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Automatic Generation and Simulation of Urban Building Energy Models Based on City Datasets for City-Scale Building Retrofit Analysis

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Abstract

Buildings in cities consume 30% to 70% of total primary energy, and improving building energy efficiency is one of the key strategies towards sustainable urbanization. Urban building energy models (UBEM) can support city managers to evaluate and prioritize energy conservation measures (ECMs) for investment and the design of incentive and rebate programs. This paper presents the retrofit analysis feature of City Building Energy Saver (CityBES) to automatically generate and simulate UBEM using EnergyPlus based on cities' building datasets and user-selected ECMs. CityBES is a new open web-based tool to support city-scale building energy efficiency strategic plans and programs. The technical details of using CityBES for UBEM generation and simulation are introduced, including the workflow, key assumptions, and major databases. Also presented is a case study that analyzes the potential retrofit energy use and energy cost savings of five individual ECMs and two measure packages for 940 office and retail buildings in six city districts in northeast San Francisco, United States. The results show that: (1) all five measures together can save 23%-38% of site energy per building; (2) replacing lighting with light-emitting diode lamps and adding air economizers to existing heating, ventilation and air-conditioning (HVAC) systems are most cost-effective with an average payback of 2.0 and 4.3 years, respectively; and (3) it is not economical to upgrade HVAC systems or replace windows in

San Franciso due to the city’s mild climate and minimal cooling and heating loads. The CityBES retrofit analysis feature does not require users to have deep knowledge of building systems or technologies for the generation and simulation of building energy models, which helps overcome major technical barriers for city managers and their consultants to adopt UBEM.

Keywords: CityBES, Urban Scale, Building Energy Modeling, EnergyPlus, Energy Conservation Measures, Retrofit Analysis

Acronym:

3D: Three-Dimensional
AFUE: Annual Fuel Utilization Efficiency
CBES: Commercial Building Energy Saver
CFD: Computational Fluid Dynamic
CityBES: City Building Energy Saver
COP: Coefficient of Performance
CPU: Central Processing Unit
CSV: Comma-Separated Values
ECM: Energy Conservation Measure
ECMs: Energy Conservation Measures
EUI: Energy Use Intensity
FileGDB: File Geodatabase
GHG: Greenhouse Gas
GIS: Geographical Information System
HVAC: Heating Ventilation and Air-Conditioning
LED: Light-Emitting Diode
SCOP: Seasonal Coefficient of Performance
SEER: Seasonal Energy Efficiency Ratio
SF: San Francisco
SHGC: Solar Heat Gain Coefficient
TMY3: Typical Meteorological Year 3
UBEM: Urban Building Energy Models
UMI: Urban Modeling Interface
U.S.: United States
VAV: Variable Air Volume

1. Introduction

With the increasingly global urbanization, more than half of the world's population lives in urban areas [1]. Many cities have adopted ambitious long-term greenhouse gas (GHG) emission reduction goals. For example, San Francisco (SF) planned to reduce GHG emission 40% below the 1990 level by 2025, and 80% by 2050 [2]. New York City also committed to reducing GHG emission 80% below 1990 level by 2050, with an interim target to reduce 40% by 2030 [3]. The building sector in the United States (U.S.) accounts for about 40% of the total primary energy consumption and GHG emissions [4]. In cities, buildings can consume up to 75% of total primary energy [5]. Buildings in SF contribute to 53% of the total GHG emission [6]. Retrofitting the existing building stock to improve energy efficiency and reduce energy use is a key strategy for cities to reduce GHG emissions and mitigate climate change.

Many cities, states, and utilities provide rebates and incentives to support building retrofits [7]. SF Energy Watch program [8], supported by the Pacific Gas and Electric, offers incentives to commercial and multi-family buildings for energy efficiency upgrades to lighting, refrigeration equipment, controls, and network-level computer power management software, etc. SF's Property Assessed Clean Energy financing program [9] helps homeowners finance energy-saving, renewable energy, and water-saving home upgrades. The New York State Energy Research and Development Authority [10] provides financial support for Commercial Real-Time Energy Management system implementation and services for up to 5 years. Florida Public Utilities [11] offers commercial electric rebates for businesses to help offset the cost of making energy-efficiency upgrades to chillers, reflective roofs, air conditioner replacements, etc. Illinois Energy Now [12] Standard Incentive Program provides incentives for common lighting retrofits, variable speed drives for heating, ventilation and air-conditioning (HVAC) equipment, demandcontrolled ventilation, boilers, and furnaces. These rebate and incentive programs were designed based on each city's building stock characteristics as well as their climate conditions. It is critical for city managers to have tools to evaluate and prioritize energy conservation measures (ECMs) for their city-scale retrofit analysis, so that they can design the rebate and incentive programs accordingly and effectively.

Data-driven models and physical models are two major methods to analyze energy use for either individual or city-scale buildings. Data-driven models [13,14] can be applied to identify operational problems or predict operational changes. However, it is difficult to predict the retrofit savings of ECMs using data-driven models. On the other hand, physical models of heat and mass flow in and around buildings can be applied to predict operational energy use, as well as indoor and outdoor environmental conditions, to evaluate the retrofit savings for a variety of ECMs. Reinhart and Davila [15] reviewed emerging simulation methods and implementation workflows for bottom-up urban building energy models (UBEM). The basic approach of UBEM is to apply the physical models to groups of buildings.

There are several tools developed to support the generation of UBEM. CitySim (http://citysim.epfl.ch) [16], developed by Ecole Polytechnique Fédérale de Lausanne University, is a tool that allows building energy simulation at the scale of an urban district. Li, et al. [17] introduced a geographical information system (GIS)-based urban building energy modeling system, using the Urban-EPC simulation engine, a modified energy performance calculator engine. Both tools used simplified resistor-capacitor network models to predict the operational energy usage for urban planners to minimize energy and emissions. Fonseca and Schlueter [18] introduced an integrated model for characterization of spatio-temporal building energy consumption patterns in neighborhoods and city districts. The model also used the resistor-capacitor model to predict building heating and cooling loads. Regarding ECM evaluation, the simplified resistor-capacitor network models can estimate savings for simple ECMs, such as replacing inefficient lighting with light-emitting diode (LED) lamps, adding wall insulation, and replacing windows. However, these tools are limited and unable to evaluate complex ECMs that have an integrated effect on multiple building systems, such as replacing HVAC systems, installing daylight sensors and controls, and adding CO_2 sensors for demand-control ventilation. To better evaluate ECMs, detailed physics-based dynamic thermal simulation engines such as EnergyPlus [19] should be used.

Urban Modeling Interface (UMI), developed by Massachusetts Institute of Technology, is a Rhino-based design environment to evaluate the neighborhood density, operational energy use (using EnergyPlus simulation), daylighting, and walkability of neighborhoods and cities [20]. UMI was used to developed UBEM for 83,541 buildings in Boston to estimate citywide hourly energy demands at the building level with the official GIS dataset provided by the Boston Redevelopment Authority and a custom building archetype library of 52 use/age archetypes [21]. After mapping and processing the Boston GIS data sources to create a city building dataset, the modeling workflow required users to create archetypes/prototypes (including envelope, HVAC, internal loads, and operational schedules), import the building footprints using UMI, extrude the building to create a three-dimensional (3D) form using Grasshopper, divide the building into the determined number of floors, add windows according to the building's window-to-wall ratio, and assign the archetypes based on the building type and year of construction. The Boston UBEM modeling workflow requires a significant amount of user effort and knowledge to manually transfer data and generate energy models for the buildings. To better support city managers and their consultants, it is crucial to have a tool that can automate the workflow to generate and simulate the UBEM based on the integrated city building dataset. This required the UBEM tool to have comprehensive archetypes/prototypes covering different building types, vintages, climate zones and to automate the model generation and simulation process. It is important to consider the impact of shading from neighborhood buildings [22–24] on the UBEM energy performance.

This study introduces CityBES (City Building Energy Saver), an open web-based platform that allows users to quickly set up and run UBEM to support city-scale building energy efficiency analysis. In this study, UBEM refers to not only the physical energy models, but also the generation and simulation of those physical models and the storage and visualization of the analysis results. CityBES addressed the limitations mentioned above by using EnergyPlus as the simulation engine, automating the UBEM generation workflow, and considering shadows from neighboring buildings. A case study using CityBES was conducted to analyze the potential retrofit energy and cost savings of five individual ECMs and two ECM packages for 940 office and retail buildings in six city planning districts of northeast San Francisco. The results generated by CityBES were analyzed to evaluate energy savings and cost-effectiveness of individual ECMs as well as ECM packages.

2. CityBES Overview

CityBES [25,26] is a web-based platform developed by Lawrence Berkeley National Laboratory (Berkeley Lab) that is freely available to any U.S. city[1]. Figure 1 shows the key components, data flow, and use cases of CityBES. There are three layers: the data layer, the simulation engine

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[1] http://citybes.lbl.gov

(algorithms) and software tools layer, and the use-cases layer. It provides a 3D visualization with GIS (see Figure 2) including color-coded simulated site energy use intensity (EUI). The example provided shows site EUI for 940 office and retail buildings in northeast SF. This study introduces the retrofit analysis feature of CityBES, which provides bottom-up physics-based detailed energy modeling of every individual building in a city or district.

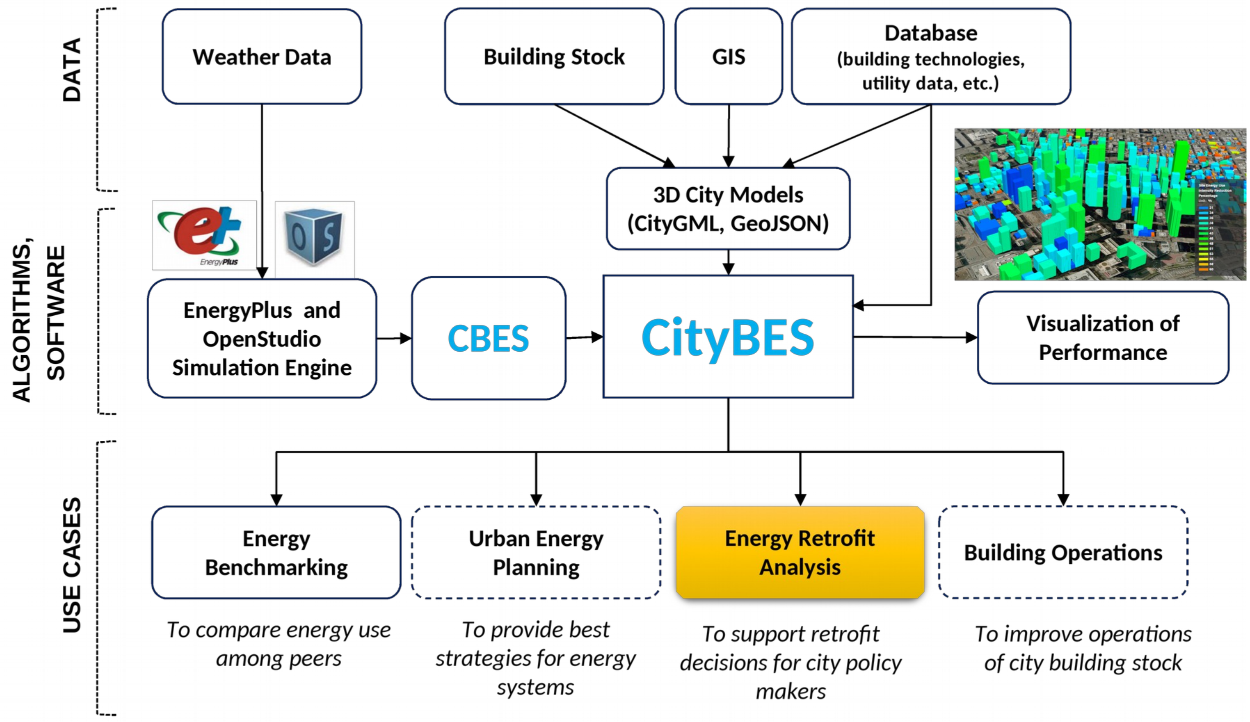
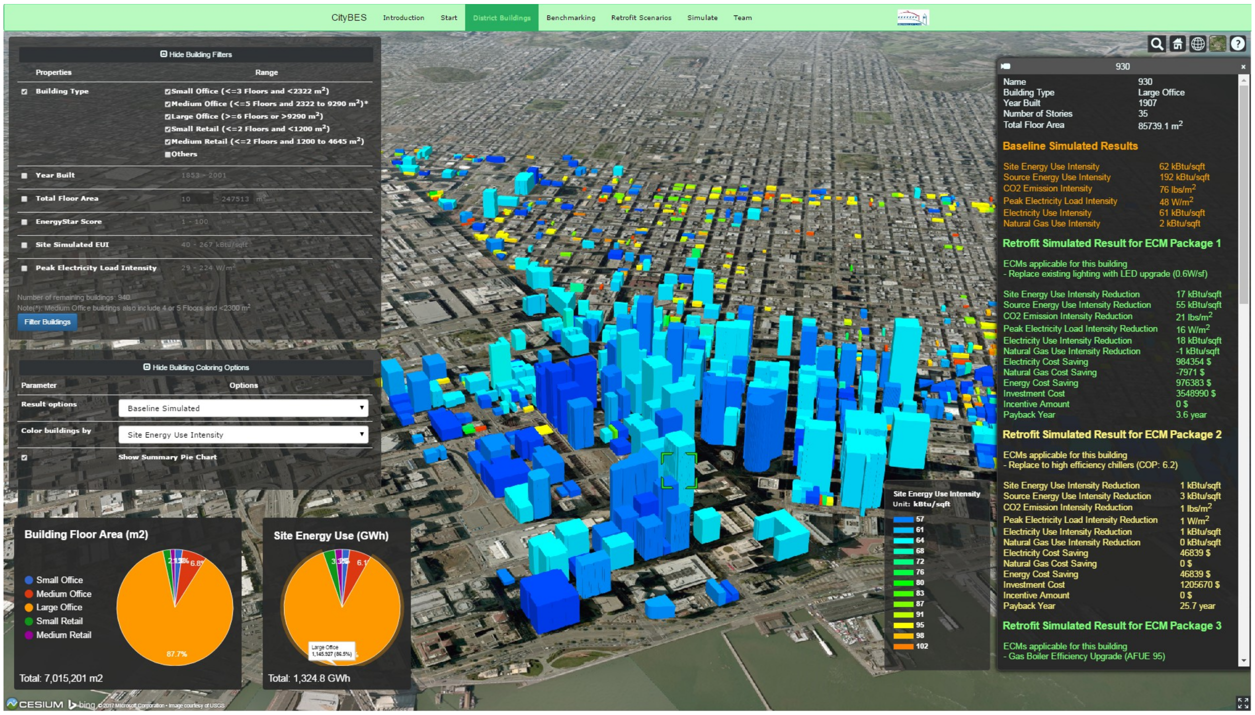


Figure 1. CityBES key components, data flow, and use cases



	Properties	Range
☑	Building Type	☑Small Office (<=3 Floors and <2322 m²) ☑Medium Office (<=5 Floors and 2322 to 9290 m²)* ☑Large Office (>=6 Floors or >9290 m²) ☑Small Retail (<=2 Floors and <1200 m²) ☑Medium Retail (<=2 Floors and 1200 to 4645 m²) ☐Others
☐	Year Built	1853 - 2001
☐	Total Floor Area	10 - 247513 m²
☐	EnergyStar Score	1 - 100
☐	Site Simulated EUI	40 - 267 kBtu/sqft
☐	Peak Electricity Load Intensity	29 - 224 W/m²

Number of remaining buildings: 940.
Note(*): Medium Office buildings also include 4 or 5 Floors and <2300 m²

Parameter	Options
Result options	Baseline Simulated
Color buildings by	Site Energy Use Intensity
☑	Show Summary Pie Chart

Total: 7,015,201 m2

Total: 1,324.8 GWh

Name	930
Building Type	Large Office
Year Built	1907
Number of Stories	35
Total Floor Area	85739.1 m²

Baseline Simulated Results

Site Energy Use Intensity	62 kBtu/sqft
Source Energy Use Intensity	192 kBtu/sqft
CO2 Emission Intensity	76 lbs/m²
Peak Electricity Load Intensity	48 W/m²
Electricity Use Intensity	61 kBtu/sqft
Natural Gas Use Intensity	2 kBtu/sqft

Retrofit Simulated Result for ECM Package 1

ECMs applicable for this building
- Replace existing lighting with LED upgrade (0.6W/sf)

Site Energy Use Intensity Reduction	17 kBtu/sqft
Source Energy Use Intensity Reduction	55 kBtu/sqft
CO2 Emission Intensity Reduction	21 lbs/m²
Peak Electricity Load Intensity Reduction	16 W/m²
Electricity Use Intensity Reduction	18 kBtu/sqft
Natural Gas Use Intensity Reduction	-1 kBtu/sqft
Electricity Cost Saving	984354 $
Natural Gas Cost Saving	-7971 $
Energy Cost Saving	976383 $
Investment Cost	3548990 $
Incentive Amount	0 $
Payback Year	3.6 year

Retrofit Simulated Result for ECM Package 2

ECMs applicable for this building
- Replace to high efficiency chillers (COP: 6.2)

Site Energy Use Intensity Reduction	1 kBtu/sqft
Source Energy Use Intensity Reduction	3 kBtu/sqft
CO2 Emission Intensity Reduction	1 lbs/m²
Peak Electricity Load Intensity Reduction	1 W/m²
Electricity Use Intensity Reduction	1 kBtu/sqft
Natural Gas Use Intensity Reduction	0 kBtu/sqft
Electricity Cost Saving	46839 $
Natural Gas Cost Saving	0 $
Energy Cost Saving	46839 $
Investment Cost	1205670 $
Incentive Amount	0 $
Payback Year	25.7 year

Retrofit Simulated Result for ECM Package 3

ECMs applicable for this building
- Gas Boiler Efficiency Upgrade (AFUE 95)

Figure 2. Screenshot of CityBES, showing color-coded simulated site EUI for 940 buildings

CityBES uses the Commercial Building Energy Saver (CBES) Toolkit [27,28], which builds on OpenStudio and EnergyPlus to provide energy retrofit analyses of individual commercial buildings (offices and retail) in U.S. cities. EnergyPlus [19] is an open-source whole building energy simulation program that models both energy consumption (for HVAC, lighting, and plug and process loads) and water use in buildings. OpenStudio [29] provides a software development kit used by CBES to create EnergyPlus models programmatically using Ruby scripts. CBES contains a prototype building database for office and retail buildings for the 16 climate zones (cliamte zone 1B to be added in future) as defined by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), and a comprehensive ECM database with cost and performance data for 82 ECMs. 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.

3. Automatic Generation of UBEM

Traditionally, the workflow to generate UBEM is complicated, which has hindered the adoption of UBEM for city-scale retrofit analysis. Cities lack resources or expertise to create and run the UBEM, especially when multiple steps are involved. However, city technical personnel are familiar with the GIS dataset in Shapefile, File Geodatabase (FileGDB), GeoJSON, or even CityGML [30] formats. They are capable of consolidating city data in such formats that can then be imported into energy modeling tools. To speed up the adoption of UBEM to support city managers, CityBES can automatically generate UBEM based on a city's GIS dataset in GeoJSON or CityGML. Figure 3 shows the workflow for the fully automated UBEM generation and simulation. CityBES first processes the city GIS data to determine the shading/neighborhood buildings, shared walls, and weather file for each building. After the processing, each building is assigned the associated weather file and neighborhood buildings as well as the GIS-based building footprint, year built, building type, building height, and number of stories. Then it leverages CBES to generate and run the baseline (without the retrofit ECMs) model as well as retrofit models for each building. CityBES has a Parallel Simulation Manager to allocate the computer resource (e.g., available cores in the central processing unit, or CPU, file storage location) and monitor the simulation progress for each building. The results are stored in the CityBES database and can be visualized and downloaded in comma-separated values (CSV) format on the website CityBES.lbl.gov.

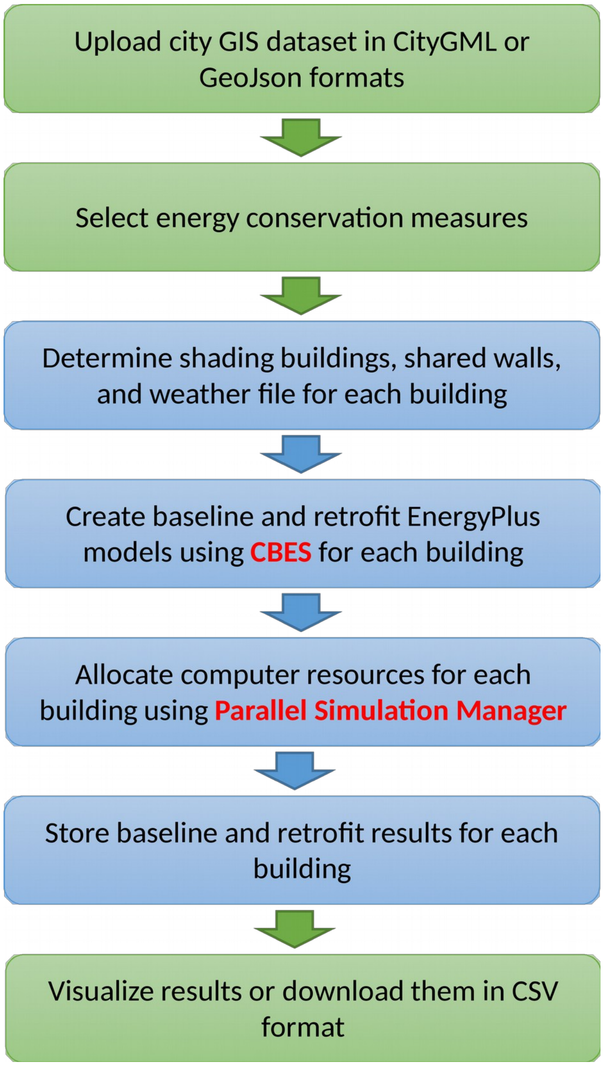
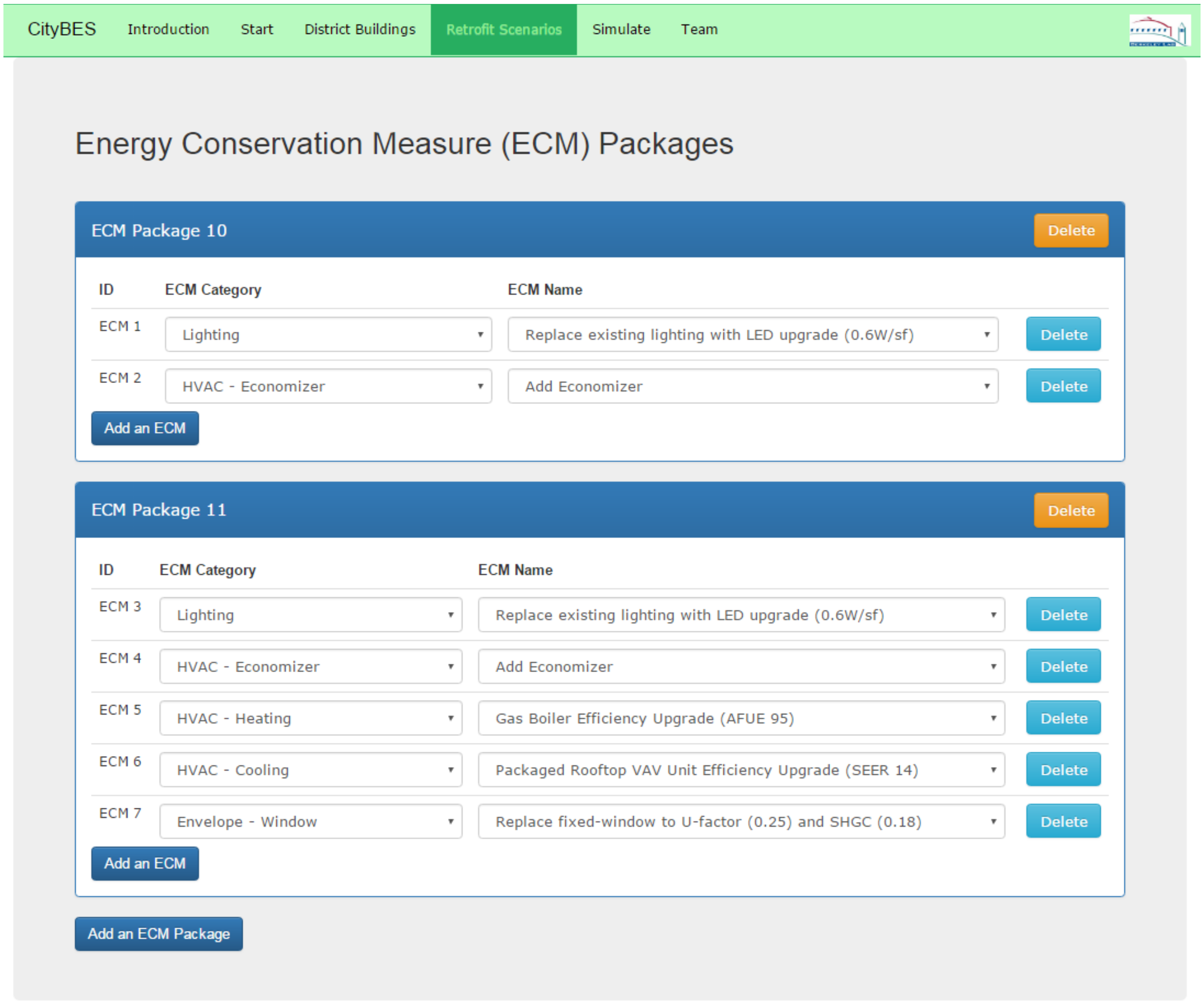


Figure 3. Workflow for the fully automated urban building energy models generation and simulation

3.1. Upload city GIS dataset and select ECMs

There are two types of input data: the city GIS dataset and the selected ECMs. For the city GIS dataset, the GIS-based building footprint, year built, building type, building height, and number of stories for each building are required data elements in GeoJSON or CityGML formats. For the ECMs, CityBES provides a graphical user interface for users to select from a comprehensive list of 82 ECMs (Figure 4).



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)
ECM 2	HVAC - Economizer	Add Economizer

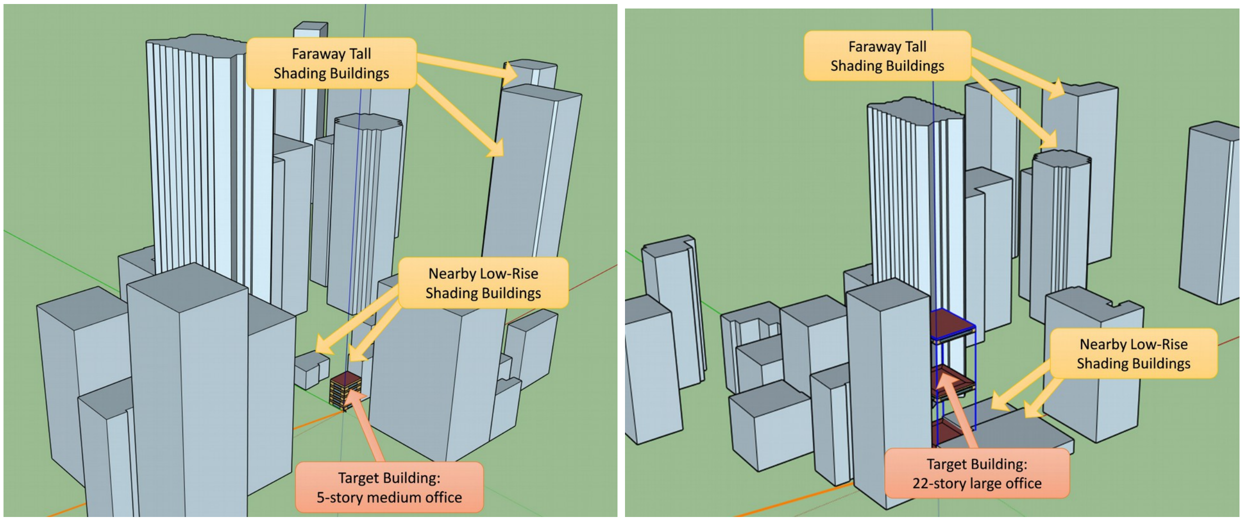
ECM Package 11

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

Figure 4. *Selection of individual ECM and ECM packages in CityBES*

3.2. Determine boundary conditions for each building

CityBES models the neighborhood buildings as shading surfaces in EnergyPlus to consider the solar overshadowing effect between buildings. Figure 5 shows two example EnergyPlus models for a five-story medium-sized office building and a 22-story large-sized office building, including nearby low-rise and faraway tall buildings in gray that shade those two target buildings. When the closest ground distance of the target building and a surrounding building is less than 2.5 times of the surrounding building’s height, the surrounding building may shade the target building, so the surrounding building is considered as a shading building of the target building. The height multiplier (2.5) is calculated based on a sun angle of 21.8°, which covers 83% of working hours (9am to 5pm) for SF (longitude 37.77 °N). Increasing the height multiplier may result in more shading buildings, but the impacts should be minimum, as the additional shading buildings only shade the target building during early morning and late afternoon in winter when the solar radiation is weak. The shading simulation time is proportional to the square of the number of shading surfaces. This study showed that EnergyPlus simulations were significantly slowed when a large number of shading surfaces were considered. To speed up the simulation, a polygon simplification was performed to determine an equivalent polygon with fewer vertices/points for the shading buildings. After the simplification, the simulation times for the two target buildings in Figure 5 were reduced from 31 and 23 minutes to 7 minutes each. Shared walls were detected between two adjoining buildings based on the GIS information. First, the model found adjacent walls for each target wall. In this study/model, two walls are adjacent when the distance between them is less than 0.5 meter. A margin of 0.5 meters was used to overcome the GIS data quality issue. All the adjacent walls' area are then added together; the target wall is determined to be a shared wall if the adjacent area is more than 50% of the target wall's area. Those shared walls are modeled as adiabatic without windows. CityBES uses a library of 877 Typical Meteorological Year 3 (TMY3) weather files for cities in the U.S. (Figure 6), and assigns the closest weather file for each building based on their GIS location. CityBES allows users to replace the default TMY3 weather file with their own weather file in the EnergyPlus EPW format.



(a) Five-story medium office (b) Twenty two-story large office

Figure 5. EnergyPlus model for a target building with its shading buildings

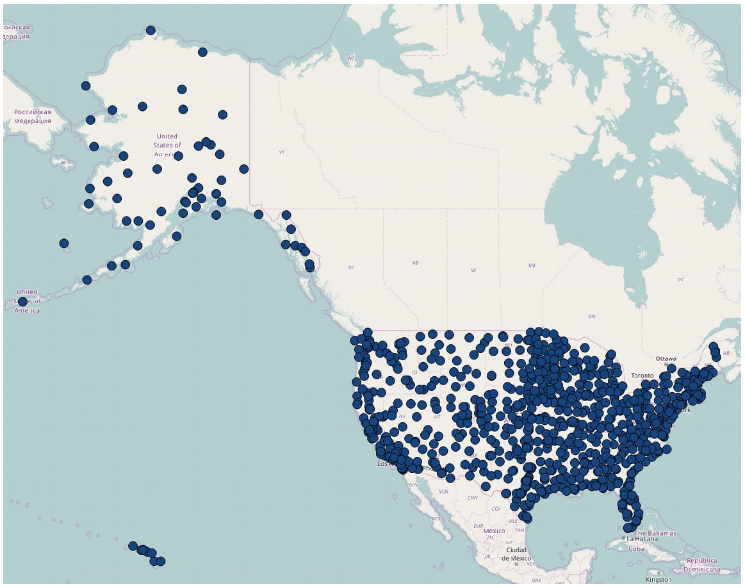


Figure 6. Locations of 877 TMY3 Weather Files used in CityBES

3.3. Create baseline and retrofit EnergyPlus models using CBES for each building

Figure 7 shows each building's input data for CBES and the major CBES database for energy model generation. For each building, CityBES passes building footprint, building type, building height, year built, and number of stories—as well as the shading buildings' footprints, shared walls, and weather file information—to CBES. CBES utilizes the prototype and zipcode databases to create the baseline model. For each selected ECM, a retrofit model is created based on the baseline model and the ECM and the cost database.

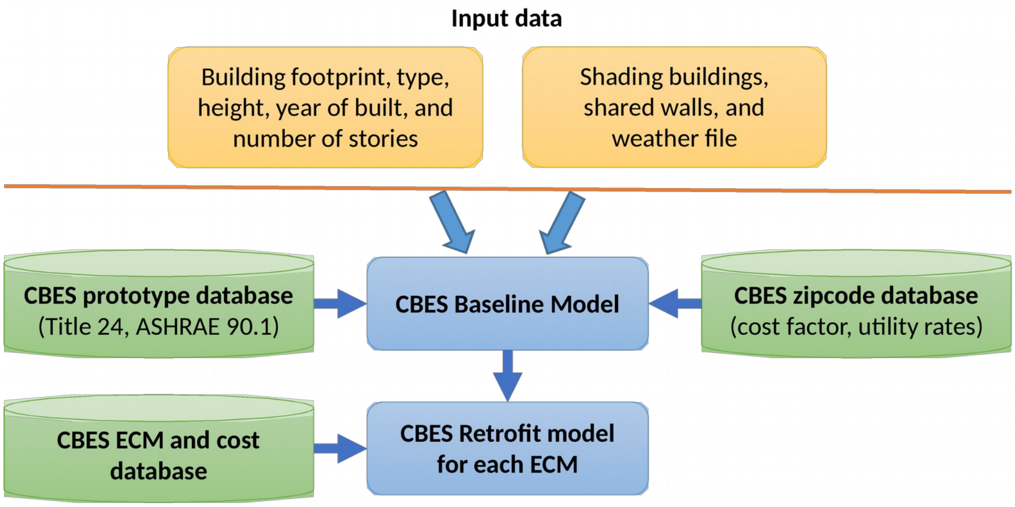


Figure 7. Input data for each building, and the major databases, of CBES

There are two major parts of each EnergyPlus model: geometry and building systems. For the building geometry, since detailed internal zoning information for the building is not available, a novel pixel-based algorithm is developed to provide automatic zoning for the arbitrary building footprint. The algorithm creates multiple thermal zones for each building to meet the requirements of ASHRAE 90.1-2013 [31] Appendix G Table G3.1-8, which introduces the method of separating thermal zones when the HVAC zones and system have not yet been designed. The interior and perimeter spaces should be separated, and the perimeter spaces should be located within 5 m (15 ft) of an exterior wall. Figure 8 shows the four main steps of the pixel-based autozoning algorithm. Step (1): fill in the interior space with white color based on the arbitrary building footprint. Step (2): separate the perimeter space in dark gray and keep the core space still in white. Step (3): separate the boundary of the core space in white and inner space in light gray. Step (4): simplify the boundary of the core space and split into thermal zones.

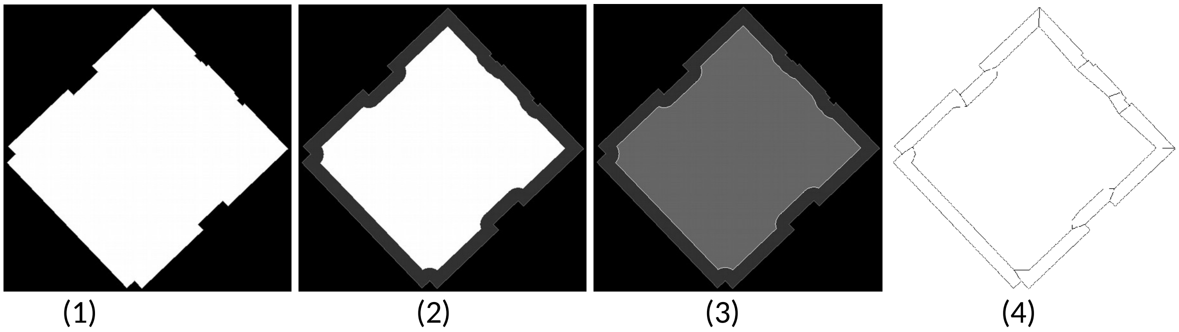


Figure 8. Main steps of the pixel-based autozoning algorithm

For building systems, CBES infers detailed building systems and 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 SF, California's building energy code, Title 24 [32] applies. The HVAC systems are determined based on the CBES prototype building [27]. For small office and small retail buildings, gas furnaces provide hot air for space heating, and packaged single zone rooftop air conditioners are used for cooling. For medium office and medium retail buildings, gas boilers are used for space heating, and packaged rooftop variable air volume (VAV) with reheat systems are used for cooling. For large office buildings, a central plant with chillers and boilers provides chilled and hot water for the central VAV with reheat systems. Title 24 has gone through about 12 three-year update cycles for the last 35 years. CBES grouped major changes in Title 24 updates into six vintages: Before 1978, 1978–1992, 1993–2001, 2002–2005, 2006–2008, and 2009–2013. Moreover, CBES adds the surrounding buildings as shading surfaces to the EnergyPlus model. Finally, one energy model is created for each building baseline as well as each ECM (individual or package). Each EnergyPlus model requires one CPU core to perform the simulation. CBES includes a run manager to run all of the EnergyPlus models simultaneously with the available CPU cores assigned by the CityBES Parallel Simulation Manager. CityBES provides cloud-based computing to automatically handle the simulation runs with a friendly progress bar to indicate the simulation status.

3.4. Visualize and download results

CityBES provides performance visualization by color-coding the 3D view of the buildings based on selected performance metrics (Figure 2). It can show site EUI, source EUI, CO_2 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, and the payback year of each retrofit scenario. CityBES allows users to download the retrofit analysis results in CSV format for each building, including baseline and retrofit results. CityBES generates sub-hourly load profiles for each building to support other analyses (e.g., district energy systems serving a group of buildings) [33,34]. It also includes a summary file with the building characteristics information (assessor's parcel number, building type, building height, number of stories, total floor area, and center longitude and latitude) and the annual baseline results. The load profiles include aggregated and detailed end uses of electricity, water, and other fuel sources, as well as space cooling loads, space heating loads, and hot water heating loads. The electricity end uses include heating, cooling, interior lights, exterior lights, miscellaneous equipment (e.g., elevators for tall buildings) and plug loads (interior equipment), fans, pumps, water systems (when heat pump water heater is used), and refrigeration. The fuel end uses cover the space heating and hot water heating, and the water end uses cover the hot water system and cooling tower.

3.5. Summary of CityBES retrofit analysis feature

CityBES can process a city's GIS datasets and produce the building stock data using the international standard CityGML format or the GeoJSON format. These data are used to automatically generate and simulate the UBEM. CityBES models the neighborhood buildings as shading surfaces to consider the solar overshadowing effect, and detects the shared walls for each building. It assigns default weather files for the buildings based on their GIS location. CityBES leverages CBES to perform retrofit analysis for quantifying and evaluating 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. A novel pixel-based algorithm is introduced to create thermal zones automatically for arbitrary building footprints, while detailed building systems and energy efficiency levels are inferred based on the local building energy code of each building's particular vintage. CityBES provides performance visualization by color-coding the 3D view of the buildings based on selected performance metrics, and allows users to download the annual retrofit results as well as sub-hourly load profiles for each building.

4. Case Study of Northeast San Francisco

Currently, CBES supports the analysis of office buildings and small- to medium-sized retail buildings in the U.S. The SF Property Information Map [35] shows that SF has 1,081 offices and 1,744 one-to-two story retail buildings with less than 4,645 m^2 (50,000 ft^2). About one-third (940) of those office and retail buildings are located in northeast SF, which includes six districts: Downtown, Nob Hill, Financial, North Beach, Russian Hill, and Chinatown. This study conducted a retrofit analysis of those 940 buildings and considered the shading effect from the other 7,741 surrounding buildings in those districts. Figure 2 shows the buildings color-coded by their simulated site EUI. shows the summary of the 940 selected buildings. They have a total floor area of 7,015,201 m^2 and use 4,769,280 GJ of the simulated total site energy annually.

Table 1. Summary of the selected 940 buildings in Northeast San Francisco

Building Type	**Building Count**	**Total Floor area (10^3 m^2)**	**Simulated annual site energy use (10^3 GJ)**
Small office (<2322 m^2 and <= 3 floors)	173	148	95

Medium office* (2322 to 9290 m^2, <= 5 floors)	149	478	290
Large office (>9290 m^2 or >=6 Floors)	279	6,153	4125
Small retail (<1200 m^2 and <= 2 Floors)	291	148	159
Medium retail (1200 to 4645 m^2 and <= 2 Floors)	48	89	95
Total	**940**	**7,015**	**4,769**

* Note: The medium office building definition also includes buildings that are <2300 m^2 with four or five floors.

SF 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 SF International Airport, 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) [36].

4.1. Preparing building data in the GeoJSON format

Creating the building dataset is the first step for the city-scale retrofit analysis. Information was drawn from a range of sources to create the building dataset. Figure 9 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 as identifiers to store the building data. Parcel-related data was merged and mapped with the building footprint data to create a master building dataset with 182 attribute fields for each building. Next, the master dataset was simplified and standardized to create 3D city models for all SF buildings in CityGML, GeoJSON and FileGDB formats. The simplified dataset has 106 attribute fields for each building, including 45 building characteristics fields and 61 energy ordinances fields.

CityGML is an XML-based international open data standard for 3D city models [30]. GeoJSON is a data format based on JSON for encoding a variety of geographic data structures [37]. 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 version 10 and above [38]. For this case study, a subset of the SF 3D city model was created with the buildings in the six selected districts.

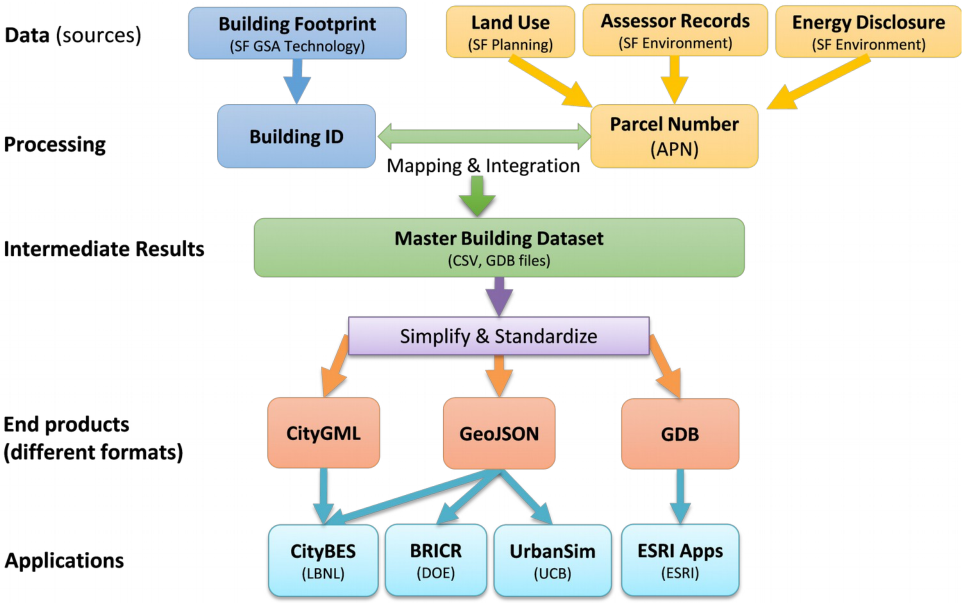


Figure 9. Data and workflow used to create the city building dataset for San Francisco

4.2. Selection of Individual ECM and ECM Packages

Five individual ECMs covering three major building systems (lighting, HVAC, and envelope) that are 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 including space cooling efficiency, heating equipment, and air-economizers (which use more outdoor air if it favors free cooling rather than mechanical cooling); the fourth ECM is a lighting upgrade to LED; the fifth ECM is a retrofit to high-performance windows. For the heating system upgrade, the gas furnace (for small-sized office and retail buildings) and gas boiler systems (for other building types) are included in the retrofit analysis. For the cooling system upgrade, which depends on building type and vintage, the packaged single zone rooftop unit (for small-sized office and retail buildings), packaged multi-zone VAV rooftop unit (for medium-sized office and retail buildings), and central VAV systems with chillers (for large-sized office buildings) are considered. Table 3 shows the cost assumption for selected ECMs provided by CBES. For the windows and lighting measures, single total cost-per-unit values are used. For the HVAC-related measures, the cost values of several capacities are provided. If the capacity of the retrofitted equipment falls within a range, a linear interpolation is used to obtain the total cost-per-unit of the equipment. If the capacity of the equipment is smaller than the minimum capacity, the total cost-per-unit of the minimum capacity is used. If the capacity of the equipment is larger than the maximum capacity, the total cost-per-unit of the maximum capacity is used. Two ECM packages were created by combining the five individual ECMs. One ECM package combined the LED and the air-economizer measures, and the other ECM package combined all of the five individual ECMs. It should be pointed out that 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).

Table 2. Description of selected ECMs

Category	Name	Description
Upgrade heating system	Gas boiler upgrade (AFUE 95)	Replace existing heating system with high-efficiency gas boiler with an annual fuel utilization efficiency (AFUE) of 95
	Gas furnace upgrade (AFUE 95)	Replace existing heating system with high-efficiency gas furnace with an AFUE of 95
Upgrade cooling system	Packaged multi-zone VAV rooftop unit upgrade (SEER 14 (SCOP 5.15))	Replace rooftop unit with a higher-efficiency unit with reheat, Seasonal Energy Efficiency Ratio (SEER) 14 (equivalent to Seasonal Coefficient of Performance (SCOP) 5.15). Cooling only includes standard controls, curb, and economizer.
	Single zone rooftop unit upgrade (SEER 14, SCOP 5.15)	Replace single zone rooftop unit with the higher-efficiency unit, SEER 14 (SCOP 5.15). Cooling only includes standard controls, curb, and economizer.
	Chillers upgrade (COP 6.27)	Replace existing chillers with higher-efficiency ones, Coefficient of Performance (COP) 6.27.
Replace windows	Replace windows with	Replace existing window glass and frame with high-performance

	U-factor: 1.43 W/m^2.K, SHGC: 0.18	windows, U-factor: 1.43W/(m^2.K), Solar Heat Gain Coefficient (SHGC): 0.18. SHGC and U-factor are 30% below 2013 Title 24 values.
Add air-economizer	Add economizer	Install economizer for existing HVAC system (includes temperature sensors, damper motors, motor controls, and dampers).
Replace lighting with LED	Replace lighting with LED (6.46 W/m^2)	Replace existing lighting with LEDs at 6.46 W/m^2. LEDs consume less power and last longer than fluorescent lamps.

Table 3. Cost assumption of the selected ECMs

Name	**Cost unit (USD)**	**Capacity**	**Total cost per unit**
Gas boiler upgrade (AFUE 95)	$/kBTU-hour	30 kBTU-hour	94.7
		50 kBTU-hour	84.0
		100 kBTU-hour	55.7
		200 kBTU-hour	42.0
		500 kBTU-hour	35.6
Gas furnace upgrade (AFUE 95)	$/kBTU-hour	10 kBTU-hour	71.0
		30 kBTU-hour	45.0
		50 kBTU-hour	39.2
		100 kBTU-hour	26.0
		200 kBTU-hour	22.9
Packaged multi-zone VAV rooftop unit upgrade (SEER 14 (SCOP 5.15))	$/ton	15 ton	6847
		25 ton	5236
		50 ton	4310
		100 ton	3320
		200 ton	2324
Single zone rooftop unit upgrade (SEER 14, SCOP 5.15)	$/ton	1 ton	2950
		5 ton	1586
		10 ton	1445
		30 ton	1606
		50 ton	1445
Chillers upgrade (COP 6.27)	$/ton	200 ton	745
		400 ton	477
		1000 ton	437
		1500 ton	381
		2500 ton	375
Replace windows with U-factor: 1.43 W/m^2.K, SHGC: 0.18	$/sf window area		26.52
Add economizer	$/ton	1 ton	387
		20 ton	111
		50 ton	93
		100 ton	55
		200 ton	44
Replace lighting with LED (6.46 W/m^2)	$/sf floor area		2.86

4.3. Retrofit Results and Analysis

CityBES was used to automatically generate the UBEM and run all simulations using EnergyPlus. After downloading the retrofit results in the CSV format, energy saving potential of individual ECMs, as well as the ECM packages for the 940 buildings, was evaluated. Figure 10 and Figure 11 show the annual site energy savings and CO_2 reduction per building type and simple payback year for the individual ECMs as well as the two ECM packages. The results indicate that replacing lighting with LEDs and adding air economizers are the most cost-effective measures (with average payback years of 2.0 and 4.3, respectively). Replacing lighting with LED saves the most energy—310.9 GWh annually, which is 23.5% of the total annual site energy consumption. Figure 12 and Figure 13 show the distribution of annual site energy saving percentage and payback years for the two ECM packages. The package with LED lighting and economizer can save 17%-31% (5th and 95th percentile) of site energy per building with 2.1 to 6.1 (5th and 95th percentile) payback years; while the package with all five EMCs can reduce 23%-38% (5th and 95th percentile) of site energy per building with 6.3 to 33.8 (5th and 95th percentile) payback years. By contrast, the payback is long for upgrading HVAC systems due to the mild climate of SF. Based on the calculated magnitude of energy savings and cost-effectiveness, this study shows that SF and its supporting utility company would obtain the most energy savings by providing incentives and rebates for upgrading lighting to LED and adding air-economizers to existing HVAC systems that don’t have them. It should be pointed out that the payback years of some ECMs are beyond their lifespan (e.g., gas boiler upgrade), indicating that those ECMs are not cost effective in the SF climate.

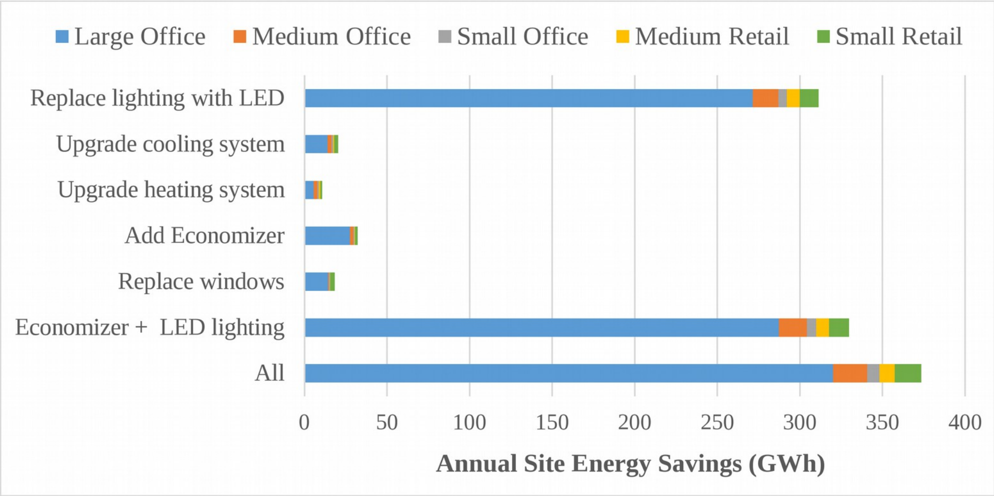


Figure 10. Annual site energy savings by building type for individual ECMs and ECM packages

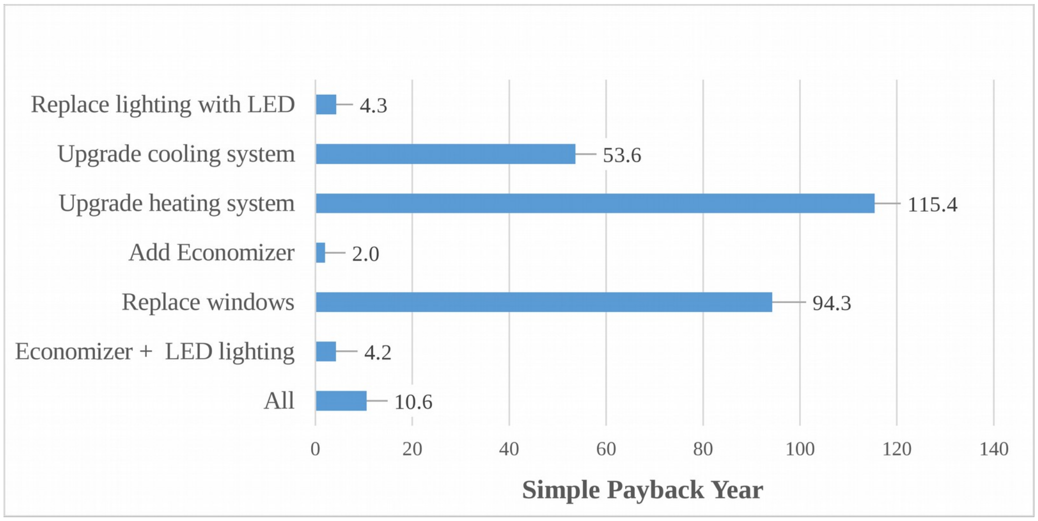


Figure 11. Simple payback year for individual ECMs and ECM packages

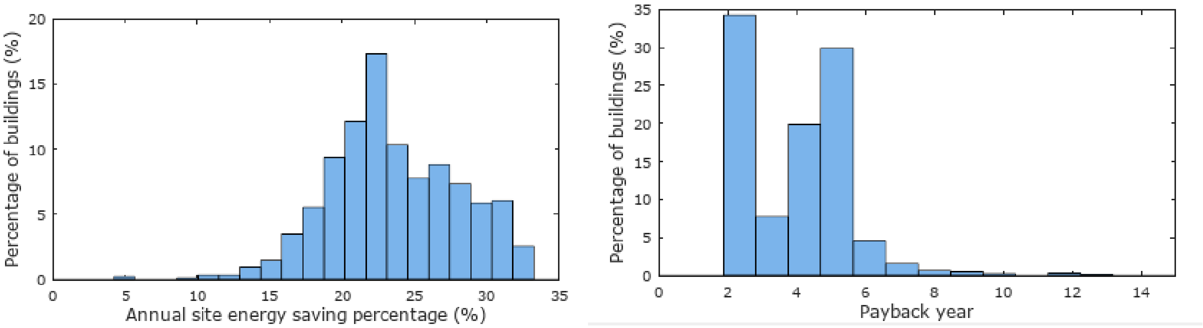


Figure 12. Distribution of site energy saving percentage and payback year for the ECM package with LED lighting and economizer

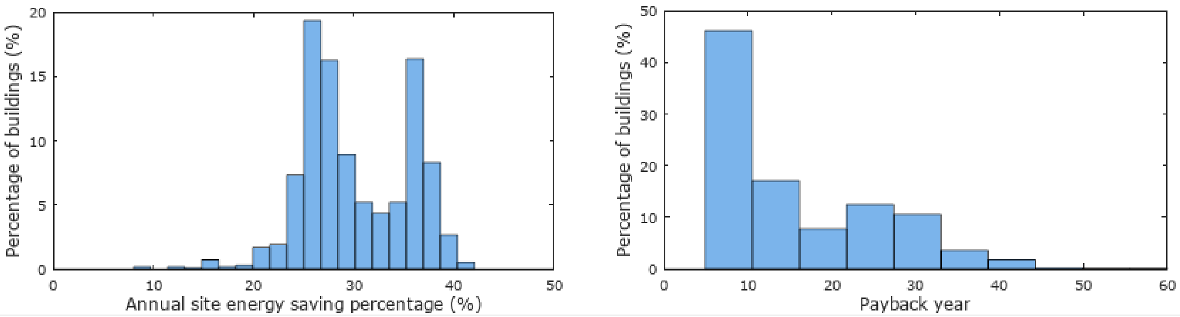


Figure 13. Distribution of site energy saving percentage and payback year for the ECM package with all five ECMs

To estimate the impacts of shading on building energy use, another set of simulations were run without modeling the neighborhood buildings as shading surfaces. The adiabatic boundary conditions were maintained for the adjacent walls. Compared to the case that considered shading from nearby buildings, the baseline annual site EUIs of the case ignoring nearby shading are 0% (5th percentile) to 10.7% (95th percentile) higher with a median of 3.0% (Figure 14) for all the simulated buildings. Due to the additional solar heat gain for the case that did not model the shading buildings, electricity consumption is increased by 0.4% (5th percentile) to 24.1% (95th percentile) with a median of 5.7%, while the natural gas consumption is reduced by -30.1% (5th percentile) to -0.9% (95th percentile) with a median of -13.2%. For the retrofit analysis, taking the ECM package with all five ECMs as an example, the annual site EUIs of the case ignoring shading from nearby buildings are 0.2% (5th percentile) to 17.4% (95th percentile) higher with a median of 5.2% (Figure 15) for all the simulated buildings. When compared with the annual site EUI savings, the percentage difference between the two retrofit cases are 0.8% (5th percentile) to41.8% (95th percentile) with a median of 12.5% (Figure 16). The positive values mean that the case that did not model shading buildings overestimated retrofit savings. These results indicate that it is very important to consider the impacts of shading from neighborhood buildings on the UBEM energy performance, especially for the retrofit analysis.

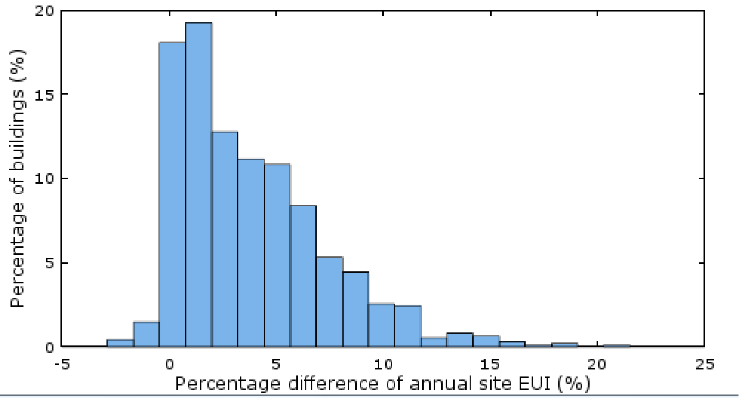


Figure 14. Percentage difference of annual baseline site EUI with and without modeling shading from nearby buildings

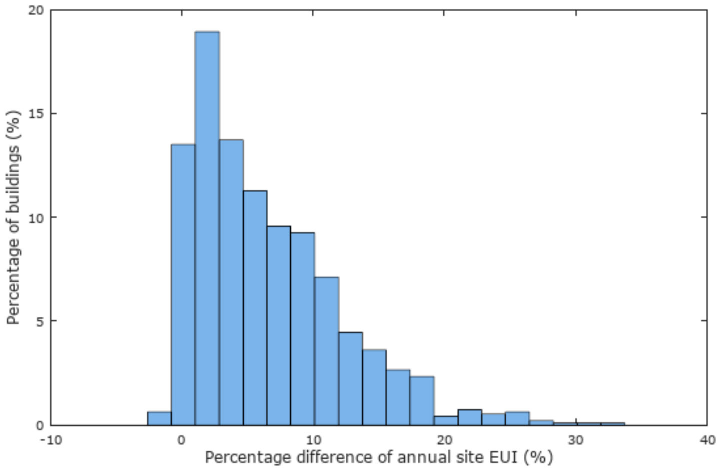


Figure 15. Percentage differences of annual retrofit site EUI with and without modeling shading from nearby buildings

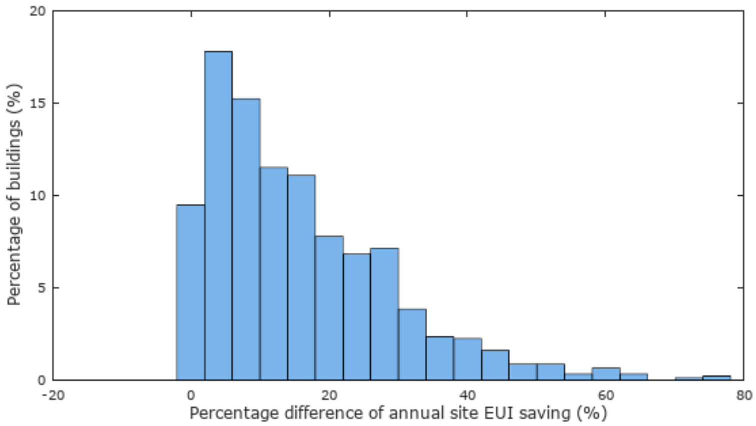


Figure 16. Percentage difference of annual site EUI saving with and without modeling shading from nearby buildings for the ECM package with all five ECMs

5. Discussion

5.1. City Data Integration

CityBES provides the function to fully automate the generation of UBEM based on the city GIS-based building dataset. One challenge for the case study is to prepare the city GIS-based building dataset with the required building characteristics information. SF city departments have public information available in different formats (e.g., county tax assessor records data in fixed-width text format, building footprint, and land use data in ShapeFile format, and energy ordinance data in Excel file format). It requires a significant amount of work to consolidate multiple datasets into a city building dataset. The data quality became a significant issue when running the simulation. There are missing data problems (the building permit database had to be manually checked, another city open dataset in free text format) to get the year built information for 19 buildings. Information on building height and the number of stories was reconciled by comparing them with those from Google 3D Map and online information. Building floor-to-floor height was ensured to stay within a rational range of 2.8 to 5.6 m. Approximately 100 buildings were removed that have footprint areas less than 10 m^2. The quality of SF GIS data has improved considerably, and will continue to improve over time.

For the automatic internal zoning of arbitrary shapes, the original building footprint of each building was provided to the CBES. Geometry processing-based methods were implemented (e.g., offset the line, find the intersection, trim the line) to handle some typical geometries (e.g., rectangular and L-shape) based on the Autozoner algorithm introduced by Dogan, et al. [39]. Some problems persisted when methods were applied to building footprint data with noises.

Therefore, the novel pixel-based autozoning algorithm was developed, which overcame the issue of GIS data with noises. Due to the page limit, we only provide brief introduction to the algorithm in this paper. We will fully describe and evaluate the pixel-based autozoning algorithm in the future study.

5.2. City-Scale model calibration

A key barrier to UBEM is a lack of availability of detailed building information (e.g., window to wall ratio, space zoning, operation schedules) and metered energy use data, which was also mentioned in the Boston UBEM study [21]. CBES includes a module to perform automatic model calibration based on monthly electricity and natural gas energy consumption [40]. However, it is hard to have access to monthly utility bill data at the individual building level at the district or city scale to perform such model calibration. This may change over time as more buildings are subject to building benchmarking ordinances that require building owners to disclose the annual total energy use of their buildings. This study used the standard (e.g., California Title 24) efficiency values to create the prototype buildings. This may affect the analysis results and thus impede cities from effectively adopting UBEM to guide energy policy. For future work, existing building energy datasets will be leveraged to improve building energy models, such as the city’s energy ordinance/benchmarking dataset, DOE Building Performance Database, and the 2012 Commercial Building Energy Consumption Survey [41].

Berkeley Lab is currently working with San Francisco Department of Environment, National Renewable Energy Laboratory, and OpenEE Meter, on a project named BayREN: Integrated Commercial Retrofit. The project will model the small- and medium-sized commercial buildings in SF to scan and identify potential buildings for retrofit with the financial support from the SF Energy Watch program. A UBEM was generated as the first step to evaluate opportunities for building retrofit in SF. The UBEM analysis provides actionable information to support city managers in energy retrofit programs. For example, SF's Energy Watch Program offers contractors financial incentives for qualified energy efficiency services including the installation of lighting, HVAC, refrigeration, commercial food service equipment, vending cooler machine controls, and computer network management systems to commercial businesses and multi-family properties in SF. The simulated results of the automatically generated model for each building would not exactly match the building's real energy consumption due to the use of limited available existing building data.

CBES App[2] is an open web-based graphical user interface using CBES as the simulation and analysis engine. It allows users to modify the detailed building information through web browsers, including the window-to-wall ratio, envelope construction, lighting, plug loads, HVAC system, service hot water system, and operation schedules. Users can also upload their monthly utility bills to the CBES App[2] to calibrate the energy model. Moreover, users can run simulation, visualize the retrofit analysis results, and download the energy models as well as the results summary. Berkeley Lab plans to connect CityBES with CBES App to allow users to modify information at the individual building level or perform model calibration with the available measured data (e.g., monthly utility bills). The updated energy models will then be used by CityBES for further analysis.

5.3. Building type coverage

The city building dataset includes other commercial building types (e.g., hotels, restaurants, schools, and hospitals) as well as residential building types, which are currently not supported by CBES. Several efforts are on-going to enhance CBES to cover those and other commercial and

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[2] http://cbes.lbl.gov

residential building types.

5.4. Computing challenge

The city building dataset developed includes all of the 177,023 SF buildings. To perform retrofit analysis for all SF buildings CityBES needs to leverage super computers (e.g., National Energy Research Scientific Computing Center) for the EnergyPlus simulations. This is an on-going effort as part of the exascale computing project (exascaleproject.org) funded by the U.S. Department of Energy's Office of Science.

For the shading calculation, the shading buildings were modeled as shading surfaces in EnergyPlus. The 22-story large office building in Figure 5 (b) (referred to Building B in the following discussion) is treated as a shading building for the five-story medium office building in Figure 5 (a). Building B is also treated as a shading building for another 79 buildings in the case study. For the case study, each building model is simulated eight times (one for baseline and seven for the retrofit analysis). Therefore, the shading calculation of Building B is performed 640 times (80 buildings * 8 EnergyPlus models per building). This modeling method is not efficient and consumes a significant amount of computing resources. Ideally, shading over all buildings in the whole city should be calculated only once; shading results of each surface can be saved in a 3D city data model (such as CityGML). EnergyPlus should be extended to read those pre-calculated shading results directly.

5.5. Localized weather conditions

It is important to consider the impact of the local weather data [42–45] and urban vegetation [46] on the UBEM energy performance. CityBES can assign the closest weather file for each building based on their GIS location. However, there is a lack of multiple TMY3 weather files across a city or district to represent the urban micro-climate (e.g., urban heat island effect).

Computational fluid dynamic (CFD) simulation can be used to generate the local climate conditions (e.g., air temperature and humidity, wind pressure) for the building energy performance simulation. CityBES does not consider impacts from urban vegetation such as tree shading and transpiration. Future development will hopefully integrate UBEM with urban micro-climate models (e.g., CFD models, Weather Research and Forecasting models [47]) to evaluate the impact of micro-climates on urban building energy performance.

5.6. CityBES availability

CityBES is freely available for any U.S. city. However, it currently requires developers to help prepare and upload the city building dataset. A user account system is currently under development that will allow public users to register an account, upload the city building data, select energy conservation measures, and perform the retrofit analysis.

6. Conclusions

This study introduces the CityBES retrofit analysis feature to automatically generate and simulate UBEMs based on city GIS dataset for city-scale building energy retrofit analysis. The case study demonstrated the use of CityBES, as a freely available public tool, to select, evaluate, and prioritize energy conservation measures for retrofitting a large number of buildings in cities. This supports city energy managers when making decisions about building energy efficiency. Collection and integration of city data into the international data standard CityGML is not only essential for the city-scale retrofit analysis, but also useful to avoid redundant data collection and integration work for future and other urban applications. More work is needed to explore how to provide these tools for city energy analysts and to determine which features are most important or usable. City-scale building energy modeling is a nascent field with growing attention and expectation to engage and support key stakeholders (urban planners, researchers, practitioners, and policy makers).

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