CityBES: A Web-based Platform to Support City-Scale Building Energy Efficiency

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ABSTRACT
Buildings in cities consume 30 to 70% of the cities' total primary energy. 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. Planning and evaluating retrofit strategies for buildings requires a deep understanding of the physical characteristics, operating patterns, and energy use of the building stock. This is a challenge for city managers as data and tools are limited and disparate. This paper introduces a web-based data and computing platform, City Building Energy Saver (CityBES), which focuses on energy modeling and analysis of a city's building stock to support district or city-scale efficiency programs. CityBES uses an international open data standard, CityGML, to represent and exchange 3D city models. CityBES employs EnergyPlus to simulate building energy use and savings from energy efficient retrofits. CityBES provides a suite of features for urban planners, city energy managers, building owners, utilities, energy consultants and researchers.

CCS Concepts

• Information systems→Database management systems→Database design and models • Information systems→Information systems applications→Spatial-temporal systems • Information systems→Information systems applications→Decision support systems→Data analytics • Computing methodologies→Modeling and simulation→Model development and analysis.

Keywords
Building stock; building simulation; urban computing; CityGML; EnergyPlus; CityBES; building retrofit; energy savings.

1. INTRODUCTION
Urbanization is one of the great challenges of this century, with linkages to climate change and the need to develop sustainable use of energy and other natural resources. Urban energy models aim to explore opportunities to address these issues by combining the data generated in cities with new energy simulation tools. Urban computational tools combine urban sensing, data management, and data analytics, to evaluate city-scale energy and environmental systems. Urban computing is an interdisciplinary field where computer science meets city-related fields, like transportation, civil engineering, energy supply and demand analysis, environmental science, economics, ecology, and sociology in the context of urban spaces [1].

With buildings responsible for about one-third of global energy consumption and a quarter of CO_2 emissions, there is a huge, untapped opportunity to create and transform cities to more sustainable environments through improving building energy efficiency [2]. More efficient buildings can generate economic benefits, reduce environmental impacts and improve people's quality of life. More than two-thirds of people in the U.S. live in urban areas. These areas face growing challenges to accelerate building retrofit activities and expand operational efficiency to reduce energy use and greenhouse gas emissions and to meet sustainability goals. Urban energy analysis is a complex, multi-scale, multi-sector challenge. Cities need to be able to evaluate their current energy use and explore how to compare, rank, contrast, and estimate strategies to reduce energy use and environmental impacts. Cities need to evaluate building retrofit opportunities for their local stock considering energy usage, vintage, size, type, ownership, and socioeconomic capabilities of each neighborhood. Advanced shared energy infrastructure, such as district heating and cooling systems, can provide huge increases in energy efficiency by combining diverse loads where the integrated energy performance of a group of buildings can be less than the simple sum of individual buildings.

Cities need quantitative decision analysis tools that combine measured data, physics- and data-driven models to support both new and retrofits building systems. Designing and operating such systems requires dynamic computer simulation and optimization to account for the complexities of energy systems, such as different types of building systems, operating patterns, uncertainty and variability of weather, user behavior. Recent efforts to develop these tools have integrated these computation models with geographical information system (GIS) to obtain input data for hundreds to thousands of buildings, and to visualize results in a form that is accessible to urban planners and designers.

Several urban energy simulation tools have been developed [3], [4], including the Urban Building Energy Models (UBEM) [4], [5], CitySim [6] and the Urban Modeling Interface (UMI) [7]. UBEM estimates citywide hourly energy demand from energy simulations of individual buildings in a city, supporting city policy makers to evaluate strategies on urban building energy efficiency. UMI is a Rhino-based design environment for architects and urban planners interested in modeling the environmental performance of neighborhoods and cities with respect to operational and embodied energy use, walkability and daylighting potential. UMI creates EnergyPlus models using simplified zoning and HVAC systems. Rhino is a commercial 3D computer graphics and computer-aided design *(*CAD*)* application software. CitySim provides decision support for urban planners to minimize energy and emissions by simulating the energy demand of buildings. CitySim uses its own XML schema to represent building information and a reduced order energy models assuming simplified zoning and HVAC systems. However, these tools are isolated, limited to specific applications, and not using open standards, which are key to share and exchange information across a wide array of urban modeling tools.

This paper introduces City Building Energy Saver (CityBES), describing the data structures, workflow automation, integration with existing urban data models, energy models, and calibration techniques. As an energy modeling and analysis urban computing platform, CityBES can provide insights to inform city stakeholders on the opportunities for new energy technologies and retrofit policies. For example, CityBES can help identify the technologies and strategies need to retrofit city buildings to save 30% to 50% of total energy. CityBES can also be used to evaluate the impact of climate change (long term warming and extreme heat waves) on building performance and occupant health, and strategies to mitigate such impact. The tool can be used to evaluate the impact of urban heat islands on building performance and strategies to mitigate such effects. One can also evaluate the feasibility of new advanced district heating and cooling (DHC) systems that target 50% energy savings through EnergyPlus' co-simulation with DHC models in Modelica. CityBES will in future be able to evaluate the potential of on-site renewable energy generation (PV or solar thermal) in buildings.

The paper begins with a review of energy modeling approaches for urban energy analysis, and highlights approaches used in CityBES. We then describe the software architecture, modeling, and analysis capabilities of CityBES. Potential use cases, challenges and the future development of CityBES are discussed as well.

2. OVERVIEW OF ENERGY MODELING METHODS

There are three approaches commonly used to model energy use in buildings. First, physics-based models use first principals to consider detailed heat and mass balance and heat transfer within and across systems and components in buildings. Second, reduced-order models simplify the spatial and temporal dynamics in buildings and their energy systems. Third, data-driven models correlate output results with limited available independent parameters using mathematical regressions, data mining, or neutral network methods to predict energy use.

2.1 Physics-based Models

Physics-based energy modeling, the highest fidelity and the most complex option, can provide accurate energy use results of real buildings. Most of the retrofit toolkits based on physics-based energy modeling utilize publicly available simulation engines, such as EnergyPlus [8], ESP-r [9], and DeST [10], and DOE 2.2 (eQuest) [11]. EnergyPlus use heat and mass balance equations to model detailed dynamics of complex mechanical systems, e.g. variable refrigerant systems, radiant cooling and heating systems, and natural ventilation. One challenge with physics-based models is the difficulty determining many of the input parameters. Another challenge is the need of measured data to calibrate energy models. The advantage of using detailed physics-based models can be the evaluation of an integrated effect. An example of an integrated effect would occur during a lighting retrofit. Upgrading the lighting system not only contributes to lighting energy savings, but also reduces the cooling load, thus reducing the space cooling energy consumption.

2.2 Reduced-order Models

A reduced-order model uses simple input and output data providing a quick evaluation of the energy performance of a building, requiring an appropriate model structure and normative values of the model parameters. There are a variety of forms of reduced order models with a resistor-capacitance (RC) model being a common model form. A well-known reduced-order model, the normative method, is a first order energy model based on quasi-steady-state heat balance equations. The normative method follows calculation standards developed by the European Committee for Standardization (CEN) and the International Organization for Standardization (ISO) [12] which defines the calculation method with a set of normative statements containing physical building parameters and building systems for different building types. The normative model based on ISO 13790 [13] is a well-known reduced-order model. The method calculates the energy use at different levels of the thermal energy demand, delivered energy per carrier, primary energy and emissions. Through simplified and unified modeling assumptions, the method forms the basis for assessing building energy performance in a standardized and transparent way. Traditionally used for energy performance ratings [14], [15], normative calculations can support retrofit analysis for large-scale energy assessment [16], [17]. Reduced-order models may not be as accurate as detailed physics-based models, yet offer advantages for simple energy analysis because of computational efficiency with fewer inputs required.

2.3 Data-driven Models

Data-driven models have been used to predict building energy consumption using simple benchmarking or more complex regression modeling, to relate building design and operational parameters with energy consumption. These methods rely on measured data, such as hourly electric data and energy use intensity databases for benchmarking. For example, many building energy baseline characterization models for measurement and verification fall into this category [18]. Some of the challenges with empirically data-driven models include: (1) the requirement of having training data to develop the model, (2) the model is limited to a specific building and may not be applicable to other buildings, and (3) there lacks a physical explanation of certain parameters of building performance. The regression model derived from statistical methods can be used to solve certain inverse problems. Differing from the conventional energy modeling processes, the inverse statistical model derives inputs from known outputs [19], allowing a building design or operational parameter to be inferred when energy consumption data are available. Regression methods applied to existing data and inverse solving techniques can be used to quickly estimate the energy consumption of individual buildings with a few parameters or to be used to derive additional information from city-wide energy consumption data. However, there is a major gap in this approach in that the energy model does not capture the dynamics of the integrated effects of energy conservation measures (ECMs).

3. CityBES

3.1 CityBES Overview

CityBES is a web-based platform to simulate energy performance of a city's building stock, from a small group of buildings in an urban district to all buildings in a city. CityBES builds upon the LBNL Commercial Building Energy Saver Toolkit [20], which provides retrofit analysis of individual commercial buildings of small and medium offices and retails. CityBES will add other commercial buildings types (e.g., large offices, hotels, hospitals) as well as residential buildings (single family and multi-family). In addition, district heating and cooling systems will be added as retrofit options. CityBES also adds new ECMs for new commercial and residential building types. To handle simulation of many buildings simultaneously, CityBES implements a parallel computing architecture to utilize high-performance computing (HPC) clusters.

CityBES uses CityGML as the data schema to represent the urban building stock. It provides 3D visualization as displayed in Figure 1, which shows color coded simulated energy performance of buildings in New York City.

CityBES is a tool to help city managers and stakeholders evaluate options to reduce energy use by quantifying and prioritizing building retrofit solutions at a large scale. The tool is capable of modeling 10,000 or more buildings and identifying deep energy savings of 30% to 50%. This concept is intended to exceed the capabilities of the current practice of evaluating retrofits of single buildings one at a time and with limited energy savings of 10% to 20%. CityBES is also designed to enable research to explore opportunities of interactions (such as simultaneous heating and cooling or opportunities for energy storage) between buildings in district-scale energy systems.

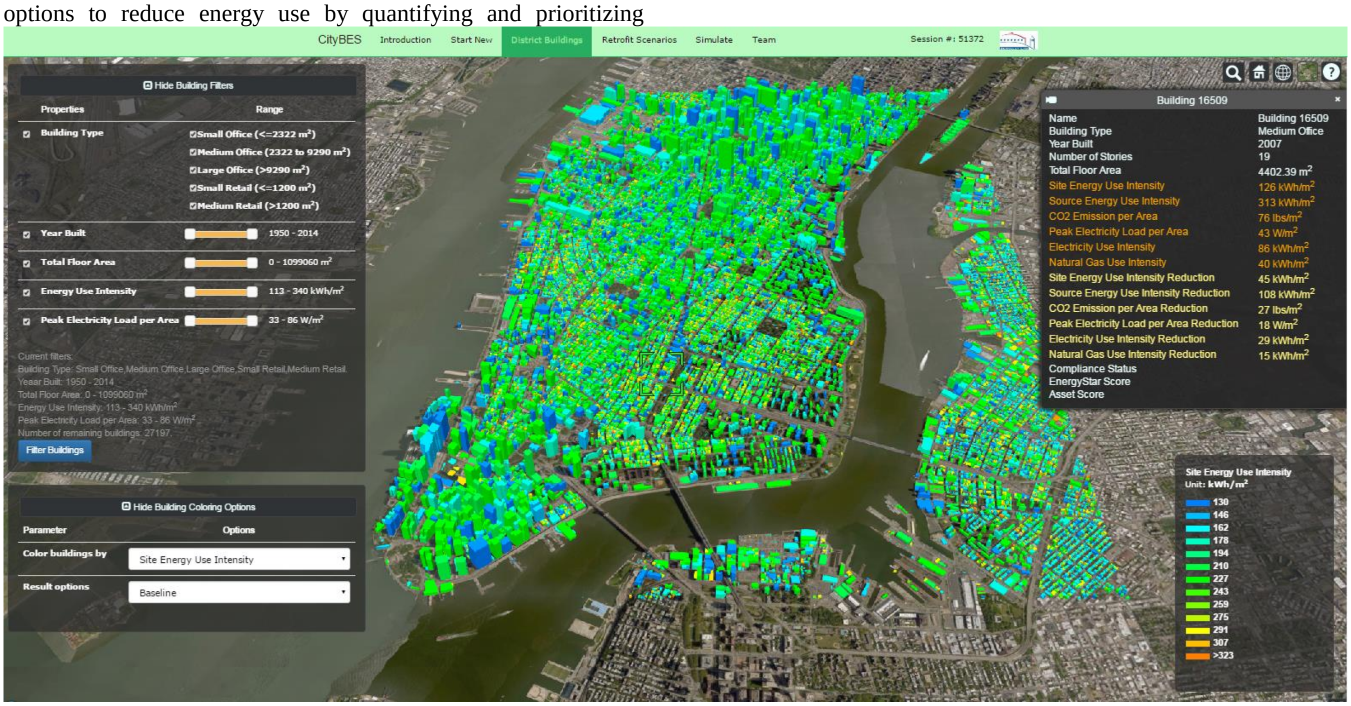

Figure 1: CityBES: Buildings in Manhattan New York (for illustrative only, using mockup building data)

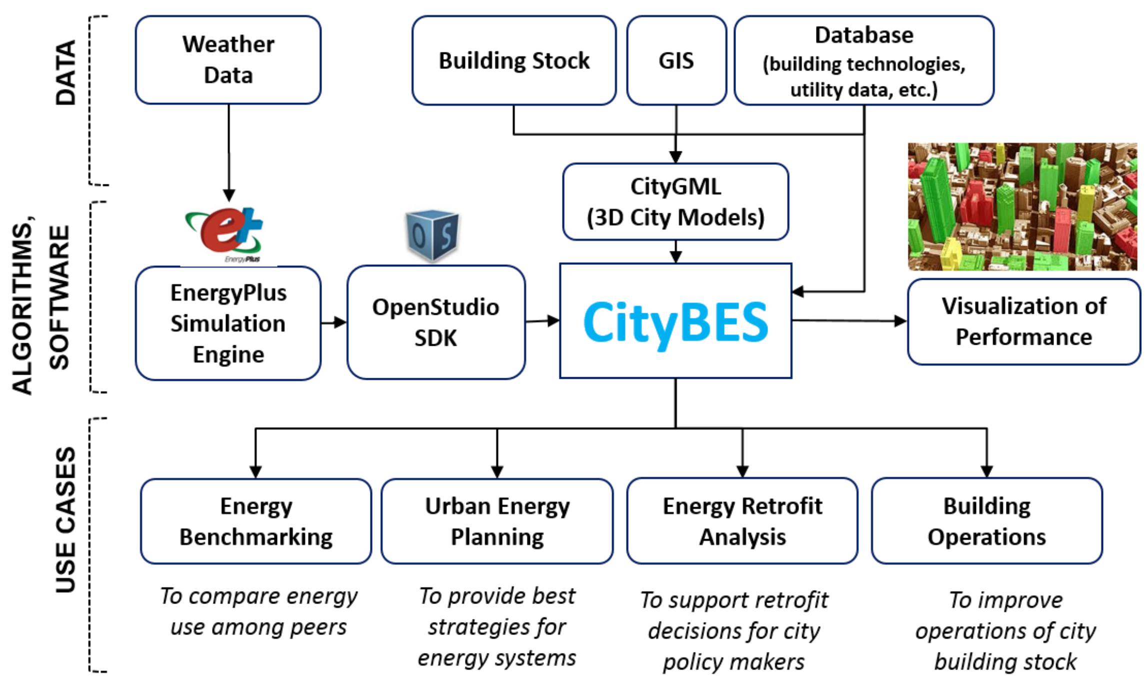

Figure 2: Software Architecture of CityBES

3.2 Software Architecture

Figure 2 shows the three layers of the software architecture of CityBES: the Data layer, the Algorithms and Software layer, and the Use Cases layer. The Data layer includes the weather data, and the 3D city model represented in CityGML compiled from building stock, GIS and other database. The Software layer includes EnergyPlus, OpenStudio [21] and CityBES. The Use Cases layer provides examples of potential applications, including energy benchmarking, urban energy planning, energy retrofit analysis, building operation improvement, as well as performance visualization.

3.3 Open 3D Data Model for Cities

Urban data models serve as the core layer of CityBES as they store data from various sources and provide inputs to the analytics, modeling, and GIS visualization. CityBES uses CityGML [22], the international open standard of the Open Geospatial Consortium (OGC), to represent and exchange 3D city models. CityGML, an XML-based open data model, is an application schema for the Geography Markup Language (GML), which provides a standardized geometry model. CityGML includes modules to represent bridges, buildings, city furniture, land use, transportation, tunnels, vegetation, water bodies, etc. Figure 3 shows some examples of CityGML objects. The CityGML provides virtual 3D city models for advanced analysis and visualization in a variety of application domains such as urban planning, indoor/outdoor pedestrian navigation, environmental simulations, cultural heritage, or facility management [23]. The CityGML version 1.0 was released in 2008, and an extended version 2.0 was adopted in March 2012.

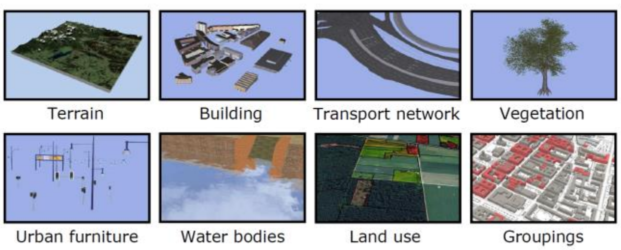

Figure 3: Examples of CityGML objects (source [24]**)**

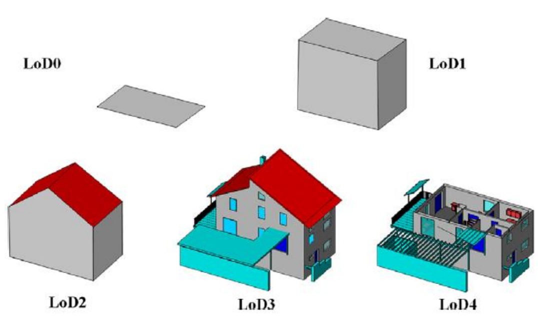

Figure 4: Five levels of details (LODs) to represent buildings in CityGML

CityGML provides a common definition of the basic entities, attributes, and relations of a 3D city model, allowing the reuse of the data in different applications. City officers are often required to provide city data in different formats for different applications, which is unnecessary redundant work. To make the city data reusable, more and more cities are creating their 3D city models using CityGML by consolidating the data from different sources. For example, Berlin 3D Portal provides CityGML data in LOD 2 for their entire 550,000 buildings in Berlin [25].

CityGML is mapped to a database as the data structure of CityBES, which is used for data management. CityGML (Figure 4) has five levels of details (LOD) to represent the city, landscape and infrastructure for building energy modeling and urban micro-climate simulations. CityGML allows user-defined objects and attributes to extend the data model for domain specific data elements. The Energy Application Domain Extension (ADE), which is under development, is used in CityBES to represent and exchange other essential data needed for building energy models, e.g., constructions and materials, operation schedules, and energy systems for lighting, plug-loads, and heating, ventilation, and air conditioning (HVAC).

3.4 Energy Modeling Approach

CityBES enables energy modeling through the OpenStudio software development kit (SDK) and the EnergyPlus simulation engine. EnergyPlus is the U.S. Department of Energy (DOE)'s flagship simulation program for modeling dynamic energy and environmental performance of buildings. It conducts detailed heat and mass balance calculations for each room in a building, and can estimate sub-hourly (from 1 to 60 minutes) energy use of building systems, including lighting, plug-loads, process-loads (e.g., elevators), HVAC and service water heating. EnergyPlus has been widely used by engineers, architects, and researchers to support the design of new buildings and the retrofit of existing buildings to increase efficiency and reduce energy use and carbon emissions. EnergyPlus is also used to support building energy codes and standards development, as well as support utility incentive programs and state and federal energy policies.

EnergyPlus has about 800,000 lines of C/C++ code. It is a console-based program that reads input and writes output to text files. EnergyPlus is free, open-source, and cross-platform; it runs on the Windows, Mac OS X, and Linux operating systems.

EnergyPlus simulation of individual buildings has been verified and validated using test cases from ASHRAE Standard 140 [26]. Datasets from cities' public building energy use disclosure and benchmarking ordinance can be used to validate the simulation results of the baseline buildings at a portfolio level from CityBES. Another dataset can be used in future is DOE's Building Performance Database (BPD) [27], which currently has more than 800K buildings and provides an estimate of energy savings from the retrofit for a group of buildings

OpenStudio is an SDK for interfacing with EnergyPlus input and output files as well as managing simulations. The OpenStudio SDK provides an object-oriented interface to the building energy model. The OpenStudio SDK can be used to rapidly create full building energy models based on limited available data; it can also be used to alter existing building energy models.

3.5 Datasets and Integration

CityBES leverages existing data from several different sources that are compiled into a central database. The database includes a CityGML file representing 3D city model that provides the majority of the data for building energy model. Other essential data in the database are weather, building characteristics, and ECMs. CityBES uses typical meteorological year weather data in EnergyPlus simulations [28], and allows user-defined weather data measured at local stations. Building characteristic data will be extracted from various city data sources, including assessors' records, GIS data, public building energy use disclosure, and energy benchmarking ordinance. CityBES also has prototype buildings that meet minimal requirements of ASHRAE 90.1 [29] and California Title 24 [30] standards at various vintages, providing default efficiency levels for buildings built at various vintages and climates. For retrofit analysis, economic data such as energy costs, investment costs, discount rate and payback years are used.

CityBES integrates more than 75 ECMs from various sources, including the Database for Energy Efficiency Resources (DEER) [31], the Advanced Energy Retrofit Guide for offices and retails [32]–[34], and RSMeans (rsmeans.com). The ECM database includes detailed descriptions of the technical specifications, modeling methods and investment costs for each ECM. In general, typical and emerging building technologies of the building envelope, HVAC, indoor lighting, plug-loads, service water heating, outdoor lighting, and building operation and maintenance were specified. 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. Table 1 shows a sample list of ECMs that can be applied during energy retrofit analysis.

CityBES provides a rich dataset as the result of the urban scale energy simulation. CityBES generates the energy consumption of the current building stock as a baseline of the city's building energy performance. Annual, monthly, and hourly energy usage data are available to characterize current energy use. Energy end uses data are available to help identify energy saving potentials for different building systems. Taking the current energy usage data as the baseline, CityBES can offer a wide array of analysis suited for city's energy efficiency program, including energy benchmarking, energy savings, greenhouse gas reductions, operation improvements, and energy costs reductions.

Table 1 Energy Conservation Measures (A Sample List) Used in CityBES

Category	Component	Name	Description
Lighting	Interior Lighting Equipment Retrofit	Replace existing lighting with LED upgrade (6.5 W/m²)	Replace existing lighting to LEDs with 6.5 W/m². LEDs consume less power and last longer than fluorescent lamps. A retrofit kit is recommended for converting ballasts. Replacement may improve lighting quality.
Plug Loads	Equipment Control	Use Plug Load Controller (30% efficient from Baseline)	Connect plug loads to a smart plug strip with some or all of the following functions: Occupancy sensing, load sensing, timers, remote control.
Envelope - Exterior Wall	Exterior Wall	Apply Wall Insulation (R21)	Apply blown-fiberglass insulation (R21) to wall cavity to maintain thermal comfort. Insulation provides resistance to heat flow, taking less energy to heat/cool the space.
Envelope - Roof	Roof	Reroof and Roof with Insulation	Demolish existing roof, install insulation (R24.83) and reroof to reduced unwanted heat gain/loss. This measure is most applicable to older roofs.
Envelope - Window	Window	Replace fixed-window to U-factor (0.25) and SHGC (0.18)	Replace existing window glass and frame with high-performance windows by changing U-factor and SHGC of window material. U-factor is a measure of thermal transmittance and SHGC stands for Solar Heat Gain Coefficient, values taken as 1.42 W/(K·m²), SHGC: 0.18.
Service Hot Water	Storage Tank	Efficiency Upgrade of the Gas Storage Water Heater	Replace existing service hot water heater with more efficient gas storage unit, better insulation, heat traps and more efficient burners to increase efficiency of (0.93).
HVAC - Cooling	Cooling System	Packaged Rooftop VAV Unit Efficiency Upgrade (SEER 14)	Replace RTU with higher-efficiency unit with reheat, SEER 14. Cooling only; include standard controls, and economizer.
HVAC - Economizer	Ventilation	Add Economizer	Install economizer for existing HVAC system (includes temperature sensors, damper motors, motor controls, and dampers).
Envelope - Infiltration	Infiltration	Add Air Sealing to Seal Leaks	Air sealing can reduce cold drafts and help improve thermal comfort in buildings. Air sealing is a weatherization strategy, which will change air exchange rate and IAQ.

4. CityBES MAIN FEATURES

CityBES implements a suite of analytics, modeling, simulation and visualization features to support its use for district and city-scale building energy efficiency analysis by urban planners, city energy managers, as well as energy consultants and researchers for city projects.

4.1 Filtering the building stock

Depending on the use case and analysis, the city building stock may need to be filtered to a subset of buildings by building type, year built, total floor area, energy use intensity (EUI), and peak electricity load per area. Figure 5 shows the design of the building stock filters, with an example to select sites built between 1950 to 1980, medium and large office buildings, with higher energy use intensities.

Figure 5: Building stock filters

4.2 Energy Benchmarking

The data needed for common energy use benchmarking include building characteristics (e.g. type/use, vintage, location and floor area), and 12 months of energy usage data. Following the data input, the Energy Star Portfolio Manager [35] and Building Performance Database (BPD) [27] application program interfaces (APIs) are provided to perform a benchmarking analysis.

The U.S. Environmental Protection Agency's Energy Star program developed an energy performance rating system, using a scale of 1 to 100, to provide a means for benchmarking the energy efficiency of an individual building to evaluate its energy performance. For assessing the Energy Star score, a minimum score of 75 is required for Energy Star certification [36]. CityBES obtains Energy Star scores for each selected buildings with monthly utility data through the Energy Star Portfolio Manager APIs; visualizes the scores by color-coding the 3D building shapes; and further filters the building stock by the score. For example, city managers may be interested to know buildings with Energy Star score lower than a certain value, say 50.

BPD is the U.S. largest dataset of information about the energy-related characteristics of commercial and residential buildings. It combines, cleanses and anonymizes data collected by Federal, State and local governments, utilities, energy efficiency programs, building owners and private companies, and makes it available to the public. CityBES can compare the EUI distribution of the selected buildings with the peer buildings in BPD, to benchmark the building energy performance in the district scale.

4.3 Building Energy Use Data Analytics

CityBES provides operational improvement recommendations from the result of the smart meter interval data analysis using an algorithm developed by Mathieu et al. [37].

CityBES analyzes weekly 24-hour daily electric load to identify higher energy consumption during non-operating hours relative to normal operating hours. This trend may indicate that the HVAC system and other electrical equipment are operating despite occupant absence during the nighttime or weekends. CityBES shows the weekly 24-hour electric load profiles, which provide electricity use patterns during operating and non-operating hours. Figure 6 shows an example of the analytic result: average weekly operating and non-operating hours, and their average electric load densities. CityBES also provides a sensitivity analysis of the whole building electricity use as a function of outdoor air temperature during four periods of the day (early morning, morning, afternoon, and night), which can infer energy use patterns, and building tightness and ventilation rates.

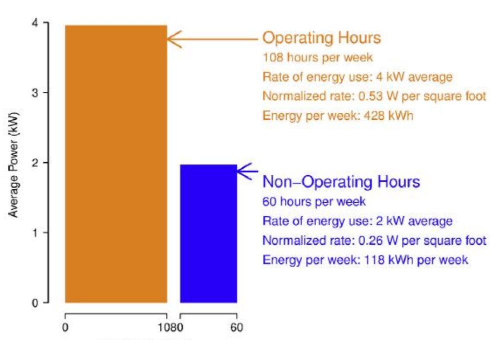

Figure 6: The weekly operating and non-operating hours, and their average power demand and energy use

4.4 Building Stock Energy Retrofit

Energy retrofit analysis is the primary use case provided by CityBES. First, building stock can be filtered based on criteria of interest (EUI, vintage, building types). Secondly, a suite of ECMs (individual and packages) can be selected from the database. Thirdly economic data such as energy costs and discount rate can be specified. CityBES runs a series of energy simulations to evaluate the selected ECMs and provides results such as energy savings, energy costs reduction, and simple payback. Retrofit measures cover most building systems and components (lighting, building envelope, equipment (i.e. plug loads), heating, ventilation, and air conditioning (HVAC), or service hot water systems) as well as operation and maintenance strategies. Some specific examples of ECMs include installing daylighting sensors for interior lighting control, replacing wall and ceiling, or roof insulation, upgrading an HVAC rooftop unit with a high-efficiency unit, adding an economizer, or upgrading to light-emitting diode (LED) lights. Hong et al. [38] identified a package of measures resulting in an estimated 20% improvement in the whole building electricity consumption. Li et al. [39] showed the three most commonly installed energy-efficient technologies in high-performance buildings are daylighting, high-efficiency HVAC systems, and improved building envelope.

For a group of buildings, CityBES will also evaluate district heating and cooling (DHC) systems as a retrofit option. DHC systems have potential of reusing thermal energy between buildings (for example waste heat from data centers can be used to heat buildings nearby), and reducing the capacity of central plant equipment (chillers and boilers) by taking advantage of the diversity of loads from different buildings.

4.5 Automated Model Calibration

There are always concerns regarding potential discrepancies between the actual and simulated energy use in buildings. CityBES adopts an automated model calibration [40] using monthly utility data to fine tune the baseline model before retrofit analysis to estimate energy savings of ECMs.

The automated model calibration uses logic linking parameter tuning with bias pattern recognition to overcome some of the disadvantages associated with traditional calibration processes. The pattern-based process contains four key steps: (1) running the original pre-calibrated energy model to obtain monthly simulated electricity and gas use; (2) establishing a pattern bias, either universal or seasonal bias, by comparing load shape patterns of simulated and actual monthly energy use; (3) using programmed logic to select which parameter to tune first based on bias pattern, weather and input parameter interactions; and (4) automatically tuning the calibration parameters and checking the progress using pattern-fit criteria.

The pattern-based calibration approach is fully automatic without any need of manual intervention. The approach employs pre-defined rules, determined by characteristics of bias patterns, to adjust the model parameters. This method is different from the traditional optimization-based automatic calibration approach which searches a parameter space according to a specific optimization algorithm to minimize the difference between the simulated and measured energy use of the building [41].

4.6 Visualization

The CityBES main screen (Figure 2) shows a 3D view of the city building stock. Users can apply filters (in a floating window) to select a subset of the building stock. When a specific building is highlighted, a list of characteristics (building name, type, vintage, and total floor area) and its energy use and potential retrofit saving data are displayed in a floating window. CityBES can visualize a suite of performance metrics of buildings by color-coding the 3D view of the buildings.

Performance metrics that can be visualized include: site or primary energy use (absolute amount or per floor area), greenhouse gas emissions, whole building peak electric demand, Energy Star score, retrofit energy savings (absolute amount and percentage), weekly operating hours, energy use breakdown into end uses (lighting, plug-loads, cooling, heating, and process loads), and code and compliance status.

5. COMPUTING REQUIREMENTS

Modeling an entire building stock in a city using CityBES can require significant computing resources. For example, a detailed EnergyPlus model for a typical commercial building can take 10 minutes to run on a 3.6 GHz desktop computer for an annual simulation at a five-minute time step. This is a computing requirement of 10^{13} FLOP. Assuming a large city such as New York with one million buildings, 20 ECMs (individual and packages) to explore for each building, each model calibration effort requiring 25 iterations, inter-building effect increasing the effort by 10X, and an integration effort of 2X, running all this in say three hours, we have 10^{13} X 10^{6} X 20 X 25 X 10 X 2 / 10^{4} = 10^{19} FLOPS, an exascale problem.

In actual applications, quite often only a subset of city buildings in the order of 100s or 1000s (e.g., residential or commercial buildings with certain characteristics) is studied. Also, energy models can be simplified in certain ways (e.g., using the perimeter and core zoning). Therefore, the simulation can be handled by today's powerful servers or HPC clusters.

6. DISCUSSION

CityBES can serve as a data and computing urban platform to help city policymakers and their consultants to evaluate district and city-scale energy efficiency issues and opportunities in buildings. CityBES is targeted for analysis of city building stocks using CityGML which provides four levels of details to represent city buildings, and allows energy simulation with different fidelities of modeling options. The data model using CityGML can help exchange data between the building energy model and other urban environmental analysis models. The integration of city building stock data in CityBES will enable integration with other tools such as the U.S. Department of Energy's Building Energy Asset Score [42] and the Building Performance Database [27]. In future, CityBES will also support other analysis such as urban energy planning and design, carbon emissions tracking system, and local laws and code compliance.

CityBES will be a valuable platform assisting users to answer important questions about technology deployment and policy such as:

1) Which types of buildings have the greatest potential for energy savings and cost-effective retrofits? This is part of a crucial effort of CityBES to show a city-wide building energy map with actual energy consumption, and estimate of energy potential savings from retrofit as well as operational improvements, for every building in the city.

2) Which energy efficiency technologies can help achieve the greatest energy savings?

3) Where in the city are there districts with the right mix of load density and diversity to support district energy systems, or local energy storage to reduce energy use?

4) How much energy savings can be expected if all buildings in a city use a specific retrofit, such as single pane to double pane windows, or fluorescent to LED lights?

5) If all buildings in a city upgrade to meet the current building energy code, how much energy savings and peak electricity demand reduction can be achieved?

6) What is the impact of climate change on energy use in the building stock and in occupant comfort in the next 30 or 50 years?

7) What is the impact of extreme heat waves on building energy demand and occupants' health?

8) If solar PV is installed on all available roof spaces of all buildings in a city, how much electricity can be generated? How does this meet city's renewable energy goal? What is the cost of such a PV deployment plan?

To develop a city-scale platform like CityBES, there are five technical challenges. The first challenge is to collect data and create the 3D city models with CityGML which need to draw data sources from various public datasets in many city departments. The second challenge is to get the energy use data of the buildings which is usually subject to data privacy and security concerns. The third is to model all types of retrofit measures using EnergyPlus and the ECM database. Fourth, the computing power required to run tens of thousands or more building energy simulations for retrofit analysis on demand is a challenge. Last but not least, we need to enhance EnergyPlus to consider inter-building effect in the urban environment, e.g. radiant heat exchange between exterior surfaces of buildings, and integration with urban microclimate simulation to consider the urban heat island effect as well and local climate conditions. More features will be added in CityBES including urban energy planning to evaluate technologies and strategies (e.g. DHC systems and community scale renewable systems) to design and optimize net-zero energy or carbon neutral communities.

7. CONCLUSIONS AND FUTURE WORK

CityBES will be a publically available web-based data and computing platform providing a suite of analytic and modeling features to improve energy efficiency and reduce carbon emissions in city buildings. CityBES uses the international standard CityGML to represent the 3D building stock in cities, and uses EnergyPlus for detailed building energy simulation to evaluate energy savings potential of a wide array of building technologies. CityBES can visualize various performance metrics of buildings by color-coding the 3D view of buildings in cities. CityBES targets audience of urban planners, energy consultants, city and utility energy program managers, and urban systems researchers. Further research is needed to understand the usability of the tool and evaluate the availability of such data to populate the analysis. Further research is also needed to obtain feedback from city stakeholder groups to organize the data outputs to provide actionable information and salient feedback for urban energy planning.

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REFERENCES

[1] Y. Zheng, L. Capra, O. Wolfson, and H. Yang, "Urban Computing," *ACM Transactions on Intelligent Systems and Technology*, vol. 5, no. 3, pp. 1–55, 2014.

[2] International Energy Agency, "Transition to Sustainable Buildings Strategies and Opportunities to 2050," 2013.

[3] J. Keirstead, M. Jennings, and A. Sivakumar, "A review of urban energy system models: Approaches, challenges and opportunities," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 6, pp. 3847–3866, Aug. 2012.

[4] C. F. Reinhart and C. C. Davila, "Urban Building Energy Modeling – A Review of a Nascent Field," *Building and Environment*, vol. 2016, 2016.

[5] MIT Sustainable Deisgn Group, "Boston Citywide Energy Model," 2016. [Online]. Available: http://web.mit.edu/sustainabledesignlab/projects/BostonEnergyModel/. [Accessed: 15-May-2016].

[6] W. Emmanuel and K. Jérôme, "A verification of CitySim results using the BESTEST and monitored consumption values," in *Building Simulation Applications BSA 2015*, 2015.

[7] C. F. Reinhart, T. Dogan, J. A. Jakubiec, T. Rakha, and A. Sang, "Umi - an Urban Simulation Environment for Building Energy Use , Daylighting and Walkability," in *Proceedings of BS2013: 13th Conference of International Building Performance Simulation Association*, 2013, pp. 476–483.

[8] DOE, "EnergyPlus," 2016. [Online]. Available: https://energyplus.net/. [Accessed: 18-May-2016].

[9] University of Strathclyde, "ESP-r," *2016*. [Online]. Available: http://www.esru.strath.ac.uk/Programs/ESP-r.htm. [Accessed: 18-May-2016].

[10] D. Yan, J. Xia, W. Tang, F. Song, X. Zhang, and Y. Jiang, "DeST — An Integrated Building Simulation Toolkit Part Ⅰ: Fundamentals," *Build Simul*, vol. 2008, no. 1, pp. 95–110, 2008.

[11] J. J. Hirsch, "eQUEST the QUick Energy Simulation Tool," 2016. [Online]. Available: http://www.doe2.com/equest/. [Accessed: 18-May-2016].

[12] CEN, *CEN/TR 15615:2008 Explanation of the general relationship between various CEN standards and the Energy Performance of Buildings Directive (EPBD). Umbrella document*. 2008.

[13] ISO, "ISO 13790: 2008 Energy performance of buildings —Calculation of energy use for spaceheating and cooling." 2008.

[14] S. H. Lee, F. Zhao, and G. Augenbroe, "The use of normative calculation beyond building performance rating systems," in *IBPSA*, 2011, pp. 2753–2760.

[15] B. Poel, G. van Cruchten, and C. A. Balaras, "Energy performance assessment of existing dwellings," *Energy and Buildings*, vol. 39, no. 4, pp. 393–403, Apr. 2007.

[16] W. J. Cole, K. M. Powell, E. T. Hale, and T. F. Edgar, "Reduced-order residential home modeling for model predictive control," *Energy and Buildings*, vol. 74, no. 2014, pp. 69–77, 2014.

[17] Y. Heo, F. Zhao, S. H. Lee, Y. Sun, J. Kim, G. Augenbroe, D. Graziano, L. B. Guzowski, and R. T. Muehleisen, "Scalable Methodology for Energy Efficiency Retrofit Decision Analysis," in *SimBuild*, 2012.

[18] J. Granderson, S. Touzani, C. Custodio, M. D. Sohn, D. Jump, and S. Fernandes, "Accuracy of automated measurement and verification (M&V) techniques for energy savings in commercial buildings," *Applied Energy*, vol. 173, pp. 296–308, 2016.

[19] F. Zhao, S. H. Lee, and G. Augenbroe, "Reconstructing building stock to replicate energy consumption data," *Energy and Buildings*, vol. 117, no. 2016, pp. 301–312, 2015.

[20] T. Hong, M. A. Piette, Y. Chen, S. H. Lee, S. C. Taylor-Lange, R. Zhang, K. Sun, and P. Price, "Commercial Building Energy Saver: An energy retrofit analysis toolkit," *Applied Energy*, vol. 159, pp. 298–309, 2015.

[21] DOE, "OpenStudio," 2016. [Online]. Available: https://www.openstudio.net/. [Accessed: 18-May-2016].

[22] Open Geospatial Consortium, "OGC City Geography Markup Language (CityGML) En-coding Standard," 2012.

[23] G. Gröger and L. Plümer, "CityGML - Interoperable semantic 3D city models," *ISPRS Journal of Photogrammetry and Remote Sensing*, vol. 71, pp. 12–33, 2012.

[24] R. Laurini, "Visual Information Systems Chapter V: Virtual 3D Cities." 2015.

[25] Business Location Center, "Berlin 3D - Download Portal," 2016. [Online]. Available: http://www.businesslocationcenter.de/en/downloadportal. [Accessed: 17-May-2016].

[26] ASHRAE, *ANSI/ASHRAE Standard 140-2011 Standard method of Test for the Evaluation of Building Energy Analysis Computer Programs*. 2012.

[27] DOE, "Building Performance Database," 2016. [Online]. Available: http://energy.gov/eere/buildings/building-performance-database. [Accessed: 17-May-2016].

[28] DOE, "Weather Data," 2016. [Online]. Available: https://energyplus.net/weather. [Accessed: 16-May-2016].

[29] ASHRAE, *ANSI/ASHRAE/IES Standard 90.1-2013 -- Energy Standard for Buildings Except Low-Rise Residential Buildings*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2013.

[30] California Energy Commission, *2016 Building Energy Efficiency Standards For Residential and Nonresidential Buildings Title 24, Part 6, And Associated Administrative Regulations In Part 1*. 2015.

[31] Inc., Itron Inc. and JJ Hirsh & Associates Synergy Consulting Quantum, "Database for Energy Efficiency Resources (DEER) Updated Study. Final Report," 2005.

[32] PNNL and PECI, "Advanced Energy Retrofit Guide, Retail Buildings. Prepared for the US Department of Energy PNNL- 20814," 2011.

[33] PNNL and PECI, "Advanced Energy Retrofit Guide, Office Buildings, Prepared for the US Department of

Energy, PNNL- 20761," 2011.

[34] ASHRAE and DOE, "Advanced Energy Design Guide for Small to Medium Office Buildings, Achieving 50% Energy Savings Toward a Net Zero Energy Building," 2014.

[35] EPA, "ENERGY STAR," *http://www.energystar.gov/*, 2015. [Online]. Available: http://www.energystar.gov/. [Accessed: 07-Apr-2015].

[36] F. Fuerst, "Building momentum: an analysis of investment trends in LEED and Energy-Star-certified properties," *Journal of Retail and Leisure Property*, vol. 8, no. 4, pp. 285–297, 2009.

[37] J. L. Mathieu, P. N. Price, S. Kiliccote, and M. A. Piette, "Quantifying Changes in Building Electricity Use , With Application to Demand Response," *IEEE TRANSACTIONS ON SMART GRID*, vol. 2, no. 3, pp. 507–518, 2011.

[38] T. Hong, L. Yang, D. Hill, and W. Feng, "Data and Analytics to Inform Energy Retrofit of High Performance Buildings," *Applied Energy*, vol. 126, pp. 90–106, 2014.

[39] C. Li, T. Hong, and D. Yan, "An insight into actual energy use and its drivers in high-performance buildings," *Applied Energy*, vol. 131, pp. 394–410, 2014.

[40] K. Sun, T. Hong, S. C. Taylor-Lange, and M. A. Piette, "A pattern-based automated approach to building energy model calibration," *Applied Energy*, vol. 165, no. 2016, pp. 214–224, 2016.

[41] J. Sanyal, J. New, R. E. Edwards, and L. Parker, "Calibrating building energy models using supercomputer trained machine learning agents," *Concurrency Computation Practice and Experience*, vol. 26, pp. 2122–2133, 2014.

[42] DOE, "Building Energy Asset Score," 2016. [Online]. Available: http://energy.gov/eere/buildings/building-energy-asset-score. [Accessed: 17-May-2016].