**Title**
Assessment of Energy Savings Potential from the Use of Demand Control Ventilation Systems in General Office Spaces in California

**Author**
Hong, Tianzhen

**Publication Date**
2010-03-31

# Assessment of Energy Savings Potential from the Use of Demand Control Ventilation Systems in General Office Spaces in California

Tianzhen Hong and William J. Fisk

Environmental Energy Technologies Division
Indoor Environment Department
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

July 8, 2009

This document was prepared as an account of work sponsored by California Energy Commission under DOE Contract No. DE-AC02-05CH11231.

# Assessment of Energy Savings Potential from the Use of Demand Control Ventilation Systems in General Office Spaces in California

**Tianzhen Hong and William J. Fisk**
**Environmental Energy Technologies Division**
**Lawrence Berkeley national Laboratory**

**July 8, 2009**

**Prepared For:**

**California Energy Commission**
**Public Interest Energy Research Program**
**Building End Use Energy Efficiency Program**

## DISCLAIMER

This report was prepared as the result of work sponsored by the California Energy Commission. It does not necessarily represent the views of the Energy Commission, its employees or the State of California. The Energy Commission, the State of California, its employees, contractors and subcontractors make no warrant, express or implied, and assume no legal liability for the information in this report; nor does any party represent that the uses of this information will not infringe upon privately owned rights. This report has not been approved or disapproved by the California Energy Commission nor has the California Energy Commission passed upon the accuracy or adequacy of the information in this report.

This document was prepared as an account of work sponsored by California Energy Commission under DOE Contract No. DE-AC02-05CH11231. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor The Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or The Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, or The Regents of the University of California.

Ernest Orlando Lawrence Berkeley National Laboratory is an equal opportunity employer.

# Executive Summary

Demand controlled ventilation (DCV) was evaluated for general office spaces in California. A medium size office building meeting the prescriptive requirements of the 2008 California building energy efficiency standards (CEC 2008) was assumed in the building energy simulations performed with the EnergyPlus program to calculate the DCV energy savings potential in five typical California climates. Three design occupancy densities and two minimum ventilation rates were used as model inputs to cover a broader range of design variations. The assumed values of minimum ventilation rates in offices without DCV, based on two different measurement methods, were 81 and 28 cfm per occupant. These rates are based on the co-author's unpublished analyses of data from EPA's survey of 100 U.S. office buildings. These minimum ventilation rates exceed the 15 to 20 cfm per person required in most ventilation standards for offices. The cost effectiveness of applying DCV in general office spaces was estimated via a life cycle cost analyses that considered system costs and energy cost reductions.

The results of the energy modeling indicate that the energy savings potential of DCV is largest in the desert area of California (climate zone 14), followed by Mountains (climate zone 16), Central Valley (climate zone 12), North Coast (climate zone 3), and South Coast (climate zone 6).

The results of the life cycle cost analysis show DCV is cost effective for office spaces if the typical minimum ventilation rates without DCV is 81 cfm per person, except at the low design occupancy of 10 people per 1000 $ft^2$ in climate zones 3 and 6. At the low design occupancy of 10 people per 1000 $ft^2$, the greatest DCV life cycle cost savings is a net present value (NPV) of \$0.52/$ft^2$ in climate zone 14, followed by \$0.32/$ft^2$ in climate zone 16 and \$0.19/$ft^2$ in climate zone 12. At the medium design occupancy of 15 people per 1000 $ft^2$, the DCV savings are higher with a NPV \$0.93/$ft^2$ in climate zone 14, followed by \$0.55/$ft^2$ in climate zone 16, \$0.46/$ft^2$ in climate zone 12, \$0.30/$ft^2$ in climate zone 3, \$0.16/$ft^2$ in climate zone 3. At the high design occupancy of 20 people per 1000 $ft^2$, the DCV savings are even higher with a NPV \$1.37/$ft^2$ in climate zone 14, followed by \$0.86/$ft^2$ in climate zone 16, \$0.84/$ft^2$ in climate zone 3, \$0.82/$ft^2$ in climate zone 12, and \$0.65/$ft^2$ in climate zone 6.

DCV was not found to be cost effective if the typical minimum ventilation rate without DCV is 28 cfm per occupant, except at high design occupancy of 20 people per 1000 $ft^2$ in climate zones 14 and 16.

Until the large uncertainties about the base case ventilation rates in offices without DCV are reduced, the case for requiring DCV in general office spaces will be a weak case.

Keywords: Building Simulation, California Building Energy Standard, Demand Controlled Ventilation, Energy Savings.

# Table of Contents

# List of Tables

# List of Figures

# 1.0 Introduction

Adequate ventilation with outdoor air is critical for occupants living or working in buildings. Too much or too little outdoor air in an occupied space can cause problems. High rates of ventilation results in higher energy usage and costs for cold or hot climates while potentially increasing some types of indoor air quality (IAQ) problems, particularly problems associated with high indoor humidity in warm-humid climates when the dehumidification capacity of the heating, ventilation, and air conditioning (HVAC) system is not designed for a high rate of entry of humid air. Low rates of ventilation, on the other hand, lead to higher indoor concentrations of a variety of indoor-generated air pollutants. In office buildings with low ventilation rates, on average, occupants are less satisfied with indoor air quality and they experience more building-related adverse health symptoms (Seppanen and Fisk 2002). Most building codes require that a minimum amount of outdoor air be provided to ensure adequate IAQ. To comply, ventilation systems typically are designed to operate with a fixed minimum outdoor air supply rate usually based on design occupancy that is much higher than occupancy levels during most of the time. While measured data on the minimum ventilation rates in existing offices are limited and subject to large measurement error, a survey of 100 U.S. office buildings supported by the U.S. Environmental Protection Agency provides the best available data (Persily and Gorfain 2008). The measurements of ventilation rates in this survey collected when HVAC systems should be supplying minimum amounts of outdoor air were analyzed by the co-author of this report and indicate that, on average, minimum ventilation rates dramatically exceed code requirements that are typically 15 to 20 cfm per occupant depending on occupant density (CEC 2008, ASHRAE 2007). The high measured ventilation rates are partly a consequence of the low average occupant density in offices but may also be due to the absence, in most office buildings, of any real-time measurement and feed-back-control system for minimum ventilation rates.

To address the problems of too much or too little outdoor air, the HVAC system can use a demand controlled ventilation (DCV) strategy to tailor the amount of outdoor air to the occupancy level. $CO_2$ sensors have emerged as the primary technology for indirectly monitoring occupancy and implementing DCV: $CO_2$ sensors monitor $CO_2$ levels in the indoor air, and the HVAC system uses data from the sensors to adjust the amount of incoming outdoor air. If the HVAC system has an outdoor air economizer, the ventilation rate will be higher than indicated by the DCV control system when weather is mild.

Under the 2008 California Building Energy Efficiency Standards (Title 24), DCV is required for a space if it is served by either a single zone system or a multi-zone system with DDC to the zone level that has an air-side economizer and a design occupant density greater than or equal to 25 people per 1000 $ft^2$ (40 $ft^2$ per person). There are four exceptions:

a. Classrooms, call centers, office spaces served by multiple zone systems that are continuously occupied during normal business hours with occupant density greater than 25 people per 1000 $ft^2$ per 121(b)2B, healthcare facilities and medical buildings, and public areas of social services buildings.

b. Where space exhaust is greater than the design ventilation rate specified in 121(b)2B minus 0.2 cfm per $ft^2$ of conditioned area

c. Spaces that have processes or operations that generate dusts, fumes, mists, vapors, or gases and are not provided with local exhaust ventilation, such as indoor operation of internal combustion engines or areas designated for unvented food service preparation, or beauty salons.

d. Spaces with an area of less than 150 $ft^2$, or a design occupancy of less than 10 people per 121(b)2B.

General office spaces are not subject to the Title 24-2008 DCV requirement; however, given the evidence described above that minimum ventilation rates in offices with DCV are, on average, much higher than required in codes, a significant energy savings from DCV was hypothesized especially for the more severe California climates. The purpose of this assessment study was to estimate the energy savings potential and cost effectiveness of DCV for general office spaces through building performance simulation. The simulations assumed features of a typical medium size office buildings and were performed for typical climate zones of California.

# 2.0 Assessment Methodology

Computer based building performance simulation provides a quick way to assess the energy impacts of DCV for office buildings. This assessment looked at the energy impact of DCV in terms of whole building energy performance which takes into account the integration and interaction of building components and systems. Instead of creating new building prototypes for this assessment, the DOE commercial benchmark (Torcellini et al 2008) for the medium-size office building was adopted. The energy simulation model was modified to comply with the prescriptive requirements of Title 24-2008 (CEC 2008), including insulation level of building envelope, lighting power level, and HVAC equipment efficiencies. The Title 24 standard occupancies were used, and DCV was implemented in the energy models. The energy usage difference between the base cases without DCV and the alternative cases with DCV are the energy savings due to the use of DCV.

## *2.0.1 The Medium Size Office Building Prototypes*

The medium size office building has a rectangular shape with an aspect ratio of 1.5 (about 164 ft x 109 ft). It has three identical stories with a total floor area of 53,627 $ft^2$. Each floor has five thermal zones: four perimeter ones and one core. All five zones are assumed to be general office occupancy. There is also a single plenum zone for each floor. Exterior walls are steel frame construction with a slab on grade foundation (no basement) and built up flat roof with insulation entirely above deck. Interior partitions are 2x4 steel frame with gypsum board. Each thermal zone also contains appropriate wood thermal mass corresponding to furniture. The window-wall-ratio is 33%. Daylighting control is not modeled. The building is served by three packaged variable air volume (PVAV) systems with gas furnace for heating. One system serves one floor.

The building size, shape, and operating schedules stay the same for all locations, but the building efficiency level varies with climate zone according to Title 24-2008 prescriptive requirements.

### 2.0.2 Major Modeling Assumptions

The energy models were modified to comply with the prescriptive requirements of Title 24-2008. Each of the three PVAV systems has an air side economizer which provides up to 100% of outdoor air for free cooling when indoor and outdoor conditions favor economizer operation.

Table 1 *summarizes the internal loads and minimum ventilation requirements for office buildings.*

Table 2 shows the prescriptive envelope requirements for nonresidential buildings. Table 3 shows the standard schedules used in the simulations.

*Table 1 – Internal Loads of Office Buildings from Title 24-2008 Nonresidential ACM Manual*

| Occupancy Type | #people per 1000 ft² | Sensible Heat per person Btu/h | Latent Heat per person Btu/h | Receptacle Load W/ft² | Hot Water Load Btu/h-person | Lighting Power W/ft² | Ventilation cfm/ft² |
|---|---|---|---|---|---|---|---|
| Office Buildings | 10 | 250 | 206 | 1.34 | 106 | 0.85 | 0.15 |

*Table 2 – Prescriptive Envelope Criteria for Nonresidential Buildings from Title 24-2008 Standards*

| | | | Climate Zone | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| Roofs/Ceilings | Metal Building | | 0.065 | 0.065 | 0.065 | 0.065 | 0.065 | 0.065 | 0.065 | 0.065 | 0.065 | 0.065 | 0.065 | 0.065 | 0.065 | 0.065 | 0.065 | 0.065 |
| | Wood Framed and Other | | 0.049 | 0.039 | 0.039 | 0.039 | 0.049 | 0.075 | 0.067 | 0.067 | 0.039 | 0.039 | 0.039 | 0.039 | 0.039 | 0.039 | 0.039 | 0.039 |
| Roofing Products | Low-sloped | Aged Reflectance | NR | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | NR |
| | | Emittance | NR | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | NR |
| | Steep Sloped (less than 5 lb/ft$^2$) | Aged Reflectance | NR | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 |
| | | Emittance | NR | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 |
| | Steep Sloped (5 lb/ft$^2$ or more) | Aged Reflectance | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| | | Emittance | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 |
| Walls | Metal Building | | 0.113 | 0.061 | 0.113 | 0.061 | 0.061 | 0.113 | 0.113 | 0.061 | 0.061 | 0.061 | 0.061 | 0.061 | 0.061 | 0.061 | 0.057 | 0.061 |
| | Metal-framed | | 0.098 | 0.062 | 0.082 | 0.062 | 0.062 | 0.098 | 0.098 | 0.062 | 0.062 | 0.062 | 0.062 | 0.062 | 0.062 | 0.062 | 0.062 | 0.062 |
| | Mass Light | | 0.196 | 0.170 | 0.278 | 0.227 | 0.44 | 0.44 | 0.44 | 0.44 | 0.44 | 0.170 | 0.170 | 0.170 | 0.170 | 0.170 | 0.170 | 0.170 |
| | Mass Heavy | | 0.253 | 0.650 | 0.650 | 0.650 | 0.650 | 0.690 | 0.690 | 0.690 | 0.690 | 0.650 | 0.184 | 0.253 | 0.211 | 0.184 | 0.184 | 0.160 |
| | Wood-framed and Other | | 0.102 | 0.059 | 0.110 | 0.059 | 0.102 | 0.110 | 0.110 | 0.102 | 0.059 | 0.059 | 0.059 | 0.059 | 0.059 | 0.059 | 0.042 | 0.059 |
| Floors/Soffits | Mass | | 0.092 | 0.092 | 0.269 | 0.269 | 0.269 | 0.269 | 0.269 | 0.269 | 0.269 | 0.269 | 0.092 | 0.092 | 0.092 | 0.092 | 0.092 | 0.058 |
| | Other | | 0.048 | 0.039 | 0.071 | 0.071 | 0.071 | 0.071 | 0.071 | 0.071 | 0.071 | 0.071 | 0.039 | 0.071 | 0.071 | 0.039 | 0.039 | 0.039 |
| Windows | U-factor | | 0.47 | 0.47 | 0.77 | 0.77 | 0.77 | 0.77 | 0.77 | 0.77 | 0.77 | 0.47 | 0.47 | 0.47 | 0.47 | 0.47 | 0.47 | 0.47 |
| | RSHG North | 0-10% WWR | 0.72 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.72 |
| | | 10-20% WWR | 0.49 | 0.51 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.51 | 0.51 | 0.51 | 0.51 | 0.51 | 0.51 | 0.49 |
| | | 20-30% WWR | 0.47 | 0.47 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.47 | 0.47 | 0.47 | 0.47 | 0.47 | 0.47 | 0.47 |
| | | 30-40% WWR | 0.47 | 0.47 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.47 | 0.47 | 0.47 | 0.47 | 0.40 | 0.40 | 0.47 |
| | RSHG Non-North | 0-10% WWR | 0.49 | 0.47 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.47 | 0.47 | 0.47 | 0.47 | 0.46 | 0.46 | 0.49 |
| | | 10-20% WWR | 0.43 | 0.36 | 0.55 | 0.55 | 0.55 | 0.61 | 0.61 | 0.61 | 0.61 | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 | 0.43 |
| | | 20-30% WWR | 0.43 | 0.36 | 0.41 | 0.41 | 0.41 | 0.39 | 0.39 | 0.39 | 0.39 | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 | 0.43 |
| | | 30-40% WWR | 0.43 | 0.31 | 0.41 | 0.41 | 0.41 | 0.34 | 0.34 | 0.34 | 0.34 | 0.31 | 0.31 | 0.31 | 0.31 | 0.31 | 0.31 | 0.43 |
| Doors, U-factor | Non-Swinging | | 0.50 | 1.45 | 1.45 | 1.45 | 1.45 | 1.45 | 1.45 | 1.45 | 1.45 | 1.45 | 1.45 | 1.45 | 1.45 | 1.45 | 1.45 | 0.50 |
| | Swinging | | 0.70 | 0.70 | 0.70 | 0.70 | 0.70 | 0.70 | 0.70 | 0.70 | 0.70 | 0.70 | 0.70 | 0.70 | 0.70 | 0.70 | 0.70 | 0.70 |
| Skylight | U-factor | Glass, curb | 1.11 | 1.11 | 1.11 | 1.11 | 1.11 | 1.11 | 1.11 | 1.11 | 1.11 | 1.11 | 1.11 | 1.11 | 1.11 | 1.11 | 1.11 | 1.11 |
| | | Glass, no curb | 0.68 | 0.68 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 | 0.68 | 0.68 | 0.68 | 0.68 | 0.68 | 0.68 | 0.68 |
| | | Plastic | 1.04 | 1.11 | 1.11 | 1.11 | 1.11 | 1.11 | 1.11 | 1.11 | 1.11 | 1.11 | 1.11 | 1.11 | 1.11 | 1.11 | 1.11 | 1.04 |
| | SHGC | Glass, 0-2% | NR | 0.46 | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | NR |
| | | Glass, 2.1-5% | NR | 0.36 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 | NR |
| | | Plastic, 0-2% | 0.69 | 0.69 | 0.69 | 0.69 | 0.69 | 0.69 | 0.69 | 0.69 | 0.69 | 0.69 | 0.69 | 0.69 | 0.69 | 0.69 | 0.69 | 0.69 |
| | | Plastic, 2.1-5% | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 |

Notes:

1. Mass, Light walls are defined as having a heat capacity greater than or equal to 7.0 Btu/h-ft2 and less than 15.0 Btu/h-ft2. Heavy mass walls are defined as having a heat capacity greater than or equal to 15.0 Btu/h-ft2.
2. No skylight SHGC requirements are defined for climate zones 1 and 16. A climate zone without a requirement is designated as "NR".

*Table 3 – Office Buildings Occupancy Schedules from Title 24-2008 Nonresidential ACM Manual*

| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Heating (ºF) | WD | 60 | 60 | 60 | 60 | 60 | 65 | 65 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 65 | 60 | 60 | 60 | 60 | 60 |
| | Sat | 60 | 60 | 60 | 60 | 60 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 |
| | Sun | 60 | 60 | 60 | 60 | 60 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 |
| Cooling (ºF) | WD | 77 | 77 | 77 | 77 | 77 | 73 | 73 | 73 | 73 | 73 | 73 | 73 | 73 | 73 | 73 | 73 | 73 | 73 | 77 | 77 | 77 | 77 | 77 | 77 |
| | Sat | 77 | 77 | 77 | 77 | 77 | 73 | 73 | 73 | 73 | 73 | 73 | 73 | 73 | 73 | 73 | 73 | 73 | 73 | 77 | 77 | 77 | 77 | 77 | 77 |
| | Sun | 77 | 77 | 77 | 77 | 77 | 73 | 73 | 73 | 73 | 73 | 73 | 73 | 73 | 73 | 73 | 73 | 73 | 73 | 77 | 77 | 77 | 77 | 77 | 77 |
| Lights (%) Uncontrolled | WD | 5 | 5 | 5 | 5 | 10 | 20 | 40 | 70 | 80 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 80 | 35 | 10 | 10 | 10 | 10 | 10 |
| | Sat | 5 | 5 | 5 | 5 | 5 | 10 | 15 | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 20 | 20 | 20 | 15 | 10 | 10 | 10 | 10 | 10 | 10 |
| | Sun | 5 | 5 | 5 | 5 | 5 | 10 | 10 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 10 | 10 | 10 | 5 | 5 | 5 | 5 |
| Lights (%) Bi-level Osensor | WD | 4 | 4 | 4 | 4 | 8 | 15 | 31 | 56 | 67 | 73 | 74 | 74 | 74 | 74 | 73 | 71 | 70 | 64 | 28 | 8 | 8 | 7 | 7 | 8 |
| | Sat | 4 | 4 | 4 | 4 | 4 | 8 | 12 | 20 | 21 | 22 | 22 | 22 | 22 | 22 | 17 | 17 | 16 | 12 | 8 | 8 | 8 | 7 | 7 | 8 |
| | Sun | 4 | 4 | 4 | 4 | 4 | 8 | 8 | 12 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 12 | 8 | 8 | 8 | 4 | 4 | 4 | 4 |
| Lights (%) Stack Osensor | WD | 4 | 4 | 4 | 4 | 9 | 17 | 34 | 60 | 68 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 68 | 30 | 9 | 9 | 9 | 9 | 9 |
| | Sat | 4 | 4 | 4 | 4 | 4 | 9 | 13 | 22 | 22 | 22 | 22 | 22 | 22 | 22 | 17 | 17 | 17 | 13 | 9 | 9 | 9 | 9 | 9 | 9 |
| | Sun | 4 | 4 | 4 | 4 | 4 | 9 | 9 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 9 | 9 | 9 | 4 | 4 | 4 | 4 |
| Lights (%) Library Osensor | WD | 4 | 4 | 4 | 4 | 8 | 16 | 33 | 60 | 73 | 80 | 81 | 82 | 82 | 81 | 80 | 78 | 75 | 66 | 28 | 8 | 8 | 8 | 8 | 8 |
| | Sat | 4 | 4 | 4 | 4 | 4 | 9 | 13 | 22 | 22 | 22 | 22 | 22 | 22 | 22 | 17 | 17 | 17 | 13 | 9 | 9 | 9 | 9 | 9 | 9 |
| | Sun | 4 | 4 | 4 | 4 | 4 | 9 | 9 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 9 | 9 | 9 | 4 | 4 | 4 | 4 |
| Lights (%) Manual Dimming | WD | 5 | 5 | 5 | 5 | 9 | 18 | 36 | 63 | 72 | 77 | 77 | 77 | 77 | 77 | 77 | 77 | 77 | 72 | 32 | 9 | 9 | 9 | 9 | 9 |
| | Sat | 5 | 5 | 5 | 5 | 5 | 9 | 14 | 23 | 23 | 23 | 23 | 23 | 23 | 23 | 18 | 18 | 18 | 14 | 9 | 9 | 9 | 9 | 9 | 9 |
| | Sun | 5 | 5 | 5 | 5 | 5 | 9 | 9 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 14 | 9 | 9 | 9 | 5 | 5 | 5 | 5 |
| Lights (%) Program Multiscene | WD | 4 | 4 | 4 | 4 | 8 | 16 | 32 | 56 | 64 | 68 | 68 | 68 | 68 | 68 | 68 | 68 | 68 | 64 | 28 | 8 | 8 | 8 | 8 | 8 |
| | Sat | 4 | 4 | 4 | 4 | 4 | 8 | 12 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 16 | 16 | 16 | 12 | 8 | 8 | 8 | 8 | 8 | 8 |
| | Sun | 4 | 4 | 4 | 4 | 4 | 8 | 8 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 8 | 8 | 8 | 4 | 4 | 4 | 4 |
| Lights (%) Combined Daylight | WD | 4 | 4 | 4 | 4 | 8 | 15 | 31 | 56 | 67 | 73 | 74 | 74 | 74 | 74 | 73 | 71 | 70 | 64 | 28 | 8 | 8 | 7 | 7 | 8 |
| | Sat | 4 | 4 | 4 | 4 | 4 | 8 | 12 | 20 | 21 | 22 | 22 | 22 | 22 | 22 | 17 | 17 | 16 | 12 | 8 | 8 | 8 | 7 | 7 | 8 |
| | Sun | 4 | 4 | 4 | 4 | 4 | 8 | 8 | 12 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 12 | 8 | 8 | 8 | 4 | 4 | 4 | 4 |
| Lights (%) Combined Dimming | WD | 4 | 4 | 4 | 4 | 7 | 14 | 29 | 53 | 64 | 70 | 71 | 71 | 71 | 71 | 70 | 68 | 65 | 60 | 26 | 7 | 7 | 7 | 7 | 7 |
| | Sat | 4 | 4 | 4 | 4 | 4 | 7 | 11 | 19 | 20 | 21 | 21 | 21 | 21 | 21 | 16 | 16 | 15 | 11 | 7 | 7 | 7 | 7 | 7 | 7 |
| | Sun | 4 | 4 | 4 | 4 | 4 | 7 | 7 | 11 | 12 | 12 | 13 | 13 | 13 | 13 | 12 | 12 | 12 | 8 | 7 | 7 | 3 | 3 | 3 | 3 |
| Equipment (%) | WD | 15 | 15 | 15 | 15 | 15 | 20 | 35 | 60 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 65 | 45 | 30 | 20 | 20 | 15 | 15 | 15 |
| | Sat | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 20 | 25 | 25 | 25 | 25 | 25 | 25 | 20 | 20 | 20 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| | Sun | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| Fans (%) | WD | off | off | off | off | off | on | on | on | on | on | on | on | on | on | on | on | on | on | on | on | off | off | off | off |
| | Sat | off | off | off | off | off | on | on | on | on | on | on | on | on | on | on | off | off | off | off | off | off | off | off | off |
| | Sun | off | off | off | off | off | off | off | off | off | off | off | off | off | off | off | off | off | off | off | off | off | off | off | off |
| Infiltration (%) | WD | 100 | 100 | 100 | 100 | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 100 | 100 | 100 |
| | Sat | 100 | 100 | 100 | 100 | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| | Sun | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| People (%) | WD | 0 | 0 | 0 | 0 | 5 | 10 | 25 | 65 | 65 | 65 | 65 | 60 | 60 | 65 | 65 | 65 | 65 | 40 | 25 | 10 | 5 | 5 | 5 | 0 |
| | Sat | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| | Sun | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |

### *2.0.3 Outdoor Air Ventilation Rates*

For the base cases without DCV, a constant outdoor air flow of either 28 or 81 cfm per occupant was used based on average weekday occupancy when the building is occupied and ventilated. These two values of ventilation rates are based on the measured results from a survey of 100 representative U.S. office buildings and unpublished analyses by the coauthor of this report. The survey is the only known U.S. study of ventilation rates and other indoor air quality conditions in a large representative sample of office buildings. Ventilation and HVAC airflow data from this survey are described by Persily and Gorfain (2008). The survey took place for a broad range of weather conditions and the author analyzed data collected when the outdoor air temperature was above 71.6°F and, consequently, outdoor air supply rates should be at the minimum. The resulting 28 cfm/person average minimum ventilation rate is based on analyses of peak measured one-hour average carbon dioxide concentrations, assuming that occupants emit 0.011 cfm of $CO_2$ and that the measured one-hour peak concentration is 80% of the true equilibrium $CO_2$ concentration. The calculation was performed before a few corrections to the $CO_2$ data, leading to a revised report by Persily and Gorfain (2008); however, these corrections have no significant impact on the average value. The 81 cfm per occupant average minimum ventilation rate is based on use of air velocity sensors to measure outdoor air flow rate, or from the difference between supply and recirculation air flow, both measured using velocity sensors. The two resulting average minimum ventilations rates are very different and, at present, it is not known which value is more accurate.

For the alternative cases with DCV, the space minimum outdoor air flow was calculated as the larger of:

- 17.6 cfm/person times the current number of occupants present, where the current number of occupants equals the design occupancy multiplied by the occupant schedule percentage listed in Table 3. The value of 17.6 cfm/per person corresponds to the ventilation rate necessary to maintain indoor carbon dioxide in an office building less than 600 ppm greater than the outdoor concentration assuming a carbon dioxide generation rate per occupant of 0.011 cfm. This 600 ppm maximum difference between indoor and outdoor concentration is specified for DCV in the California Building energy Efficiency Standards (CEC 2008).

and

- 0.15 cfm/ft$^2$ times the space floor area based on Table 1.

Table 3 lists the occupant schedule with the percentage values representing the number of occupants in the building divided by the design number of occupants, converted to a percentage. During weekday periods of system operation, the workday average occupancy is 50% of the peak occupancy. With a design occupant density of 10 people/1000 ft$^2$ for office buildings, the design outdoor air flow based on the per person requirement is the larger of 0.15 cfm/ft$^2$ and a time varying rate that is always less than or equal to 0.176 cfm/ft$^2$ (17.6 cfm/occ *

(10/1000) occupants per ft$^2$). Table 4 summarizes the minimum outdoor air supply rates for all cases.

*Table 4 – Minimum Outdoor Air Requirement*

| Case Description | Design (Peak) Occupant Density (#people per 1000 ft$^2$) | Design OA cfm/ft$^2$ based on 28 cfm/person in base cases or 17.6 cfm per person in DCV cases | Design OA cfm/ft$^2$ based on 81 cfm/person in base cases or 17.6 cfm per person in DCV cases | Title 24 Required Minimum OA cfm/ft$^2$ | Actual OA Supply cfm/ft$^2$ |
|---|---|---|---|---|---|
| Base Cases | 10 | 0.14 | 0.40 | NA | 0.14 or 0.40 |
| | 15 | 0.21 | 0.61 | NA | 0.21 or 0.61 |
| | 20 | 0.28 | 0.81 | NA | 0.28 or 0.81 |
| DCV Cases | 10 | 0.176 (weekday avg. = 0.088) | 0.176 (weekday avg. = 0.088) | 0.15 | Varies with time (0.15 to 0.176) |
| | 15 | 0.264 (weekday avg. = 0.132) | 0.264 (weekday avg. = 0.132) | 0.15 | varies with time (0.15 to 0.264) |
| | 20 | 0.352 (weekday avg. = 0.176) | 0.352 (weekday avg. = 0.176) | 0.15 | varies with time (0.15 to 0.352) |

For both the base cases and the DCV cases, the PVAV systems have air side economizers. Therefore the actual outdoor air flow can exceed the minimum ventilation rate when economizers operate.

### 2.0.4 Climate Zones

Five cities representing the five typical climate regions were chosen and summarized in Table 5. The Title 24 standard weather data for the chosen five climate zone was used in the simulations.

*Table 5 – Five Typical California Climate Zones*

| Description | Title 24 Climate Zone | Representative City |
|---|---|---|
| North Coast | 3 | San Francisco |
| South Coast | 6 | Los Angeles |
| Central Valley | 12 | Sacramento |
| Desert | 14 | China Lake |
| Mountains | 16 | Mt. Shasta |

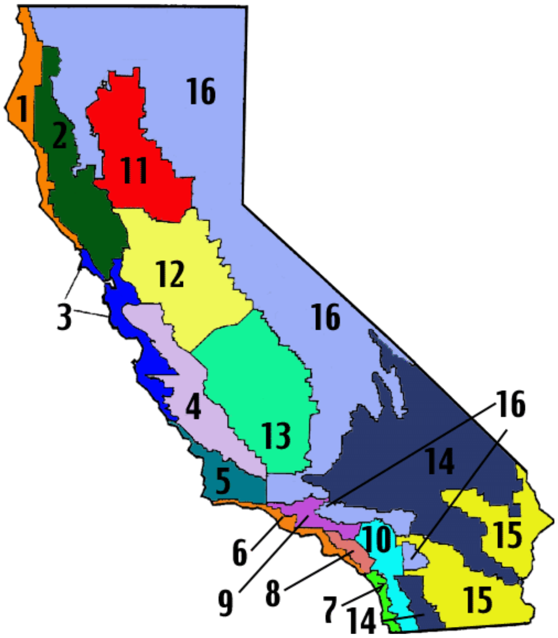

Figure 1 – California Climate Zone Map

### *2.0.5 Simulation Tool*

EnergyPlus version 3.0, released in November 2008, was used to simulate the whole building energy performance of the selected medium size office building. The DCV algorithm implemented in EnergyPlus 3.0 is based on the calculation of space minimum outdoor air requirements for varying number of occupants and a constant component based on space floor area. EnergyPlus 3.0 calculates the system-level outdoor air requirement as the sum of space outdoor air flows, without considering zone air distribution effectiveness or system ventilation efficiency as required by ASHRAE standard 62.1-2007 (ASHRAE 2007). This works fine for single zone systems or multi zone systems serving zones with same design occupancy and schedule. In this assessment, all spaces are assumed to be general offices with same design occupancy and schedule.

### *2.0.6 Cost Estimates*

In the DCV measure analysis (Taylor 2002) for Title 24-2005, the DCV cost for a single zone system was estimated to be $575 which included parts and labor. Adjusted for inflation and multi zones, the DCV cost for each of the three PVAV systems were estimated to be $3085 (average $617 per zone X 5 zones). On the per building conditioned floor area basis, the DCV cost is $0.1726/ft$^2$.

Based on a 15 year life cycle and 3% discount rate for an installed DCV system, the present value (PV) of energy costs were estimated to be $1.37/kWh for electricity and $7.3/Therm for natural gas (Eley 2002).

These costs data were used in the life cycle cost calculations summarized in Table 6.

# 3.0 Simulation Results and Analysis

A total of forty five EnergyPlus simulation runs were performed to evaluate the energy savings potential of DCV for the medium size office building at three design occupancy levels, two minimum outdoor air ventilation rates, and across five climate zones.

Table 6 summarizes the simulation results and calculated energy usage and costs savings. The Occupant Density column lists both the design and the peak occupancy levels. The peak occupancy density is the design occupancy density multiplied by the maximum value of the occupant schedule during weekday hours. The Design OA column lists the equivalent outdoor air rate per floor area converted from the outdoor air rate per occupant. The next four columns show the whole building energy use per conditioned floor area. The HVAC Energy Cost PV $/ft$^2$ column shows the HVAC energy cost (including cooling, heating and fan energy cost) in present value per floor area. The HVAC Energy Cost Savings PV $/ft$^2$ column is calculated as follows:

*HVAC energy cost savings = HVAC Energy Cost of the without DCV case - HVAC Energy Cost of the with DCV case*

The source energy is calculated as follows for all five climate zones:

*Source Energy kBtu = Electricity kWh * 3.413 * 3.095 + Natural Gas kBtu * 1.092*

The source energy factor of 3.095 for electricity and 1.092 for natural gas were obtained from NREL report by Deru and Torcellini (2007).

The DCV Life Cycle Cost Savings NPV $/ft$^2$ column calculates the life cycle cost savings of DCV in terms of net present value (NPV) by subtracting the DCV costs from the HVAC energy cost savings.

*Table 6 – Simulation Results and Calculated Energy Usage and Costs Savings*

| Location | Occupant Density #people/1000 ft². Design, Peak | Cases | Design OA cfm/ft² | Building Electricity Use kWh/ft² | Building Gas Use kBtu/ft² | Building Source Energy kBtu/ft² | Building Source Energy Savings % | HVAC Energy Cost PV $/ft² | HVAC Energy Cost Savings PV $/ft² | DCV Cost $/ft² | DCV Life Cycle Cost Savings NPV $/ft² |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CZ 3 | 10, 6.5 | Base Case I (28 cfm/person) | 0.14 | 11.55 | 2.58 | 127.5 | -0.1% | 5.48 | (0.02) | 0.17 | (0.19) |
| | | Base Case II (81 cfm/person) | 0.4 | 11.61 | 2.89 | 128.6 | 0.7% | 5.58 | 0.09 | 0.17 | (0.08) |
| | | DCV | 0.176 | 11.56 | 2.67 | 127.7 | n.a. | 5.49 | n.a. | n.a. | n.a. |
| | 15, 9.75 | Base Case I (28 cfm/person) | 0.21 | 11.87 | 2.54 | 131.0 | 0.1% | 5.91 | 0.02 | 0.17 | (0.16) |
| | | Base Case II (81 cfm/person) | 0.61 | 12.19 | 2.85 | 134.7 | 2.9% | 6.37 | 0.47 | 0.17 | 0.30 |
| | | DCV | 0.264 | 11.87 | 2.44 | 130.8 | n.a. | 5.90 | n.a. | n.a. | n.a. |
| | 20, 13 | Base Case I (28 cfm/person) | 0.28 | 12.20 | 2.48 | 134.5 | 0.2% | 6.36 | 0.02 | 0.17 | (0.15) |
| | | Base Case II (81 cfm/person) | 0.81 | 12.90 | 2.95 | 142.5 | 5.8% | 7.35 | 1.01 | 0.17 | 0.84 |
| | | DCV | 0.352 | 12.19 | 2.35 | 134.2 | n.a. | 6.34 | n.a. | n.a. | n.a. |
| CZ 6 | 10, 6.5 | Base Case I (28 cfm/person) | 0.14 | 12.76 | 2.07 | 140.0 | -0.1% | 7.09 | (0.02) | 0.17 | (0.20) |
| | | Base Case II (81 cfm/person) | 0.4 | 12.86 | 2.12 | 141.2 | 0.7% | 7.24 | 0.13 | 0.17 | (0.04) |
| | | DCV | 0.176 | 12.77 | 2.08 | 140.2 | n.a. | 7.11 | n.a. | n.a. | n.a. |
| | 15, 9.75 | Base Case I (28 cfm/person) | 0.21 | 13.16 | 1.93 | 144.2 | 0.0% | 7.63 | 0.01 | 0.17 | (0.17) |
| | | Base Case II (81 cfm/person) | 0.61 | 13.39 | 2.00 | 146.8 | 1.8% | 7.95 | 0.33 | 0.17 | 0.16 |
| | | DCV | 0.264 | 13.15 | 1.92 | 144.1 | n.a. | 7.62 | n.a. | n.a. | n.a. |
| | 20, 13 | Base Case I (28 cfm/person) | 0.28 | 13.56 | 1.84 | 148.5 | 0.1% | 8.18 | 0.02 | 0.17 | (0.15) |
| | | Base Case II (81 cfm/person) | 0.81 | 14.14 | 1.99 | 154.9 | 4.2% | 8.98 | 0.82 | 0.17 | 0.65 |
| | | DCV | 0.352 | 13.55 | 1.81 | 148.3 | n.a. | 8.16 | n.a. | n.a. | n.a. |
| CZ 12 | 10, 6.5 | Base Case I (28 cfm/person) | 0.14 | 12.63 | 2.70 | 139.4 | -0.5% | 6.97 | (0.07) | 0.17 | (0.24) |
| | | Base Case II (81 cfm/person) | 0.4 | 12.90 | 3.72 | 143.3 | 2.3% | 7.40 | 0.36 | 0.17 | 0.19 |
| | | DCV | 0.176 | 12.67 | 2.94 | 140.1 | n.a. | 7.04 | n.a. | n.a. | n.a. |
| | 15, 9.75 | Base Case I (28 cfm/person) | 0.21 | 13.05 | 2.88 | 144.1 | 0.3% | 7.56 | 0.05 | 0.17 | (0.12) |
| | | Base Case II (81 cfm/person) | 0.61 | 13.43 | 3.69 | 149.1 | 3.7% | 8.14 | 0.63 | 0.17 | 0.46 |
| | | DCV | 0.264 | 13.02 | 2.70 | 143.6 | n.a. | 7.50 | n.a. | n.a. | n.a. |
| | 20, 13 | Base Case I (28 cfm/person) | 0.28 | 13.45 | 3.11 | 148.7 | 0.7% | 8.12 | 0.11 | 0.17 | (0.06) |
| | | Base Case II (81 cfm/person) | 0.81 | 14.06 | 3.81 | 156.0 | 5.4% | 9.01 | 1.00 | 0.17 | 0.82 |
| | | DCV | 0.352 | 13.40 | 2.72 | 147.6 | n.a. | 8.01 | n.a. | n.a. | n.a. |
| CZ 14 | 10, 6.5 | Base Case I (28 cfm/person) | 0.14 | 13.18 | 2.93 | 145.5 | -0.4% | 7.73 | (0.04) | 0.17 | (0.22) |
| | | Base Case II (81 cfm/person) | 0.4 | 13.63 | 4.65 | 152.2 | 4.0% | 8.47 | 0.69 | 0.17 | 0.52 |
| | | DCV | 0.176 | 13.19 | 3.34 | 146.1 | n.a. | 7.78 | n.a. | n.a. | n.a. |
| | 15, 9.75 | Base Case I (28 cfm/person) | 0.21 | 13.61 | 3.13 | 150.4 | 0.6% | 8.34 | 0.12 | 0.17 | (0.05) |
| | | Base Case II (81 cfm/person) | 0.61 | 14.25 | 4.64 | 158.9 | 6.0% | 9.32 | 1.10 | 0.17 | 0.93 |
| | | DCV | 0.264 | 13.53 | 3.10 | 149.5 | n.a. | 8.22 | n.a. | n.a. | n.a. |
| | 20, 13 | Base Case I (28 cfm/person) | 0.28 | 14.07 | 3.70 | 156.0 | 1.5% | 9.01 | 0.26 | 0.17 | 0.09 |
| | | Base Case II (81 cfm/person) | 0.81 | 14.94 | 4.78 | 166.6 | 7.8% | 10.28 | 1.54 | 0.17 | 1.37 |
| | | DCV | 0.352 | 13.91 | 3.13 | 153.6 | n.a. | 8.75 | n.a. | n.a. | n.a. |
| CZ 16 | 10, 6.5 | Base Case I (28 cfm/person) | 0.14 | 11.89 | 5.23 | 134.1 | -0.3% | 6.13 | 0.02 | 0.17 | (0.15) |
| | | Base Case II (81 cfm/person) | 0.4 | 11.98 | 9.96 | 140.2 | 4.1% | 6.61 | 0.50 | 0.17 | 0.32 |
| | | DCV | 0.176 | 11.82 | 6.25 | 134.4 | n.a. | 6.11 | n.a. | n.a. | n.a. |
| | 15, 9.75 | Base Case I (28 cfm/person) | 0.21 | 12.18 | 6.14 | 138.2 | 1.0% | 6.60 | 0.15 | 0.17 | (0.02) |
| | | Base Case II (81 cfm/person) | 0.61 | 12.38 | 10.40 | 145.0 | 5.6% | 7.18 | 0.73 | 0.17 | 0.55 |
| | | DCV | 0.264 | 12.09 | 5.82 | 136.9 | n.a. | 6.46 | n.a. | n.a. | n.a. |
| | 20, 13 | Base Case I (28 cfm/person) | 0.28 | 12.50 | 7.73 | 143.3 | 2.1% | 7.15 | 0.28 | 0.17 | 0.10 |
| | | Base Case II (81 cfm/person) | 0.81 | 12.88 | 10.94 | 150.9 | 7.0% | 7.90 | 1.03 | 0.17 | 0.86 |
| | | DCV | 0.352 | 12.38 | 6.04 | 140.3 | n.a. | 6.87 | n.a. | n.a. | n.a. |

Figures 2 to 6 show HVAC energy costs in PV $/ft² for each of the five climate zones. Figures 7 to 9 show DCV life cycle cost savings in NPV $/ft² for three design occupancy levels.

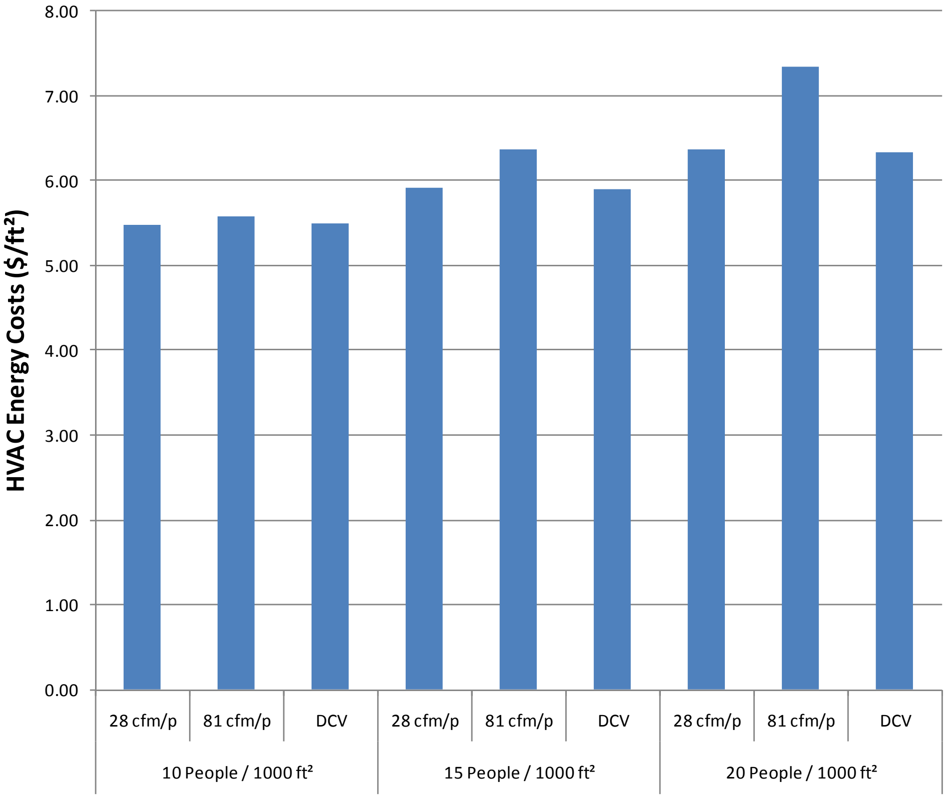

Figure 2 – HVAC Energy Costs (PV $/ft$^2$), Climate Zone 3

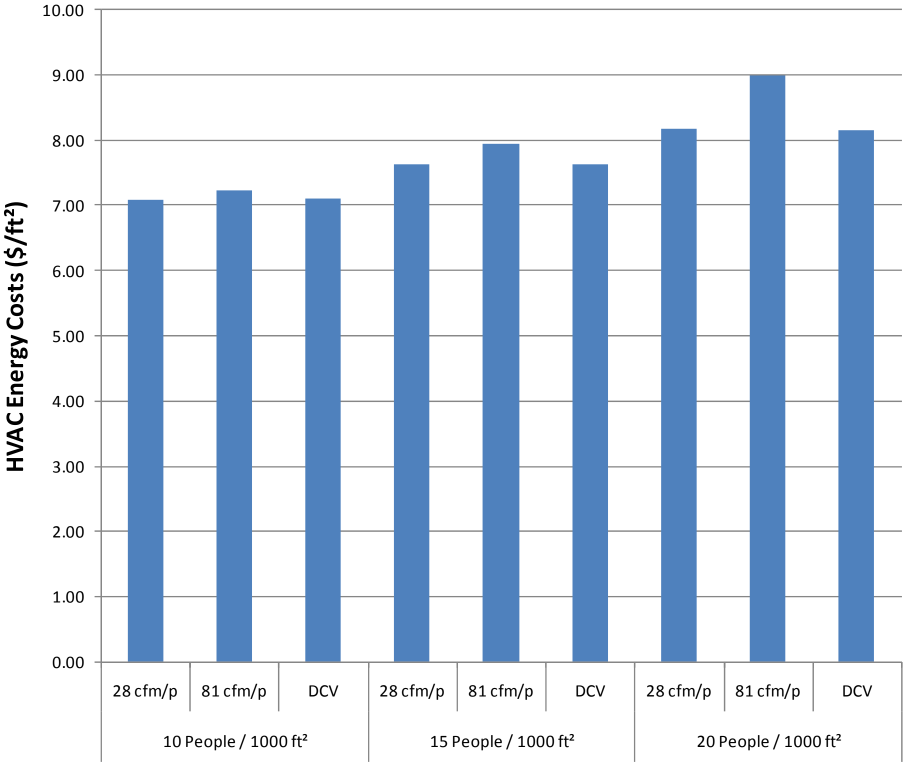

Figure 3 – HVAC Energy Costs (PV $/ft$^2$), Climate Zone 6

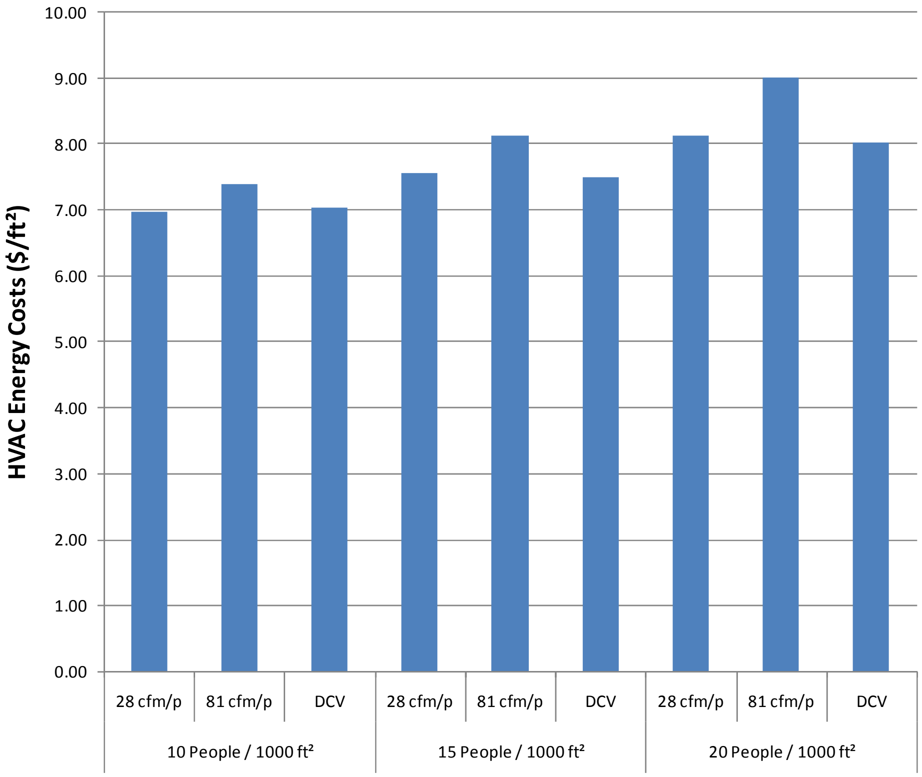

Figure 4 – HVAC Energy Costs (PV $/ft$^2$), Climate Zone 12

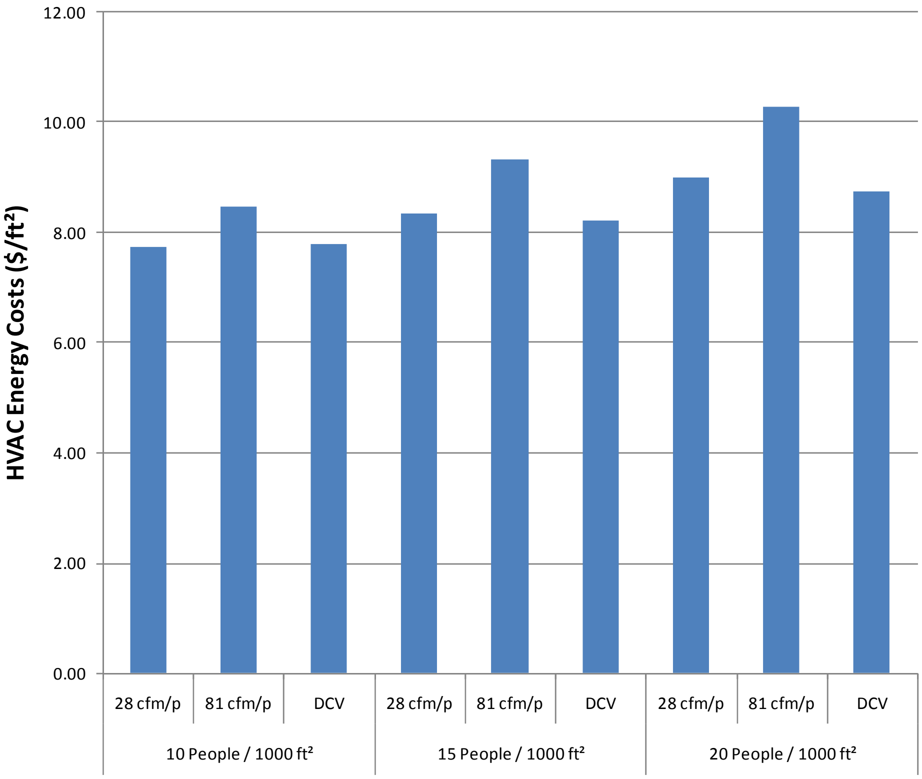

Figure 5 – HVAC Energy Costs (PV $/ft$^2$), Climate Zone 14

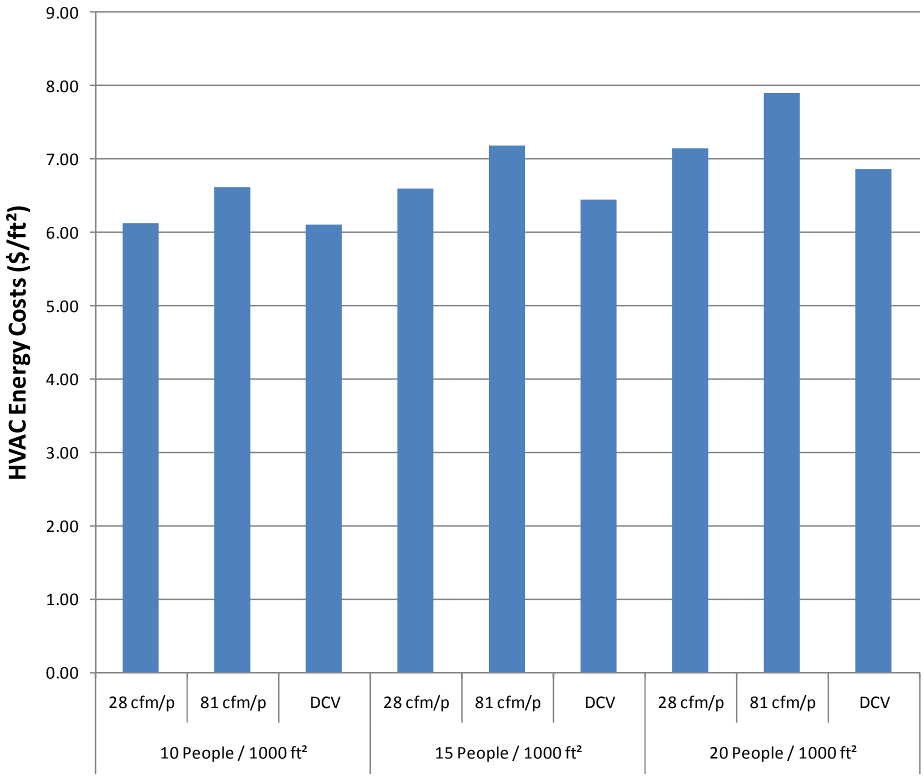

Figure 6 – HVAC Energy Costs (PV $/ft$^2$), Climate Zone 16

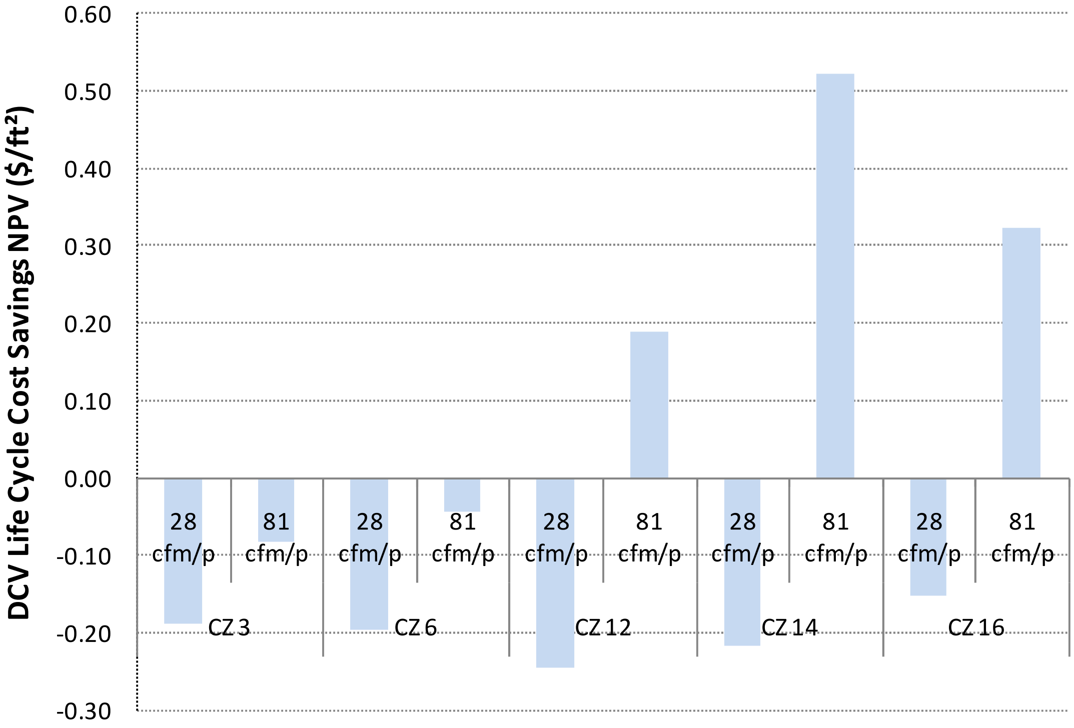

Figure 7 – DCV Life Cycle Cost Savings (NPV $/ft$^2$) at 10 People / 1000 ft$^2$

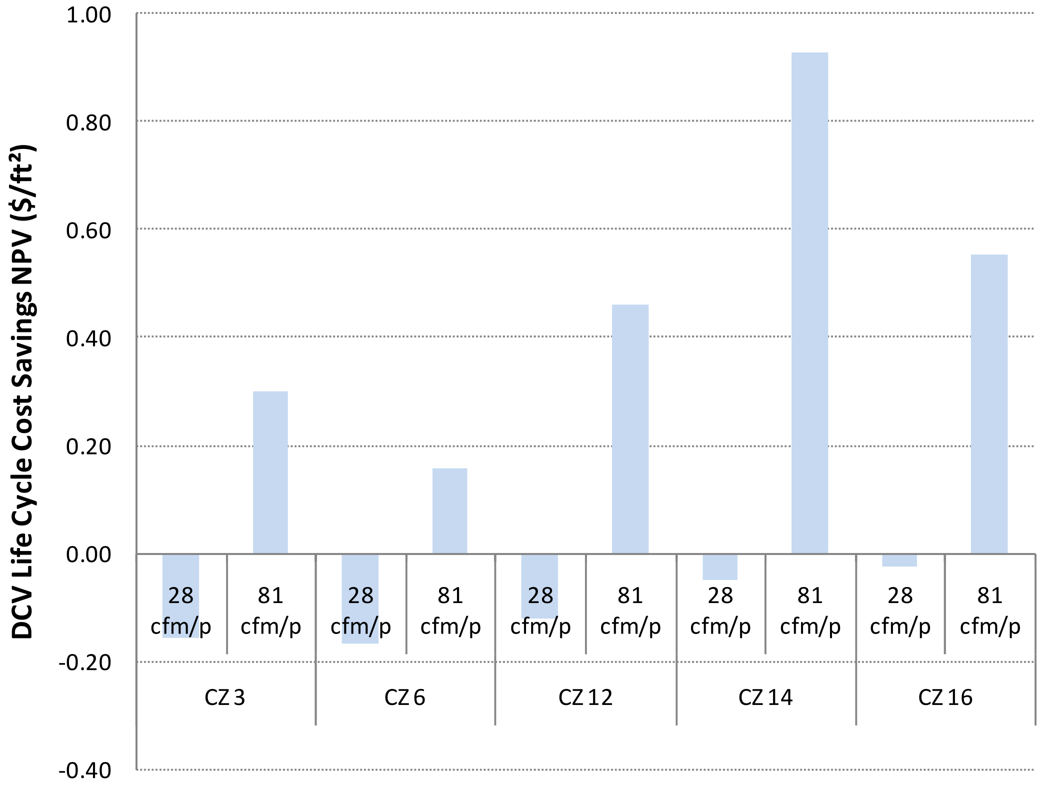

Figure 8 – DCV Life Cycle Cost Savings (NPV $/ft$^2$) at 15 People / 1000 ft$^2$

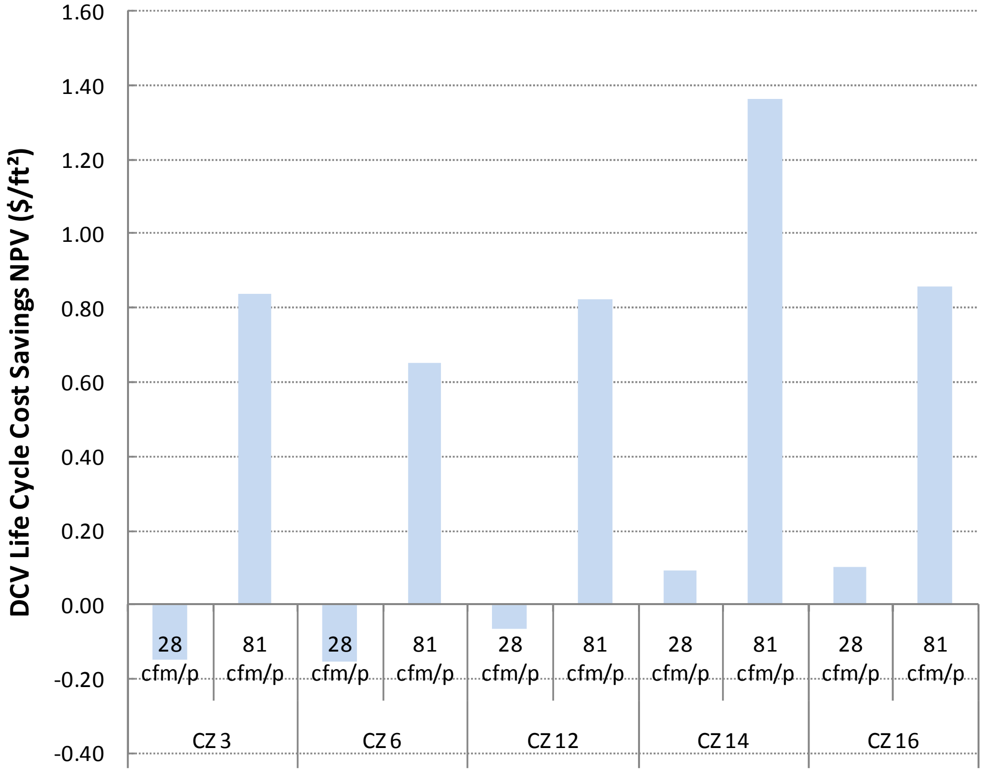

Figure 9 – DCV Life Cycle Cost Savings (NPV $/ft$^2$) at 20 People / 1000 ft$^2$

From Figures 7 to 9, it can be seen that with the reference design outdoor ventilation rate of 28 cfm/person, only for climate zones 14 and 16 do the calculations indicate a marginal life cycle cost savings for DCV when the design occupancy is at 20 people / 1000 ft$^2$. This is probably due to the fact that the DCV cases have higher design ventilation rates than the cases without DCV at a fixed ventilation rate of 28 cfm/person for all three occupant density levels. For the base case, fixed ventilation rate of 81 cfm/person, the without-DCV cases always have higher ventilation rates than the DCV cases for all three occupant density levels.

From Figure 7 at design occupancy of 10 people per 1000 ft$^2$, DCV is cost effective (positive NPV savings) compared with the fixed outdoor ventilation rate of 81 cfm/person for climate zones 12, 14, and 16. The largest estimated savings is \$0.52/ft$^2$ in climate zone 14, followed by \$0.32/ft$^2$ in climate zone 16, and \$0.19/ft$^2$ in climate zone 12.

From Figure 8 at design occupancy of 15 people per 1000 ft$^2$, DCV is cost effective compared with the fixed outdoor ventilation rate of 81 cfm/person in all five climate zones, with the largest savings of NPV \$0.93/ft$^2$ in climate zone 14, followed by \$0.55/ft$^2$ in climate zone 16, \$0.46/ft$^2$ in climate zone 12, \$0.30/ft$^2$ in climate zone 3, and \$0.16/ft$^2$ in climate zone 6. The savings are much higher than those at design occupancy of 10 people per 1000 ft$^2$.

From Figure 9 at design occupancy of 20 people per 1000 ft$^2$, DCV is cost effective except when compared with the fixed outdoor ventilation rate of 28 cfm/person at climate zones 3, 6, and 12. The largest savings compared with the fixed outdoor ventilation rate of 81 cfm/person is NPV \$1.37/ft$^2$ in climate zone 14, followed by \$0.86/ft$^2$ in climate zone 16, \$0.84/ft$^2$ in climate zone 3, \$0.82/ft$^2$ in climate zone 12, \$0.65/ft$^2$ in climate zone 6. The savings are much higher than those at design occupancy of 15 people per 1000 ft$^2$.

The largest estimated DCV life cycle cost savings and energy savings occur for climate zone 14 --this is due to the significant heating demand in winter and cooling in summer. For cooling dominant climates like climate zone 6, the DCV savings mostly come from the reduction of outdoor air cooling during summer, while for heating dominant climates like climate zone 16, the DCV savings mostly come from the reduction of outdoor air heating during winter.

# 4.0 Discussion

This analysis has estimated the energy and life cycle cost impacts of using DCV in general office spaces in various California climate zones. For reference, when DCV was not employed the fixed minimum outdoor air ventilation rate was assumed to equal either 28 or 81 cfm per occupant. Three design occupant densities were employed; however, per the occupancy schedule in Table 3, the actual peak occupant density was only 65% of the design occupant density. The analyses indicate the potential for significant energy and life-cycle cost savings from DCV in general office spaces if the base case fixed ventilation rate without DCV is 81 cfm per occupant. While this ventilation rate comes from measured survey data, a much lower rate of 28 cfm/occupant is derived from the same survey based on application of a different measurement method. With this lower reference ventilation rate, the modeling indicates that DCV is not cost effective except in the most severe California climates and in buildings with a high design occupant density of 20 persons per 1000 $ft^2$. Unfortunately, it is not known which of these estimates of base case ventilation rates without DCV is more accurate. Also, the survey that yielded the ventilation rate data is from buildings throughout the U.S., while data from a representative survey of California office buildings would serve as a better reference.

While the main source of uncertainty is the uncertain base case ventilation rate as described above, other sources of uncertainty should be mentioned. The analysis was performed for only a single office building prototype and results would vary somewhat with building size and features. DCV capital costs and future energy costs are uncertain. Also, the EnergyPlus program used for the modeling bases the ventilation rates in buildings with DCV on the number of occupants present in the building while actual DCV systems respond to the indoor concentration of occupant-generated $CO_2$ which lags in time behind occupancy. The projected energy savings would be larger, but probably only modestly larger, if EnergyPlus modeled DCV based on occupant-generated $CO_2$.

# 5.0 Conclusions

DCV in general office spaces is expected to save significant energy and be cost effective only if typical ventilation rates without DCV are very high relative to the minimum rate required in codes. Until the large uncertainties about ventilation rates without DCV are reduced, the case for requiring DCV in general office spaces will be a weak case.

# 6.0. Acknowledgments

The authors thank Brad Meister at the California Energy Commission for contract management, Mark Hydeman and Steve Taylor at Taylor Engineering for providing cost data for the demand control ventilation systems and Mike Sohn and Fred Buhl from Lawrence Berkeley National Laboratory for reviewing a draft of this report..

# 7.0 References

1. ASHRAE. ASHRAE Standard 62.1-2007 Ventilation for acceptable indoor air quality. 2007. American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta.
2. California Energy Commission. California building energy efficiency standards for residential and nonresidential buildings. CEC-400-2008-01-CMF, December 2008.
3. Deru M. and Torcellini P. Source Energy and Emission Factors for Energy Use in Buildings. Technical report NREL/TP-550-38617, June 2007.
4. Eley Associates and New Building Institute. Utility Cost Forecasts: Years 2005 through 2035. February 2002.
5. Persily, A.K. and Gorfain J., Analysis of ventilation data from the U.S. Environmental Protection Agency Building Assessment Survey and Evaluation (BASE) Study, NISTIR-7145-Revised. 2008, National Institute for Standards and Technology: Bethesda. MD.
6. Taylor Engineering. Demand controlled ventilation – measure analysis for Title 24-2005. 2002.
7. Torcellini P., Deru M., Griffith B., Benne K., Halverson M., Winiarski D., Crawley D. DOE commercial building benchmark models. 2008 ACEEE Summer Study on Energy Efficiency in Buildings. Conference paper NREL/CP-550-43291, July 2008.
8. Seppanen O. and Fisk W.J. Association of ventilation system type with SBS symptoms in office workers. Indoor Air 12(2): 98-112, 2002.