

# City-Scale Building Retrofit Analysis: A Case Study using CityBES

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## Abstract

This paper presents a case study using CityBES to analyze potential retrofit savings of different energy conservation measures for city-scale building stocks. CityBES is a web-based tool designed to support city-scale building energy efficiency, including currently implemented features of energy retrofit analysis, and visualization of city building energy disclosure datasets. This case study uses CityBES to evaluate five common retrofit measures for 540 small and medium-sized office and retail buildings in downtown San Francisco. The results show: (1) all five measures together can save 22-48% of site energy per building, (2) replacing lighting with LED lights and adding air economizers to existing HVAC systems are most cost-effective, (3) the payback is long for upgrading HVAC systems due to the mild climate of San Francisco that does not have much cooling or heating loads.

## Introduction

Buildings in cities consume 30 to 70% of the cities' total primary energy (Natural Resources Defense Council and Institute for Market Transformation, 2017). Retrofitting the existing building stock to improve energy efficiency and reduce energy use is a key strategy for cities to reduce green-house-gas emissions and mitigate climate change. Many cities, states and utilities provide rebates and incentives to support building retrofits. San Francisco (SF) Energy Watch program (SF Environment, 2016), supported by PG&E, offers incentives to commercial and multifamily buildings for energy efficiency upgrades to lighting, refrigeration equipment and controls, network level computer power management software, etc. New York State Energy Research and Development Authority (NYSERDA, 2016) provides financial support for Commercial Real Time Energy Management (RTEM) system implementation and services for up to five years. Florida Public Utilities (FPU, 2016) offers commercial electric rebates for businesses to help offset the cost of making energy-efficiency upgrades to chillers, reflective roof, air conditioner replacement, etc. Illinois Energy Now (Illinois Energy Now, 2016) Standard Incentive Program provides incentives for common retrofit of lighting, variable speed drives for HVAC equipment, demand-controlled ventilation, boilers, and furnaces. Those rebate and incentive programs were designed based

on city building stock characteristics as well as their climate conditions.

It is critical for city managers to have tool to evaluate and prioritize energy conservation measures (ECMs) for the cities-scale analysis so they can design the rebates and incentives accordingly. Reinhart and Davila (Reinhart & Davila, 2016) reviewed emerging simulation methods and implementation workflows for bottom-up urban building energy models. They found that significant progress had recently been made towards the development of simulation workflows to estimate overall operational building energy use across neighborhoods. However, these analyses require a significant amount of effort to set up and run the models. Recently, Hong et al. (Hong, Chen, Lee, & Piette, 2016) introduced CityBES, City Building Energy Saver, a web-based platform for users to quickly set up and run city-scale building energy models to support city-scale building energy efficiency analysis. It uses the international standard CityGML (OGC, 2017) to represent the 3D building stock in cities, and uses EnergyPlus for detailed retrofit analysis of a wide array of building technologies. An initial release of CityBES with retrofit analysis feature is freely available for public use.

This paper presents a case study using the retrofit analysis feature of CityBES to evaluate the energy saving potential and cost effectiveness of individual ECMs as well as ECM packages for small and medium office and retail buildings in San Francisco.

## CityBES Overview

CityBES (LBNL, 2016) is a web-based platform developed by Lawrence Berkeley National Lab, USA. It is publicly available at <http://citybes.lbl.gov>, and provides a set of features to support building energy efficiency analyses including energy retrofit analysis, energy benchmarking, urban energy planning, and building operation improvements through data analytics (e.g., smart meter data analysis and load shape benchmarking).

*Figure 1* shows the software architecture and use cases of CityBES. It provides 3D visualization with geographical information system (GIS) as displayed in *Figure 2*, which also shows color-coded simulated energy performance of buildings in SF.

CityBES builds upon the Commercial Building Energy Saver Toolkit (CBES) (Hong et al., 2015), which provides energy retrofit analysis of individual commercial buildings of small and medium offices and retails. The

retrofit analysis features consider the energy saving potential of a city's building stock, from a small group of buildings in an urban district to all buildings in the entire city.

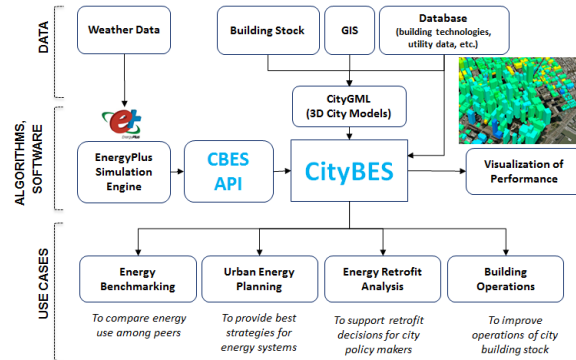


Figure 1. CityBES software architecture and use cases

CityBES integrates more than 75 ECMs from CBES, Commercial Building Energy Saver (cbes.lbl.gov, Hong et al., 2015). The ECM database includes a detailed description of the technical specifications, modeling methods and investment costs for each ECM. The measures and modeling of those building systems are systematically applied to the CityBES framework through EnergyPlus simulation for the city building stock retrofit analysis.

CityBES uses an international open data standard, CityGML, as the data schema to represent and exchange 3D city models. Alternatively, it also provides the feature for users to upload 2D building footprint in GeoJSON format, with additional properties of building height, number of stories, building type, and year of built for each building.

CityBES allows users to export the retrofit analysis results of each building to CSV format for further analysis. It also generates sub-hourly load profiles for each building to support the analysis of district energy systems.

## Case Study

This section provides a simple case study to demonstrate the use of CityBES for retrofit analysis. It includes ten steps: (1) select case study buildings, (2) obtain weather files, (3) prepare building data in CityGML format, (4) setup the case study buildings in CityBES, (5) define individual ECMs and ECM packages, (6) create energy models, (7) run simulation, (8) visualize retrofit analysis results, (9) export results to CSV file, and (10) perform retrofit analysis. Those steps are described in the following sections.

The case study is not designed to automatically select the ECMs and identify the optimal retrofit packages with various investment criteria (e.g., energy savings, energy cost savings, GHG reduction, and payback).

## Overview of the case study buildings

Currently, CBES supports analysis of small and medium-sized office and retail buildings in the U.S. We began our search of the data from San Francisco Property Information Map (San Francisco Planning Department, 2017), and found 3,866 commercial buildings with gross floor area less than 6,503 m<sup>2</sup> (70,000 ft<sup>2</sup>) in San Francisco. We selected downtown San Francisco with 540 small and medium-sized office and retail buildings for the retrofit analysis, and considered the shading effect from other 1,087 neighborhood buildings. Figure 3 shows the buildings color coded by their simulated site energy use intensity (EUI). Table 1 shows the summary of the 540



Figure 2. Screenshot of CityBES

selected buildings. They have a total floor area of 873,202 m<sup>2</sup> and use 186 GWh site energy annually.



Figure 3. 540 SMB office and retail buildings

Table 1. Summary of the selected buildings

Building Type	Building Count	Floor area (10 <sup>3</sup> m <sup>2</sup> )	Simulated annual site energy use (GWh)
Small office	143	152	28
Medium office	99	463	79
Small retail	233	120	38
Medium retail	65	138	41
<b>Total</b>	<b>540</b>	<b>873</b>	<b>186</b>

### San Francisco climate condition

San Francisco has a mild year-round climate (ASHRAE Climate Zone 3C) with moist winters and dry summers. It is strongly influenced by the cool currents of the Pacific Ocean on the west side of the city, and the water of SF Bay to the north and east. Temperatures reach or exceed 80 °F (27 °C) on an average of only 21 and 23 days a year at downtown and San Francisco International Airport (SFO), respectively. The dry period of May to October is mild to warm, with the normal monthly mean temperature peaking in September at 62.7 °F (17.1 °C). The rainy period of November to April is cooler, with the normal monthly mean temperature reaching its lowest in January at 51.3 °F (10.7 °C). On average, there are 73 rainy days a year, and annual precipitation averages 23.65 inches (601 mm) (Wikipedia, 2016).

### Prepare building data in CityGML format

Creating the building dataset is the first step for the city-scale retrofit analysis. For this case study, we collected the information from a range of sources to create the building dataset. Figure 4 shows the workflow to create the dataset. There are currently no unique identifiers for buildings in SF. The land use, assessor records, and energy disclosure databases use the assessor's parcel number (APN) as identifiers to store the building data. We merged the parcel-related data, and mapped them with the building footprint data to create a master building dataset with all of the fields from each dataset. Next, the master dataset was simplified and standardized to create 3D city models in CityGML, GeoJSON and File geodatabase (FileGDB) formats. GeoJSON is a data format based on

JSON for encoding a variety of geographic data structures (GeoJSON WG, 2017). FileGDB is a collection of binary files in a folder on disk that can store, query, and manage both spatial and nonspatial data, which can be used by ArcGIS 10 and above (GDAL, 2017). For CityBES retrofit analysis, the building footprint, year of built, building type, gross floor area, and number of stories for each building are required.

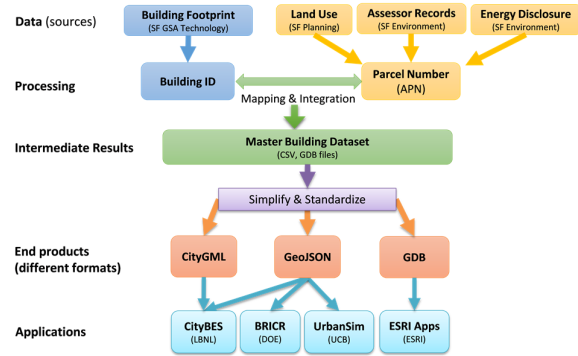


Figure 4. Creation of city building dataset for SF

### Setup the case study buildings in CityBES

The GeoJSON formatted building data were used to create the case study building dataset. Figure 5 shows the Building Dataset Manager in CityBES that we developed and used to setup the case study. We define a unique name for the building dataset, as well as the property names for the building characteristics. After the building dataset was created, it was added to the Building Dataset list on the Start page (Figure 6).

Figure 5. Manage Building Datasets in CityBES



CityBES
Introduction
Start
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# Start an Analysis

Please start an analysis by selecting a building dataset.

Building Datasets

San Francisco Downtown with 1627 Buildings
Please select a building dataset
San Francisco Downtown with 1627 Buildings
San Francisco Commercial Buildings Energy Performance Ordinance

Figure 6. Start an Analysis page of CityBES

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# Energy Conservation Measure (ECM) Packages

ECM Package 10

ID	ECM Category	ECM Name	
ECM 1	Lighting	Replace existing lighting with LED upgrade (0.6W/sf)	Delete
ECM 2	HVAC - Economizer	Add Economizer	Delete

Add an ECM

ECM Package 11

ID	ECM Category	ECM Name	
ECM 3	Lighting	Replace existing lighting with LED upgrade (0.6W/sf)	Delete
ECM 4	HVAC - Economizer	Add Economizer	Delete
ECM 5	HVAC - Heating	Gas Boiler Efficiency Upgrade (AFUE 95)	Delete
ECM 6	HVAC - Cooling	Packaged Rooftop VAV Unit Efficiency Upgrade (SEER 14)	Delete
ECM 7	Envelope - Window	Replace fixed-window to U-factor (0.25) and SHGC (0.18)	Delete

Add an ECM

Add an ECM Package

Figure 7. Define ECM and ECM packages in CityBES

### Define energy conservation measures

Five ECMs, commonly used in the U.S. commercial building retrofitting projects, were selected for the retrofit analysis as shown in Table 2. Within the five ECMs, three are HVAC measures covering efficiency of cooling and heating equipment as well as air-economizer; one is for lighting upgrade to LED; another one is replacement with high-performance windows. Two ECM packages were created by combining the five individual ECMs. One ECM package combined the LED and economizer measures, and the other ECM package combined all the five ECMs (Figure 7).

Table 2. Description of selected ECMs

Category	Name	Description
HVAC - Heating	Gas Boiler Upgrade (AFUE 95)	Replace existing heating system with high-efficiency gas boiler with an annual fuel utilization efficiency of 95 (AFUE 95)
HVAC - Cooling	Packaged Rooftop Unit Upgrade (SEER 14)	Replace RTU with a higher-efficiency unit with reheat, SEER 14. Cooling only includes standard controls, curb, and economizer.
Envelope - Window	Replace windows with U/SHGC (0.25/0.18)	Replace existing window glass and frame with high-performance windows (U-factor: 0.25 Btu/(h·ft <sup>2</sup> ·°F), SHGC: 0.18. SHGC and U-factor are 30% below Title 24 values.
HVAC - Economizer	Add Economizer	Install economizer for existing HVAC system (includes temperature sensors, damper motors, motor controls, and dampers).
Lighting	Replace lighting with LED (0.6 W/ ft <sup>2</sup> )	Replace existing lighting with LEDs at 6.5 W/m <sup>2</sup> [2.4 Btu/h/ft <sup>2</sup> ]. LEDs consume less power and last longer than fluorescent lamps.

### Create energy models

CityBES passes the high level inputs of building type, year built, and location to CBES, which then infers detailed building energy efficiency levels (e.g., insulation of envelope, lighting systems, HVAC systems and equipment efficiency) based on the local building energy code of that particular vintage. In the case of San Francisco, California's building energy code Title 24 applies. Finally one energy model is created for each building baseline as well as each ECM (individual or package).

### Run simulation

For each target building, we modeled the surrounding buildings as shading surfaces in EnergyPlus to consider the overshadowing impacts from the neighborhood (Figure 8). CityBES allows users to use the default EnergyPlus weather files, or to provide custom weather

files (Figure 10). For each building, we run eight EnergyPlus simulations: one for the baseline, five for the individual ECMs, and two for the ECM packages. This requires 4,320 EnergyPlus runs. The CityBES is hosted on a local server with 72 cores of 2.30 GHz CPU. CityBES provides a resource management feature to assign each EnergyPlus simulation to each core effectively. Users can leave the webpage while the simulations are running. A user-friendly progress bar provides a way to visualize the simulation progress.

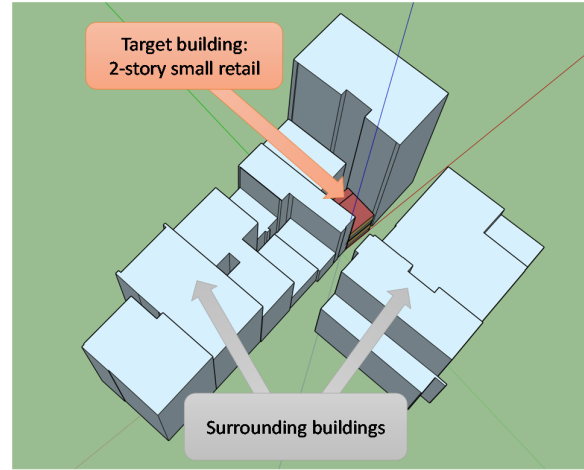


Figure 8. EnergyPlus model of each target building

### Visualize the results

CityBES provides a feature to color-code the buildings with the simulation results (Figure 9). It can show site EUI, source EUI, CO2 emission intensity, peak electricity load intensity, electricity use intensity, and natural gas use intensity of the baseline and retrofit results. It also displays the electricity cost savings, natural gas cost savings, total cost savings, investment cost, incentive amount, and the payback year of each retrofit scenario (Figure 12).

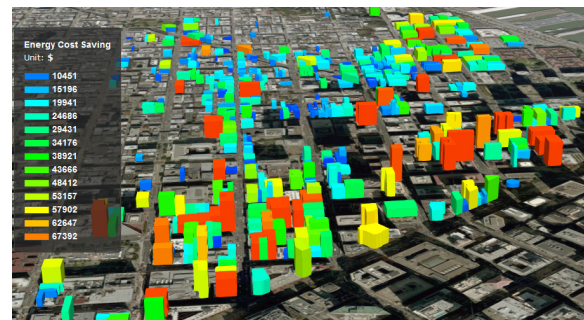


Figure 9. Color-coding the buildings with annual energy cost savings for all five ECMs together

CityBES

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## Simulation settings

Note: When the simulation is done, you can look at the results by color coding the buildings at the "District Buildings" tab.

A simulation for your session is running now. Please wait.

By default TMY3 weather file will be used in EnergyPlus simulations. Check the following box to choose a custom weather file.

☒ **Use custom EnergyPlus weather file**

Uploaded weather file:

USA\_CA\_San.Francisco.Intl.AP.724940\_TMY3.epw

Upload a new weather file:

No file chosen

The **Uploaded weather file** (EPW format) will be used in the analysis.  
If you would like to upload a new weather file (EPW format), please **Choose** the new EPW file and Click the **Upload selected EPW file** button.  
The file should have [EPW format](#).

Simulate

Simulation Status: 270/540 finished.  

50%

Figure 10. Simulation settings for the retrofit analysis

## Download retrofit analysis results

Download retrofit analysis results in CSV format

Note: The retrofit analysis results include the baseline results and retrofit savings of each retrofit scenario for each building. The baseline results include annual energy use intensity for site energy, source energy, electricity and natural gas, and the CO2 emission rate and peak electricity load. The retrofit results include the energy savings of each baseline results, as well as the investment cost, incentive amount and payback year for each retrofit scenario.

Figure 11. Download retrofit analysis results in CityBES

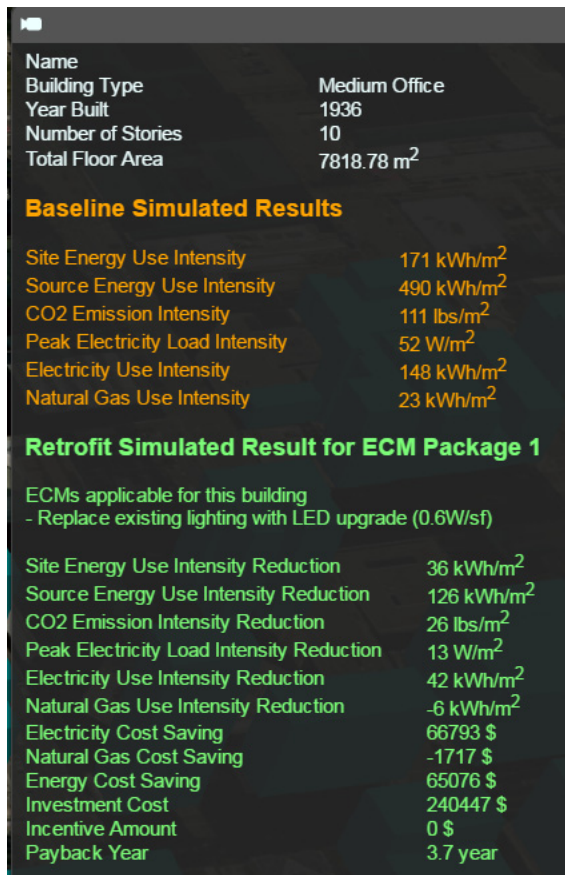


Figure 12. Simulation results of the baseline and one retrofit package for one building

### Export retrofit analysis results to CSV files

CityBES provides the function for users to download the retrofit analysis results in CSV format (Figure 11). It generates the results for each individual building, including the baseline and retrofit results.

### Detailed analysis of the retrofit results

After downloading the retrofit results in CSV format, we evaluate the energy saving potential of the individual ECMs as well as the ECM packages for the 540 buildings. Figure 13 shows the distribution of annual site energy saving percentage for the ECM package with all five ECMs. The result shows all five measures together can save 22-48% of site energy per building. Figures 14 to 16 show the annual site energy savings and CO<sub>2</sub> reduction per building type and simple payback year for the individual ECMs and ECM packages. The results indicate that replacing lighting with LEDs and adding air economizers are most cost effective measures. By contrast, the payback is long for upgrading HVAC systems due to the mild climate of SF. For SF, it is good to design a program to provide incentives and rebates for upgrading lighting to LED and adding economizer for existing HVAC systems. It should be pointed out that the payback years of some ECMs are beyond their lifespan

(e.g. gas boiler upgrade), which are not cost effective ECMs for San Francisco climate.

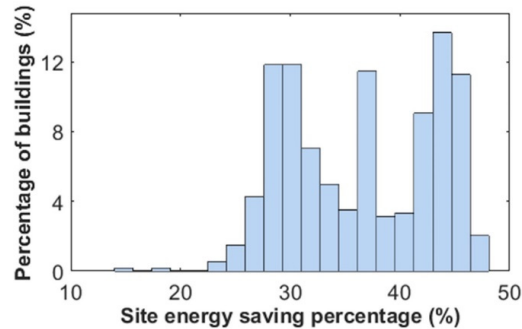


Figure 13. Distribution of site energy saving percentage for the ECM package with all five ECMs

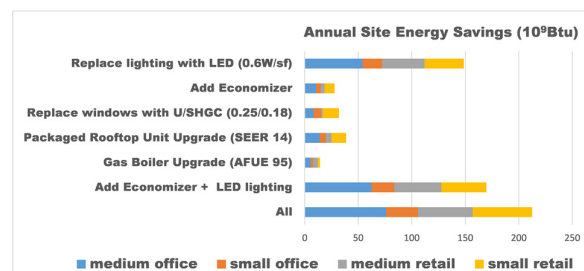


Figure 14. Annual site energy savings per building type for the individual ECMs and ECM packages

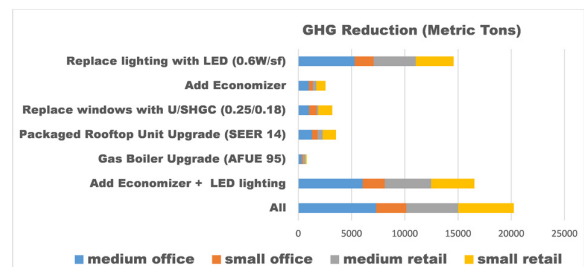


Figure 15. Annual CO<sub>2</sub> reduction per building type for the individual ECMs and ECM packages

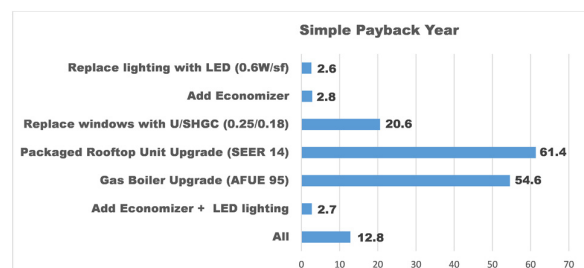


Figure 16. Simple payback year for the individual ECMs and ECM packages

## Discussion

The biggest challenge for the case study is to prepare the city building dataset in CityGML format with the required building characteristics information. The city building dataset includes other building types (e.g., large offices, hotels, hospitals) that are currently not supported by CBES. Several efforts are on-going to include these building types in CBES.

The city building dataset also includes measured annual energy data for some buildings via the SF energy ordinance program. CityBES is in the process of integrating the automatic model calibration (Sun et al., 2016) feature in CBES.

The city building dataset we consolidated includes all the 177,023 SF buildings. To perform retrofit analysis for all the SF buildings, it requires CityBES to leverage super computers (e.g., NERSC) for the EnergyPlus simulations. This is an on-going effort as part of the exascale computing project (exascaleproject.org) funded by United States Department of Energy's Office of Science.

## Conclusion

CityBES can provide analysis of city-scale building energy efficiency retrofits. This case study demonstrated the use of CityBES to select, evaluate and prioritize energy conservation measures for retrofitting a large number of buildings in cities. Consolidating city data into the international data standard CityGML is not only essential for the city-scale retrofit analysis, but also useful to avoid redundant work for future applications. More work is needed to explore how to provide these tools for city energy analysts and determine which features are most important.

## Acknowledgment

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