quality impacts, this study considers three potential locations for the installation of central power plants. Air quality impacts are evaluated for the South Coast Air Basin of California, in the year 2010, using a three-dimensional air quality model. Results are compared to air quality impacts from two potential DG scenarios to meet the same power demand as that of the central power plant case.

Even though emissions from central generation are lower than emissions from the DG technology mix considered herein, central generation concentrates emissions in a small area, whereas DG spreads emissions throughout a larger cross-section of the air basin. As a result, air quality impacts from central generation are more significant than those from DG. The study also shows that assessment of air quality impacts from distributed and central generation should not only consider emissions levels, but also the spatial and temporal distribution of emissions and the air quality that results from atmospheric chemistry and transport – highly non-linear processes.

Finally, analysis of population exposure to ozone and $PM_{2.5}$ shows that central generation located in coastal areas upwind from populated areas would cause the highest population exposure and even though emissions from central generation are considerably lower than DG emissions spread throughout the basin, results show that central generation causes a higher pollutant exposure than DG.

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1. Introduction

Distributed generation (DG) is characterized by the widespread installation of many stationary power generators close to the point of electricity use within an urban air basin. In contrast, conventional, centralized power plants tend to be located in remote areas from which electricity must be transmitted to end users. However, increasing electricity demand combined with stressed transmission lines, and increasingly challenging right-of-way and environmental obstacles to transmission line additions may force even central power generation back into air basins. Recent power plant applications in southern California confirm this trend (CEC, 2007a). In addition, the Renewable Portfolio Standard for California requires a high deployment of renewable electricity production by the year 2020. The intermittent nature of renewable sources like wind and solar power may require additional power generation that is needed to ramp-up and ramp-down electricity production quickly to compensate for the intermittent renewable sources (Porter, 2007). Generally, fast-response dispatchable technologies are based upon fossil fueled power generators that produce an emissions impact.

DG has the potential to meet the power demands in the near future. Deployment of DG technologies might provide additional benefits such as increased energy efficiency, electrical reliability, power quality, and reductions in production costs. Furthermore, power generation near the place of consumption minimizes electricity transmission losses and can be used for cogeneration of heating and cooling, generally termed as combined cooling, heating and power (CCHP). In addition, DG could provide dispatchable balancing power to compensate for the high deployment of intermittent sources of electricity, like wind power (Østergaard, 2005). However, deployment of DG introduces new emissions sources that are spread throughout an air basin, in a manner that is spatially and

temporally different from central generation, which concentrates pollutant emissions in a limited number of emitting foci.

Previous studies evaluated different DG technologies and suggested that only the lowest emitting DG technology (fuel cells) could be competitive with combined cycle power generation from an emissions perspective (Ianucci et al., 2000; Allison and Lents, 2002; Heath et al., 2006). These studies provide valuable insights, but assume outdated emission factors for DG, only consider emissions impacts and do not account for atmospheric chemistry and transport in the airshed, which must be accounted for to determine ambient air quality impacts.

Rodriguez et al. (2006) studied the potential air quality impacts of DG in the South Coast Air Basin of California (SoCAB) in the year 2010. Rodriguez et al. presented a series of possible DG implementation scenarios, and estimated their air quality impacts with respect to a baseline 2010 scenario that included no DG or other additional in-basin generation. Air quality impacts of DG reported by Rodriguez et al. were small due to expected low market penetration of DG by 2010. However, that study assumed that if no DG were installed, electricity would be imported from outside the basin, and as a result, no emissions from central generation would be introduced into the SoCAB in the central generation case. Hence, no real comparison between DG and in-basin central generation was shown.

The present study considers the possibility that limitations in the transmission of electricity could require additional in-basin generation. In-basin generation could be met either by DG or by central generation. This work analyzes the air quality impacts of in-basin central generation in the SoCAB in the year 2010, and compares central generation impacts to the air quality impacts of DG. In addition, the present work assesses the variability of human exposure due to central and distributed power generation.

2. Model formulation

The University of California, Irvine – California Institute of Technology (UCI-CIT) atmospheric chemistry and transport model is used to analyze the air quality in the SoCAB. The UCI-CIT model stems from the CIT model developed by McRae and Seinfeld (1982) and incorporates later developments in chemistry (Harley et al., 1993; Griffin et al., 2002a), in aerosol formation (Meng et al., 1998; Pun et al., 2002; Griffin et al., 2002b, 2003), in new numerical solution of advection (Nguyen and Dabdub, 2001). The UCI-CIT model has been applied extensively to study the air quality of the SoCAB (Griffin et al., 2002a; Nguyen and Dabdub, 2002; Carreras-Sospedra et al., 2006). The computational domain for this study, shown in Fig. 1, corresponds to an irregular region composed of 994 columns of cells. Each column resolves a 5 km by 5 km region in the x, y plane and extends 1100 m in height. The columns are partitioned into 5 cells in the z direction.

The UCI-CIT model includes the CalTech Atmospheric Chemistry Mechanism (CACM) (Griffin et al., 2002a,b; Pun et al., 2002). This chemical mechanism is intended for use in three-dimensional urban/regional atmospheric models, with O_3 formation and secondary organic aerosol (SOA) production. CACM includes 191 species and 361 reactions to accurately describe the chemical processes.

2.1. Meteorological conditions

The Southern California Air Quality Study (SCAQS) was a comprehensive campaign of atmospheric measurements that took place in the SoCAB, during August 27–29, 1987. The study collected an extensive set of meteorological and air quality data that has been used widely to validate air quality models (Meng et al., 1998; Griffin et al., 2002a,b; Pun et al., 2002; Moya et al., 2002). Zeldin et al. (1990) indicated that August 28, 1987 is representative of the meteorological conditions in the SoCAB, which makes it suitable for modeling an air quality episode. In addition, the August 27–28, 1987 episode is statistically within the top 10% of severe ozone-forming meteorological conditions. Hence, meteorological conditions for August 28 are used herein as the basis for comparing DG to central generation air quality impacts.

The SCAQS episode in August 27–29, 1987 was characterized by a weak onshore pressure gradient and warming temperatures aloft. The wind flow was characterized by a sea breeze during the day and a weak land-mountain breeze at night. The presence of a well-defined diurnal inversion layer at the top of neutral and unstable layers near the surface, along with a slightly stable nocturnal boundary layer, facilitated the accumulation of pollutants throughout the SoCAB, which lead to a high ozone concentration episode.

2.2. Emissions

Baseline emissions for the simulations are based on the emissions inventory developed by the South Coast Air Quality Management District (SCAQMD) for the 2003 Air Quality Management Plan (AQMP) to demonstrate attainment of the 1-h ozone standard (SCAQMD, 2003). This emissions inventory includes current emission controls planned for 2010 and other measures that would reduce baseline emissions to a level at which ozone concentration would not exceed the federal 1-h air quality standard (120 ppb). Emissions from distributed or central generation cases of the current study are estimated using a separate methodology described subsequently and added to these baseline emissions.

2.2.1. Sample distributed generation scenarios

A distributed generation scenario is defined by a set of parameters that determine which technologies and in what manner (spatially and temporally resolved) DG is deployed in an area of
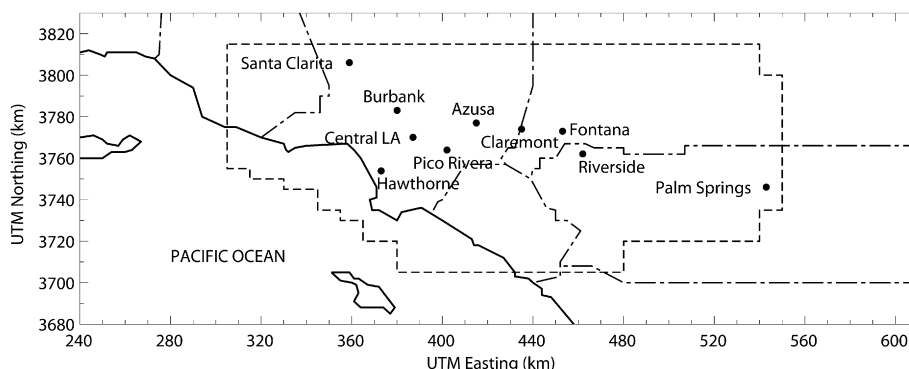

Fig. 1. Computational domain of the UCI-CIT airshed model that represents the South Coast Air Basin of California.

interest. This set of parameters includes: (a) *DG market penetration*: the total capacity of DG installed in the basin, (b) *DG technology mix*: the set of technologies that are expected to be deployed in DG installations, (c) *Emissions associated with each DG unit type*: the emissions released by each DG technology based upon existing performance and regulations, (d) *Spatial distribution of the DG within the basin*: the spatial allocation of emissions from DG, based upon socio-economic factors and land-use data, (e) *Operational duty cycle of each DG unit*: the temporal variation of emissions from each type and application of DG, and (f) *Emissions displaced by DG installation*: the potential to remove existing emissions due to combined heat and power (CHP), substituting for boilers or other heating, cooling, or electrical applications.

Early projections suggested that the total fraction of energy demand met by DG could be as high as 20% of the electricity load growth by 2020 (Tomashefsky and Marks, 2002). Newer reports show that only 337 MW of generating capacity was installed with support from the Self Generation Incentive Program by the end of 2008 (CPUC, 2009). While this does not account for all DG installations, this level suggests a slower trend. Rodriguez et al. (2006) evaluated the air quality impacts of various DG market penetration levels from 2002 to 2010. Only scenarios that assumed a penetration of 20% or more of the increased electricity demand from 2002 to 2010 produced discernable air quality impacts on ozone and $PM_{2.5}$. This level of market penetration corresponds to a generating capacity of 1062 MW.

The current study selects two sample DG scenarios presented by Rodriguez et al. that consider a high penetration of DG, namely 20% of the increased demand from 2002 to 2010. The first DG scenario, DG scenario 1, corresponds to a case in which DG market penetration is developed based upon the methodology developed by Samuelsen et al. (2005) and Medrano et al. (2008). The methodology employs detailed land-use geographical information systems (GIS) data and market studies for DG implementation that can produce a realistic estimate of the DG technology mix that could be installed in the SoCAB. In addition, the methodology accounts for the potential of CHP applications, assuming that only 30% of the heat can be recovered due to thermodynamic limits, heat losses and temporal mismatch between thermal demand and excess heat production. The technology mix of DG scenario 1 is presented in Table 1. The second DG scenario, DG scenario 2, assumes an alternative DG technology mix, which is also presented in Table 1. In addition, the spatial distribution of DG installations is proportional to the distribution of population density in the SoCAB in 2010, to assess the impacts of spatial allocation of emissions. Finally, DG scenario 2 does not include emissions displacements due to CHP. The analysis of these two different DG scenarios illustrates a range of potential air quality impacts from DG installations due to the different parameters assumed in the DG scenario development.

2.2.2. Central power plant scenarios

Fossil fuel-based power generation in California mostly uses natural gas (NG), although there are a few coal-based power plants (CEC, 2007b). In the case of the SoCAB, restrictive emission standards in the South Coast Air Quality Management District (SCAQMD) only allow for use of natural gas power plants. Therefore, this study analyzes the air quality impacts of a prototypical state-of-the-art, low emissions NG combined cycle power plant.

Emission factors are obtained from the High Desert Power Plant Project (CEC, 2000), which was installed in the Mojave Desert, and came on-line in April 2003. The power plant consists of three 240-MW combined cycle gas turbines with selective catalytic reduction systems for oxides of nitrogen (NO_x) control. The present study analyzes the air quality impacts of the operation of a plant under two scenarios: 1) continued normal operation during 24 h, and 2) discontinuous operation that includes two start-up (2 h event^{-1}) and two shut-down events (1 h event^{-1}), and a total of 18 h of normal operation, which is considered herein a 'worst-day' scenario in terms of pollutant emissions. To compare the same central generation capacity with the capacity installed in the DG scenarios, the sample plant considered in this study has five 240-MW combined cycle turbines, with a total capacity of 1200 MW. Gas-phase and aerosol phase chemical speciation of emissions is based upon speciation of a natural gas reciprocating internal combustion engine (ARB, 2008). In addition, size resolution of particles is based upon measurements of particles emissions from a gas turbine combustor (Brundish et al., 2005).

To assess the effect of location on the potential air quality impacts of installing a new central power plant, three locations are selected for this study: 1) Huntington Beach, Orange County, 2) Etiwanda, San Bernardino County, and 3) El Segundo, Los Angeles County. These locations are selected because they already have licensed the installation of central power plants, and they could be amenable to installing extra capacity in the future. Huntington Beach represents a location that is generally upwind from Riverside, which typically experiences poor air quality during episodes. On the other hand, Etiwanda represents a location that is far downwind from Los Angeles, the main focus of emissions in the SoCAB, and near the area with the poorest air quality conditions. Finally, El Segundo is located upwind from central Los Angeles. The installation of a power plant in El Segundo has the potential to impact a highly populated area just downwind during an episode. Hence, these three locations are illustrative of the variety of air quality impacts that central generation could produce.

2.2.3. Comparison of emissions from central power plants and distributed generation

Emissions that result from the scenario development methodology for the two distributed generation scenarios and from the two central generation scenarios are presented in Table 2. Total emissions from normal operation of a central power plant are significantly lower than emissions from DG, except for oxides of nitrogen (NO_x) and ammonia (NH_3). NO_x emissions from DG scenario 1 are lower than NO_x emissions from central generation due to the emissions displacement of CHP applications associated with the DG installations. On the other hand, total emissions from central generation under 'worst-day' conditions are comparable to

Table 1
Parameters for two sample distributed generation scenarios (from Rodriguez et al., 2006).

DG scenario[a]	Description	Penetration (% of increased demand)	Technology mix[b] (%)					
			GT	ICE	MTG	FC	PV	Hybrid
1	GIS land-use distribution, technology mix depends on activity sector, realistic duty cycles, and CHP	20	48	18	15	10	5	4
2	Population-weighted spatial distribution, DG operated base-loaded	20	30	30	25	7	8	–

[a] DG scenarios 1 and 2 correspond to scenarios R3 and PW2010 presented in Rodriguez et al. (2006).
[b] GT: gas turbines; ICE: natural gas internal combustion engines; MTG: micro-turbine generators; FC: fuel cells; PV: photovoltaic; hybrid: gas turbine + fuel cell hybrid systems.

Table 2
Daily emissions from selected distributed generation scenarios and from central generation under normal conditions of operation and under discontinuous operation ('worst-day').

	Pollutant emissions (tons day^{-1})					
	ROG	CO	NO$_x$	NH$_3$	SO$_x$	PM$_{10}$
DG scenario 1 (R3)	0.64	9.06	−0.35	0.80	0.12	0.97
DG scenario 2 (PW2010)	0.80	8.19	2.54	0.25	0.10	0.61
Normal Central	0.04	1.05	1.08	1.60	0.00	0.06
Worst-day Central	0.86	20.63	1.99	1.60	0.07	1.09

emissions from the DG scenarios. However, emissions from DG are spread throughout the air basin, whereas emissions from central generation are concentrated as an elevated point source. As a result, air quality impacts from DG are likely to be different from those of central generation due to the spatial distribution of emissions.

3. Air quality impacts and exposure

Fig. 2 shows air quality impacts on peak ground-level ozone concentrations throughout the basin produced by the DG and central generation scenarios, plotted as the difference between scenario concentrations and those of the baseline case. In general, impacts on peak ground-level ozone concentrations are related to NO$_x$ emissions. In the SoCAB, NO$_x$ concentrations are typically high, leading to volatile organic compounds (VOC)-limited ozone production conditions. Small additions of NO$_x$ emissions under VOC-limited conditions tend to decrease ozone concentration. Hence, scenarios with increases in NO$_x$ emissions produce reductions in peak ozone concentration in some regions of the basin (Fig. 2(b)–(f)). On the contrary, the DG scenario 1 (Fig. 2(a)) reduces NO$_x$ emissions, and hence, produces small increases in peak ozone concentrations. The range of impacts on O$_3$ in the DG scenarios is ±1 ppb. Impacts on O$_3$ due to central generation depend upon
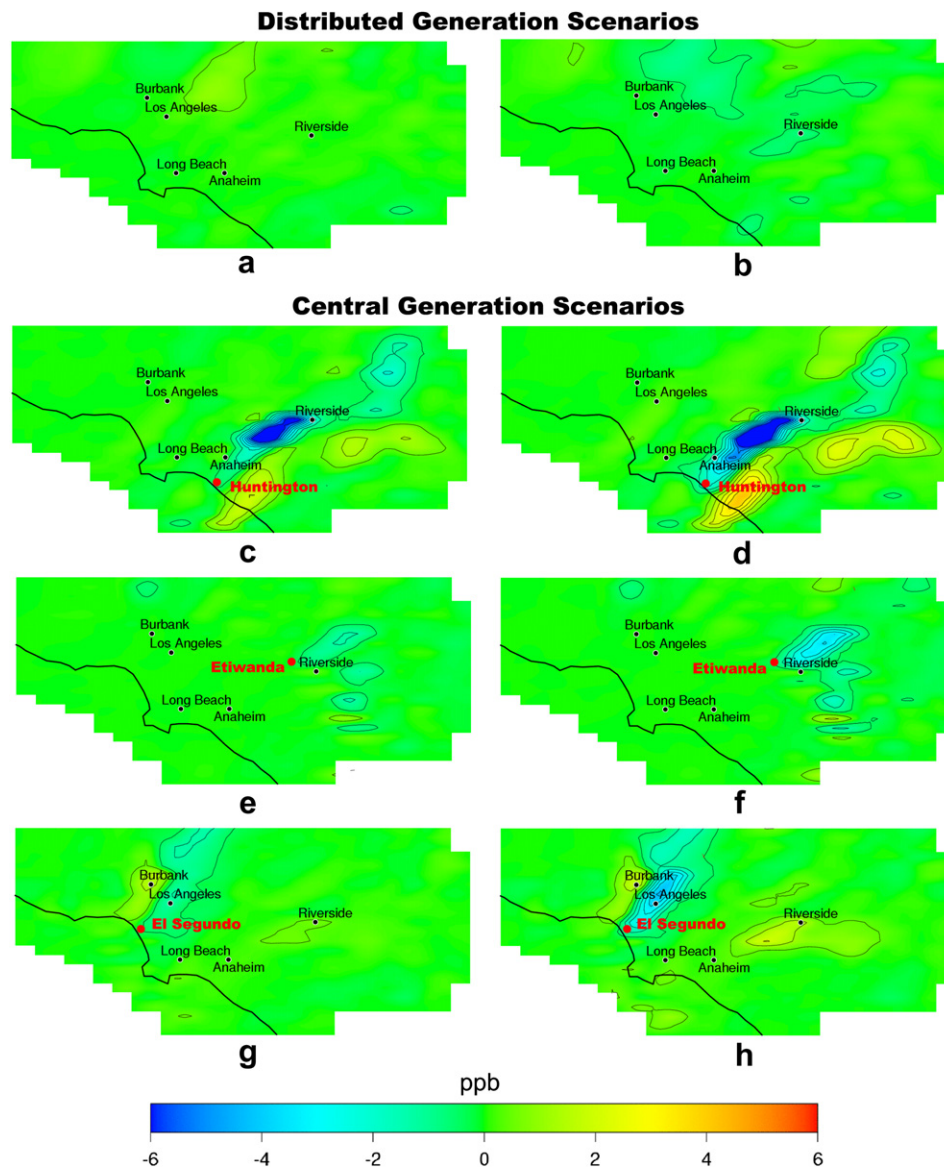

Fig. 2. Increase in peak O$_3$ concentration with respect to the base case (negative values represent decreases in concentration with respect to base case): (a) DG scenario 1, (b) DG scenario 2, (c) normal operation of Huntington Beach central power plant, (d) 'worst-day' operation of Huntington Beach central power plant, (e) normal operation of Etiwanda central power plant, (f) 'worst-day' operation of Etiwanda central power plant, (g) normal operation of El Segundo central power plant, (h) 'worst-day' operation of El Segundo central power plant.

location and operating conditions. Impacts on O_3 due to the plant installed in Etiwanda are significantly smaller than the impacts produced by scenarios that install the plant in Huntington Beach and El Segundo. Under normal conditions, the plant in Huntington Beach reduces peak O_3 concentrations by 11 ppb in some locations, but, it also increases peak O_3 concentrations by 2 ppb in other locations. Operation of the same plant under 'worst-day' conditions leads to decreases in peak O_3 concentrations of 13 ppb and increases of 6 ppb in various locations as shown in Fig. 2(f). In addition, the geographic area affected by increases in ozone concentration due to 'worst-day' operating conditions is larger than the area affected by the same plant operated under normal conditions regardless of installation location.

Air quality impacts on 24-h average $PM_{2.5}$ concentrations are presented in the difference plots of Fig. 3. Changes in $PM_{2.5}$ are due to changes in direct emissions of particles from the scenarios and due to changes in secondary formation of aerosol due to the addition of NO_x and sulfur oxides (SO_x). Impacts of DG on 24-h average $PM_{2.5}$ concentrations are smaller than 1 $\mu g\,m^{-3}$, whereas central generation under normal conditions increases $PM_{2.5}$ concentrations by as much as 4 $\mu g\,m^{-3}$. Operation of central generation under 'worst-day' conditions produces increases in 24-h average $PM_{2.5}$ concentrations up to 15 $\mu g\,m^{-3}$. Impacts on $PM_{2.5}$ due to direct emissions of particles are localized near the location of the central power plant and correspond to the highest impacts. On the other hand, impacts on secondary $PM_{2.5}$ occur far downwind from the central plant, leading to increases in 24-h average $PM_{2.5}$ of less than 3 $\mu g\,m^{-3}$. Importantly, these increases occur in locations that are already highly impacted by PM episodes.

Note that other studies have simulated elevated sources using a plume-in-grid model, which incorporates a plume model into a conventional Eulerian model, such as the UCI-CIT model
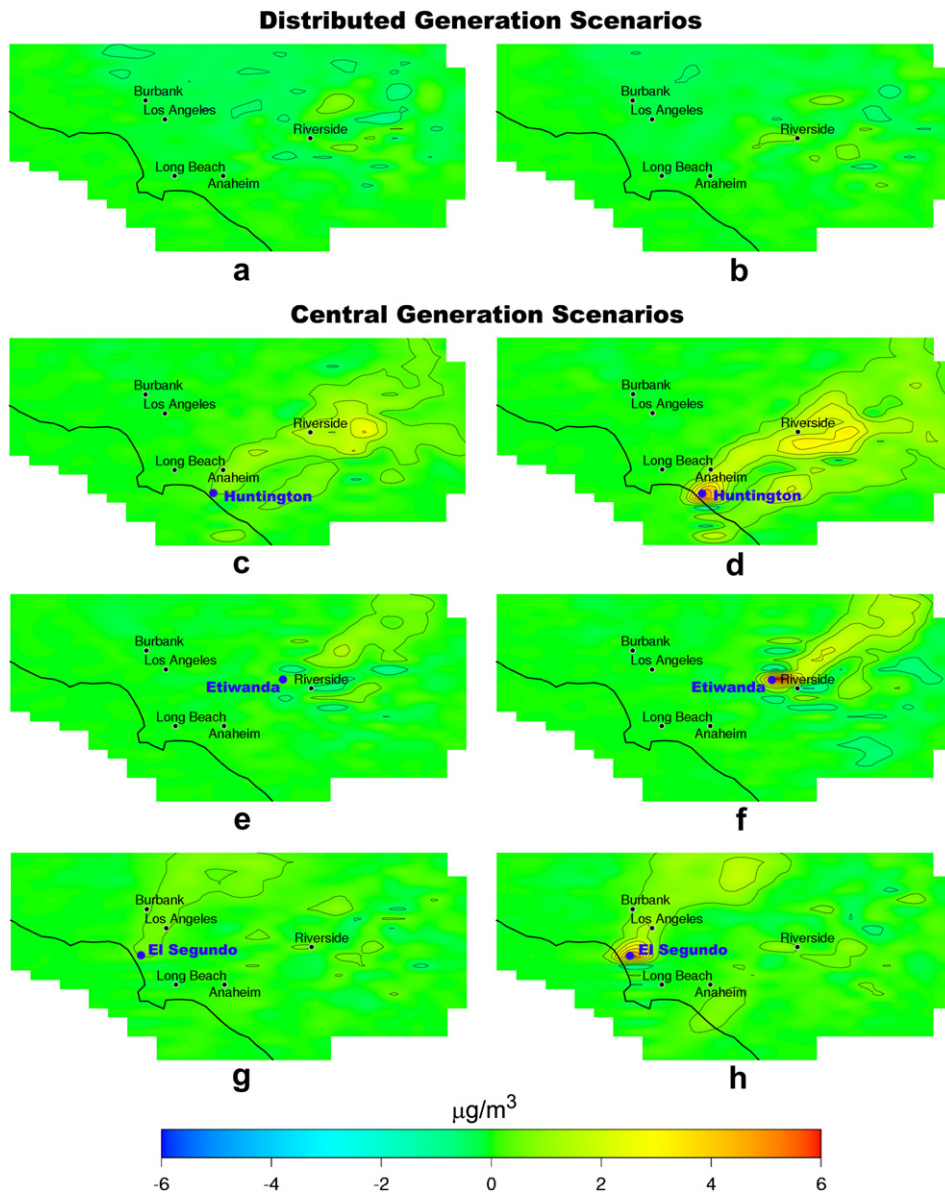

Fig. 3. Increase in 24-h average $PM_{2.5}$ concentrations with respect to the base case (negative values represent decreases in concentration with respect to base case): (a) DG scenario 1, (b) DG scenario 2, (c) normal operation of Huntington Beach central power plant, (d) 'worst-day' operation of Huntington Beach central power plant, (e) normal operation of Etiwanda central power plant, (f) 'worst-day' operation of Etiwanda central power plant, (g) normal operation of El Segundo central power plant, (h) 'worst-day' operation of El Segundo central power plant.
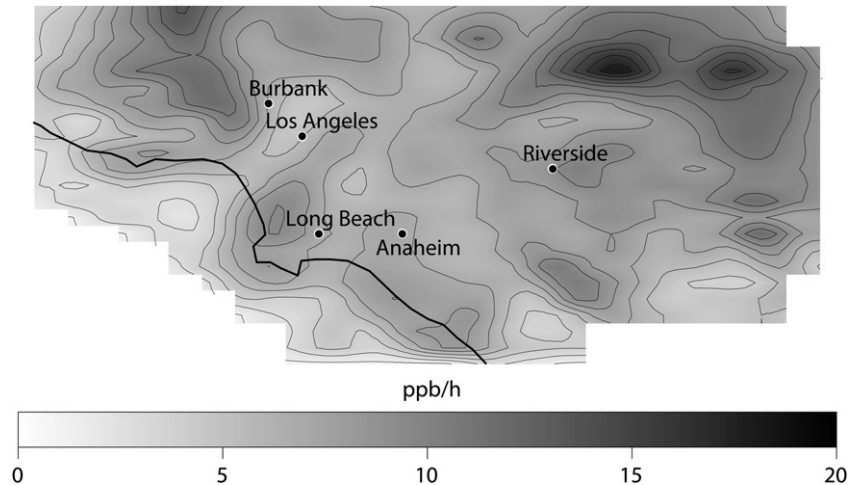
Fig. 4. Maximum ozone reactivity in the South Coast Air Basin of California estimated for the base case 2010, without the addition of distributed or central generation.

(Karamchandani et al., 2002; Vijayaraghavan et al., 2006). The plume effect generally retards the reactivity of pollutants from the stack, resulting in air quality impacts of elevated sources using the plume-in-grid model that are smaller in intensity, but more widespread in area, in comparison with the impacts obtained with a conventional air quality model.

3.1. Spatial sensitivity of air quality impacts

As shown in Figs. 2 and 3, the intensity and distribution of air quality impacts from power plants depends greatly upon the location of the plant. Atmospheric transport due to wind determines the distribution of a plume and emissions from other local sources determines how the emissions from a power plant interact through chemical and physical processes with the surrounding atmosphere. As a result, meteorological conditions are an important factor for determining the air quality impacts. The present article focuses on a meteorological episode that is most representative of the typical meteorology of the SoCAB under high ozone and PM formation conditions. While a single episode cannot fully represent the air quality impacts of point sources, this particular episode reflects the most common meteorological conditions for the area. Hence, conclusions from this study can be used to describe the most common impacts expected for the scenarios presented here.

Ozone is formed through the oxidation of VOC and the catalytic cycle of NO–NO$_2$ formation. In the presence of VOC and sunlight, NO
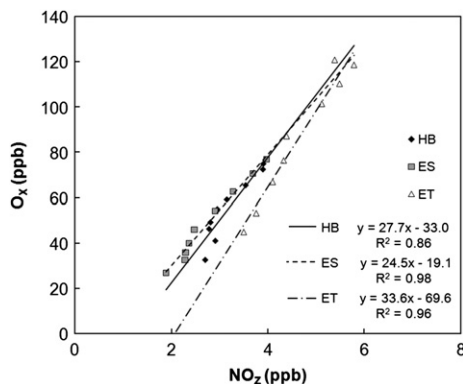

Fig. 5. Ozone production potential calculated based on Springston et al. (2005) in the three plumes: Huntington Beach (HB), El Segundo (ES), and Etiwanda (ET).

oxidizes to NO$_2$ and then it photolyzes back to NO, producing a number of ozone molecules for every NO$_x$ molecule before NO$_x$ is removed by termination reactions. Thus, the presence of VOC is key to the resulting air quality impacts from a point source that emits large quantities of NO$_x$. The capacity of a VOC mixture to provide a reactive environment that yields high concentrations of ozone is determined by ozone reactivity scales (Carter, 1994; Griffin et al., 2004).

The ozone-forming potential of a VOC and CO mixture, $P(O_3)$, is calculated as follows, based on Griffin et al. (2004):

$$P(O_3) = k_{CO,OH}[CO][OH] + \sum_i k_{i,OH} Y_i [ROG_i][OH], \qquad (1)$$

where $k_{i,OH}$ represents the kinetic rate constant for the reaction between OH and species i, Y_i represents the stoichiometric yield of peroxy radicals in the reaction between OH and reactive organic gas (ROG) species i, and the bracket notation represents mixing ratios.

The overall reactivity depends upon the total amount of VOC and the VOC chemical composition, and hence, on baseline emissions. The total daily reactivity estimated for 2010 is presented in Fig. 4. Peak ozone production potential occurs in the northeastern part of the domain, where peak ozone occurs. Overall, high rates of ozone production are located downwind in the same areas as the areas that exhibit high ground-level ozone concentrations. Although ozone precursors are mostly emitted in the central part of the domain — around Los Angeles and Long Beach — ozone production potential peaks downwind, where the sinks of ozone are considerably lower than those near the central part. The three power plants considered in this study are located in areas with moderate-to-low ozone reactivity potential. Only the power plant located in Etiwanda shows high reactivity downwind from the plant.

Even though ozone reactivity is positive throughout the basin, the most prominent impacts from power plants result in a reduction in ozone concentration. Previous studies based on field measurements of plume concentrations determined that concentrations of NO$_x$ below 10 ppb enhance ozone formation, whereas concentrations above 15 ppb suppress ozone formation (Ryerson et al., 2001; Springston et al., 2005). In contrast, current simulation results show that ozone formation is suppressed even at lower NO$_x$ concentrations. Average NO$_x$ concentrations in the plume from each power plant are above 15 ppb only until 9:00 am (see Fig. 7(a)). In addition, NO$_x$ concentrations in the plumes from Huntington Beach and Etiwanda are below 10 ppb during the afternoon hours. Even under these low NO$_x$ concentrations in the plumes, ozone concentrations decrease in this region due to emissions from the power
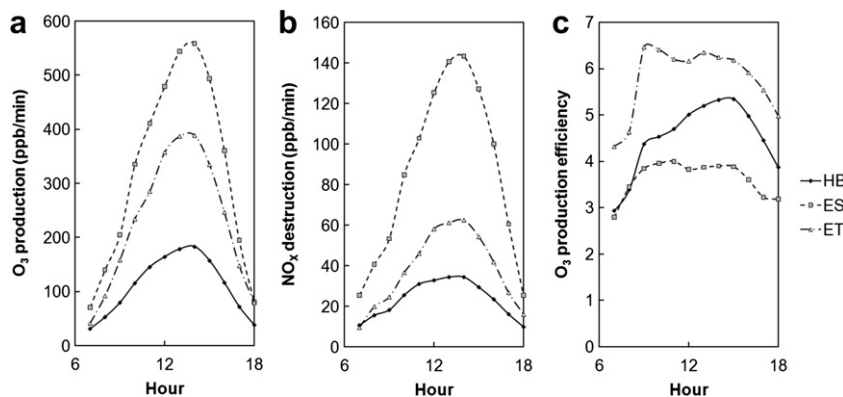
Fig. 6. Alternative ozone production potential based on Griffin et al. (2004) in the three plumes: Huntington Beach (HB), El Segundo (ES), and Etiwanda (ET). The figures present: (a) O_3 production during day-light, $P(O_3)$, (b) NO_x destruction, $L(NO_x)$, (c) ozone production efficiency, $OPE = P(O_3)/L(NO_x)$.

plants, as shown in Fig. 2. However, it is interesting to note that the smallest decrease in ozone concentration occurs for the plant in Etiwanda, because it is located in an area with higher ozone production potential compared to the other plants. Springston et al. (2005) calculated values of ozone production efficiency (OPE) as the ratio between the ozone produced ($O_x = O_3 + NO_2 + PAN + NO_3 + 2NO_3 + 3N_2O_5$, where PAN corresponds to peroxyalkyl nitrates) and the ozone oxidized ($NO_Z = NO_Y - NO_x$, where $NO_Y = NO_x + HONO + HNO_3 + N_2O_5 + NO_3 + PAN$). The OPE values are then obtained by the slope of the plot of O_x concentrations versus NO_Z concentrations, as shown in Fig. 5. The OPE values reported by Springston et al. are more than four times smaller than the values obtained for the SoCAB, because those values correspond to an isolated plume in a remote area, far from other anthropogenic emissions. An alternative way to calculate OPE based upon the ratio between O_3 production and NO_x destruction (following Griffin et al., 2004) provides values that agree better with the ones reported by Springston et al. The values of O_3 production, NO_x destruction and OPE values are presented in Fig. 6. Qualitatively, both methods to determine ozone reactivity show the same trend in reactivity for the three power plant locations. Namely, O_3 production efficiency is largest in Etiwanda, and smallest in El Segundo. Hence, if location of a power plant is based upon OPE values alone, then El Segundo would be the preferred power plant location amongst the three.

The increase in NO_x, which produces a dip in ozone concentrations in the plumes, leads to an increase in nitric acid that is available to form nitrates in the aerosol phase, increasing the concentration of $PM_{2.5}$. However, formation of nitrates in the SoCAB is directly related to the availability of ammonia, as suggested by

Nguyen and Dabdub (2002). Hence, the largest increases in $PM_{2.5}$ occur downstream from Huntington Beach power plant location, because there are high emissions of ammonia released downwind from that location. Overall, whereas the impacts from direct emissions of $PM_{2.5}$ are not sensitive to location, the impacts of power plant location on secondary aerosol depend strongly on the presence of ammonia downwind from the plume. Fig. 7 shows the concentrations of NO_Z, mainly constituted by HNO_3, downwind from each of the three power plant locations. Concentrations of NO_Z downwind from Etiwanda are significantly higher than for the other two power plant locations, because ammonia emissions downwind from the plant in Etiwanda are not as high.

3.2. Spatial sensitivity of human exposure

The spatial distribution of air quality impacts is not necessarily correlated with population density. To assess human exposure to air quality impacts analysis of population-weighted concentrations was accomplished. This analysis considers the change in peak ozone and daily average $PM_{2.5}$ concentration due to central and distributed generation multiplied by local population density to quantify the change in exposure expressed as person·ppb for ozone and person·($\mu g\,m^{-3}$) for $PM_{2.5}$ for a given area.

The basin-wide increases in population exposure for each case are presented in Table 3. Interestingly, all scenarios except DG scenario 1 introduce additional NO_x emissions that reduce peak ozone concentrations and exposure. Only DG scenario 1 causes a net reduction in NO_x emissions, which leads to a slight increase in ozone exposure. In the case of particulate matter, central generation
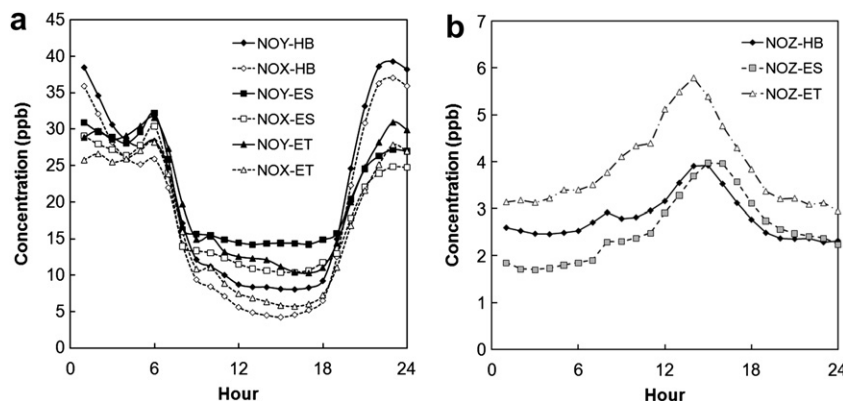

Fig. 7. Hourly average concentrations of (a) NO_x and NO_Y, and (b) NO_Z in the plumes of the three power plants: Huntington Beach (HB), El Segundo (ES), and Etiwanda (ET).

Table 3
Increase in pollutant exposure due to changes in peak ozone and daily average $PM_{2.5}$ concentrations estimated for distributed and central electricity generation scenarios. The ranking in exposure of each scenario is included in parentheses.

	Increase in pollutant exposure	
	O_3 10^6 person ppb	$PM_{2.5}$ 10^6 person µg m^{-3}
DG scenario 1 (R3)	0.72 (1)	−1.50 (8)
DG scenario 2 (PW2010)	−1.71 (5)	−1.22 (7)
Huntington Beach normal	−1.39 (4)	4.19 (3)
Huntington Beach worst-day	−3.64 (7)	10.77 (1)
El Segundo normal	−1.01 (3)	2.17 (4)
El Segundo worst-day	−4.61 (8)	6.96 (2)
Etiwanda normal	−0.78 (2)	−0.02 (6)
Etiwanda worst-day	−2.48 (6)	1.07 (5)

scenarios increase exposure to $PM_{2.5}$, except for the plant in Etiwanda when it is operating under normal conditions. Moreover, DG scenarios cause the overall lowest pollutant exposure to $PM_{2.5}$. Any benefits from ozone reductions are largely offset by the deleterious effects from particles released or produced in the atmosphere as a result of emissions from the central plants located in Huntington Beach and El Segundo. Finally, both the normal-operation case for Etiwanda and DG scenario 2 produce benefits in ozone and $PM_{2.5}$ exposure, separately. Benefits for both pollutants occur despite the fact that these scenarios introduce net increased emissions. These results show the non-direct relationship between human exposure and direct emissions. In particular, exposure depends upon the spatial and temporal distribution of emissions and how these emissions interact with atmospheric chemistry and transport to form secondary pollutants and disperse species of concern to human health in relation to population.

4. Conclusions

Air quality impacts caused by central generation of electricity are contrasted with the effects of distributed generation with comparable capacity. Emissions from central generation under "normal" operating conditions are significantly lower than emissions from DG to meet the same electricity demands. Only NH_3 emissions and NO_x emissions from DG scenarios that include the use of CHP are lower in some of the DG cases compared to the central generation cases. Emissions from central generation under 'worst-day' conditions are comparable to the emissions from DG. Even though emissions from central generation are lower than emissions from the DG scenarios considered herein, central generation concentrates emissions in a small area, whereas DG spreads emissions throughout a large area of the air basin. As a result, air quality impacts from central generation are greater and more concentrated than the impacts from DG. In addition, impacts of central generation were found to depend strongly upon the location of the power plant. Amongst the three locations explored in this study, the plant located in Huntington Beach — upwind from the areas with high ozone and $PM_{2.5}$ concentrations — has the greatest negative air quality impact.

Air quality simulations show that implementation of DG would potentially cause smaller air quality impacts than central generation located in the SoCAB, even though DG installations release more emissions than central generation. This is especially evident if the central power plant is installed near the coast, upwind from areas with typically poor air quality. This study shows that assessment of air quality impacts from distributed and central generation should not only consider the magnitude of air pollutant emissions. Assessment of air quality impacts requires detailed understanding of the implementation scenarios, temporally and spatially resolved

emissions, and the solution of atmospheric chemistry and transport in an airshed model to determine air quality impacts.

Analysis of population exposure to ozone and $PM_{2.5}$ shows that central generation located in coastal areas upwind from populated areas would cause the most adverse effects, even if emissions from central generation are considerably lower than DG emissions spread throughout the basin. Conversely, human exposure from central generation located downwind from the central area of the SoCAB would be comparable to the effects from DG. In conclusion, exposure to pollutants is not strictly related to total pollution emissions, but rather is affected by the spatial and temporal distribution of emissions and resulting atmospheric chemistry and transport that leads to high ground-level concentrations near population centers.

Acknowledgements

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