A FRAMEWORK FOR ESTIMATING THE POTENTIAL ENERGY SAVINGS OF NATURAL VENTILATION RETROFITS FOR CALIFORNIA COMMERCIAL BUILDINGS

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ABSTRACT

This paper proposes an approach for estimating the potential energy savings of retrofitting existing commercial buildings in California for natural ventilation. 308 baseline commercial building models are developed in EnergyPlus based on a characterization of the existing California commercial building stock. Each baseline model and five retrofit options are simulated in the 16 California Climate Zones using TMY3 weather files and energy savings are calculated. Building weights are developed and applied to expand the estimated energy savings to the statewide level. Based on the findings, recommendations will be made to assist policy makers, building designers and owners in making informed decisions regarding the efficacy of natural ventilation retrofits.

INTRODUCTION

Background

Retrofitting existing commercial buildings with natural ventilation systems offers the prospect of large savings in energy consumption for commercial buildings in California. These savings, and the consequent reduction in greenhouse gas emissions, are a critical component of California's strategy to meet the reductions mandated by state legislation

A methodology has been developed to estimate the contribution natural ventilation retrofits can make towards meeting the emissions reductions mandated by Assembly Bill 32 (AB 32), the Global Warming Solutions Act, and to meeting the goal of 50% energy savings for existing commercial buildings by 2030, as stipulated in the California Public Utilities Commission's (CPUC) Energy Efficiency Strategic Plan (CPUC 2008). This approach seeks to answer the question: how aggressive would these retrofits for natural ventilation have to be to achieve energy savings on the order of the CPUC's goal of 50%. Answering this question involves investigating a range of retrofit scenarios some of which are not common or cost effective, but might be necessary to reach significant savings. The most basic natural ventilation retrofit scenario examined is the installation of operable windows on the facade to allow wind driven ventilation of the interior. More intensive options are a system control retrofit that allows the building's energy management system to manage a changeover mixed mode strategy, or the installation of a thin radiant topping slab over the existing concrete slab to provide low energy cooling.

Development of Building Models

The Department of Energy has sponsored the development of commercial reference building models in EnergyPlus to be used for assessing building technologies and developing energy codes and standards (Deru *et al.* 2011). These sixteen commercial building prototypes are designed to be representative of approximately two thirds of the US commercial building stock, as reported in the Commercial Buildings Energy Consumption Survey (CBECS) database. Pacific Northwest National Laboratory (PNNL) has used the commercial reference building models to estimate national energy savings associated with the new ASHRAE Standard 90.1-2010 (Thorton *et al.* 2011). Building on the PNNL approach, our methodology for estimating the potential energy savings of natural ventilation retrofits in California commercial buildings uses EnergyPlus and the DOE commercial reference building models but involves significant modification of the models to represent the particular characteristics of the existing commercial building stock in California.

Development of Baseline Building Models for California

Of the sixteen DOE commercial reference building types, eleven were selected for modeling based on potential for natural ventilation (Table 1). These eleven models were modified to be more representative of the existing California commercial building stock, based on data from the California Commercial End-Use Survey (CEUS) and other sources. The CEUS database contains detailed information on 2,703 California commercial buildings including data on construction types, mechanical systems, age, location, and energy consumption (CEC 2006). Building survey data from CEUS were first categorized by building type, location (climate region) and vintage (Table 1).

Because our approach relied on the data in the CEUS database, it was subject to certain limitations of this database. There are two major limitations of the CEUS database that affect the scope of our methodology. First, because the CEUS survey was conducted from 2002 through 2006 the database is limited to buildings constructed in or before 2003. This limits our study to buildings constructed before 2003. The second limitation of the CEUS database is that, to protect the identity of buildings in CEUS, location data was limited to large climate regions, i.e. aggregated versions of the climate zones defined for use in California's Building Energy Efficiency Standards, commonly referred to as Title 24 (CEC 2008). Figure 1 shows the geographical distribution of these aggregated climate regions.

Figure 1: Map of the aggregated California climate regions

Characteristics relating to building form, fabric, program and equipment were identified for each unique category of building type, climate region and vintage. Unique baseline building models were then developed for each of these building categories, resulting in 308 baseline models. Table 2 shows the source of each building model input.

The CEUS database provides both numerical variables (e.g. window-to-wall ratio) and categorical variables (e.g. glazing type and wall construction type) which were used to inform building model inputs. For numerical variables, model inputs were calculated for each building type using the mean of the numerical variable, weighted by floor area, for all representative buildings in the CEUS database. For categorical variables, the statistical mode of that categorical variable, weighted by floor area, was used. Further description of each building model input is provided in the following subsections.

Table 1: Building model categories

CLIMATE REGION	BUILDING TYPE	VINTAGE
North Coast	Large office	Pre 1941
Central Valley	Medium office	1941-1978
Mountains	Small office	1979-1990
Desert	Large hotel	1991-2003
Central Coast	Small hotel	
South Coast	Stand-alone retail	
South Inland	Strip mall	
	Outpatient Healthcare	
	Warehouse	
	Primary school	
	Secondary school	

Form

The floor area and aspect ratio of each building model is the same as its corresponding DOE commercial reference building model.

Wind pressure coefficients for our modeled buildings were derived from full scale and atmospheric boundary layer wind tunnel tests of generic buildings (Banks et al, 2012, Lo 2012). Wind pressure coefficients were developed that allow the multi-zone airflow model in EnergyPlus to approximate the measured ventilation behavior. In some situations, such as single-sided ventilation, these pressure coefficients were used in the place of the actual mean pressure coefficients, since these did not differ significantly between window locations. Reduced ventilation rates due to the sheltering of nearby buildings were also reflected in the pressure coefficient assumptions.

Fabric

The window, wall, floor and roof construction materials were determined from the CEUS database. The thickness of the insulation was then varied to match the minimum U-value from the relevant year of Title 24 Standard.

The EnergyPlus Airflow Network *Detailed Opening* was used to model operable windows. Occupant use of the windows was modeled using a stochastic model of window use (Rijal 2007). Rijal's model provides a prediction of window use behavior based on studies of measured window use in several naturally ventilated office buildings. This model uses indoor operative temperature and outdoor air temperature to determine the probability of a window being opened or closed.

The model was implemented in EnergyPlus using the Energy Management System module (EMS). This window opening model, though it is based on measured data in office buildings, is applied to all building types because similar window opening behavior models do not exist for the other buildings types.

Unintentional infiltration through the building façade was modeled by specifying an effective leakage area for each building surface. Air tightness values for infiltration were obtained from a report by Persily and Ivy (2001) that gives mean values for the effective leakage area of the envelopes of different building types. The same effective leakage area was applied to all vintages of each building type based on previous research by Persily (1998) that suggests that there is no correlation between building age and air tightness.

Program

The relevant year of Title 24 Standard is used as the source for lighting and occupancy densities, plug and process loads, minimum ventilation rates, and hot water demand for all building models.

Equipment

Three versions of each of the sixteen DOE commercial reference building models were previously developed to account for variations based on the age of existing building stock: new construction, post-1980 construction, and pre-1980 construction. The HVAC equipment types and efficiencies for each version are based on the minimum requirements of ANSI/ASHRAE/IESNA Standard 90.1-2004 for new construction, ASHRAE Standard 90.1-1989 for post-1980 construction, and an analysis of historical equipment efficiencies for pre-1980 construction (Deru et al. 2011).

HVAC system types and efficiencies for all four CEUS vintages were modeled using those defined in the post-1980 construction versions of the DOE reference building models for the following two reasons. First, the two most recent vintages, 1979-1990 and 1991-2003, are well represented, as an average, by Standard 90.1-1989. The next ASHRAE Standard 90.1 was not released until 2001, so most of the buildings constructed between 1990 and 2003 were built to the 1989 standard. Buildings built from 1979-1990 were mostly built under previous, less stringent standards. Applying the 1989 standard to the buildings built in this earlier era will lead to a conservative estimate for energy savings for this particular vintage.

Second, the two oldest vintages, pre-1941 and 1941-1978, likely do not contain their original equipment and possibly have had comprehensive upgrades that involve changing systems types (i.e. converting from CAV to VAV). When considering expected equipment life, it is reasonable to assume that buildings constructed before 1979 would have undergone at least one major HVAC equipment retrofit. Depending on the age and use of the building, and when the retrofit took place, system types and equipment efficiencies may vary significantly. The post-1980 construction versions were therefore seen as a good middle-of-the-road representation for this large source of variation in potential performance.

Table 2: Sources for building model inputs

BUILDING MODEL INPUT CATEGORY	BUILDING MODEL INPUT	SOURCE
Form	Window to wall ratio Orientation	CEUS
	Floor area Aspect ratio	DOE building models
	Wind pressure coefficients	Wind tunnel testing (Banks et al 2012, Lo 2012)
Fabric	Glazing type Wall, floor and roof construction types	CEUS
	Wall, floor, roof and window constructions	Title 24 Standard
	Envelope air tightness	Measured data (Persily 2001)
	Window opening behavior model	Measured data (Rijal 2007)
Program	Lighting density Occupant density Plug and process loads Ventilation rates Hot water demand Operating schedules and setpoints	Title 24 Standard
Equipment	HVAC equipment Hot water equipment Refrigeration equipment	Post-1980 DOE building models

Development of Retrofit Building Models

Determining which building retrofit scenarios to model for this project was challenging. The selected set was chosen based on consultation with industry engineers and literature review of relevant research. While many valid, cost-effective options are excluded from the study, the options selected are meant to represent a range of aggressive yet realistic technologies. Some of these technologies, though they might not be cost-effective right now, may nonetheless be necessary to reach the CPUC's goal of 50% energy savings for commercial buildings.

McConehey (2008) gives guidelines for solar and internal gain limits for naturally ventilated and mixed mode buildings. In this project, it is assumed that all existing buildings will undergo energy efficiency retrofits to meet these guidelines.

Additionally, it is assumed that HVAC systems will be commissioned before the natural ventilation retrofit. The HVAC commissioning will involve control improvements and equipment upgrades which vary by system type and were determined through consultation with industry engineers.

In order to isolate the energy savings of the energy efficiency measures from the energy savings of natural ventilation, it is necessary to simulate three different baseline models. The first baseline model represents existing buildings. The second represents existing buildings having undergone non-HVAC energy efficiency retrofits. The third baseline represents existing buildings having undergone both HVAC and non-HVAC retrofits. All three baseline models have non-operable windows.

In addition to the three baseline models, three different mixed mode retrofit scenarios combining natural ventilation with mechanical cooling and/or ventilation were simulated. Every mixed mode scenario includes both the non-HVAC and HVAC energy efficiency measures. The mixed mode models all have operable windows but they differ in HVAC control strategies and HVAC system type.

In total there are 6 scenarios listed for each building model: one baseline and five retrofit variations. They are listed below, in order of increasing intensity of retrofit, and described in the subsequent subsections.

A. Baseline
B. Baseline with non-HVAC energy efficiency measures
C. Baseline with non-HVAC energy efficiency measures and optimized HVAC
D. Mixed mode: operable windows with concurrent control
E. Mixed mode: operable windows with changeover control
F. Mixed mode: operable windows with radiant slab system

<u>Baseline</u>

The baseline model represents existing buildings. All model inputs are determined as described in Table 2.

<u>Baseline with non-HVAC energy efficiency measures</u>

Cooling loads were reduced through improved windows, reduced internal loads, overhangs, and other measures, including ceiling fans. The combination of measures selected depends on building type.

<u>Baseline with non-HVAC energy efficiency measures and optimized HVAC</u>

An HVAC retrofit was added to the second baseline. The details of the HVAC retrofit measures differ based on system type. In the case of a variable air volume (VAV) system, the VAV system has increased turn-down on the terminal boxes (down to 10% flow rate), near-optimal supply air temperature reset control, fan static pressure reset control, and mechanical ventilation at night for pre-cooling.

<u>Mixed mode: operable windows with concurrent control</u>

Operable windows were installed. Remodeling of the interior to maximize the fraction of the occupied floor area that can be naturally ventilated was assumed. The system controls remain the same as the baseline models, with concurrent control involving signaling to occupants when it is advantageous to open the windows, e.g. with a red light / green light system. When it is advantageous for occupants to open windows, the window opening behavior model of Rijal (2007) is used, otherwise the windows are closed.

In the case of VAV systems, if the natural ventilation meets the cooling load, as it would be expected to do, the VAV system flow rate turns down to its minimum value, reducing fan energy consumption and the supply air temperature is reset to its maximum value, removing the need for chiller operation.

<u>Mixed mode: operable windows with changeover control</u>

A control system retrofit was modeled that allows for a changeover control strategy. Changeover control involves an interlock between the operable windows and the HVAC system such that the HVAC system does not supply air to the space when the windows are open. The same window opening behavior model mentioned above was used during all occupied hours to define the window opening status.

<u>Mixed mode: operable windows with radiant slab system</u>

Operable windows were installed and a radiant topping slab added on to the existing concrete slab. The radiant slab retrofit was based on a thin, lightweight concrete topping slab installed in a 30,000 ft^2 office building in San Francisco, as described by Bourne *et al.* (2000). The VAV system was removed, and minimum outside air was provided by a Dedicated Outdoor Air System

(DOAS) serving the core zones. Natural ventilation provides comfort cooling when possible and also provides the minimum fresh air required in zones within 20ft of the perimeter. The radiant slab is pre-cooled at night using chilled water directly from an evaporative cooling tower. The use of a cooling tower at night, when the wet bulb temperature is at its lowest, allows the radiant cooling system to operate at its peak efficiency, providing cooling at its lowest unit energy cost. The concrete floor slab is pre-cooled at night when cooling was needed during the preceding day according to the adaptive thermal comfort model of ASHRAE Standard 55.

Climate and Weather Files

Natural ventilation energy savings potential is highly dependent on the suitability of the climate for such systems. Buildings were therefore simulated in all sixteen of the California Climate Zones defined for use in Title 24. Figure 2 shows the geographical distribution of the California Climate Zones. The 308 California baseline building models were simulated using their corresponding California Climate Zone TMY3 weather file.

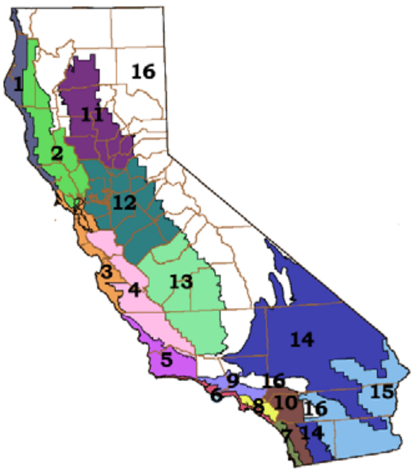

Figure 2: Map of the California Climate Zones

EXPANDING RESULTS

Estimating Statewide Energy Savings from Building Models

An approach was developed to expand the results from the individual California building models to an estimate for statewide energy savings. A recent report from Pacific Northwest National Laboratory presents their methodology for using the DOE commercial building prototypes and statistical weights based on national disaggregated construction volume data to estimate national energy savings associated with the new ASHRAE Standard 90.1-2010 (Thorton *et al.* 2011). Our approach borrows from their methods, but we base our weights on the statewide disaggregated energy data publically available in the CEUS Consultant Report (Pigeon-Bergmann *et al.* 2006) and the energy data in the CEUS database (CEC 2006). The CEUS Consultant Report dataset contains statewide annual electricity use for the year 2002 disaggregated by building type, size and location. For example, it indicates that all the large offices in Forecasting Climate Zone 6, which corresponds roughly with the city of Sacramento (Figure 3), used 885,104,047 kWh of electricity in 2002.

Mapping CEUS Buildings to DOE Commercial Building Prototypes

To develop weights for each California baseline building model, we first mapped the CEUS building categories onto the most closely corresponding DOE commercial building prototypes. This involved assigning each CEUS building usage to a DOE commercial building prototype based on building type and size, as presented in Table 3.

Not all building usage categories included in the CEUS survey are included in our analysis (Figure 4). Some buildings (hospitals, restaurants, data centers, etc.) have ventilation and / or cooling requirements that would prohibit natural ventilation. The miscellaneous building category was too diverse to include in this study. Colleges were censored from the version of the CEUS database that our team received from the California Energy Commission to protect their anonymity.

Figure 4 shows that the modeled buildings capture roughly 55% of total building energy use in CEUS.

Climate Zones

In order to estimate potential energy savings for the entire state of California, with its varying climates, it is important to understand the distribution of energy use by climate zone.

Energy use information in the CEUS Consultant Report is tied to the Forecasting Climate Zones. The Forecasting Climate Zones were developed for utility forecasting and their boundaries are determined by utility service areas. Figure 3 shows that the Forecasting Climate Zone borders sacrifice climatic similarity to maintain the utility service boundaries (e.g. Forecasting Climate Zone 1).

Table 3: Mapping of CEUS building types to DOE reference building models

CEUS		DOE
Building type	**Building usage**	**Reference building model name**
Small & large Office	Administration and management Assorted/multi-tenant Financial/legal Government services Insurance/real estate Medical/dental office Other office Software development	Small office (0-10,000 ft^2) Medium office (10,000-200,000 ft^2) Large office (>200,000 ft^2)
Retail	Shop in enclosed mall Shop in strip mall	Strip mall
	Auto sales Department/variety store Other retail store Retail warehouse/clubs	Stand-alone retail
Food store	Convenience store Liquor store Other food store Small general grocery Specialty/ethnic grocery	
Unrefrigerated warehouse	Conditioned warehouse, high bay Conditioned warehouse, low bay Unconditioned warehouse, high bay Unconditioned warehouse, low bay	Warehouse
School	Daycare or preschool Elementary school	Primary school
	Middle/secondary school	Secondary school
Health	Clinic/outpatient care Medical/dental lab Nursing home	Outpatient healthcare
Lodging	Hotel Motel Other lodging Resort	Small hotel (<75,000 ft^2) Large hotel (>75,000 ft^2)

The 16 California Climate Zones, depicted in Figure 2, are generally recognized as a better representation of climatic similarity than the Forecasting Climate Zones. Furthermore, each California Climate Zone has a representative city with an associated TMY3 weather file which provides sufficient climatic data for our simulations.

Weights for the California Baseline Building Models

Annual statewide energy use data in the CEUS Consultant Report is categorized by CEUS building type, size and Forecasting Climate Zone. By contrast, our building models are categorized by DOE reference model type and vintage and simulated using Title 24 specific TMY3 weather files. Weights were calculated using the energy data from both the CEUS Consultant Report and the CEUS database to expand the energy use of the building models up to statewide energy use.

The calculation of these weights required knowledge of the California Climate Zone and Forecasting Climate Zone of each building in the CEUS database. Because our non-confidential version of the database does not contain this detailed location data, the calculation of the building weights was performed by collaborators from the California Energy Commission. They provided us with 308 building weights, one for each California baseline building model.

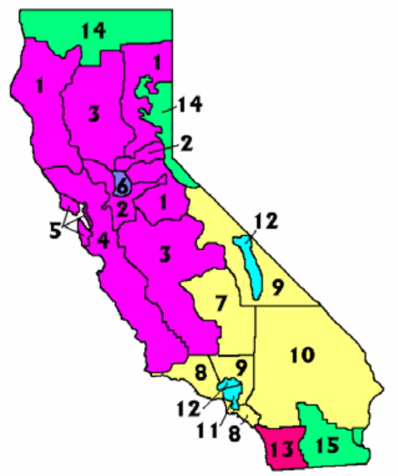

Figure 3: Map of the Forecasting Climate Zones

Applying Weights and Estimating Savings

Each building weight, when multiplied by the energy use of its corresponding baseline model, gives the statewide energy use for all the existing buildings that baseline model represents. The estimated energy savings from a particular retrofit option can then be calculated by taking the weighted difference of the baseline model and the retrofit model, as represented by the following equation:

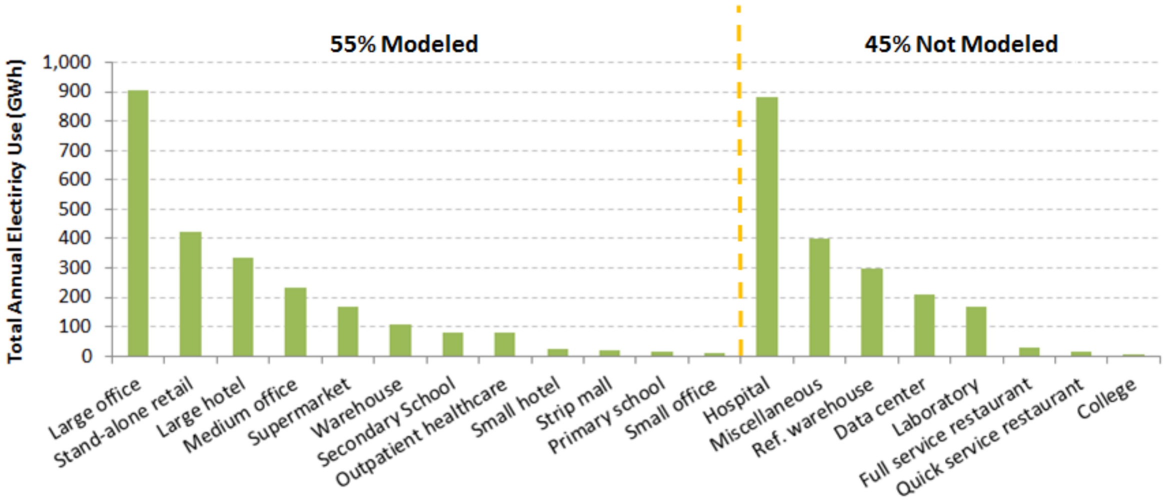

Figure 4: Total annual energy use from the CEUS database (n=2704)

$$\omega_n \times \Delta e_{n,m} = \Delta E_{n,m}$$

Where,

ω_n = the weight for the *n*th baseline model (dimensionless)

$\Delta e_{n,m} = e_{n,b} - e_{n,m}$

$e_{n,b}$ = the energy use of the *n*th baseline model (kWh)

$e_{n,m}$ = the energy use of the *m*th retrofit option of the nth baseline model (kWh)

$\Delta E_{i,j}$ = the total estimated energy savings due to performing the *m*th retrofit option on all buildings in California represented by the *n*th baseline model (kWh)

This equation can be used to estimate, for example, the energy savings from optimizing existing VAV systems and installing operable windows and non-HVAC energy efficiency measures in all large offices built from 1941-1978 in California Climate Zone 12.

The total estimated statewide savings due to a particular retrofit is calculated according to:

$$S_m = \sum_{n=1}^{308} \Delta E_{n,m}$$

Where,

S_m = the total estimated statewide savings in all California commercial buildings due to the implementation of the *m*th retrofit option.

Uncertainty Analysis

The end goal of the methodology outlined in this report is ambitious. It requires a complex approach involving many elements that will contribute to uncertainty in the energy savings estimate. Each of the building model inputs listed in Table 2 has a level of uncertainty associated with it. In order to put a bound on the level of uncertainty due to building model inputs, a Monte Carlo experiment will be performed. The results of the Monte Carlo analysis will be presented with the estimates for energy savings.

CONCLUSION

The state of California has set many aggressive energy and carbon reduction goals, including that by the California Public Utilities Commission of 50% energy savings in commercial buildings by 2030. Many of the climates in California seem well suited to save energy through natural ventilation. The methodology outlined in this paper will help to determine the extent that natural ventilation can contribute towards achieving these ambitious goals. For each commercial building type and vintage examined in each of the Title 24 climate zones, the approach will highlight the most cost-effective strategies for reducing energy consumption and carbon emissions. The methodology will also provide insight into which strategies, if any, will lead California's existing commercial buildings past 50% energy savings.

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