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URBAN AIR QUALITY IMPACTS OF DISTRIBUTED GENERATION

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ABSTRACT

Distributed Energy Resources (DER) have the potential to meet a significant portion of increased power demands of the future. DER applications can potentially provide benefits in electrical reliability and power quality, in addition to reducing total energy costs in combined cooling, heating and power (CHP) applications. However, the shift from a central generation paradigm to distributed generation results in different emissions characteristics and profiles from both a spatial and temporal perspective. Distributed generation is characterized by many sparsely distributed stationary sources within an urban air-shed compared to central generation where emissions sources are much larger, but typically located outside the air-shed in more remote locations. As a result, high market adoption of fuel-driven (non-renewable) distributed generation (DG) technologies, such as reciprocating engines and microturbines, may influence the air quality within a region.

The present paper estimates air quality impacts for a representative distributed generation scenario in the South Coast Air Basin (SoCAB) of California. Simulations are based on the year 2010 with comparison to a base case scenario with no DG emissions. The DG scenarios are developed for a reasonable percentage of power met by DG, representative spatial distribution and temporal operation, and a mix of DG technologies and emissions factors. The resultant emissions inventory for each DG scenario is then provided as input to a three-dimensional air quality model including detailed atmospheric chemistry and transport for simulation of the SoCAB. Preliminary air quality results suggest that there will

be an air quality impact, that the impacts will not be uniform throughout the air-shed, and that individual criteria pollutant concentrations may either rise or fall with the introduction of DG.

Keywords: Distributed generation (DG), distributed energy resources (DER), air quality, air quality impacts, scenarios, air quality model

INTRODUCTION

Distributed Generation (DG) has a strong potential to play an important role in the more efficient and competitive emerging electric power industry. DG can fulfill the needs of many customers and provide benefits in many applications. Among them, DG can provide critical customer loads with emergency stand-by power; support available capacity to meet peak power demands; improve user power quality; and provide low-cost total energy in Combined Cooling, Heating and Power (CHP) applications.

California, as one of the first regions in the US facing the restructuring of the electric power industry, will likely be one of the first locations with widespread adoption of DER. According to the strategic plan for DG developed by the California Energy Commission [1], more than 2,000 MW can be currently classified as DG in California. From January 2001 through May 2002, 192 DG projects were proposed throughout the state, representing more than 400 MW of new generation.

The implementation of a paradigm shift from central generation to distributed generation would result in

significantly different emissions profiles with increased and widely dispersed stationary source emissions increases in several air basins (compared to central generation outside of the basin). One would like to determine whether increases in pollutant emissions in the air basin would lead to ambient ozone levels that exceed the proposed new 8-hour ozone standard. Also, increases in NO_x emissions can trigger increases in secondary particulate formation that could impact compliance with proposed Federal PM_{2.5} standard. The determination of these and other potential air quality impacts is of significant strategic importance to the advancement of DG technology. In addition, these impacts need to be assessed before public policy decisions are made to facilitate application of DG in urban air basins.

In a recent study Lents et al. [2] determined the forms of DG that are most likely to improve environmental quality, and to reduce air pollution in California. Their strategy was to comparatively analyze the level of pollutant emissions associated with a range of DG technologies and fuel types. They concluded that only the lowest emitting DG with significant waste heat recovery is evenly marginally competitive with combined cycle power production from a criteria pollutant emissions perspective. However, in cases where waste fuel is being flared or directly emitted within the basin (e.g., in landfills), in-basin pollutant emissions can be reduced if this fuel is used to drive the DG units.

Ianucci et al. [3] evaluated the net air emissions effects from the potential use of cost-effective distributed generation in California. First, the study used the available DG technologies and their costs to assess the economic market potential for DG for both utilities and large commercial/industrial customers in years 2002 and 2010. Second, total emissions were calculated for the selected years, given the estimated market penetration levels for each type of DG, and compared with central-generation only scenario. The study concluded that the current California central generation mix is so clean that virtually no cost-effective distributed generation source could lower net emissions, even including line losses. Fuel cells resulted in a marginal market penetration, due their high cost, but showed great promise because their air emissions are much lower than central station generation.

Significantly, neither of the above studies determined the air quality impacts associated with the DG emissions. Air quality is affected by a host of factors over and above the direct emission of criteria pollutants that the DG may emit. These factors include homogeneous and heterogeneous atmospheric chemistry, mass transport, photochemical reactions, spatial and temporal variations in emissions, geography, meteorology, etc. These air quality impacts can only be determined using a detailed and fully coupled air quality model that includes these phenomena.

Our research group is leading a California Energy Commission (CEC) Project entitled '*Air Quality Impacts of Distributed Generation*' that is both determining realistic scenarios for DG application in SoCAB and assessing air quality impacts with a detailed air quality model. Its main two objectives are to: (1) construct a set of distributed generation implementation scenarios for the South Coast Air Basin (SoCAB) in California; and (2) evaluate in those scenarios the potential air quality impact of DG by application to an air

quality model for SoCAB. The model is a state-of-the-art, discretized (into 5-km X 5-km cells), comprehensive modeling system for urban air pollution based on many years of SoCAB simulation efforts at the California Institute of Technology (CIT). This paper presents the parameters considered for the development of a DG implementation scenario and illustrates the capabilities and results from analysis of a specific DG scenario.

NOMENCLATURE

C_i :	Mean concentration of species i
K :	Eddy diffusivity tensor
Q_i :	Source term for the elevated point sources of species i
R_i :	Rate of generation of species i by chemical reaction
u :	Mean wind velocity

List of Acronyms

CARB:	California Air Resources Board
CEC:	California Energy Commission
CHP:	Combined Cooling, Heating and Power
DER:	Distributed Energy Resources
DG:	Distributed Generation
FC:	Fuel Cell(s)
ICE:	Internal Combustion Engine
LCC:	Lurmann-Carter-Coyner Chemical Mechanism
MCFC:	Molten Carbonate Fuel Cell(s)
MTG:	Microturbine Generator
NO _x :	Nitrogen Oxides
NG:	Natural Gas
PEMFC:	Proton Exchange Membrane Fuel Cell(s)
PM _{2.5} :	Particulate Matter (less than 2.5 microns)
PV:	Photovoltaics
SCAQMD	South Coast Air Quality Management District
SoCAB:	South Coast Air Basin
SOFC:	Solid Oxide Fuel Cell(s)

SCENARIO DEVELOPMENT

To fully characterize how distributed generation resources may be implemented in SoCAB one needs to develop a detailed suite of information and characteristics that we call a DG scenario. The current study will investigate a large number of specific DG scenarios to span the spectrum of possible instances of DG application in SoCAB. The general characteristics and features that are included in each DG scenario include the following:

1. Fraction of energy needs met by DG
2. DG allocation (types of DG units and number of DG units of each type)
3. Emissions specification for each DG
4. Spatial distribution of DG in SoCAB
5. DG duty cycle (temporal variation for each DG type and application)
6. Emissions displaced
7. Estimation of emissions, performance degradation, and/or geometrical features not available for each DG

Once all of the above 7 items are fully specified, the DG scenario is fully characterized and the corresponding DG emissions inventory for each of the discrete cells in the computational model can be developed. This DG emissions inventory is then formatted as a model input file and added to the baseline emissions inventory for use in the model to assess the air quality impacts of the DG emissions. The baseline emissions inventory includes the emissions forecasted for 2010 by the California Air Resources Board (CARB) and South Coast Air Quality Management District (SCAQMD) [4].

Fraction of Energy Needs met by DG

The “Fraction of energy met by DG” parameter has a strong influence in the final air quality impact that a DG scenario exhibits. A high penetration scenario implies that DG units throughout the basin meet a considerable portion of the total energy needs of the SoCAB. In this case, DG emissions significantly contribute to the total SoCAB pollutant emissions. However, for the same level of emissions, air quality impacts might be very different depending on other DG scenario characterization parameters such as spatial distribution of the DG power or duty cycle. In addition, these impacts are not easy to predict without a detailed and comprehensive model due to the highly non-linear processes that govern the coupled transport and atmospheric chemistry of an air basin.

According to the California Energy Commission Strategic Plan for DG [1], the forecasted adoption of DG in California for the year 2020 could be as high as 20% of the electricity load growth. The current DG scenarios are considered high penetration scenarios if the power demand met by DG is greater than 10% of the increased SoCAB power. Medium penetration is assigned to cases with about 10% of the increased power demands met by DG.

Since the fraction of energy met by DG is quite uncertain, a wide variety of DG penetration levels will be investigated in the DG scenarios to span the spectrum of possible air quality impacts.

DG Allocation

For this study we are including distributed generation power capacities that range from a few kilowatts (kW) up to 50 megawatts (MW). The 50 MW limit on DG is selected due to the permitting construct of the SoCAB. The DG technologies that are likely to be implemented in the SoCAB include commercial technologies (natural gas fired combustion turbines (up to 50 MW) and natural gas fired internal combustion engines (ICE)), and emerging technologies (solar photovoltaics (PV), fuel cells (PEMFC, MCFC and SOFC), gas turbine fuel cell hybrids, natural gas fired micro-turbine generators (MTGs), and external combustion Stirling engines).

The specific mix of DG technologies that is likely to be installed in any one region of the SoCAB in 2010 is very difficult to forecast. The technology mix is dependent on the number and type of energy customers in that region as well as a host of other economic and regulatory variables (e.g. electricity prices, gas prices, DG incentives, transmission constraints, emissions standards, etc.) that exist in that particular zone.

Every market segment can be preferentially associated with specific DG technologies that are likely to be

predominant, mainly because their capacity and features are best suited to the energy demands of that segment. In general terms, residential applications in the range 1-5 kW will likely favor fuel cells and photovoltaics; commercial and small industrial sectors, with capacities ranges of 25-500 kW are more suited for PV, MTGs, small ICEs and FCs; large commercial and institutional sectors, in the range of 500-2MW, will likely favor natural gas reciprocating engines and gas turbines; and finally the large institutional and industrial sectors with 2-50 MW capacity will be mainly served by gas turbines. This relationship between DG type and market sector, together with spatial distributions of such in SoCAB are used to estimate the distribution and duty cycle of technologies in each of the discretized cells of the model on the basis of land use zoning classification data.

The current paper does not present a detailed market penetration analysis for the various DG technologies in SoCAB, but rather determines a reasonable mix of technologies based on previous studies [3,5], input from an industry stakeholder workshop, current understanding of technology features, and intuition.

Diesel and petroleum distillate fueled units are not included in the current mix of DG technologies since the SCAQMD does not permit them to run on a continual basis as DG units.

Emissions Specifications

There is a wide range of emissions factors that are either available or estimated from each of the DG technologies. Some DG technologies are environmentally friendly, with zero emissions (e.g., wind mills, photovoltaics, etc.) or almost zero emissions (e.g. fuel cells systems), while others may emit more pollutants than central station power. For this study we have selected the emissions factors proposed by Lents et al. [2], which are best estimates from a compilation of sources. However, it is worth noting that significant disparities in the emissions rates are available in literature sources, which adds uncertainty to the evaluation of DG environmental impacts. As a result, the current project will eventually determine model output sensitivities to emissions rates as well as search out measurements and verifiable performance data to include in the analyses. Recently approved DG emissions limits by ARB for 2003 and 2007 will also be considered for reference case scenarios.

The contribution of DG emissions compared to total emissions estimates in the SoCAB for 2010 is large enough to raise concerns about the eventual air quality impacts of DG deployment. For example, a hypothetical, very high penetration DG scenario (20% of total power met by DG) where all DG are MTGs, could lead to NO_x emissions from the DG that are about 12% of total SoCAB NO_x emissions inventory.

Spatial distribution of DG in SoCAB

It is important to capture the spatial distribution of emissions in an air basin in order to accurately determine species concentrations that contribute to air quality. The location of the emissions, together with meteorology, mass transport, photochemical reaction times, the mixture of chemical compounds (both gases and aerosols), radiation intensity, etc. all contribute to the eventual air quality

prediction (e.g., ozone, NO_x, PM₁₀ concentrations). To accurately estimate the spatial distribution of DG adoption, a detailed market penetration study should be conducted at the scale of model resolution. However, this is beyond the scope of the current study, so reasonable estimates of DG power in 2010 are developed based strictly upon demographic and economic parameters that can be correlated to power (e.g., population data, population growth data, electricity consumption data, etc.).

In the example DG scenario presented in this paper, the forecast of DG power in each cell is proportional to the number of inhabitants forecasted for 2010 in that cell, i.e., the DG spatial distribution is population weighted. Although this estimate of having DG spatial adoption proportional to the population is not very realistic, it illustrates the disperse and non-uniform nature of distributed energy. Better spatial distribution estimates based on land-use, economic, and electricity consumption data are under development.

DG Duty Cycle

The DG duty cycle parameter accounts for the temporal variation of DG power production that leads to the overall capacity factor (# of hours operating/total hours) for each of the individual DG devices. The actual duty cycle for an individual DG unit depends upon maintenance schedules, economics, power demand, and many other factors. For a specific scenario some DG technologies (e.g. high temperature fuel cells) will likely operate as base-loaded devices, i.e. they will operate essentially continuously. This is due to both economic (high efficiency and high capital cost portend continuous operation for reasonable payback) and operational factors (high temperature operation leads to long start-up, and high thermal stresses associated with transients). On the other hand, many other DG types are expected to operate primarily during peak hours. The combined DG duty cycle of all DG units operating in each cell results in a different set of pollutant emissions for each hour of the simulation. The air quality impacts of this duty cycle can be assessed by the air quality model, which is capable of accepting DG emissions profiles that vary on an hourly basis.

Emissions Displaced

Many of the DG technologies that will be adopted in the following years will be used in CHP applications because the higher overall energy efficiency of CHP improves the economics of certain DG projects, and can significantly decrease operating costs. Waste heat produced during electricity generation can be captured by a heat recovery system that provides useful heat to meet facility thermal loads. Therefore, DG/CHP can replace the heat produced by burning fuel in a boiler and avoid the associated emissions into the basin. For retrofit DG/CHP applications, old, more polluting boilers are likely to be displaced, whereas for new applications displacement of emissions from new equipment (e.g., more efficient boilers) should be considered.

Another source of displaced emissions could be by application of DG on waste gases from solid landfills or oil fields, which displaces either direct hydrocarbon emission or

flared gas emissions. According to Lents et al. [2], all DG units in this type of application reduce ozone related emissions compared to a central station combined cycle power plant. Because of this fact, most of the landfills in the SoCAB have already implemented DG [6] to substitute for flares and produce on-site power and heat.

Other DG applications in which emissions could be displaced include the replacing of old central power plants in the basin and the substitution of lower emitting DG technologies for the diesel generators that are extensively used in Los Angeles port and vicinity. All of these potential displacements of emissions should be taken into account in the development of realistic DG scenarios.

Estimation of emissions, performance degradation, and/or geometrical features not available for each DG

As some of the DG technologies are just emerging in the marketplace, certain features of these technologies, including accurate pollutant emissions rates, are not readily available. In addition, understanding of features such as continuous versus peak power applicability, size of equipment, availability of fuel, stack height, etc. may need to be estimated for the current study. Currently our group is carrying out a detailed emissions measurement process for various DG types in a DG testing facility, which should complete some of the missing data. When data are still not available, reasonable estimates or assumptions will be considered.

Another significant factor that must be estimated for the current study is the degradation rate for technologies installed in the earlier years between now and the study year of interest. All DG technologies experience some degradation in efficiency performance and many may also degrade in the pollutant emissions performance. Scarce data is available for accurate accounting of DG vintage as it pertains to degradation in performance – so that degradation must be estimated. Finally, some technologies are expected to substantially improve their emissions and efficiency performance over the next several years. This improvement in performance must also be estimated for accurate development of a DG scenario.

DESCRIPTION OF AIR QUALITY MODEL

The model used for the simulation of the scenarios is the Caltech (CIT) Airshed Model. The CIT model is under continuous development at University of California, Irvine in collaboration with researchers from the California Institute of Technology and other institutions [7-11]. The computational domain consists of a grid of 994 cells, each 5 by 5 kilometers in area, with 5 vertical layers of different heights up to 1100 meters of altitude relative to the surface. The domain encompasses a large part of the South Coast Air Basin (SoCAB) and part of the ocean.

The CIT Airshed model is a 3-D Eulerian gas-phase photochemical model that predicts the transport and chemical reactions of air pollutants in the South Coast Air Basin. This gas-phase model is coupled with a 3-D, size-resolved and chemically resolved aerosol module. The model is based on the numerical solution of the atmospheric diffusion equation:

$$\frac{\partial C_i}{\partial t} + \nabla \cdot (\bar{u} C_i) = \nabla \cdot (K \nabla C_i) + R_i + Q_i \quad (1)$$

where C_i is the mean concentration of species i , $\bar{u}$ is the mean wind velocity, K is the eddy diffusivity tensor, R_i is the rate of generation of species i by chemical reaction and Q_i is a source term that accounts for ground level and elevated point sources of species i . The condition of net upward flux equal to the difference between area emission and dry deposition fluxes is applied to the surface boundary condition, whereas a no-flux boundary condition is imposed at the top of the domain. Initial conditions and lateral boundary conditions are based on extrapolation of measured pollutant concentration trends and estimates elaborated by the California Air Resources Board (CARB).

An hourly-based emission inventory is needed as an input for the simulation. Other properties of the domain such as land use, topography and surface roughness are also required to run the model.

An intensive monitoring period carried out in August 27-29, 1987, throughout the Los Angeles area, called the Southern California Air Quality Study (SCAQS), provided a detailed set of meteorological data in addition to an extensive compilation of air quality measurements. During SCAQS, vertical profiles of temperature, humidity, and wind velocity and direction were obtained along with their temporal and spatial distribution. Posterior analysis techniques were applied to these measurements in order to obtain a spatially complete meteorological field for use in model simulations. The meteorological conditions for this episode were characterized by a dominant wind blowing from sea to inland during the day, and by a weak land-mountain breeze at night. A weak onshore pressure gradient and warming temperatures aloft enhanced the formation of ozone. Also the presence of a well-defined inversion layer over a neutral or unstable mixing layer favored the accumulation of pollutants [9].

The chemical mechanism used in the air quality model is based on the LCC mechanism [12] with extensions by Harley et al. [9] and includes 47 gas-phase species. The gas-phase chemical-transport model is coupled with an aerosol module, which includes 19 size resolved aerosol-phase species, in 8 different bins within 0.04-10 micrometers in diameter size. The aerosol model includes advection, turbulent diffusion, condensation/evaporation, nucleation, emissions and dry deposition. For the simulation of condensation/evaporation of inorganic volatile species, the thermodynamic model SCAPE2 [13,14] is incorporated.

The CIT Airshed Model has been validated for the August 1987 episode [9, 10] and it has already been used in several studies of SoCAB air quality and emissions impacts. A development of a new mechanisms to reproduce the formation of secondary organics aerosols, by Griffin et al. [11], a study of control measures on NOx/VOC and their effect on particulate matter formation, by Nguyen and Dabdub [15], and a prediction of air quality impacts due to the implementation of control measures to particulate matter emissions from diesel engines (in progress), are examples of the CIT Airshed Model applicability.

DESCRIPTION OF PROPOSED DG SCENARIOS

To illustrate the scenario development process and the capabilities of the air quality model, one DG scenario with air quality results is presented below. A base case scenario for the 2010 emissions inventory without DG deployment is also simulated.

Base case scenario

The base case scenario represents the forecasted pollutant emissions inventory for the SoCAB for an August day of 2010 provided by the CARB. In this inventory no DG power is included. Therefore, simulation of this base case scenario predicts the evolution of pollutant concentrations with no DG adoption within the basin.

The boundary conditions for the model were scaled down according to the emissions inventory for 2010 that CARB provided, and a two-day episode is simulated to dampen the effect of initial conditions on the simulation results. Only the second day simulation results are presented.

The emissions inventory used for the simulation of this base case estimates about 600 Mg/day of NO_x emissions in the SoCAB. VOCs emissions are estimated at about 1200 Mg VOC/day and are divided into 11 different specific hydrocarbon compounds that are included in the air quality model. In addition, emissions of CO are projected to be 3.7 Gg CO/day, while primary particulate matter emissions are estimated at 1.1 Gg PM₁₀/day. Completing the emissions inventory are SO_x and NH₃ emissions that are estimated at 125 Mg SO_x/day and 150 Mg NH₃/day, respectively.

The spatial and temporal distribution of emissions varies depending on the species, although the general trend is correlated to industrial activity and commuting in automobiles. Hence, higher emissions levels exist in the proximity of downtown Los Angeles, peaking between 6:00am and 9:00am in the morning and again near 6:00pm in the evening. NO_x emissions, for instance, are spatially allocated primarily along the main commuting corridors (freeways), and these emissions are higher during the rush hours, decreasing dramatically near midnight. CO emissions are spatially and temporally allocated similar to NO_x, showing their main dependence on automobile emissions in the basin. VOCs emissions, which are also contributed by industrial activity to a large degree, appear in more disparate locations in relation to the main transportation thoroughfares. All known point sources, estimated automotive emissions, and area sources of pollutants are considered in the detailed analyses that CARB, SCAQMD and others accomplish to establish an emissions inventory as described herein [4].

The dominant winds in the SoCAB are from west to east during a typical day, with the San Bernardino and San Gabriel Mountains forming and a natural downwind barrier to mass transport. These geographical features enhance the accumulation of pollutants in the SoCAB, especially in downwind locations up against the mountains such as Riverside, one of the most impacted regions. Moreover, the warm and sunny weather predominant in the area together with the lack of natural scavenging processes, such as rain, facilitates the formation of photochemical smog and ozone. All

of these features are captured in the comprehensive air quality model used in this study.

Simulation results for the base case simulation are summarized in Table 1. Note that the ozone, NO₂, and PM_{2.5} concentrations peak in the eastern portions of the SoCAB (Riverside and San Bernardino) while CO and PM₁₀ concentrations peak in Los Angeles. This is the case since CO and PM₁₀ concentrations depend more directly on emissions of these species while O₃, NO₂, and PM_{2.5} are primarily produced as secondary pollutants. Also note that the relatively high ozone prediction for this case (198 ppb at 5:00pm), which exceeds that current state 1-hour standard (see Table 2), indicates that the baseline scenario is an “uncontrolled” scenario. This baseline scenario assumes that no additional air pollution control measures will be adopted between now and 2010 and calculates expected growth rates and spatial distribution for all emissions as described above.

Table 1. Maximum hourly average concentration of different species for the base case scenario for 2010.

Species	Maximum	Location	Time
O ₃	198 ppb	San Bernardino	17:00
NO ₂	84 ppb	Riverside	20:00
CO	1561 ppb	Los Angeles	22:00
PM _{2.5}	164 µg/m ³	San Bernardino	23:00
PM ₁₀	331 µg/m ³	Los Angeles	07:00

The baseline simulation ozone prediction should be viewed in light of the ozone design 1-hour peak value, which was 330 ppb in 1990 and 211 ppb in 2000. Thus, according to the simulation results, a smaller improvement in air quality is expected to occur for this decade, which will experience significant growth in total basin activity including industrial emissions, vehicle miles traveled, etc. Therefore, even with only current emissions control strategies and increased source emissions overall air quality is expected to improve in the SoCAB. In addition, new versions of the baseline emissions inventory that consider control measures that will likely be implemented between now and 2010 are under development. The application of additional control strategies will lead to a significant reduction in ozone concentration and consequently lower the expected peak ozone values for 2010.

Due to high solar radiation during the episode simulated, NO₂ levels were low compared with air quality standards (Table 2). Both NO₂ photo-dissociation and OH radical formation, which are driven by sunlight, favor the consumption of nitrogen dioxide. Thus, as previously expected, NO₂ concentrations are below the 1-hour peak indicator (for year 2000, 1-hour peak indicator was 213 ppb). This is consistent with measurements and observations in the SoCAB made over several years. Similar to NO₂, predicted CO concentrations are

low compared with typical maximum values and the current state standard due to reaction with OH radicals. Other scenarios can be simulated with lower sunlight intensity, which would produce higher concentrations of NO₂ and CO.

Table 2. California Ambient Air Quality Standards [16]

Species	State Standard	Federal Standard	Averaging time
O ₃	90 ppb	120 ppb	1 hr
NO ₂	250 ppb	—	1 hr
CO	9 ppm / 20 ppm	9 ppm / 35 ppm	8 hr / 1 hr
PM _{2.5}	—	65 µg/m ³	24 hr

The main contributors to the formation of secondary particulate matter in Southern California are nitric acid and ammonia. Nitric acid is formed via oxidation of NO_x whereas ammonia is emitted directly from agricultural activities (primarily dairy farming in eastern regions of the SoCAB). NO_x can react along two different paths that yield nitric acid: (1) NO₂ oxidation by OH yielding to HNO₃, which is typical for daytime chemistry and (2) NO₂ oxidation by O₃ yielding to NO₃ followed by reaction with NO₂ to form N₂O₅, which in presence of higher relative humidity at night yields HNO₃. The rapid photolysis rate of NO₃ radical makes this second path only important at night. Indeed, for this particular scenario, this second path is the dominant route for producing secondary PM, (primarily PM_{2.5}), which produces maximum PM_{2.5} concentrations around midnight. In addition, the maximum is located near San Bernardino, where farming activities are intensive, indicating the importance of the reaction between ammonia and nitric acid in the formation of secondary aerosols in the SoCAB.

Finally, simulation results confirm the strong dependence of PM₁₀ concentrations on direct emissions from fossil fuel combustion, exhibiting a maximum concentration in the morning rush hours around Los Angeles. However, the absolute value of PM₁₀ concentrations might be reduced by additional control measures adopted for the basin by 2010.

Sample DG scenario

A sample medium penetration DG scenario was developed for this paper. The main characteristics of this scenario are as follows:

1. 10% of the increased electricity demands (reference year 2002) are met by DG.
2. Mixing of technologies: 34% natural gas fired ICE, 46% MTG, 10 % FC and 10% solar PV.
3. Spatial distribution of DG is proportional to population forecasts for 2010.
4. FCs are operated as base load generators; MTGs and ICEs operate as peaking units only 6 hours per day (from 11:00am to 5:00pm).
5. No in-basin emissions are displaced.

- Emissions from each of the DG sources are estimated on the basis of previous studies [2,3] and in-house measurements.

This sample scenario is not meant to accurately characterize expected deployment, but rather represents educated guesses and intuition based on previous market analyses. [2]. Although this scenario is not intended to be a realistic forecast for DG deployment in the SoCAB, it presents a simplified reasonable case that allows us to show the process of DG scenario development and to apply such to the air quality model.

AIR QUALITY RESULTS AND DISCUSSION

The implementation of this DG scenario introduces new emissions throughout the basin. On a daily basis, the suite of DG in the sample DG scenario introduces VOC emissions of 0.5 Mg, which implies a total basin increase of 0.05%. NOx emissions are increased by 2.5 Mg (~0.4% increase) whereas CO emissions are increased by 5.6 Mg (~0.15% increase). DG implementation also results in an increase of 23 kg of SOx emissions (0.02% increase). Although these values are relatively small in comparison to total basin emissions (dominated by automobile emissions), the DG emissions are not evenly distributed either in time or in space that can lead to non-intuitive impacts on air quality. The primary increases in emissions of the sample DG scenario are concentrated in the downtown Los Angeles area between 11 am and 5 pm. Results from simulation of the sample DG scenario are summarized in Table 3.

Table 3. Maximum hourly average concentration of different species for the DG scenario

Species	Maximum	Location	Time
O ₃	198 ppb	San Bernardino	17:00
NO ₂	84 ppb	Riverside	20:00
CO	1824 ppb	Los Angeles	23:00
PM _{2.5}	167 µg/m ³	San Bernardino	24:00
PM ₁₀	379 µg/m ³	Los Angeles	07:00

Simulation results show no significant change in the absolute maximum concentration of ozone in the SoCAB. The absolute maximum concentrations of NO₂ and PM_{2.5} are increased by 1 ppb and 3 µg/m³, respectively. The PM₁₀ absolute maximum is increased by 48 µg/m³ (a 15 % increase) while CO maximum concentration is increased by 263 ppb (a 17 % increase).

Besides the absolute maximum concentrations presented in Table 3, other impacts of DG scenarios can be determined by application to the comprehensive air quality model. These

impacts include spatially and temporally resolved impacts (both positive and negative) such as the location, time and value of maximum increase or decrease in the concentrations of each pollutant species. Table 4 presents the maximum impacts of the sample DG scenario for some of the major pollutant species of concern (O₃, NO₂, CO, PM_{2.5}, PM₁₀). Note that very significant changes in air quality are introduced in certain regions at certain times by the sample DG scenario, indicating reasons for concern. For example, PM₁₀ increases of 130 µg/m³, CO increases of 290 ppb, and O₃ increases of 6 ppb are attributable to the sample DG scenario. On the other hand, significant reductions in pollutant concentrations at certain times and in certain locations are also attributable to the sample DG scenario as indicated in Table 4. These results support the need for air quality studies of the type presented in this paper.

Table 4. Maximum change in pollutant concentration (Sample DG Scenario – Base Case Scenario)

Species	Maximum Increase	Time	Maximum Decrease	Time
O ₃	6 ppb	20:00	12 ppb	20:00
NO ₂	16 ppb	20:00	5 ppb	21:00
CO	290 ppb	22:00	98 ppb	03:00
PM _{2.5}	46 µg/m ³	07:00	34 µg/m ³	24:00
PM ₁₀	130 µg/m ³	07:00	34 µg/m ³	23:00

Figure 1 presents that major differences in pollutant species concentrations between the base case and the sample DG scenario throughout the basin. The major changes in the pollutant concentrations occur near Los Angeles. This fact is related to the population weighted spatial distribution of DG in the sample scenario. In addition, some primarily residential regions, despite being highly populated, exhibit low emission rates in the base case leading to relative larger impacts of the population weighted sample DG scenario.

Figure 1. Difference in pollutant mixture fraction (moles of pollutant/total moles) between the sample DG scenario and the base case (units in ppb): (a) Ozone at 8:00 pm, (b) NO₂ at 8:00 pm and (c) CO at 10:00 pm.

Another point to be considered is the NO_x-VOC regime of different regions of the SoCAB. Depending on the ratio NO_x/VOC of a given area, an increase in NO_x emissions may lead to either an increase or a decrease in ozone concentration. The area of Los Angeles is characterized by high NO_x/VOC ratio. In this region O₃ production is *VOC limited*, thus, the increase in NO_x emissions produced by DG leads to a decrease in ozone concentrations (Fig. 1a). In other regions, such as downwind locations like Riverside, the NO_x/VOC ratio is smaller, and closer to a *NO_x limited* regime. In this regime, the increase in NO_x emissions from DG leads to increases in ozone.

The impacts of the DG implementation on NO₂ and CO are related to effects on ozone concentration. Since ozone photolysis produces OH radicals, which are the main oxidant for NO₂ and CO, the concentration of these two species increase in the areas where there is a decrease in ozone concentration. In addition to atmospheric chemistry consumption of NO₂ and CO, CO and NO₂ concentrations are also related to their direct emission rates. The spatial distribution of DG in the sample scenario therefore produced significant NO₂ and CO concentration differences in the downtown Los Angeles area.

The impacts of the sample DG scenario on concentrations of particulate matter follow trends that are similar to NO₂ and CO as shown in Figure 2. The main increase in both PM₁₀ and PM_{2.5} concentrations is located near downtown Los Angeles. South of Riverside exhibits also a significant increase. The increase in secondary particulate matter formation is mainly related to the increase in NO₂ concentrations in various regions of the basin for the sample DG scenario case. As mentioned above, NO₂ can be oxidized to form nitric acid and ultimately, secondary particulate matter. Figure 2 shows the difference in PM 24-hour concentrations between the sample DG scenario and the base case.

Figure 2. Difference in PM 24-hour average concentration between the sample DG scenario and the base case (units in $\mu\text{g}/\text{m}^3$): (a) PM_{2.5} and (b) PM₁₀.

CONCLUSIONS

We have presented the characterization process for the development of distributed generation scenarios in the South Coast Air Basin (SoCAB) for 2010, as well as a state-of-the-art

comprehensive air quality model. A base case and sample DG scenario were developed and applied to the air quality model to assess environmental impacts of potential DG installation throughout the SoCAB. The model has demonstrated sensitivity to increases of less than 1% of total NO_x and VOC emissions characteristic of a medium DG penetration scenario. Preliminary air quality results suggest that widespread DG application will have air quality impacts, that the impacts will not be uniform throughout the SoCAB, and that individual criteria pollutant concentrations may either rise or fall in certain regions with the introduction of DG. The approach is capable of providing valuable insights into air quality impacts of DG through investigation of a suite of DG scenarios with various spatial and temporal distributions and a wide variety of DG technology characteristics. The approach may even be able to provide guidance regarding the preferred locations and times for DG operation in the basin. Preliminary results provide strong justification for comprehensive air quality simulations with a wide range of potential impacts that are not necessarily intuitive.

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