Modeling City Building Stock for Large-Scale Energy Efficiency Improvements using CityBES

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ABSTRACT

Buildings in San Francisco consumed 52% of total primary energy. Improving building energy efficiency is one of the key strategies cities are adopting towards their energy and climate goals. Urban building energy models (UBEM) can support city managers to evaluate and prioritize energy conservation measures for investment and to design effective incentive and rebate programs. This paper introduces methods to develop a standardized dataset of city building stock, and it demonstrates the use of a UBEM tool, City Building Energy Saver (CityBES), for an urban-scale energy retrofit analysis of building stock in the city of San Francisco. CityBES is an open web-based data and computing platform providing city-scale building energy modeling and performance visualization and benchmarking. CityBES utilizes an international standard CityGML to represent the three-dimensional building stock in cities. As an application example, 940 office and retail buildings in six districts of northeast San Francisco were modeled and analyzed with CityBES to evaluate energy savings for five selected measures. The analysis found that replacing existing lighting with LED and adding an air economizer to HVAC systems are cost-effective measures with combined savings per building between 17% to 31%. The CityBES retrofit analysis feature does not require users to have deep knowledge of building systems or building energy models, which helps overcome barriers for city managers and their consultants to adopt UBEM.

Introduction

Urbanization is one of the great challenges in the current century, with linkages to climate change and the need for sustainable use of energy and other natural resources. Buildings in cities consume 30 to 70% of the total primary energy (NRDC and IMT 2017). Retrofitting the existing building stock to improve energy efficiency and reduce energy use is a key strategy for cities to reduce greenhouse gas emissions and mitigate climate change. Many cities, states, and utilities provide rebates and incentives to support building retrofits. San Francisco (SF)'s Energy Watch program (SF Environment 2016), supported by PG&E, offers incentives to commercial and multifamily buildings for energy efficiency upgrades (e.g., lighting, refrigeration equipment and controls, and network level computer power management software). New York State Energy Research and Development Authority (NYSERDA 2016) provides financial support for Commercial Real-Time Energy Management 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 heating ventilation and air-conditioning (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 and their consultants to have tools to evaluate and prioritize energy conservation measures (ECMs) at the city-scale, so they can design rebates and incentives effectively. Urban energy models aim to explore energy saving opportunities at a large scale by combining the data generated in cities with energy simulation tools. Urban computing is an interdisciplinary field where computer science meets the research and development related to smart cities (i.e. the smart interaction with and/or use of transportation, civil engineering, energy supply and demand, environmental science, economics, ecology, and sociology in the context of urban spaces through monitoring via electronic devices) (Zheng et al. 2014).

Reinhart and Davila (2016) reviewed emerging simulation methods and workflows for developing bottom-up urban building energy models. They found that significant progress had recently been made towards the development of workflows to estimate overall operational building energy use across neighborhoods. However, these methods require a significant amount of effort for setting up and running the models.

This paper introduces the methods, data, and workflow to develop CityGML datasets for building stock in cities using the City of San Francisco as an example. The paper presents an analysis using CityBES to simulate and evaluate energy savings of five individual ECMs and two ECM packages for 940 selected office and retail buildings in six districts of northeast San Francisco. The CityBES retrofit analysis feature provides essential default assumptions based on experts' knowledge as well as industry standards and thus does not require users to have deep knowledge of building systems or of building energy models, which helps overcome barriers for city managers and their consultants to adopt UBEM.

Overview of CityBES

CityBES is a web-based platform developed by Lawrence Berkeley National Laboratory that is freely available at CityBES.lbl.gov (Hong et al. 2016). Figure 1 shows the key components, data flow, and current and planned use cases of CityBES. There are three layers: the data layer, the simulation engine and software tools layer, and the use-cases layer. It provides a 3D visualization with GIS (see Figure 2) including color-coded simulated performance metrics such as the energy use intensity (EUI) of the site.

CityBES uses the Commercial Building Energy Saver (CBES) Toolkit, which builds on OpenStudio and EnergyPlus to provide energy retrofit analyses of individual commercial buildings in U.S. cities (Hong et al. 2015). EnergyPlus is an open-source whole building energy simulation program that models both energy consumption (for HVAC, service hot water, lighting, and plug and process loads) and water use in buildings (U.S. DOE BTO 2018). OpenStudio provides a software development kit used by CBES to create EnergyPlus models (National Renewable Energy Laboratory 2017). CBES contains a prototype building database for office and retail buildings for several climate zones[1], and a database with cost and performance data of 82 different ECMs. The ECM database includes detailed descriptions 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

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[1] As defined by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (Source, NNNN)

through EnergyPlus simulation for the city building stock retrofit analysis. More detailed description of the modeling methods can be found in Chen et al. (2017).

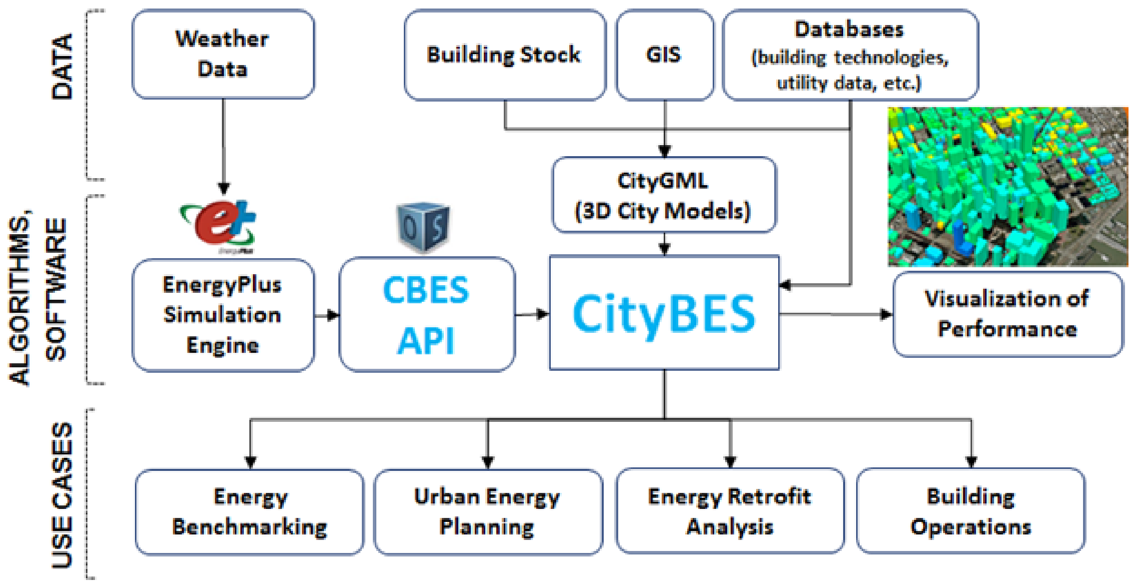

Figure 1. CityBES data flow and use cases (API: Application Programming Interface)

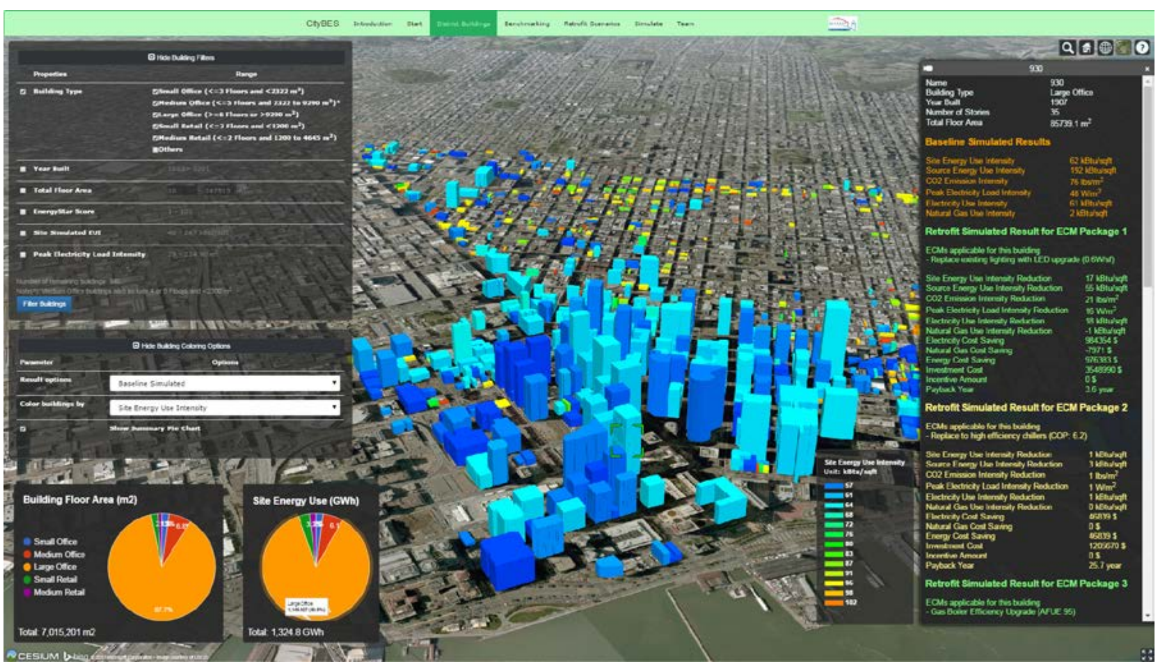

Figure 2. Screenshot of CityBES, showing color-coded simulated site EUI for 940 buildings in San Francisco

Building Stock of San Francisco

Figure 3 shows the workflow used to create the dataset of San Francisco building stock. The land use, assessor records, and energy disclosure databases use the Assessor Parcel Number (APN) as parcel identifiers to store the building data. We first consolidated the parcel-related data and mapped them with the building footprint data to create a master building dataset with all the fields from each dataset. Next, the master dataset was simplified and standardized to create 3-D city models in CityGML for all the San Francisco buildings. Building Energy Data Exchange Specification (BEDES) was used to standardize the terms in the building dataset. The final dataset products were provided in CityGML, GeoJSON, and FileGDB formats that can be used by various urban modeling and analysis tools.

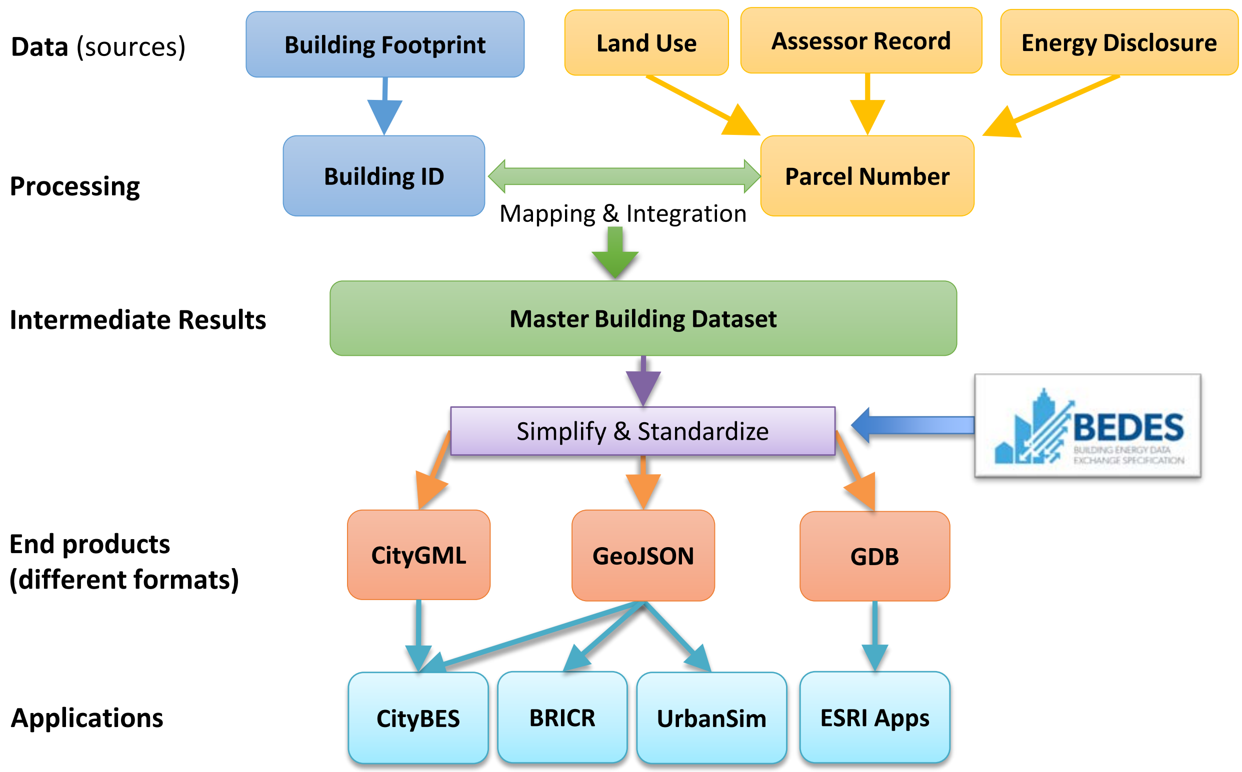

Figure 3. Data sources and workflow to create the city-scale buildings dataset

There are about 177,000 buildings in the San Francisco building footprint dataset. We eliminated building structures with a height less than 2.5 m (8.2 ft) and a floor area less than 30 m^2 (323 ft^2), which resulted in 171,474 buildings. There are 128,967 buildings with the year-built information.

Representing Building Stock in CityGML

Creation of a standard representation of building stock in cities is the first important step in urban building energy modeling. CityGML is an international Open Geospatial Consortium standard for the representation and exchange of 3D city models (OGC 2017). CityGML defines the 3D geometry, topology, semantics, and appearance of urban objects, including buildings and their components, bodies of water, city furniture (street lighting, traffic lights), transportation infrastructure (streets, roads, bridges, tunnels), and vegetation.

The CityGML files were generated based on the CityGML 2.0 schema, particularly the building[2] and generic[3] parts. Table 1 lists the mapping of the attributes to the standardized CityGML elements. As not every attribute can be mapped to a standard CityGML element, the rest of attributes were named as CityGML generic types (gen::_GenericsAttribute) to keep the records of the collected information. For example, the annual site energy use intensity (EUI) of buildings in the year of 2015, available from the SF disclosure dataset named “SiteEUI_15”, is represented using a generic attribute defined in the generic schema with an element as *<gen::doubleAttribute name = “SiteEUI_15”>.*

Table 1. CityGML elements and GeoJSON attributes mapping

Description	**GeoJSON Attribute**	**CityGML Element**
The unique building ID	OBJECTID	gml:id
The building name	name	gml:name
The delta between medium first return and the minimum ground elevation	gnd1st_del	bldg:measuredHeight
The year built	YRBUILT	bldg:yearOfConstruction
Property class code	RP1CLACDE	bldg:Usage
Number of stories	STOREYNO	bldg:storeysAboveGround
Beginning of viable address range for the parcel	FROM_ST	xal:ThoroughfareNumberFrom
Ending of viable address range for the parcel	TO_ST	xal:ThoroughfareNumberTo
Name of street	STREET	xal:ThoroughfareName
Type of street	ST_TYPE	xal:ThoroughfareTrailingName
The ZIP code	zipcode	xal:PostalCodeNumber
Geometry	geometry	bldg:lod1Solid

In particular, the property class code, which was mapped to a BEDES facility type, was further mapped to the standardized CityGML building usage dictionary, BuildingUsageType, from the CityGML External Code List.[4]

As a single CityGML file for San Francisco is too large (2.75 GB) to view or edit in general GIS or city building data visualization and analysis tools, the master buildings dataset was transformed into 16 CityGML files (varying in size between 20 MB and 368 MB). This was made in accord with the partition of the 16 planning districts of San Francisco. The CityGML

[2] http://schemas.opengis.net/citygml/building/2.0/building.xsd
[3] http://schemas.opengis.net/citygml/building/2.0/building.xsd
[4] http://bp.schemas.opengis.net/07-062/Codelists/CityGML_ExternalCodeLists.xml

files became thus more easily to handle and when compressed, the total size of these 16 files was 116 MB. These planning districts are groups of census tracts and are used in various areas of the planning process, including analysis, management, and some parts of the general plan.[5] Figure 4 shows the geographical locations and names of these districts and provides an example of the 2-D visualization of three CityGML files partitioned by planning districts: namely, Downtown, South of Market, and Mission.

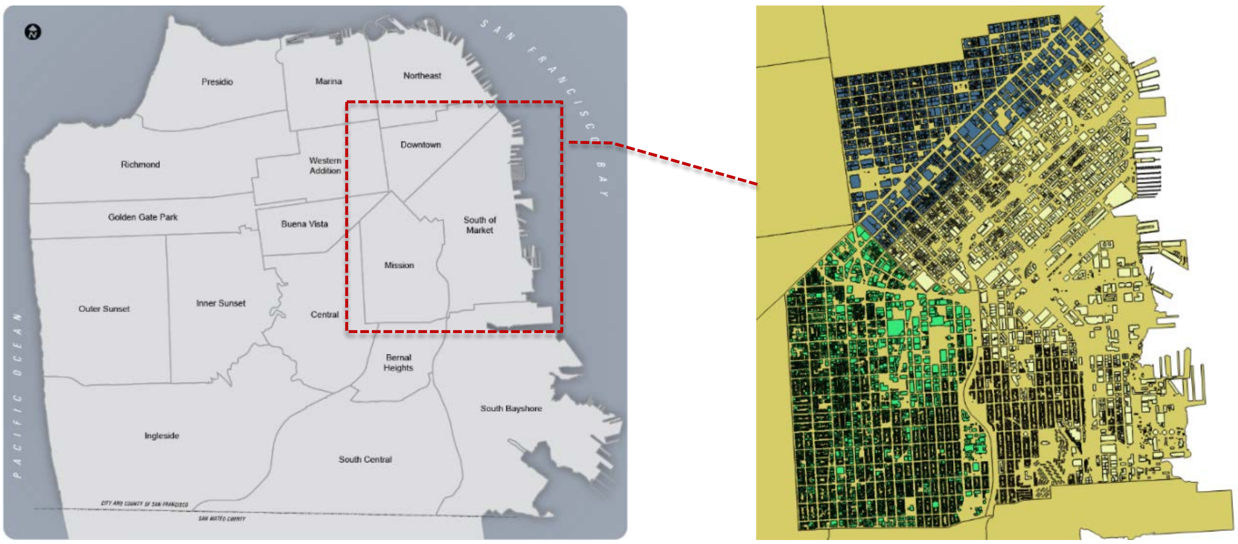

Figure 4. Partitioning of the CityGML files according to the 16 planning districts in San Francisco

The developed 16 CityGML files for San Francisco can be used for urban visualization, analysis, and modeling using various urban computational tools that support data interoperability with CityGML.

Retrofit Analysis of the Selected 940 Buildings

Currently, CBES supports the analysis of office buildings and small- to medium-sized retail buildings in the United States. The SF Property Information Map (San Francisco Planning Department 2017) shows that SF has about 1,100 offices and 1,700 one-to-two story retail buildings with a total heated area of 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. Table 2 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 annual total site energy.

Table 2. 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)

[5] https://data.sfgov.org/Geographic-Locations-and-Boundaries/Planning-Districts/ttns-6zj3/about

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 m2 with four or five floors.

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 3. Within the five ECMs, three are HVAC measures including space cooling efficiency, upgrade of heating equipment, and adding air-economizers; the fourth ECM is a lighting upgrade to LED; the fifth ECM is a replacement 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 4 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, greenhouse gas reduction, and payback).

Table 3. Summary of the selected ECMs

Category	**Replacements feature**	
Heating system	Gas boiler	Replace existing heating system with a high-efficiency gas boiler with an annual fuel utilization efficiency (AFUE) of 95
	Gas furnace	Replace existing heating system with a high-efficiency gas furnace with an AFUE of 95
Cooling system	Packaged multi-zone VAV rooftop unit	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	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	Replace existing chillers with higher-efficiency ones, Coefficient of

		Performance (COP) 6.27.
Ventilation	Add economizer	Install economizer for existing HVAC system (includes temperature sensors, damper motors, motor controls, and dampers).
Lighting	Replace lighting	Replace existing lighting with LEDs at 6.46 W/m^2. LEDs consume less power and last longer than fluorescent lamps.
Windows	Replace windows	Replace existing window glass and frame with high-performance 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.

Table 4. Cost assumptions of the selected ECMs

Energy Conservation Measure	**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

CityBES was used to automatically generate the UBEM and run all simulations using EnergyPlus. Figure 5 and Figure 6 show the annual site energy savings per building type and simple payback year for the ECMs. 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 7 and Figure 8 show the distribution of annual site energy saving percentage and payback years when implementing two different cases of ECMs, i.e., Economizer + LED lighting and/or All ECMs respectively. The package with LED lighting and economizer can save between 17% and 31% (5th and 95th percentile) of site energy per building with 2.1 to 6.1 (5th and 95th percentile) payback years; while the case with all five EMCs can reduce 23% to 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. 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 San Francisco climate.

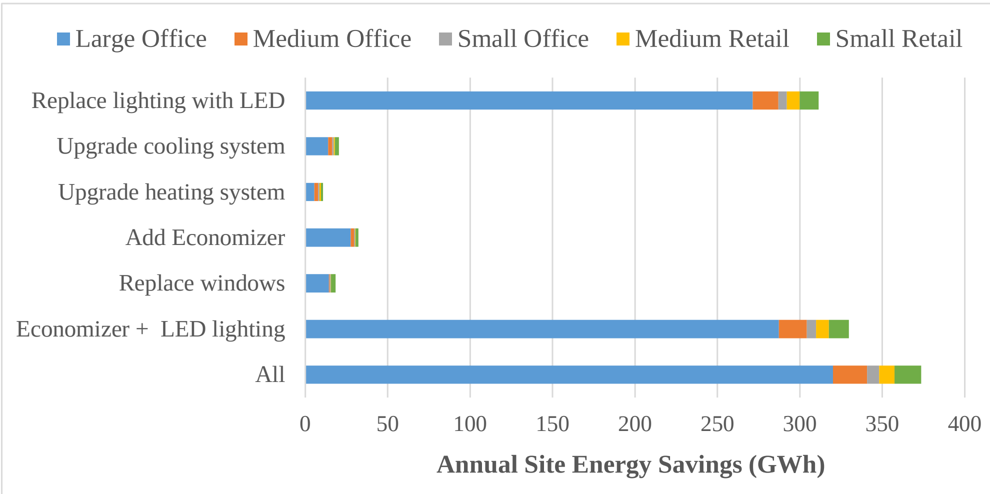

Figure 5. Annual site energy savings by building type for ECMs

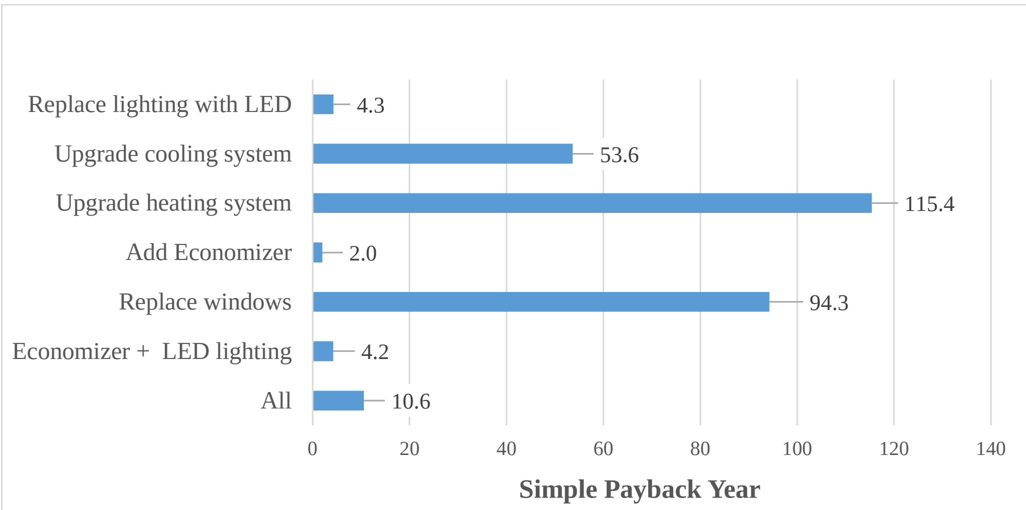

Figure 6. Simple payback year for ECMs

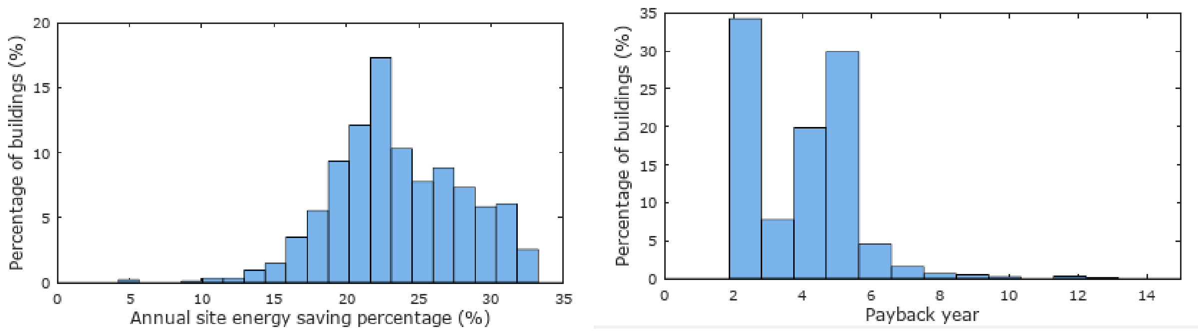

Figure 7. Distribution of site energy saving percentage and payback year for the implementation of Economizer + LED lighting

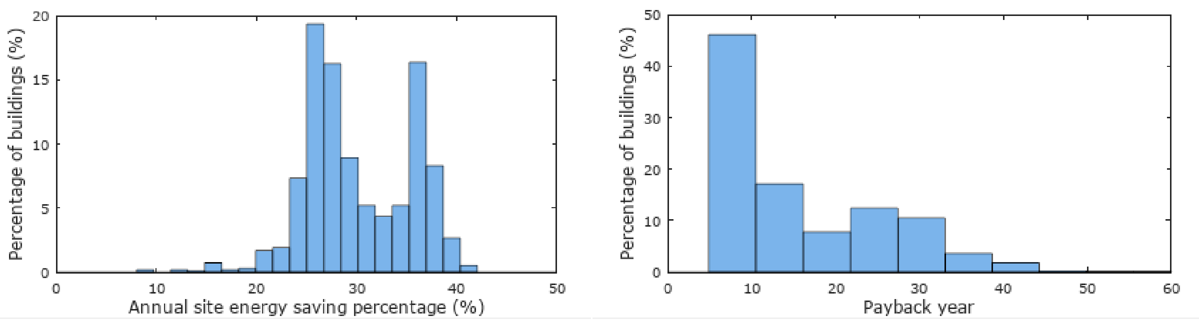

Figure 8. Distribution of site energy saving percentage and payback year when implementing all five ECMs

Discussion

A key barrier to UBEM is a lack of availability of detailed building information (e.g., window to wall ratio, space zoning, operation schedules, types and efficiency of energy systems) and metered energy use data, which was also mentioned in the Boston UBEM study (Cerezo Davila, Reinhart, and Bemis 2016). CBES includes a module to perform automatic model calibration based on monthly electricity and natural gas energy consumption (Sun et al. 2016). 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 energy use of their buildings. This study used the standard (e.g., California Title 24) efficiency values to create the prototype buildings. For future work, more existing building datasets will be leveraged to improve building energy models, such as the city's building permit records, energy ordinance/benchmarking dataset, DOE Building Performance Database, and the 2012 Commercial Building Energy Consumption Survey.

Conclusion

This study developed a method and workflow to integrate various data sources from cites' public records to create a CityGML-based standardized dataset of building stock. 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 of dataset development for urban analysis tools or applications. CityBES was used to select, evaluate and prioritize energy conversation measures for retrofitting a large group of buildings in San Francisco. Based on the calculated energy savings and cost-effectiveness, this study shows that City of San Francisco 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 currently don't have them.

The presented methods, data, and CityBES tool could be adopted by other U.S. and international cities. More work is needed to fill in the research gaps (e.g., collecting and using detailed building asset and energy data from various sources), and explore how to provide these tools for city energy analysts and determine which features are most important.

Acknowledgment

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