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# A methodology for developing Distributed Generation scenarios in urban areas using geographical information systems


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**Abstract:** The implementation of Distributed Generation (DG) may lead to increased pollutant emissions that adversely affect air quality. This work presents a systematic methodology to characterise DG installation in urban basins. First, a set of parameters that characterise a DG implementation scenario is described. Second, a general approach using Geographic Information Systems (GIS) data is presented. Third, the methodology is demonstrated by application to the South Coast Air Basin (SoCAB) of California. Results show that realistic scenarios in the SoCAB concentrate DG technologies nearby industrial zones and introduce pollutant mass increments no larger than 0.43% with respect to baseline emissions.

**Keywords:** Distributed Generation; DG; scenarios; land-use data; GIS; air quality; urban basins; urban areas; emissions; Combined Heat and Power; CHP; spatial distribution; duty cycle.

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## 1 Introduction

Distributed Generation (DG) of electrical power has the potential to supply a significant portion of the increasing power demands in California and elsewhere (CEC, 1999). DG is characterised by the implementation of many stationary power generators allocated throughout urban air basins. In contrast, central-generation sources are typically placed outside those basins. DG can fulfil the energy needs of numerous customers and provide benefits in multiple applications. For instance, DG can deliver 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 Heat and Power (CHP) applications.

This potential shift from central to distributed power generation may increase pollutant emissions and lead to higher levels of ambient ozone and Particulate Matter (PM) concentrations. Researchers have performed preliminary mass balance estimates of pollutant emissions impacts due to the potential use of DG (Allison and Lents, 2002; Ianucci et al., 2000). However, these studies are limited to estimations of the mass of pollutant emissions only, and do not address air quality impacts. Also, Heath et al. (2003) considered the potential for increased human inhalation exposure to air pollutants when power plants are replaced by DG. Yet, Heath et al. (2003) restricted their work to pollutants emitted directly into the atmosphere using a simplified plume model.

Edwards et al. (2002) are among the earliest researchers to use GIS data to analyse the viability of DG. First, they used GIS data to identify adjacent electrical power users that hypothetically could be joined together to form a microgrid using DG systems. Second, GIS data was applied to identify local land-use restrictions such as noise, air quality limits, and density of buildings that may inhibit or prevent installation of economically attractive DG technologies. This research did not address the air quality impacts of DG; however, a thorough investigation of these effects can be found in Rodriguez et al. (2005, 2006).

Among other things, assessment of air quality impacts of DG requires a systematic means of determining the spatial and temporal distribution of emissions that result from realistic installations of DG in the geographic region of interest. Of course there are other requirements for a complete assessment (e.g., a detailed atmospheric chemistry and transport model), but, the current paper focuses upon a systematic methodology for developing DG installation, operation, and emissions scenarios. The methodology is then applied to the SoCAB of California to demonstrate its capabilities.

The systematic methodology includes application of GIS data to a geographically-resolved airshed, use of market studies for DG penetration, chemically resolved emissions measurements, technology types and features, local emissions regulations, time resolved and sector dependent electricity demands, and other information (e.g., stack height, plume temperature and velocity, co-generation emissions off-set) to develop the DG scenarios.

Regulatory bodies are currently establishing air pollutant emissions limits for DG technologies. The current methodology is an important part of the analysis required to establish informed emissions regulations. Simulation of future air quality in many regions of the world requires consideration of DG that will rely upon the current methodology for appropriate accounting of DG impacts. Urban planners, third party DG equipment installers, DG manufacturing companies, and others can use the current methodology for assessment of DG operation within an impacted urban airshed. The methodology presented herein is a crucial component for determining where, when or whether DG can be introduced into urban airsheds.

The parameters identified for the characterisation of a DG scenario are presented in Section 2. The systematic approach designed to develop DG realistic implementation scenarios is detailed in Section 3. Finally, the distribution of DG power, the mix of DG technologies, and the air emissions resulting from the application of the methodology to realistic scenario development in the SoCAB are discussed in Section 4.

## 2 Characterisation of DG scenarios

A detailed description of the manner in which DG resources are implemented requires characterisation of several parameters. Important parameters include the operating characteristics of the DG units, DG spatial and temporal distribution (operating duty cycle), and other features of the particular instance of DG use. The current methodology identifies the collection of information and characteristics that are required to fully describe all the DG characteristics of a "DG Implementation Scenario". These parameters are applicable to all urban airsheds where DG adoption is expected.

A DG scenario can be completely described by seven key parameters, each with various factors that contribute to full characterisation. The seven parameters include:

- total fraction of energy demands that are met by DG in the scenario
- mix of DG resources to meet those demands
- emissions associated with each DG unit type
- spatial distribution of the DG within the basin

- operational duty cycle of each DG
- assessment of emissions that are displaced by DG installation
- other estimates that are required to account for DG implementation and that relate emissions to the requirements of the Air Quality Model (AQM).

These seven parameters that can fully describe a DG implementation scenario are described subsequently.

## *2.1 Fraction of energy demand met by Distributed Generation (DG)*

The fraction of energy met by DG has a strong influence in the final air quality impacts of a DG scenario. A high penetration scenario implies that DG units meet a considerable portion of the total energy needs of the urban basin.

Several research studies have investigated the potential market adoption of DG. For example, the California Energy Commission Strategic Plan for DG (Tomashefsky and Marks, 2002) forecasted adoption of DG in California for the year 2020 that could be as high as 20% of the electricity load growth. Other studies have reached similar conclusions with regard to DG market penetration (see for example Little, 2000), but, the rate of DG adoption and amount adopted in any air basin is a matter of significant debate. As a result, the fraction of energy met by DG is uncertain, and a wide variety of DG penetration levels are recommended to span the spectrum of possible air quality impacts.

## *2.2 Distributed Generation (DG) mix*

DG is defined as an electric power source connected directly to the distribution network, or on the customer side of the meter, or to an independent load (Ackermann et al., 2001). Although the capacity range is not relevant in this definition, a practical maximum DG electric generation capacity of 50 MW is adopted in this study. In general, DG systems are comprised of a wide variety of technologies. The DG technologies that are likely to be implemented in the SoCAB include Natural Gas (NG) fired combustion turbines (GT) and NG fired reciprocating Internal Combustion Engines (NG ICE), solar Photovoltaics (PV), Low Temperature Fuel Cells (LTFC), High Temperature Fuel Cells (HTFC), NG fired Micro-Turbine Generators (MTG) and fuel cell-gas turbine hybrid systems (hybrid). Diesel and petroleum distillate fuelled units are not included in the current mix of DG technologies since they are usually not permitted in to run on a continual basis. These types of units are typically permitted to run as back-up generators.

The specific mix of DG technologies to be installed in any region for any future year is challenging to forecast. The technology mix is dependent on the number and type of energy customers in that region and a host of other economic and regulatory variables (e.g., electricity prices, gas prices, DG incentives, transmission constraints, emissions standards, etc.)

Each market segment predominantly uses specific types of DG technologies because the DG capacity levels and features happen to be best suited to meet the energy demands of that market segment. For example, residential applications in the range of 1–5 kW will likely favour FCs and PV; 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 500–2 MW, might favour NG reciprocating engines and GTs; and finally the large institutional and industrial sectors with 2–50 MW capacity will be mainly served by GTs. This relationship between DG type and market sector should be used in the development of realistic DG scenarios. In addition, if information is available that can identify the spatial distribution of market segments this relationship should be used to determine the spatial distribution of DG. This relationship also helps to estimate the distribution and duty cycle of technologies.

### *2.3 Spatial distribution of Distributed Generation (DG)*

It is important to capture the spatial distribution of emissions within the air basin to determine the local species concentrations that affect the air quality. A detailed market penetration study is necessary to estimate accurately the spatial distribution of DG adoption. When a detailed market study is not available, reasonable estimates of DG power can be developed based upon demographic and economic parameters that can be correlated to power (e.g., population data, population growth data, electricity consumption data, land-use data).

### *2.4 Distributed Generation (DG) duty cycle*

The DG duty cycle accounts for the temporal variation of DG power production that leads to the overall capacity factor (number of hours of operation/total hours) for each DG device. The actual duty cycle for an individual DG unit depends upon maintenance schedules, economics, power demand, and other factors. For a specific scenario some DG technologies will likely operate as base-loaded devices, i.e., they will operate continuously. For example, high temperature FCs are usually base-loaded 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, 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 at each hour.

### *2.5 Emissions specifications*

There is a wide range of emissions factors that are either available as measured data or estimated by various investigators for each DG technology type. Some DG technologies emit zero or near zero pollutants (e.g., PV and FC systems). On the other hand, some DG technologies emit more pollutants than central station power plants. An example set of data that characterises DG emissions from various technologies is proposed by Allison and Lents (2002).

### *2.6 Emissions displaced*

Many DG technologies will be adopted within urban basins as CHP applications, since the higher overall energy efficiency of CHP can improve the economics of DG projects. Waste heat produced during electricity generation is captured by a recovery system that provides heat to meet facility thermal loads. As a result, DG/CHP replaces the heat produced by burning fuel in a boiler leading to a reduction (displacement) of boiler-associated emissions. For retrofit DG/CHP applications, emissions from old, more-polluting boilers are displaced, whereas for new applications displacement of emissions from new equipment (i.e., more efficient and lower polluting boilers) is considered.

Emissions can also be displaced by operating DG on waste gases from solid landfills, oil fields, or biomass gas emissions. In these cases, the DG application displaces either direct hydrocarbon emissions or flared gas emissions depending upon the current status of the waste gas handling. According to Allison and Lents (2002), all DG units in this type of application reduce ozone related emissions compared to a central station combined cycle power plant. Many landfills have already implemented DG (Lenssen, 2001) to substitute for flares and produce on-site power and heat.

Other DG applications in which emissions could be displaced include the replacement of old central power plants and the substitution of lower emitting DG technologies for the diesel generators.

### *2.7 Combined Heat and Power (CHP) emissions displacement*

Emissions displacement is accounted when DG installations include CHP. Several parameters for emissions displacement are estimated such as the fraction of DG installed technologies with CHP; the average heat recovery capacity factor; the old and new boilers mix being displaced, and their corresponding efficiencies and emission factors. A detailed description of the approach developed to assess displaced emissions is presented elsewhere (Samuelsen et al., 2005).

### *2.8 Other estimates*

As some of the DG technologies emerge in the marketplace, certain features of these technologies, including accurate pollutant emissions rates and emissions speciation, are not readily available. In addition, features such as continuous vs. peak power applicability, size of equipment, fuel availability or emissions stack height often need to be estimated. While emissions are being measured from various DG types (Phi et al., 2004), data are often not available. Therefore, reasonable estimates or assumptions are applied when necessary.

A significant factor that must be estimated is the degradation rate for each of the DG technologies. All DG technologies experience some degradation in efficiency performance and many may also degrade in the pollutant emissions performance. When degradation data is not available, degradation must be estimated. The adoption rate of DG power in any region is uncertain. Therefore a variety of adoption rate trends must be estimated. Finally, some technologies are expected to improve substantially their emissions and efficiency performance over the next several years. This improvement in performance must also be considered for accurate development of a DG scenario.

## 3 GIS land-use data

Realistic predictions of air quality impacts depend on the assumptions that finally define the spatial and temporal distribution of DG operation and emissions. This paper presents a systematic approach used to develop realistic DG implementation scenarios.

This approach relies on DG market penetration literature data and land-use GIS data to estimate the spatial distribution of DG power as well as the mix of DG technologies. In the following sections the characteristics of GIS data are described, and the systematic approach that is applied to develop a realistic DG implementation scenario is detailed.

To use land-use GIS data for the development of DG scenarios for AQMs, the information contained at the resolution of the GIS data set must be converted to the resolution of the AQM grid. Since GIS data typically has a finer resolution, the systematic aggregation of land parcels inside each cell with the same generic land-use type is accomplished using the GIS software ArcMap. The main challenge in this aggregation process is to correctly distribute land-use polygons that are shared by several AQM grid cells. The final result is a database of land-use information in model cell coordinates each with an associated distribution of surface areas for the land-use types of interest.

## 4 Methodology for realistic DG scenarios

GIS land-use categories can be related to market segments, and those segments associated preferentially with specific DG technologies, specific duty cycles, differing rates of DG adoption, etc. As a result, one can characterise a DG scenario with a set of DG technologies that are likely to be predominant in certain market segments and certain regions because their capacity and operating characteristics are best suited to the energy demands of that market segment. The steps required to develop realistic scenarios based on GIS land-use data, DG size, DG type, expected or known DG emissions, and other available data and insights is presented in this section following a ten-step methodology. These ten steps are:

*Step 1*: Define the market sectors of interest (for which market studies or information is available) into which the original larger number of high-level land-use categories of the GIS data are aggregated, and convert the GIS data resolution to match that of the AQM resolution using GIS conversion tools (e.g., ArcGIS).

*Step 2*: Once the market sectors are identified and developed as comprising all land-uses of interest, one must divide the area of each sector and each cell, $A_{i,k}$, into sub-categories according to power demand (<50 kW, 250–1,000 kW, 1–5 MW, 5–20 MW, and 20–50 MW). The basis for this disaggregating process is information that is available for energy consumption in various market sectors that are segregated into power level categories. The current paper identifies several example reports on energy consumption surveys in the commercial, residential and manufacturing sectors that have been produced by the EIA (1999a, 1999b, 2000) as useful for this purpose. These reports relate total floor space of various establishment types in each sector to the annual electricity consumption. From these data the average power demand for each establishment is estimated. The results of these analyses are normalised by dividing the area of each size category by the total area in that sector to get a relative area per sector ($i$) and per size category ($j$), which is represented by $S_{i,j}$. If no similar data is available for a market sector of interest then either one must commission a study to determine this information or estimates must be developed. The equation that relates total area to area per size category for each of the sectors considered is:

$$A_{i,j,k} = S_{i,j} \cdot A_{i,k}. \tag{1}$$

*Step 3*: Determine DG power in all the disaggregated areas (per size category and per sector) using a new factor called the "Adoption Rate Relative Intensity". This factor relates land-use area to the relative amount of DG power adopted as a function of size category and market sector. The adoption rate relative intensity factor, $R_{i,j}$, accounts for the fact that a certain amount of real state that is occupied by a certain economic sector will adopt DG technology at a rate that differs from that of other sectors. Values for this factor are based on a report that describes Combined Heating and Power (CHP) penetration in the commercial and industrial sectors in California (CEC, 1999) together with the authors' insights for other categories.

DG power associated with each of the size categories in each sector and each cell, $P_{i,j,k}$ is described by the following equation:

$$P_{i,j,k} = \frac{A_{i,j,k} R_{i,j}}{\sum_i \sum_j A_{i,j,k} R_{i,j}} P_{Tot,k}. \tag{2}$$

The total DG power in cell $k$, $P_{Tot\ k}$, is determined as a function of the assumed total implementation of DG power in the region of interest (portion of increased power demand met by DG):

$$P_{Tot,k} = \frac{\sum_i \sum_j A_{i,j,k} R_{i,j}}{\sum_k \sum_i \sum_j A_{i,j,k} R_{i,j}} \cdot P_{Tot,\text{region}} \tag{3}$$

where $P_{Tot,\text{region}}$ is the assumed total implementation of DG power in the region of interest.

*Step 4*: Determine the temporal variation of DG power due to the variety of duty cycles of the various DG units in each of their particular applications. The temporal variation of the DG power due to the variety of duty cycles of the units is introduced into this procedure as a function of the particular market sector that the particular types of DG units are serving. Average load profiles are calculated for each sector based on hourly electric data obtained from the local utility. To apply the sector specific duty cycle a normalised vector factor, $D_{i,h}$, is determined. This factor describes the hourly power load profile expected in each sector. The peak power for a particular sector in a cell, $P_{i,k}$, can occur at any one hour of the day in a particular sector. Thus, multiplying the normalised duty cycle by the peak sector power in each cell produces the total power per sector and per cell and operating in hour $h$:

$$P_{i,k,h} = P_{i,k} D_{i,h}. \tag{4}$$

*Step 5*: Determine the relative contribution to total power in each cell by every DG type considered. Six tables are developed (one for each sector), in which the relative expected contribution of each DG type in each size category, $W_{i,l,j}$, is presented. Table 1 presents the relative contributions of DG technology types for the industrial sector as an example. The rest of the tables for the other sectors can be found elsewhere (Samuelsen et al., 2005). The relative contribution factors for all six sectors are based on market penetration studies of DG technology types in the industrial sector (Little, 2000), utility sector (Ianucci et al., 2000), and building sector (Boedecker et al., 2000) and the authors' or other expert estimates on market distribution of DG technology types in each of the size categories. The equation that determines the relative contribution of each DG technology in each cell for a particular hour of the day, $T_{l,k,h}$, is given by:

$$T_{l,k,h} = \frac{\sum_i \sum_j W_{i,l,j} \cdot P_{i,j,k,h}}{P_{Tot,k,h}}. \quad (5)$$

**Table 1** Estimated relative contributions of DG technology types in the industrial sector as a function of size class

| *Size categories* | *LT Fuel Cells* (%) | *HT Fuel Cells* (%) | *MTGs* (%) | *NG ICEs* (%) | *PV* (%) | *GT* (%) | *Hybrid* (%) |
|---|---|---|---|---|---|---|---|
| <50 kW | 0.0 | 0.3 | 0.7 | 0.0 | 0.0 | 0.0 | 0.0 |
| 50–250 kW | 0.0 | 2.1 | 13.6 | 0.0 | 0.0 | 0.0 | 0.0 |
| 250–1,000 kW | 0.0 | 2.9 | 0.0 | 10.1 | 0.0 | 9.7 | 2.5 |
| 1–5 MW | 0.0 | 0.0 | 0.0 | 10.1 | 0.0 | 9.7 | 2.5 |
| 5–20 MW | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 22.7 | 0.0 |
| 20–50 MW | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 13.0 | 0.0 |
| *Total* | *0.0* | *5.2* | *14.4* | *20.1* | *0.0* | *55.1* | *5.0* |

*Step 6*: Apply weighting factors for relative DG adoption rates that depend on the location within the basin. These factors may include such items as local zoning restrictions and environmental dispatch considerations. The systematic procedure presented thus far, uses average DG adoption factors for all cells throughout the basin.

*Step 7*: Calculate pollutant emissions in each cell and at the time resolution of the AQM, based on the emissions factors $e_l$ for each DG type presented in Tables 2 and 3. The total emissions of generic pollutant *X*, at time *h*, and in cell *k*, are:

$$M_{X,k,h} = \sum_l P_{l,k,h} \cdot e_{l,X}. \quad (6)$$

*Step 8*: Apply further speciation of the criteria pollutants ($NO_x$, VOC, $SO_x$, and PM) at the level required by the AQM.

**Table 2** Emissions factors used to develop DG scenarios in the current study for DG units installed in the period 2003–2006

| *Generation type* | *Efficiency* (*based on HHV*) | *CO* (lbs/MWh) | *VOC* (lbs/MWh) | $NO_x$ (lbs/MWh) | $SO_x$ (lbs/MWh) | *PM* (lbs/MWh) | $CO_2$ (lbs/MWh) | $NH_3$ (lbs/MWh) |
|---|---|---|---|---|---|---|---|---|
| MTG | 0.27 | 2.85 | 0.05 | 0.70 | 0.01 | 0.08 | 1500 | 0.00 |
| GT (<3 MW) | 0.24 | 0.31 | 0.04 | 0.46 | 0.01 | 0.09 | 1660 | 0.17 |
| GT (>3 MW) | 0.36 | 0.21 | 0.02 | 0.13 | 0.01 | 0.06 | 1130 | 0.06 |
| NG ICE | 0.32 | 1.77 | 0.44 | 0.44 | 0.01 | 0.07 | 1270 | 0.00 |
| LT FC | 0.36 | 0.10 | 0.90 | 0.07 | 0.01 | 0.06 | 1130 | 0.00 |
| HT FC | 0.48 | 0.10 | 0.02 | 0.07 | 0.01 | 0.05 | 850 | 0.00 |
| Hybrid | 0.70 | 6.00 | 1.00 | 0.50 | 0.004 | 0.03 | 580 | 0.00 |

**Table 3** Emissions factors used to develop DG scenarios in the current study for DG units installed in the period 2007–2010

| *Generation type* | *Efficiency (based on HHV)* | *CO* (lbs/MWh) | *VOC* (lbs/MWh) | *$NO_x$* (lbs/MWh) | *$SO_x$* (lbs/MWh) | *PM* (lbs/MWh) | *$CO_2$* (lbs/MWh) | *$NH_3$* (lbs/MWh) |
|---|---|---|---|---|---|---|---|---|
| MTG | 0.27 | 0.10 | 0.02 | 0.07 | 0.01 | 0.08 | 1500 | 0.00 |
| GT (<3 MW) | 0.24 | 0.31 | 0.04 | 0.46 | 0.01 | 0.09 | 1660 | 0.17 |
| GT (>3 MW) | 0.36 | 0.21 | 0.02 | 0.13 | 0.01 | 0.06 | 1130 | 0.06 |
| NG ICE | 0.32 | 1.77 | 0.44 | 0.44 | 0.01 | 0.07 | 1270 | 0.00 |
| LT FC | 0.36 | 0.10 | 0.02 | 0.07 | 0.01 | 0.06 | 1130 | 0.00 |
| HT FC | 0.48 | 0.10 | 0.02 | 0.07 | 0.01 | 0.05 | 850 | 0.00 |
| Hybrid | 0.70 | 0.10 | 0.02 | 0.07 | 0.004 | 0.03 | 580 | 0.00 |

*Step 9*: Account for any emissions displacement such as that associated with the replacement of a boiler that could occur if the DG installations include CHP. The procedure to account for CHP emissions displacement described above is to be applied in this step. The resulting net emissions fluxes are calculated by direct subtraction of emissions fluxes that account for displaced emissions.

*Step 10*: Include other realistic factors that can affect the final emissions levels for the particular year to be simulated. These factors include the rates at which individual DG technologies will be adopted vs. time, and any performance degradation for the particular DG units that are installed between when they are installed and the year of the simulation. The performance degradation can include both an increase of criteria pollutant emissions and a decrease of electrical efficiency that usually occurs throughout the lifetime of any DG unit. As practically no public data is available on DG performance degradation, an estimate of 3% annual increase in criteria pollutant emissions is considered for realistic DG scenarios.

## 5 Methodology application to SoCAB

The methodology can be used to develop both realistic scenarios and scenarios that are developed for scientific completeness, sensitivity analyses, and/or to determine the potential impacts of unexpected outcomes. The latter type of scenario is called a ‘spanning’ scenario. This manuscript focuses on the systematic approach applied to develop realistic DG scenarios. To demonstrate this methodology the current work presents its application to the SoCAB of California, as an example.

### *5.1 GIS land-use and other data used for the SoCAB application*

The development of realistic DG implementation scenarios is built upon available high resolution GIS land-use data of the five counties that comprise the SoCAB, namely Los Angeles, Orange, San Bernardino, Riverside, and Ventura counties. The latest GIS data set was collected in the year 2000 (P. Gutierrez, Southern California Association of Governments, personal communication, 2002). These data consist on the counties divided into land parcels of different area and shape (polygons). The number of parcels per county is considerably large. For example the total number of individual land parcels in Los Angeles County alone is more than 40,000. The land parcels have a resolution of 2 acres (0.0081 $km^2$). Each polygon is associated with a database that contains an ID number, total area, and zone classification code. Figure 1 shows a small region near Long Beach that illustrates the typical number and resolution of the land parcel polygons. Black lines in the figure represent the location of the $5 \times 5$ km model resolution in this same region. The GIS database contains 132 different specific land-use types that are aggregated into 13 generic land-use types.

**Figure 1** Generic land-use categories in Long Beach area

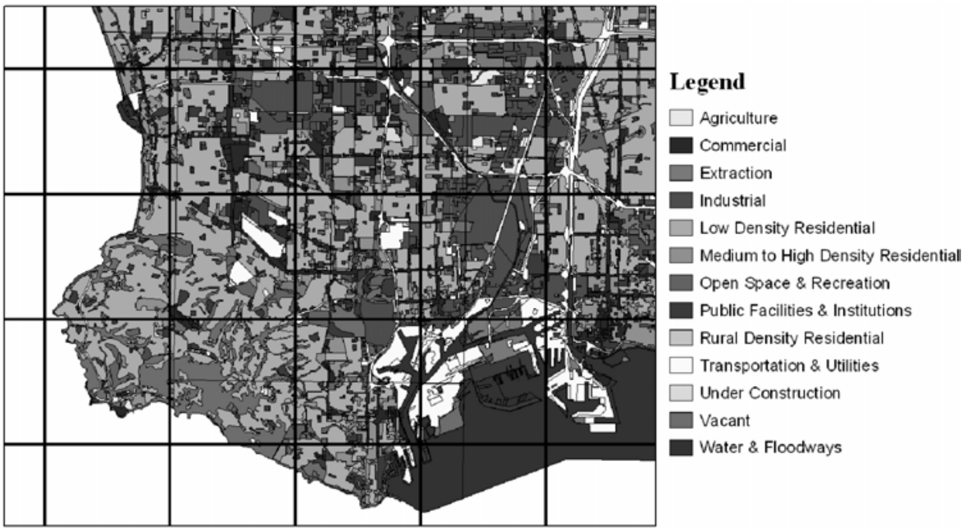



Table 4 presents a summary of five realistic scenarios that have been formulated using the methodology applied to SoCAB. Tables 2 and 3 summarise the emissions factors for DG systems installed in the periods 2003–2006 and 2007–2010, respectively, that were used in the development of these scenarios. These values are used in the development of all realistic DG scenarios and are based in the emissions factors provided by Allison and Lents (2002) as well as the emissions limits for 2003 and 2007 imposed by the corresponding California agencies.

**Table 4** Summary of realistic DG implementation scenarios developed for the SoCAB in year 2010

| *Name* | *Common parameters* | *Increased power demand* (%) | *DG power adoption* | *CHP displacement* |
|---|---|---|---|---|
| R1 | Technology mix depends on activity sector, high penetration of low emission technologies, GIS land-use distribution, realistic duty cycles, low performance degradation | 5 | Linear | Yes |
| R2 | | 10 | Linear | Yes |
| R3 | | 20 | Linear | Yes |
| R4 | | 5 | Low early[a] | Yes |
| R5 | | 5 | Linear | No |

[a]98% of DG installed in the period 2007–2010.

In addition, spanning scenarios have been developed using the emissions factors of Allison and Lents (2002) directly, since they represent the best estimates from a compilation of various sources. These data, however, include emissions factors that are higher than the current regulated limits for DG units by the California air quality regulatory agencies. Whenever this occurred, the values selected to characterise a specific DG unit were the applicable standards levels instead of the emissions factors of Allison and Lents (2002).

### *5.2 Application of the ten-step methodology to SoCAB*

This section presents the specifics, assumptions and other considerations of applying the general ten-step methodology for realistic scenarios discussed above to SoCAB.

*Step 1*: In the case when applying Step 1 to SoCAB, six market sectors are selected to comprise the original 13 land-uses identified as of interest in ArcGIS. Table 5 shows the correspondence between the original 13 land-use categories and the six selected energy market sectors.

**Table 5** Aggregation of land-use types into energy sectors

| *Sector* | *Land-use types considered in that sector** |
|---|---|
| Low density residential | Low density residential |
| | Rural density residential |
| Medium to high density residential | Medium to high density residential |
| Commercial | Commercial |
| Industrial | Industrial |
| Agriculture and water pumping | Agriculture |
| Other | Extraction |
| | Public facilities and institutions |
| | Transportation and utilities |
| | Under construction |

*The rest of the land-use categories (Vacant, Water and Flood Ways, and Open Space and Recreation) assumed with zero DG power.

*Step 2*: In the SoCAB case power demand was divided into the following categories: <50 kW, 250–1,000 kW, 1–5 MW, 5–20 MW and 20–50 MW. Two of the sectors of interest (Agriculture and Other) required the development of estimated $S_{i,j}$ since no data was available for these sectors. Reasonable estimates were made based on the $S_{i,j}$ of the other sectors and insights of the research team. Table 6 shows the resulting normalised area factors that are applied to disaggregate (split) the sector areas (groups of GIS land-use areas) into specific areas for each DG size category.

**Table 6** Normalised area factors $S_{i,j}$ for each DG size category for the different sectors

| *Size category* | *Low density residential* (%) | *Medium and high density residential* (%) | *Commercial* (%) | *Industrial* (%) | *Agriculture* (%) | *Other* (%) |
|---|---|---|---|---|---|---|
| <50 kW | 99 | 95 | 55 | 0 | 80 | 0 |
| 50–250 kW | 1 | 5 | 17 | 5 | 10 | 5 |
| 250–1,000 kW | 0 | 0 | 20 | 15 | 10 | 15 |
| 1–5 MW | 0 | 0 | 8 | 22 | 0 | 22 |
| 5–20 MW | 0 | 0 | 0 | 30 | 0 | 30 |
| 20–50 MW | 0 | 0 | 0 | 28 | 0 | 28 |
| Total | 100 | 100 | 100 | 100 | 100 | 100 |

*Step 3*: Table 7 presents the current estimates for the adoption rate relative intensity factors for the SoCAB case. The adoption rate relative intensity factors of Table 7 are well grounded in the literature and the authors' insights that are currently available. However, these factors can be refined and modified at any time as additional detailed market penetration studies are completed and as information becomes available for DG market penetration in California.

**Table 7** Adoption rate relative intensity factors per size category and per sector, $R_{i,j}$

| *Size category* | *Low density residential* | *Medium and high density residential* | *Commercial* | *Industrial* | *Agriculture* | *Other* |
|---|---|---|---|---|---|---|
| <50 kW | 1.6 | 16.4 | 7.9 | 7.9 | 3.2 | 1.0 |
| 50–250 kW | 8.3 | 208.1 | 151.7 | 151.7 | 8.6 | 19.1 |
| 250–1,000 kW | 0.0 | 0.0 | 141.5 | 141.5 | 8.6 | 17.9 |
| 1–5 MW | 0.0 | 0.0 | 221.5 | 221.5 | 0.0 | 27.9 |
| 5–20 MW | 0.0 | 0.0 | 0.0 | 376.9 | 0.0 | 47.6 |
| 20–50 MW | 0.0 | 0.0 | 0.0 | 567.2 | 0.0 | 71.6 |

*Step 4*: For the SoCAB application the sector duty cycles were estimated from data available on the Southern California Edison web page (SCE, 2002) using a resolution of 1-hour (the current AQM time step).

*Step 5*: The relative contribution to total power in each cell by every DG type considered using one table for each of the six market sectors of interest as described above were directly applied to the SoCAB case.

*Step 6*: No local information on forecasted DG penetration in certain zones of the SoCAB due to any potential driver has been included in the approach thus far, since data was not available to suggest preferential DG adoption at any particular location or set of locations in the SoCAB. However, if at any time preferential DG adoption rates that apply to the spatial distribution of DG in the urban basin under study are available one should apply a normalised adoption rate factor in this step.

*Step 7*: Pollutant emissions calculations for each ground-level cell at each time step were accomplished for the SoCAB case as described above.

*Step 8*: For the SoCAB example the species considered are associated with the CACM chemical mechanism (Griffin et al., 2002), which requires specific mass fluxes of NO, $NO_2$, $SO_2$, $SO_3$, 23 specific volatile organic compounds, and 18 types and 8 size classes of PM.

*Step 9*: Emissions displacement calculations that account for CHP emissions displacement were applied to the SoCAB case as described above.

*Step 10*: Both a realistic exponential increase and a less realistic linear increase of the accumulated DG power installed in the period 2003–2010 have been implemented in the application of the current methodology to the SoCAB case.

## 6 Analysis of DG realistic scenarios for the SoCAB

The systematic approach described above was used to develop five realistic DG implementation scenarios for the SoCAB (R1, R2, R3, R4 and R5). In the particular case of applying the current systematic approach to SoCAB, 13 land-use categories were determined to be sufficient to characterise all land uses required for the development of DG Scenarios. Figure 2 presents a bar chart with the total areas for the 13 generic land-use categories. The ‘Vacant’ land-use category has the largest area compared to the other categories (more than 12,000 $km^2$). However, as exhibited in Table 5, this category does not contribute to DG penetration. After the vacant area, the “Low Density Residential” land-use category comprises about 3,000 $km^2$ of the SoCAB. The third and forth land-use categories with significant areas in the SoCAB are ‘Agriculture’ and “Transportation and Utilities”, respectively.

Table 8 shows the increase in criteria pollutant and $CO_2$ emissions for each DG scenario. R1 serves as the reference for other realistic cases. Namely, the other four scenarios introduce a specific variation in only one of the parameters that define R1. R1 assumes that 5% of the increased power demand from 2002 to 2010 will be met by DG. This percentage accounts for 0.27 GW of DG power. The spatial distribution of DG is based on land-use data and DG operation follows realistic duty cycles corresponding to different activity sectors in each computational cell. In addition, different DG technologies are deployed depending on the activity area of use. All the other realistic scenarios exhibit the same emissions spatial distribution as R1. Scenarios R2 and R3 implement a larger DG penetration, i.e., 10% and 20% of the increased power demand, respectively. $NO_x$ emissions are reduced by the same proportion in R2 and R3 with respect to R1, given the increase in emission displacement due to CHP applications. The DG adoption rate in scenario R4 assumes an exponential penetration rate that results in 98% of the total adopted DG float installed in the period 2007–2010. R4 is also the scenario with the lowest CO and VOC emissions. Finally, scenario R5 neglects emissions displacement due to CHP and has the highest $NO_x$ emissions. Note that scenarios R1 and R5 only differ in the CHP parameter and direct comparison can be applied to assess the effect of emissions displacement. R1 emissions are reduced by 112% for $NO_x$, 44% for $CO_2$, and 19% for CO emissions due to the application of CHP. In general, realistic scenarios introduce mass increments no larger than 0.43% with respect to baseline emissions. Baseline emissions are emissions forecasts for the whole SoCAB basin in 2010 and account for population growth, but do not consider any future emissions control measures or contributions due to DG power. Although basin-wide emission increments are small, the additional emissions by DG are placed over highly populated and industrialised regions, where they have the potential to lead to noticeable air quality impacts (Rodriguez et al., 2006).

**Figure 2** Total surface in the 13 generic land-use categories in the South Coast Air Basin of California

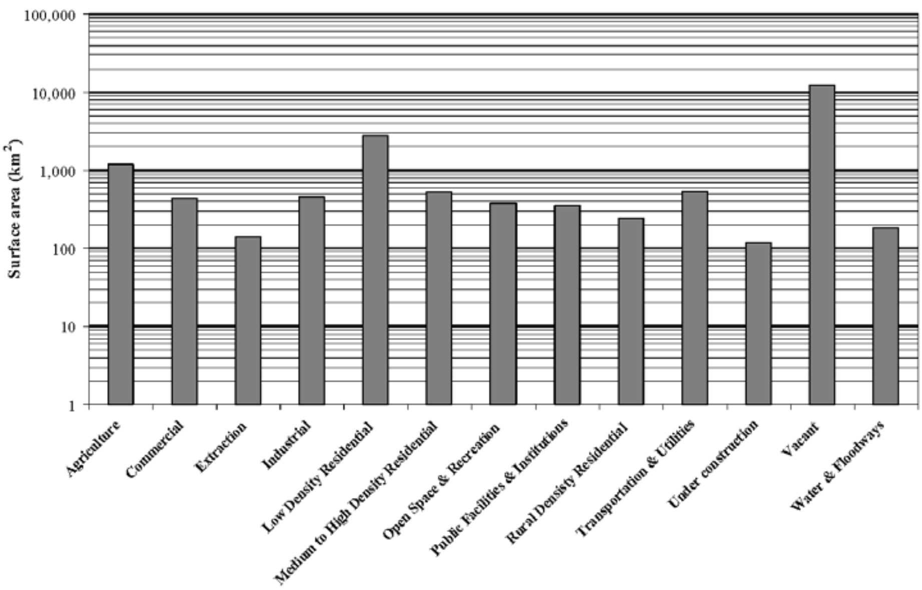
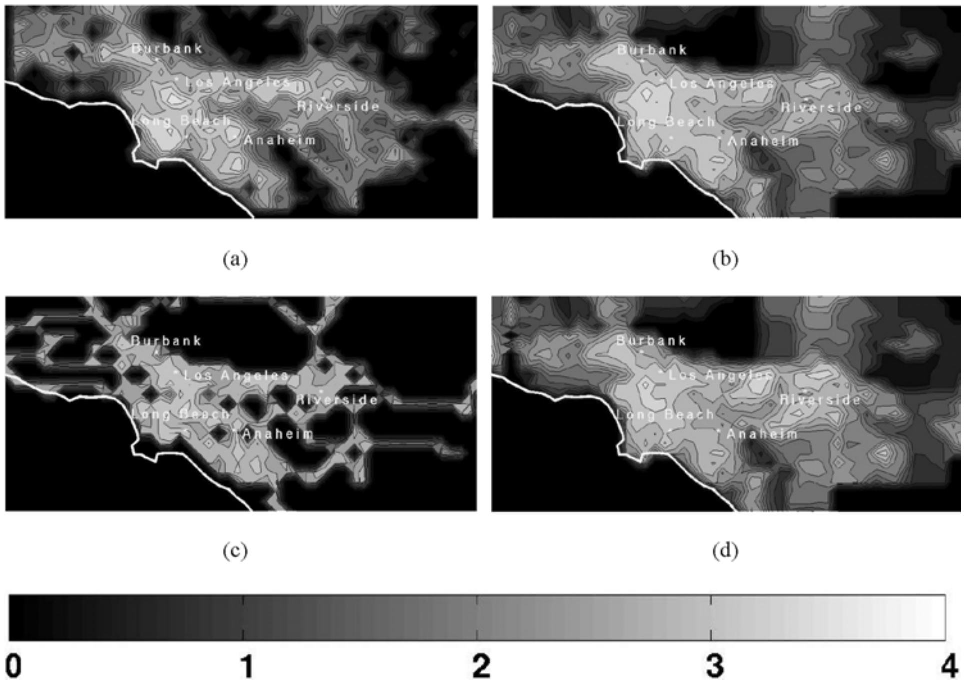



**Table 8** Basin-wide absolute increase of primary criteria pollutant and $CO_2$ emissions per each DG realistic scenario

| *Name DG scenario* | *CO* (ton/day) | *$NO_x$* (ton/day) | *VOC* (ton/day) | *$NH_3$* (ton/day) | *$SO_x$* (ton/day) | *PM* (ton/day) | *$CO_2$* (ton/day) |
|---|---|---|---|---|---|---|---|
| #R1 | 2.26 | –0.09 | 0.16 | 0.20 | 0.03 | 0.24 | 1760 |
| #R2 | 4.53 | –0.18 | 0.32 | 0.40 | 0.06 | 0.49 | 3520 |
| #R3 | 9.06 | –0.35 | 0.64 | 0.80 | 0.12 | 0.97 | 7040 |
| #R4 | 1.22 | –0.29 | 0.11 | 0.18 | 0.03 | 0.24 | 1740 |
| #R5 | 2.79 | 0.75 | 0.19 | 0.20 | 0.04 | 0.28 | 3140 |
| Baseline basin-wide SoCAB emissions 2010 | 3285.2 | 681.2 | 633.8 | 185.1 | 125.6 | 371.6 | 478,904 |

Figure 3 presents a contour plot of the DG power (on logarithmic scale) for realistic DG scenario R1, which uses a land-use weighted spatial distribution, and compares it with other spatial distributions used for spanning DG scenarios; namely, population weighted, freeway density weighted, and population growth weighted spatial distributions. Except for the non-realistic freeway spatial distribution of DG power, which applies a DG distribution proportional to freeway density, the other three distributions show relatively similar patterns with some differences that are worthy of note. The realistic scenarios (land-use weighted) concentrate DG technologies nearby industrial zones such as Long Beach, Riverside and Los Angeles. In contrast, population-weighted distribution of DG, used in most spanning scenarios, is relatively smooth throughout the domain and places DG predominantly in the central area of Los Angeles. The population growth-weighted distribution is very similar to the population-weighted distribution, but assigns more DG power in areas with projected urban growth, such as Riverside or San Bernardino.

**Figure 3** Comparison amongst four spatial distributions of DG power in the SoCAB: (a) land-use weighted; (b) population weighted; (c) freeway density weighted and (d) population growth weighted




The application of the 10-step systematic approach for developing realistic DG implementation scenarios provides a reasonable distribution of DG power among sectors and among DG types in the SoCAB for 2010. Figure 4 presents the basin-wide DG power distribution amongst the various sectors and power size categories for realistic scenario R1. About 60% of total DG power is implemented in the industrial sector and more than 30% is going to the commercial-institutional sector (the sum of categories ‘commercial’ and ‘other’). Only a small fraction of the DG power that is anticipated for installation in the SoCAB by 2010 is installed to meet power demands in the residential sectors. However, the actual number of DG units may be higher as power capacities of these units will be in the range of 1–10 kW.

**Figure 4** Basin-wide DG power distribution among sectors and DG power sizes for DG realistic scenario R1

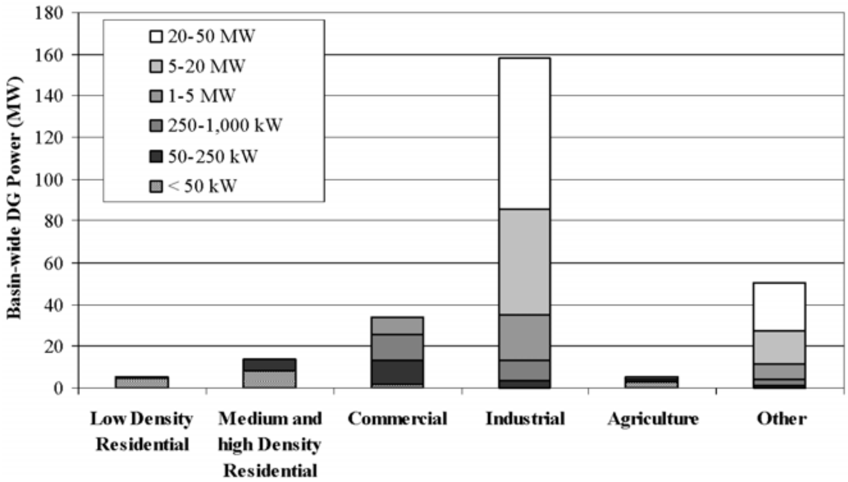



Figure 5 presents the basin-wide relative contribution of each type of DG technology considered in the current study for realistic scenario R1. Almost 50% of the DG market is being met by GTs, whereas ICEs, MTGs, PV, and FC account for 17%, 15%, 5%, and 10% of the total 2010 DG power market, respectively. The novel fuel cell-gas turbine hybrids accounts for the remaining 4% of the DG power. These figures are presented on a total power contribution basis, and do not reflect accurately the number of units installed, but, rather the contribution to total power demands met by each DG technology type. For example, a single large industrial GT contributes much more to the power demand and emissions than a host of small FCs installed in the residential sector.

**Figure 5** Basin-wide DG power distribution by DG type for realistic scenario R1

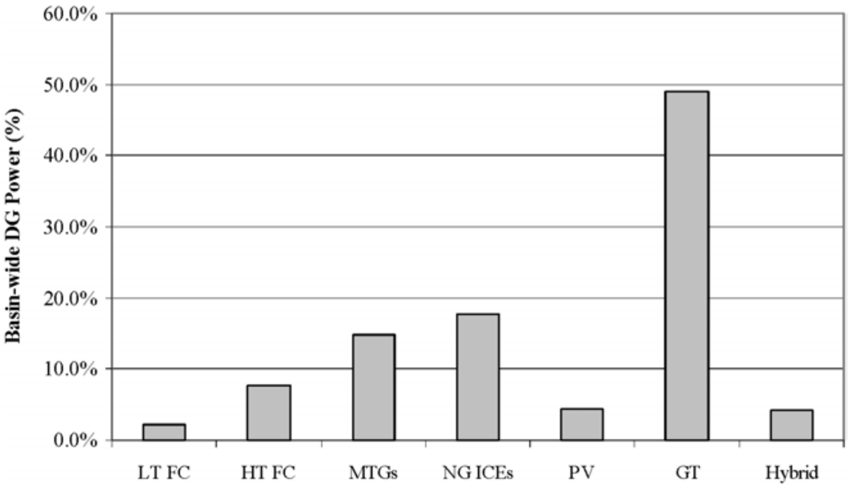
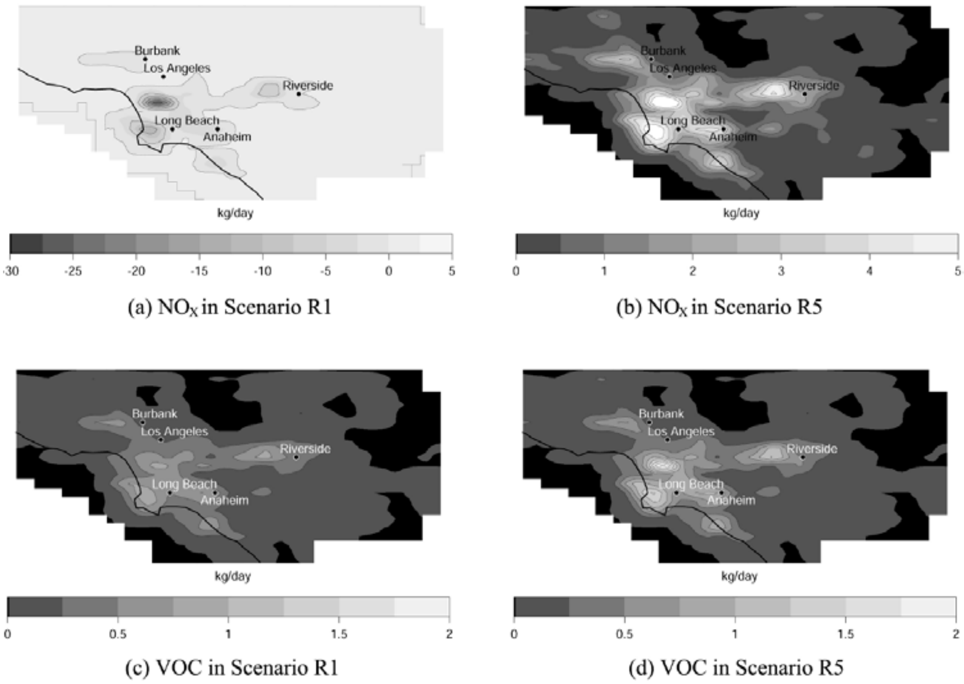


Figure 6 presents the net resulting emissions from application of DG technology in SoCAB that were derived by application of the current methodology. Figure 6(a) presents net DG $NO_x$ emissions for case R1, while Figure 6(b) presents net DG $NO_x$ emissions for case R5. Note that the only difference between cases R1 and R5 is that case R1 includes the DG CHP considerations of the current methodology whereas case R5 excludes CHP. Note that net $NO_x$ emissions from DG in case R1 are all negative (Figure 6(a)) due to displacement of emissions through use of CHP. The peak negative values (up to –30 kg/day) tend to occur in the most industrialised areas of the SoCAB between downtown Los Angeles and Long Beach, where CHP adoption is highest. The case that excludes CHP (case R5 of Figure 6(b)) shows net increases in $NO_x$ emissions (up to 5 kg/day) that are more disperse due to DG applications primarily in Long Beach, south of Anaheim and near Riverside. Figure 6(c) and 6(d) present net DG Volatile Organic Compound (VOC) emissions for cases R1 and R5, respectively. Because the VOC emissions of boilers are similar in magnitude to those of the DG the net VOC emissions from DG are not significantly affected by the consideration of CHP (compare Figure 6(c) (with CHP) and Figure 6(d) (without CHP)). For both cases R1 and R5 net DG VOC emissions are increased up to 2 kg/day in relatively dispersed regions near Los Angeles, Long Beach, Anaheim and Riverside.

**Figure 6** Basin-wide DG emissions distributions for two applications of the methodology



### *6.1 Summary of findings from SoCAB application of methodology*

The application of this general methodology to the SoCAB for the year 2010 produced the following findings:

- CHP emissions displacements associated with most of the realistic scenarios lead to significant reductions in some criteria pollutant emissions and $CO_2$ emissions. For $NO_x$, displaced boiler emissions are higher than $NO_x$ emissions directly produced by DG, resulting in net negative values for realistic scenarios with CHP.
- Realistic DG implementation scenarios introduce small basin-wide mass increments no larger than 0.43% with respect to baseline emissions.
- The spatial distribution of DG power based on GIS land-use data results in DG scenarios that concentrate large capacity DG technologies nearby industrial zones due to the relatively high adoption rate intensity factor estimated for the industrial sector.
- The calculation of basin-wide DG power distribution amongst the various sectors showed that 60% of total DG power is implemented in the industrial sector and nearly 32% is going to the commercial-institutional sector.
- Results of basin-wide relative contribution of each type of DG technology showed that 49% of the DG market is being met by GTs, whereas ICEs, MTGs, PV, FC, and GT-FC hybrids account for 17%, 15%, 5%, 10% and 4% of the total 2010 DG power market, respectively.

## 7 Conclusions

This paper describes a systematic methodology for development of realistic DG implementation scenarios. The methodology is applied to the SoCAB to demonstrate capabilities and present results. The methodology is novel in using land-use GIS data as a foundation for the DG scenario development. The characterisation of these DG scenarios is the first step required to assess environmental impacts of DG in urban basins.

A realistic assessment of DG emissions for use in regulatory policy or urban planning must include detailed consideration of several parameters in a systematic approach such as that contained in the current methodology. The application of this methodology to the SoCAB demonstrates the usefulness of the tool developed herein. Use of the current systematic methodology assures reasonable consideration of the multitude of factors that influence DG air quality impacts.

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## Nomenclature

| | |
|---|---|
| $A_{i,j,k}$ | Area of sector *i* in size category *j* in cell *k* |
| $A_{i,k}$ | Area of sector *i* in cell *k* |
| $D_{i,h}$ | Duty cycle factor in sector *i* and hour of the day *h* |
| $e_{l,X}$ | Emission factor for species *X* of DG type l |
| $P_{i,j,k}$ | DG power (in MW) of specific sector *i* in size category *j* in cell *k* |
| $P_{Tot,k}$ | Total DG power (in MW) assigned to cell *k* |
| $P_{Tot,SoCAB}$ | Total DG power (in MW) estimated for the SoCAB in 2010 |
| $R_{i,j}$ | Adoption rate relative intensity for sector *i* in size category *j* |
| $S_{i,j}$ | Relative area of sector *i* in size category *j* |
| $T_{l,k}$ | Relative contribution to DG power of DG type l in cell *k* |
| $W_{l,I,j}$ | Relative weight for DG type *l* in sector *i* and size category *j* |
| *Subscripts* | |
| *h* | Index for hour of day (24 total hours) |
| *i* | Index for market sector (6 total sectors) |
| *j* | Index for size category (6 total categories) |
| *k* | Index for cell number (994 total cells in three-dimensional model) |
| *l* | Index for DG unit type (7 types) |
| *List of acronyms* | |
| AQM | Air Quality Model |
| CACM | Caltech Atmospheric Chemistry Mechanism |
| CEC | California Energy Commission |
| CHP | Combined Heat and Power |
| $CO_2$ | Carbon dioxide |
| DG | Distributed Generation |
| FC | Fuel Cell(s) |
| GT | Gas Turbine(s) |
| HTFC | High Temperature Fuel Cell(s) |
| ICE | Internal Combustion Engine(s) |
| GIS | Geographic Information System |
| LTFC | Low Temperature Fuel Cell(s) |
| MTG | Micro Turbine Generator(s) |
| $NO_x$ | Nitrogen Oxides |
| NG | Natural Gas |
| PM | Particulate Matter |
| PV | Photovoltaics |
| SoCAB | South Coast Air Basin |
| $SO_x$ | Sulphur Oxides |