

Review

Comparative Review of Simplified Building Energy Analysis Tools for Retrofitting Existing US Buildings

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Abstract

Estimates of potential energy savings from selected energy efficiency measures (EEMs) typically require specialized expertise, time-intensive building audits, and detailed engineering analyses. To address this challenge, several simplified retrofit assessment toolkits have been developed worldwide; however, they lack the ability to identify the optimum retrofit package, calibrate energy models, are designed to serve users' specific needs, and have different level of data requirements. In this paper, a comparative evaluation of four openly available simplified building retrofit assessment toolkits, developed in the US, is carried out using two well-defined prototypical buildings consisting of a place of worship and an office building. This assessment compares the results of toolkits with those obtained from the state-of-the-art whole-building energy simulation tool EnergyPlus to gauge the analysis prediction accuracies and modeling capabilities for the four simplified building retrofit assessment tools. The results of this analysis guide practitioners on selecting retrofit analysis tools that best fit their needs, available datasets, and required accuracy levels. Additionally, the tools were applied to real-life buildings with the recommended retrofit suggestions being discussed with building owners to gauge their practical deployment. This discussion led to the identification of future directions for retrofit tool developments.

Keywords: building energy modeling; cost–benefit analysis; energy efficiency measures; energy savings; retrofit analysis

1. Introduction

The development of energy-efficient and innovative building technologies in the built environment has been incentivized and accelerated by the need of addressing climate change and achieving energy transition while maintaining indoor environmental quality and comfort levels [1]. With buildings accounting for almost 36% of global carbon emissions while consuming one-third of global energy, inefficient energy performance of existing building stocks has led to nearly 1% annual increase in CO₂ emissions since 2010 [2]. Space heating and cooling account for around 50% of building energy demand and 80% of direct CO₂ emissions [3]. Thus, measures that reduce heating and cooling demands are essential strategies for building decarbonization [3]. New buildings can meet the demand reduction goals through implementation of stricter energy efficiency standards and improved building codes. However, large proportion of existing building stocks worldwide were constructed over five decades ago and require substantial energy-efficient improvements [3]. Therefore, retrofitting existing building stocks is an important step for improving energy efficiency in the building sector.



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Traditional decision-making regarding impactful retrofit energy measures relies on specialist knowledge, entailing time-consuming building energy audits and engineering analyses to identify cost beneficial improvements [4]. Whole-building energy simulation packages such as EnergyPlus and eQUEST are often utilized to quantify energy benefits and saving potential of suggested retrofits when conducting detailed energy audits [4]. However, the complexity and time-consuming nature of the building energy simulation process makes it significantly crucial to adopt rapid assessment strategies to reduce the modeling efforts and facilitate decision-making for building retrofits [1]. The lack of capital and qualified workforce for small businesses also creates a need for the development of easy-to-use, low-cost tools capable of identifying cost-effective energy-efficient retrofit analysis tools [5].

Rapid assessment retrofit tools could provide effective options to accelerate the adoption of energy efficiency measures. At minimum, these tools include: (1) user-friendly interfaces for easy input of data and graphical display of the output, and (2) underlying engineering algorithms that are based on physical principles [6]. The currently available rapid assessment retrofit analysis tools adopt three different benchmarking approaches encompassing (i) data-driven benchmarking methods use real measured data, smart meter data, predefined databases to gauge a building's energy performance; (ii) measurement-based benchmarking analysis approaches compare energy consumption of individual buildings with reference metrics such as EUI (i.e., energy use intensity) estimated based on monitored or measured data from buildings of similar types; and (iii) model-based benchmarking approaches that utilize estimations from whole-building simulation tools [5].

In recent years, multiple retrofit analysis toolkits have been developed around the world that utilize one or multiple benchmarking strategies to provide users with insights into the potential cost and energy benefits of retrofitting their facilities. However, these tools vary widely on the specific quantitative assessments they provide to the end users to facilitate their retrofit analysis. Many of the available tools also lack the ability to allow users to select retrofit measures based on their needs and depend on a pre-specified set of energy efficiency options. Tools' abilities to allow users to evaluate specific energy retrofit measures have shown to enhance users' sense of support during the energy audit process, leading to increased likelihood of actual implementation of recommended measures [7]. Additionally, most of these tools also lack the ability to run optimal package energy analysis and calibrate energy analysis models [5], leading to limited effectiveness in recommending retrofit measures.

These statements remain true for the tools developed by the US Department of Energy (DoE) to identify opportunities to enhance the energy efficiency of existing building stocks. To this end, a user-friendly Simplified and Automated Building Energy Retrofit (SABER) tool has been developed [7]. SABER enables users to develop calibrated energy models of existing buildings and evaluate optimal retrofit opportunities through EnergyPlus simulations. The platform features a graphical user interface that allows users to input basic building information, generate detailed whole-building energy models, and assess selected retrofit measures for performance and energy savings.

However, these efforts to continuously build retrofit analysis tools to overcome existing limitations have flooded the US (United States of America) market with multiple tools with varied levels of accuracy, use case, data requirements, and required user expertise in energy analysis.

The main objective of this study is to provide US users with a guideline on capabilities and requirements of different tool by carrying out a comparative review of the retrofit analysis tools present in the US market to support more informed implementation of the toolkits. Specifically, the review assessments will consider four open-source retrofit analysis toolkits developed in the US, and compare their analysis approaches, input requirements,

and output results, as well as their abilities to evaluate different building types, climates, and retrofit measures. Additionally, the toolkits will also be implemented on four real-life facilities to identify how their results differ from real-life retrofit implementations and suggest future work to cover that gap.

First, a review of the existing literature is conducted to examine ongoing research on retrofit analysis toolkit development at both the global and national (US) levels, identify the need for a comparative evaluation of tools in the US context, and establish the research aim and questions of the study. Next, selected retrofit analysis tools will be evaluated in terms of their accuracy and data requirements by comparing their retrofit assessment results with those obtained from EnergyPlus for the same retrofit measures. This comparison is performed using two well-defined prototypical buildings to provide a consistent benchmark across the selected tools. In addition, the practical applicability of the retrofit recommendations is examined by applying the selected toolkits to four real-world existing buildings and discussing the proposed retrofit measures with the respective building owners. The resulting feedback is used to identify challenges associated with actual implementation and to inform future research directions for the improvement and development of retrofit analysis toolkits.

2. Literature Review

To conduct a literature review on existing toolkits suitable for energy analysis of existing buildings, the Scopus database was searched for journal articles published between 2022 and 2026. This search focused on identifying literature covering studies and evaluations related to energy retrofit analysis tools, implementation of retrofit analysis tools, or comparative analyses of building energy retrofit tools. To facilitate this search, the following search string was used: "TITLE-ABS-KEY(("energy retrofit*" OR "building retrofit*" OR "energy renovation*" OR "building renovation*" OR "energy efficiency retrofit*") AND ("analysis tool*" OR "assessment tool*" OR "decision support tool*" OR "decision support system*" OR "simulation tool*" OR "modelling tool*" OR "modeling tool*" OR "retrofit tool*" OR "retrofit assessment" OR "retrofit analysis" OR "energy analysis") AND ("comparative stud*" OR compar* OR benchmark* OR evaluat* OR implement* OR application OR "case stud*")) AND PUBYEAR > 2021 AND DOCTYPE(ar) AND SRCTYPE(j)". This search string resulted in the identification of 157 publications.

To further refine the literature search, only 34 studies that focused on comparative study for retrofit tools and/or the use of individual/combine retrofit tools were considered.

The resulting reported literature revealed that current research focuses on addressing four specific challenges associated with building energy retrofit assessments. The first challenge is the need for a large amount of data to develop reliable building energy models. This challenge is addressed by utilizing automated geometry generation, BIM (Building Information Model)-to-BEM (building energy model) workflows, GIS (Geographic Information System)-based urban modeling, UAV (Unmanned Aerial Vehicle)-derived building information, and LLM-assisted model generation [8–14]. The second challenge is related to the selection of optimal retrofit packages that can balance desired energy performance with cost, carbon reduction, indoor environmental quality, heritage conservation, or renewable energy integration [15–32]. The third evaluated challenge encompasses the diversity of the existing building stocks and the computation burden of conducting a district or city-scale building energy analysis using archetypes, representative buildings, and automating building-by-building simulation workflows [8,11,12,28,30,32–35]. Lastly the fourth addressed challenge focused on methods to improve preliminary decision support for users who lack access to detailed building data and modeling expertise to conduct accurate building energy retrofit analysis by utilizing publicly available data, predefined retrofit configurations, expert-driven retrofit rankings, and machine learning approaches [36–40].

Additionally, the development of tools in different countries including Denmark [33], Italy [17,31,39], Taiwan [20], Egypt [22], Portugal [36], India [34], Canada [28], Sweden [37], Latvia [38], China [11], and the United States [12,41] showed that retrofit tool development is increasingly being adapted to be specific to local existing building stocks, climate, regulations, available data, heritage constraints, and decision-making requirements.

Moreover, the reviewed literature can be divided based on underlying energy simulation principles using physics-based and data-driven analysis methodologies. Most tools developed adopted physics-based approaches and relied on energy simulation engines such as Energy-Plus, OpenStudio, DesignBuilder, TRNSYS, or simplified engineering heat-balance methods to assess baseline and post-retrofit energy performance [8–13,15,16,18–20,22,24,27–35,41]. These tools focused on conducting detailed retrofit analysis including evaluation of individual measures and retrofit packages, while other tools adopted data-driven approaches. For instance, AI4EF (Artificial Intelligence for Energy Efficiency) used machine learning models trained on historical building data to predict retrofit-related outcomes [38] or to develop the Swedish open ecosystem platform using publicly available Energy Performance Certificates data, benchmarking, surrogate models, and sensitivity analysis for preliminary retrofit advice [37]. Database of pre-calculated retrofit solutions has also been used to develop the Building Energy-Saving Tool for Sustainable Residential Buildings (BEST) to perform preliminary residential retrofit analyses [39] along with use of expert ranking to identify alternate retrofit solutions during the development of Expert-Driven Retrofit Assessment Platform (EDRAP) [40]. Utilization of data-driven-based tools remained restricted to preliminary analysis of retrofit measures.

Even though multiple tools have been developed worldwide to support energy simulation towards retrofitting analysis, calibration functionality of the baseline energy models have not been consistently considered. Only a small number of studies discuss calibration of simulation models against measured building energy data [10,18,34]. Other developed tools reported only the difference in the results of their simulation with utility bills and external reference data [9,15,20] or compared their results with publicly available databases [11,17].

Additional literature reviews of existing tools for energy and retrofit analysis have been reported [5,42–44]. These reviews focused on assessing and comparing the toolkits capable of evaluating residential and/or commercial buildings. The evaluated retrofit analysis toolkits were categorized based on their building energy modeling methods including (i) empirical data-driven methods, (ii) normative methods, and (iii) physics-based energy modeling approaches [6]. Moreover, Seddiki, Bennadji [43] categorized the toolkits based on their calculation methods including empirical data-driven methods, pre-simulated databases, simplified normative calculation methods, and advanced modeling approaches. Similarly, Gonzalez-Caceres, Rabani [42] grouped the toolkits based on their evaluation type encompassing (i) renovation assessments, (ii) financial assessments, and (iii) transfer of knowledge.

Table 1 summarizes building retrofit analysis tools identified through literature review.

In addition to the toolkits listed in Table 1, other analysis tools have been recently developed by the US Department of Energy to conduct energy and retrofit analysis of existing buildings. These tools include: (i) Lawrence Berkeley National Laboratory's Building Efficiency Targeting Tool for Energy Retrofits (BETTER) [47], (ii) the Department of Energy's Building Energy Asset Score [48], (iii) Energy Star Portfolio Manager [49], and (iv) Lawrence Berkeley National Laboratory's Commercial Building Energy Saver (CBES) [5]. Additionally, the Simplified and Automated Building Energy Retrofit (SABER) tool [7] has been developed by the University of Colorado Boulder to address the need for a simplified retrofit analysis tool capable of automated model calibration, retrofit package analysis, and life cycle cost assessment.

Table 1. Summary of toolkits reviewed by existing literature.

Tool	Simulation Engine	Calibration	Region	Reference
Commercial Building Energy Asset Scoring Tool	EnergyPlus	No	US	[45]
Buildbee (previously known as Simuwatt)	EnergyPlus	Yes	US	[6]
California Building Energy Code Compliance Software	EnergyPlus	No	California	[6]
Commercial Building Energy Saver	EnergyPlus	Yes	California	[5]
HOT2XP	HOT2000	Yes	Canada	[43]
BEOpt	EnergyPlus	No	US	[46]
MulTEA	DOE2.2	Yes	US	[44]
CityBES	EnergyPlus	Yes	US	[44]
XeroHome	EnergyPlus	No	Some regions of US	[44]
DanCTPlan	EnergyPlus	No	Denmark	[33]
e-Decision Support System	Simplified calculation	No	Italy	[17]
AutoBPS (Building Performance Simulation)	EnergyPlus	No	China	[8]
BESTAI (Building Energy Simulation and Analysis)	EnergyPlus	No	Taiwan	[20]
ERDSS (Energy Retrofit Decision Support System)	DesignBuilder	No	Egypt	[22]
RenoDSS	EnergyPlus	No	Poland and Spain	[13]
CNZP (Community Annual Net-Zero Planning)-DSS	EnergyPlus	No	India	[34]
Data2BEM	EnergyPlus	Yes	UK	[10]
EnPROVE	EnergyPlus	No	Poland	[29]
AI4EF (Artificial Intelligence for Energy Efficiency)	Data-Driven	No	Latvia	[38]
BEST (Building Energy Saving Tool)	Data-Driven	No	Italy	[39]
CityEL	EnergyPlus	No	China	[11]
EFFESUS (Energy Efficiency for EU Historic Districts' Sustainability) DSS	Steady-State Calculation	No	Spain	[11]

While these tools aim to address the needs for more accurate (ability to calibrate building energy models) and detailed retrofit assessments (ability to evaluate retrofit packages and conduct life cycle cost analyses) to facilitate informed decision-making, they have flooded the US market, causing confusion on how to select the most suitable toolkits. Since the selection of an appropriate toolkit depends on several factors encompassing the level of desired accuracy, amount of building information available, and users' knowledge and expertise, there is a need to undertake a comparative study to facilitate the selection of appropriate tools. Additionally, even though these tools might assist in selecting the most energy-efficient and cost-effective retrofit measures, users might refrain for the deployment of the recommended retrofit projects due to specific building use, availability of certified installers, cultural and demographic constraints, and lack of reliable energy sources [31]. Capturing these factors can guide future upgrades and/or development of toolkits to facilitate the identification of practical retrofit measures.

Therefore, the main goals of this research are two-fold: (1) to comparatively evaluate selected US retrofit analysis toolkits based on their accuracy thresholds, data requirements, analytical capabilities, and user expertise levels, thereby providing guidelines for selecting appropriate toolkits for various retrofit assessment needs; and (2) to assess the practical applicability of the retrofit recommendations generated by these toolkits by identifying building-specific, market, demographic, cultural, and infrastructure-related barriers that may influence their deployment.

To achieve these goals, the study and the adopted methodology focus on answering the following two research questions (RQ):

RQ1: How do the selected retrofit analysis toolkits compare in terms of accuracy thresholds, data requirements, analytical capabilities, and user expertise levels?

RQ2: What building-specific, market, demographic, cultural, and infrastructure-related factors influence the practical implementation of retrofit measures recommended by these toolkits, and how can these factors inform future toolkit improvements and developments?

2.1. Review of Selected US-Based Retrofit Analysis Toolkits

This study focused on reviewing toolkits developed to perform energy assessments for US existing buildings, available under open-source licenses, and focused on conducting retrofit analysis for commercial only or residential and commercial buildings. The selected tools include (i) Lawrence Berkeley National Laboratory's Building Efficiency Targeting Tool for Energy Retrofits (BETTER) [47], (ii) the Department of Energy's Building Energy Asset Score [48], (iii) Energy Star Portfolio Manager [49], (iv) Lawrence Berkeley National Laboratory's Commercial Building Energy Saver (CBES) [5], and (v) the Simplified and Automated Building Energy Retrofit (SABER) tool [7].

The selected retrofit analysis tools are readily and freely accessible to any user worldwide and are suitable for application to real-world existing buildings. Moreover, the selected tools are easy to use with readily available documentation and resources.

2.1.1. Building Efficiency Targeting Tool for Energy Retrofits (BETTER)

The BETTER tool (Version 1.8.2) utilizes an inverse modeling algorithm, referred to as the Inverse Modeling Toolkit (IMT), developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) to analyze building energy usage and suggest potential retrofit measures [47]. The tool conducts a regression analysis using monthly energy usages and ambient temperatures to develop an inverse model using the change point modeling approach. The tool utilizes inverse modeling to calculate energy use parameters like heating sensitivity, cooling sensitivity, heating slope, cooling slope, and baseload for a given building. These parameters are then compared to the reference benchmark parameters. Currently, BETTER includes reference benchmarking statistics for offices, hotels, K-12 schools, multifamily housing units, public libraries, hospitals, and worship facilities. Benchmarking for the hotels is available only for Tunisia, while benchmarking for offices is available for the United States and Mexico. Users can select their energy saving at three different ranges: Conservative, Nominal, and Aggressive [50]. The Conservative range moves the saving target to one standard deviation worse than the median performance of the benchmarking. The Nominal range keeps the saving target to the median performance of the benchmarking. Lastly, the Aggressive range moves the saving target to one-half standard deviation better than the median performance of benchmarking. Additionally, the tool also allows users to select goodness-of-fit measures for the inverse model to assess to what extent variations in outdoor air temperature should explain variations in building energy use intensity. Custom portfolio analysis can also be conducted by providing data for 30 distinct buildings of the same building type. After comparing energy use parameters, BETTER recommends a set of qualitative energy efficiency options (from a total of 15 measures) that can benefit the evaluated building and the total energy and cost reductions that can be achieved by implementing all recommended measures [47]. Table 2 shows the relationship between the calculated energy use parameters and energy efficiency measure recommendations. Overall, the BETTER tool is easy to use and requires minimal computational efforts with runtime for a single building analysis ranging between 5 and 10 s. However, the BETTER tool does not provide any specifications for the recommended EEMs and does not estimate their cost of implementation to assess their cost benefits. The BETTER tool determines energy cost savings based on estimations

of how much total energy use could be reduced if the building achieved user selected performance targets. Users can either enter their monthly utility cost data to make the estimated cost savings more accurate, or BETTER can select the default unit price for the applicable fuel type. Figure 1 shows the savings breakdown report produced by BETTER.

Table 2. List of energy use parameters and associated qualitative energy efficiency measures used in the BETTER tool.

Energy Use Parameters	Energy Efficiency Measure Recommendations
Low Cooling Change Point	<ul style="list-style-type: none"> • Increase Cooling Setpoints • Add/Fix Economizer • Upgrade Windows to Reduce Solar Heat Gain
High Heating Change Point	<ul style="list-style-type: none"> • Decrease Heating Setpoint • Ensure Adequate Ventilation Rate • Upgrade Windows to Improve Thermal Efficiency
High Electricity Baseload	<ul style="list-style-type: none"> • Reduce Equipment Schedule • Reduce Lighting Load • Reduce Plug Load
High Cooling Sensitivity	<ul style="list-style-type: none"> • Ensure Adequate Ventilation Rate • Increase Cooling System Efficiency • Upgrade Windows to Improve Thermal Efficiency • Upgrade Windows to Reduce Solar Heat Gain
High Heating Sensitivity	<ul style="list-style-type: none"> • Ensure Adequate Ventilation Rate • Increase Heating System Efficiency • Upgrade Windows to Improve Thermal Efficiency
High Electricity Heating Change Point	<ul style="list-style-type: none"> • Decrease Infiltration • Add Wall/Ceiling/Roof Insulation
High Electricity Cooling Change Point	<ul style="list-style-type: none"> • Decrease Infiltration • Add Wall/Ceiling/Roof Insulation
High Electricity Heating Sensitivity	<ul style="list-style-type: none"> • Decrease Infiltration • Use High Efficiency Heat Pump for Heating • Add Wall/Ceiling/Roof Insulation
High Fossil Fuel Baseload	<ul style="list-style-type: none"> • Upgrade to Sustainable Resource for Water Heating

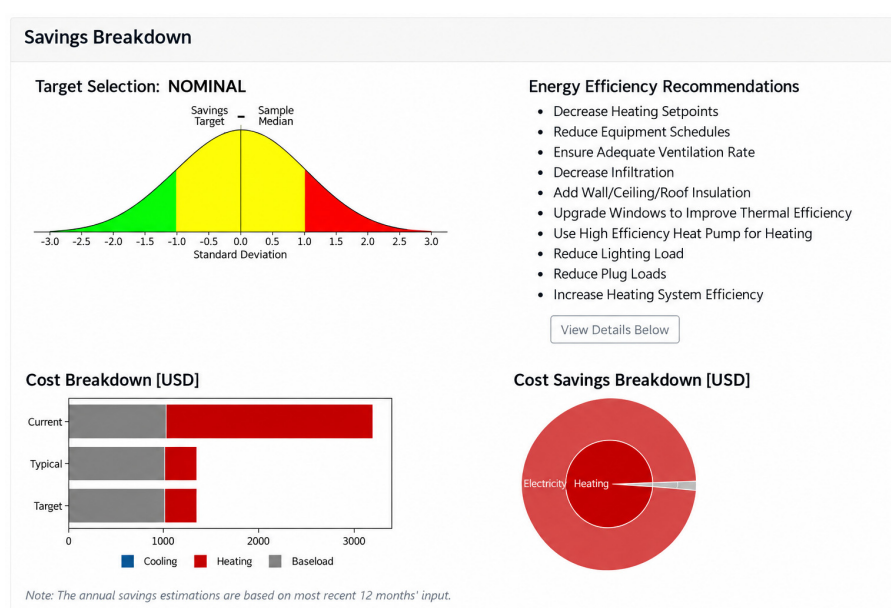


Figure 1. Energy and cost savings breakdown and energy efficiency recommendations estimated by BETTER.

2.1.2. DOE's Asset Score

DOE's Asset Score (Version 2023.0.0) is a web-based tool developed by DOE in partnership with the Pacific Northwest National Laboratory that utilizes a 10-point scale to evaluate the energy efficiency of an existing facility based on its physical characteristics and building energy systems. The tool utilizes whole-building energy simulation results to estimate the EUI and assign a score to the building [51]. It collects information related to building footprint, orientation, number of floors, envelope components, fenestration, lighting fixtures, mechanical components, water service heating, and operation schedules. Specifically, the tool has a drag and drop user interface where users can create a simplified geometry of their building by creating individual blocks in rectangular, H, L, T, and U shapes. Each block can be assigned a use-type among the following options: Assisted Living Facility, City Hall, Courthouse, Education, Library, Lodging, Medical Office, Multi-family Common Area, High-Rise Multi-family (4 floors or greater), Low-Rise Multi-family (fewer than 4 floors), Parking Garage (Heated Only), Parking Garage (Ventilation Only), Police Station, Post Office, Retail, Senior Center, and Warehouse non-refrigerated. The use type of buildings is utilized to define a pre-determined operation schedule. For each block, the user can define a specific roof, wall, window, and floor type. The tool also includes pre-defined Heating Ventilation and Air Conditioning (HVAC) and hot water system types that can be assigned to each individual block. In addition, each block can also have its own user-defined lighting system as well.

Based on the collected information, a simplified EnergyPlus energy model for the evaluated building is developed to determine its EUI. The Asset Score tool enables building owners and managers to evaluate their facility's current energy performance by using a score scale, ranging from 1 to 10, that depends on the building type and its EUI value [48]. Before scoring, the users are also provided with a list of potential retrofit measures that they can select to assess the change in the building's score when the measures are implemented.

Asset Score reports the cost of retrofit implementation as a qualitative range rather than as an absolute value with the retrofit capital costs sourced from Advance Energy Retrofit Guide and RSMeans. For energy costs, Asset Score utilizes COMNET (Commercial Buildings Energy Modeling Network) time-of-use energy cost data [48]. Additionally, to perform life cycle analysis, Asset Score assumes a 0% discount rate and a 25-year study period.

A set of EUI values is compiled by simulating the energy model of the prototypical building models corresponding to the building type being evaluated. The prototypical models represent the building type under various design and operation conditions by varying the building size and location. The evaluated building is assigned a score of 10 if its EUI corresponds to the upper 5th to 10th percentile of simulated EUIs of prototypical building models. A score of 8 to 9 is achieved if the evaluated building's EUI is 30% lower than that of a prototype building, complying with the minimum of ASHRAE Standard 90.1-2004. Scores of 5 to 6 are given to the evaluated buildings whose EUIs are equal to the median EUI achieved in the simulation environment. Lastly, the lowest asset score of 1 is given when the building EUI is lower than the 95th percentile of all modeled EUI values [48]. The tool also evaluates potential building upgrades using a set of EEMs selected by the user. Based on the chosen EEMs, an asset score is calculated to assess potential EUI improvement for the building [48]. Figure 2 shows the simplified geometry of a facility with the drag and drop option to add necessary HVAC systems.

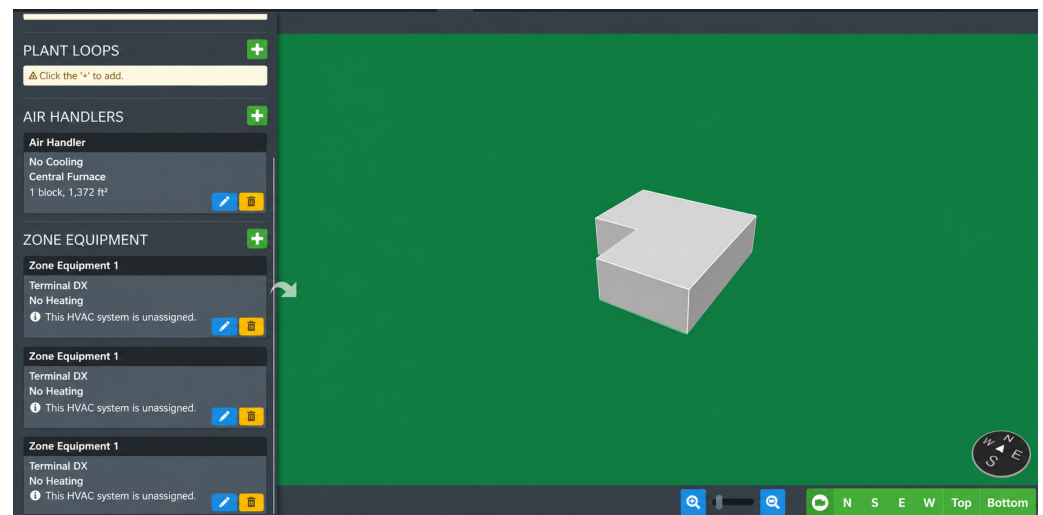


Figure 2. Simplified geometry of a facility with the drag and drop options to add necessary HVAC systems.

2.1.3. Energy Star Portfolio Manager (ESPM)

The Energy Star Portfolio Manager (ESPM) tool utilizes a regression-based modeling approach, based on the PRISM (PRinceton Scorekeeping Method) methodology [52], to evaluate the energy consumption of existing buildings and benchmark their performance [53]. PRISM is a statistical procedure that utilizes monthly billing data to develop an EUI metric normalized for weather variations [52]. The ESPM tool utilizes a degree-day modeling approach coupled with building-specific features including the number of occupants, operating hours, and number of different electrical equipment to develop a building-specific inverse model using multi-linear regression analysis. Regression coefficients are calculated by fitting the model to data collected by the Commercial Buildings Energy Consumption Survey (CBECS). In addition to this data, users can provide data related to conditioned and unconditioned floor areas, ceiling heights, number of weekdays, weekly operating hours, seating capacity, number of computers, and number of commercial refrigeration/freezer units. If users do not have access to this information, they have the option to select default values.

The ESPM tool then benchmarks the energy performance of the evaluated building with a score, ranging between 1 and 100, reflecting the fraction of comparable buildings that have higher normalized source EUIs [53]. For example, an Energy Star score of 55 indicates that the evaluated building's EUI is better than 55 percent of similar buildings nationwide. Users can also input updated utility data at periodic intervals to track their building's performance. Additionally, ESPM utilizes the building's actual utility cost data when it is entered directly by the user or transferred from the utilities.

Figure 3 shows the output of Energy Star Portfolio Manager.

2.1.4. Commercial Building Energy Saver (CBES)

The CBES tool allows users to analyze the energy performance of buildings using pre- and post-retrofit conditions as well as identify optimal energy retrofit measures based on their energy and cost benefits. Depending on the user's expertise level and the degree of the input data available, CBES provides three levels of retrofit analysis including (1) Load Shape Analysis (Level 1) to identify potential building operation problems as well as unexpected changes in energy use patterns; (2) Preliminary Retrofit Analysis (Level 2) to perform a basic assessment of select retrofit measures including their energy and cost benefits; and (3) detailed retrofit analysis (Level 3) to perform EnergyPlus-based modeling using data provided by the user including detailed building description and its operational

characteristics. CBES includes a large database of retrofit options compiled using Database for Energy Efficiency Resources, Advanced Energy Retrofit Guide for Office Buildings, Advanced Energy Retrofit Guide for Retail Buildings, Advanced Energy Design Guide for Small to Medium Office Buildings, Small HVAC System Design Guide, and RSMeans. CBES retrofit database includes detailed descriptions of the technical specifications, modeling methods, and investment costs for each retrofit option.

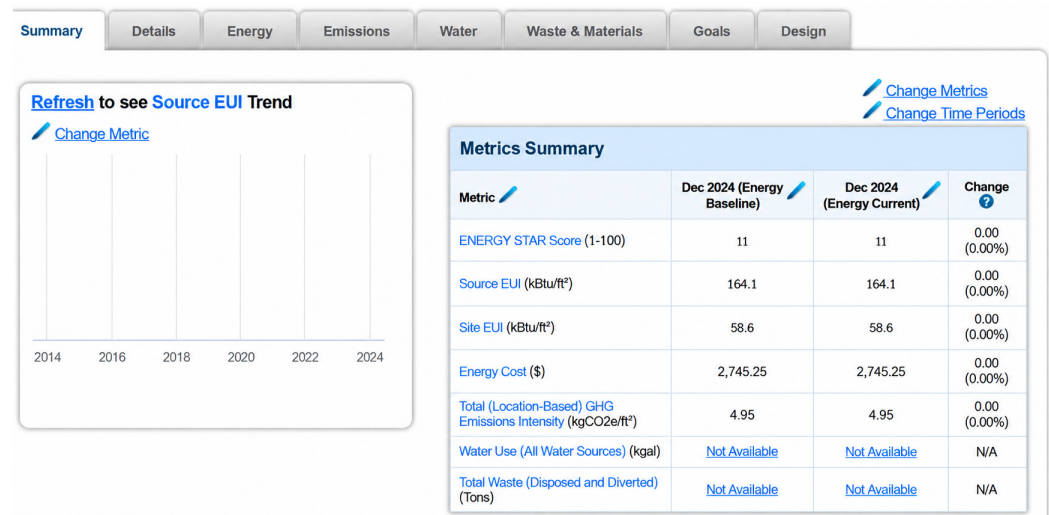


Figure 3. Summary output screen for Energy Star Portfolio Manager.

The preliminary retrofit analysis utilizes the SQL database containing pre-simulated results of about 10 million Energy-Plus simulations. Each simulation calculated the energy performance of different EEMs in conjunction with 7 prototype buildings, 16 climates, and 6 vintages. Users can provide their investment criteria (maximizing energy cost saving, maximizing energy savings, minimizing CO₂ emissions, minimizing investment costs, minimizing payback period) before preliminary analysis. Using the investment criteria and SQL database, CBES provides users with individual and package retrofit options. Users are also given the opportunity to provide energy prices for estimating energy cost savings. The implementation cost data of multiple Energy Conservation Measures (ECMs) were compiled using the Database for Energy Efficiency Resources (DEER), the Advanced Energy Retrofit Guide for Office Buildings, Advanced Energy Retrofit Guide for Retail Buildings, Advanced Energy Design Guide for Small to Medium Office Buildings, Small HVAC System Design Guide, and RSMeans [5].

The detailed retrofit analysis conducted by CBES employs advanced automated calibration algorithms to estimate the energy savings of EEMs. The calibration method utilizes a pattern-based approach comparing the monthly measured and simulated energy use of the evaluated building to establish any bias. The bias is then categorized as universal if it is consistent year-round or seasonal if it varies depending on the season. Based on the bias category, different sets of model parameters are adjusted during the calibration process. CBES adjusts one parameter at a time and runs the simulation to check for successful model calibration. If the model is not calibrated, it determines a new bias category and adjusts the next parameter [5]. The calibration stops when the difference between the simulated and measured monthly electricity and natural gas data meets the criteria defined in ASHRAE Guideline 14; that is, the Normalized Mean Bias Error (NMBE) is less than 5%, and the Coefficient of Variation of the Root Mean Square Error (CVRMSE) is less than 15%. CBES can calibrate 16 main parameters including occupant density, lighting power density, electric equipment power density, outdoor air flow rate, infiltration rate, cooling efficiency,

heating efficiency, fan efficiency, cooling setpoint, heating setpoint, economizer presence, window U-value, window Solar Heat Gain Coefficient (SHGC), HVAC operation schedule, lighting schedule, and electric equipment schedule.

CBES utilizes EnergyPlus models created using user input to evaluate individual and package retrofit measures. Selection of individual retrofit measures is based on the result of level 2 analysis.

Moreover, the CBES tool utilizes EnergyIQ and Energy Star Portfolio Manager to perform benchmarking analysis utilizing building description and monthly utility data [5]. The tool is also capable of calculating energy cost savings, energy savings, electricity usage/cost savings, natural gas usage/cost savings, electricity usage, natural gas, electricity demand charges, energy costs, CO₂ emissions, investment costs, and payback periods at preliminary and detailed retrofit analysis level. At the detailed retrofit analysis level, the tool also allows users to create up to four packages based on selecting individual measures to conduct packaged retrofit analysis. Figure 4 shows the preliminary data input screen of CBES. Table 3 shows the ECM that can be evaluated by CBES.

Table 3. ECM that can be evaluated by CBES.

ECM #	Measure Abbreviation	Category	Name
1	M_L1	Lighting	Replace existing lighting with T8 upgrade (0.7 W/sf)
2	M_L2	Lighting	Replace existing lighting with T5 upgrade (0.67 W/sf)
3	M_L3	Lighting	Replace existing lighting with LED upgrade (0.6 W/sf)
4	M_C1	HVAC—Cooling	Single zone rooftop unit efficiency upgrade (SEER 12.5)
5	M_C2	HVAC—Cooling	Single zone rooftop unit efficiency upgrade (SEER 14)
6	M_C1	HVAC—Cooling	Packaged Rooftop VAV Unit Efficiency Upgrade (SEER 12.5)
7	M_C2	HVAC—Cooling	Packaged Rooftop VAV Unit Efficiency Upgrade (SEER 14)
8	M_H1	HVAC—Heating	Gas Furnace Efficiency Upgrade (AFUE 92)
9	M_H1	HVAC—Heating	Gas Boiler Efficiency Upgrade (AFUE 92)
10	M_H2	HVAC—Heating	Gas Furnace Efficiency Upgrade (AFUE 95)
11	M_H2	HVAC—Heating	Gas Boiler Efficiency Upgrade (AFUE 95)
12	M_Econ1	HVAC—Economizer	Add Economizer
13	M_Inf1	Envelope—Infiltration	Add Air Sealing to Seal Leaks
14	M_Plug1	Plug Loads	Plug Load Efficiency Upgrade (25% efficient from Baseline)
15	M_Plug2	Plug Loads	Use Plug Load Controller (30% efficient from Baseline)
16	M_R1	Envelope—Roof	Reroof and Roof with Insulation
17	M_R2	Envelope—Roof	Apply Cool Roof Coating with Reflectivity
18	M_SHW1	Service Hot Water	Efficiency Upgrade of the Gas Storage Water Heater
19	M_W1	Envelope—Exterior Wall	Apply Wall Insulation (R15)
20	M_W2	Envelope—Exterior Wall	Apply Wall Insulation (R19)
21	M_W3	Envelope—Exterior Wall	Apply Wall Insulation (R21)
22	M_Win1	Envelope—Window	Replace fixed-window to U-factor (0.29) and SHGC (0.2)
23	M_Win2	Envelope—Window	Replace fixed-window to U-factor (0.25) and SHGC (0.18)
24	M_R3	Envelope—Roof	Apply Top Floor Ceiling Insulation(R30)
25	M_R4	Envelope—Roof	Apply Top Floor Ceiling Insulation(R38)
26	M_HVACThermostat1	HVAC—Operation & Maintenance	Add Programmable Thermostat
27	M_Daylighting1	Lighting—Controls	Install daylighting sensors for interior lighting control
28	M_L5OccupancySensor	Lighting—Controls	Install Wall-Mounted Occupancy Sensors
29	M_Fan1	HVAC—Ventilation	Replace Air Filter
30	M_SHW5	Service Hot Water	Improve Water Tank Insulation
31	M_SHW4	Service Hot Water	Upgrade to Gas Instantaneous Water Heater
32	M_CeilingFan1	HVAC—Ventilation	Add Ceiling Fan

Basic information

*Building type: Office - small 1 story

Year built: 1940

California zip code: 96128

Gross floor area (square feet): 1392

**Retail floor area percentage (%): 0.0

Note: * More customization (such as number of stories) can be done in Detailed Retrofit Analysis. ** Only required for mixed use buildings.

Update Saved at 20 Nov 11:23

Investment criteria

Priority for measure selection: Maximizing energy savings

*Maximum budget (\$):

*Maximum payback year:

Note: *Optional

Update Saved at 20 Nov 11:23

Energy price

Electricity (\$/kWh): 0.166667

Natural gas (\$/therm): 0.917

Electricity demand (\$/kW): 2.52

Update Saved at 20 Nov 11:23

CO2 emission factors

Electricity (lb/MWh): 386.655

Natural gas (lb/MWh): 399.484

Update Saved at 20 Nov 11:23

Note: The default values of Energy price and CO2 emission factors are based on the zip code, and automatically updated when the zip code is changed. You are welcome to overwrite the default values.

Energy Data

Smart meter data (Green Button Data format)

Service Type: Electricity, Natural Gas

Uploaded: No, No

Select a new XML file: Browse... No file selected.

Update Saved at 20 Nov 11:22

The smart meter data must be Green Button Data format. The electricity data should have hourly or sub-hourly interval for the recent year. Uploading smart meter data will automatically generate values for monthly energy data below. Or, if smart meter data are NOT available, input monthly energy usage data below.

Monthly energy data

First Bill Date: 2019 Jan 1

The Bill Start Date and Bill End Date below will be automatically updated when the First Bill Date above is changed. The Bill Periods (number of days) are used in the Building Model Calibration.

Bill Start Date	Bill End Date	Electricity Usage (kWh)	Natural Gas Usage (Therm)
2023 Nov 1	2023-Nov-30	3113.00	
2023 Dec 1	2023-Dec-31	3670.00	
2024 Jan 1	2024-Jan-31	4315.00	
2024 Feb 1	2024-Feb-29	3025.00	
2024 Mar 1	2024-Mar-31	2846.00	
2024 Apr 1	2024-Apr-30	1998.00	
2024 May 1	2024-May-31	1363.00	
2024 Jun 1	2024-Jun-30	590.00	
2024 Jul 1	2024-Jul-31	63.00	
2024 Aug 1	2024-Aug-31	414.00	
2024 Sep 1	2024-Sep-30	651.00	
2024 Oct 1	2024-Oct-31	1866.00	

Update Saved at 20 Nov 11:26

Figure 4. Preliminary data input screen for CBES tool.

2.1.5. Simplified and Automated Building Energy Retrofit (SABER)

SABER is a Python (Version 3.15)-based tool with an interactive graphical user interface (GUI) allowing users to model and analyze individual, combined, and optimized retrofit options for existing buildings [7]. SABER utilizes user input for building geometry, occupancy type, and energy systems, as well as utility data to generate detailed whole-building energy simulation model of the existing building based on predefined model templates. The developed building energy model is then calibrated based on the provided utility data. SABER requires at least 12 months of utility data and can process up to three years of utility data. The calibration procedure used by SABER is based on adjusting operational schedule parameters, especially electricity and natural gas baseloads and monthly heating and cooling setpoints [7]. Heating setpoints are constrained to be within the 10–25 °C range; cooling setpoints are set to vary between 15 °C and 35 °C. These ranges are the default bounds and can be changed by the user. A building energy model is considered calibrated when the relative error between simulated and utility electricity/gas consumption is within 5% for each month. The calibrated model accuracy is ultimately checked using CVRMSE and NMBE against ASHRAE Guideline 14 monthly calibration criteria.

Using the calibrated building energy model, SABER can assess the impact of several individual and packaged energy efficiency measures. SABER allows users to analyze energy and cost benefits among multiple retrofit measures selected by the user or through an optimization process defined by a preselected objective function and a set of constraints. To identify the cost benefits for each retrofit measure, SABER can perform life cycle cost analysis. Users are given freedom to select the economic parameters for the analysis including discount rates, energy prices, analysis periods, implementation costs of the evaluated retrofit measures. However, SABER can also utilize default implementation costs [46].

In summary SABER allows users to (i) automatically generate building energy model suitable for EnergyPlus using user-specified input data, (ii) automatically calibrate the existing building model to match simulation predictions with utility data, (iii) estimate cost and energy savings of individual and packaged energy efficiency measures, and (iv) identify the most cost-effective combination of retrofit measures based on user selected cost functions and constraints using a predefined optimization algorithm. Figure 5 shows one of input screens for SABER tool where users can enter information regarding building location, utility data, and available building system information.

Figure 5. Input screen for the SABER tool.

3. Methodology

To address the two research questions outlined in Section 2, this study adopts a two-step analysis approach as illustrated in Figure 6. In Step 1, two prototypical buildings are selected for a systematic comparative analysis against a well-established whole-building simulation tool, EnergyPlus, using (1) a Place of Worship [54] and (2) a Small Office building. EnergyPlus simulations are first performed for both prototypes to establish baseline energy consumption and generate representative monthly utility data. Because these buildings are prototypical models rather than real facilities, the baseline EnergyPlus simulations are treated as the ground-truth reference for the comparative analysis. The selected retrofit analysis toolkits are then applied to both building prototypes to identify sets of recommended retrofit measures. For each toolkit, the required input data, recommended measures, estimated energy savings, estimated energy cost savings, and life cycle cost outputs, where applicable, are documented. To evaluate the accuracy of toolkit-predicted energy savings, each recommended retrofit measure, whether individual or packaged, is independently implemented in EnergyPlus and its associated energy and cost benefits are estimated relative to the baseline model. The resulting EnergyPlus-predicted savings are then compared with the savings reported by each toolkit, and the prediction differences between all the toolkits and EnergyPlus are calculated and reported. This approach enables a controlled and systematic comparative analysis of the performance of the selected toolkits for two different prototypical buildings.

In Step 2, the selected retrofit analysis toolkits are applied to four real-world existing buildings to identify potential retrofit measures and their associated energy savings. The recommended measures are then discussed with the respective building owners to assess their practical feasibility. These discussions are used to identify cases in which recommended retrofit measures with high predicted energy saving potential may still be difficult or infeasible to implement because of building-specific operational, financial, market, cultural, regulatory, or infrastructure-related constraints. The identified barriers are subsequently synthesized to highlight practical limitations of current retrofit assessment tools and to identify opportunities for future tool developments and upgrades, so that retrofit recommendations better reflect real-world implementation conditions.

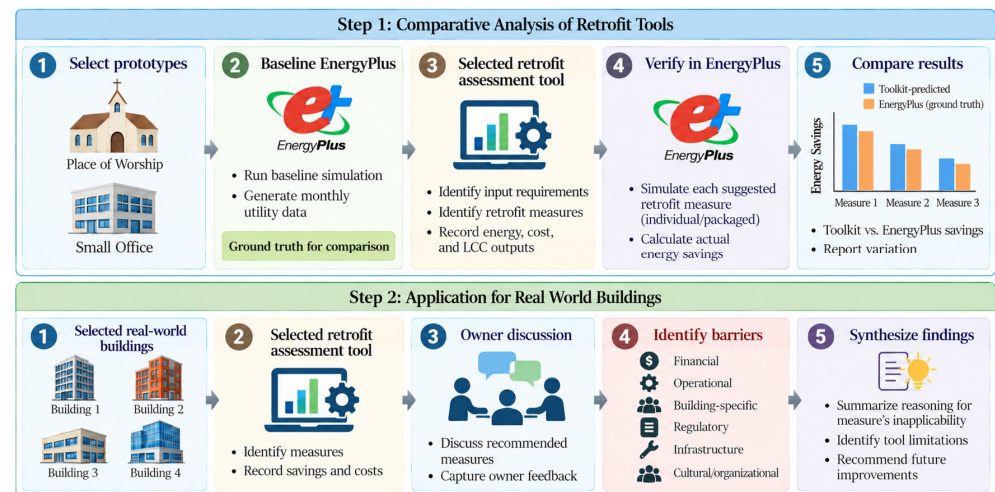


Figure 6. Adopted methodology for the comparative analysis of selected retrofit analysis toolkits.

4. Comparative Analysis of Retrofit Tools

Out of five selected retrofit analysis tools in Section 2, only four tools can be used to conduct a comparative retrofit analysis with the whole-building detailed energy simulation engine, as ESPM is not capable of performing any retrofit analysis. The capabilities and limitations of four selected retrofit analysis tools are evaluated by applying them to perform energy retrofit analysis for two prototypical buildings: (1) Place of Worship [54] and (2) Small Office Space. Both the buildings are in ASHRAE climate zone 3C (i.e., San Francisco and San Diego, California). The baseline energy simulation for both the prototypical models was conducted using EnergyPlus. The simulation provided baseline monthly utility data, yearly total site energy consumption, yearly total site electricity consumption, yearly total site natural gas consumption, yearly total site heating energy consumption, and yearly total site cooling energy consumption.

To verify the retrofit analysis and energy saving estimates calculated by each tool, suggested retrofit measures were implemented in respective EnergyPlus models, and the percentage energy savings were calculated and used for the comparative analysis with the simplified retrofit analysis tools.

4.1. Prototypical Buildings

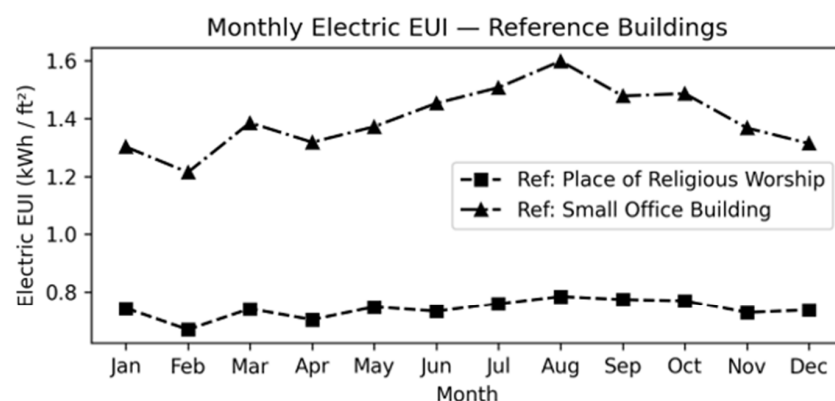
The prototypical place of worship located in San Francisco, CA, has three main conditioned zones: a large meeting area, classroom area, and office area. The occupied floor area is approximately 12,600 ft² (1171 m²), with the meeting area accounting for about half of the total area. The building has a relatively low window-to-wall ratio of about 11.5%, with simple glazing rated at approximately SHGC 0.54 and U-factor 1.03 Btu/hr-ft²-F (5.85 W/m²·K). The lighting power density is estimated to be 1.4 W/ft² (15.07 W/m²) in the classroom and office area and 0.9 W/ft² (9.69 W/m²) in the meeting space. The building is served by packaged rooftop air conditioning systems with natural gas heating and DX cooling, with heating efficiency of 0.78 and cooling COP of 3.27.

The prototypical office building located in San Diego, CA, is a single-story office with five conditioned thermal zones: one core zone and four perimeter zones. The total conditioned floor area is approximately 5500 ft² (511 m²). The average window to wall ratio of the office building is 23%, using single-pane windows with a U-factor of about 1.027 Btu/hr-ft²-F (5.83 W/m²·K) and SHGC of 0.76. The average lighting power density is estimated to be 1.01 W/ft² (10.87 W/m²). The HVAC system consists of five packaged A/C units with rated COP of 2.34 and five gas furnaces with efficiency of 0.8, one serving each conditioned zone.

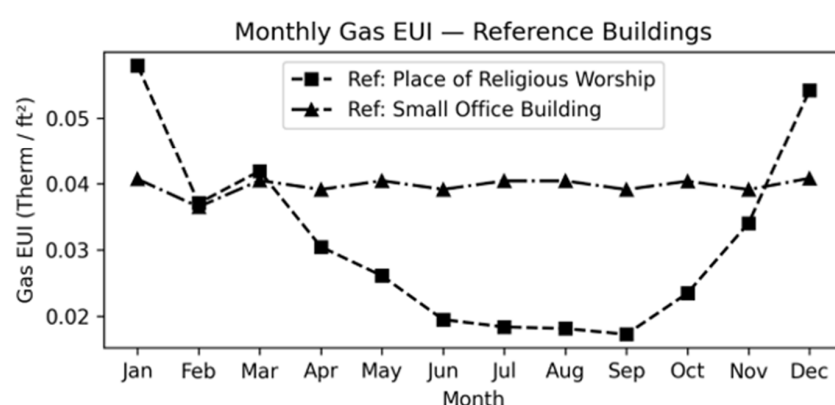
Table 4 summarizes the main features of the prototypical buildings and associated EnergyPlus simulation settings. Figure 7 shows the monthly electricity and natural gas consumption of both the prototypical buildings estimated using EnergyPlus. These electricity and natural gas data are used as utility data for the evaluated simplified retrofit analysis tools.

Table 4. Summary of main characteristics of the two prototypical buildings and respective EnergyPlus simulation settings.

	Prototypical Place of Worship	Prototypical Office Building
Location	San Francisco, CA	San Diego, California
Facility Type	Place of Worship	Small Office
Square Footage (sq.ft.)	12,600 ft ² (1171 m ²)	5500 ft ² (511 m ²)
Aspect Ratio	1.93	1.5
Orientation	North	North
Built Year	Pre 1980	2013
Wall Insulation (U-Factor no Film [Btu/h·ft ² ·°F (W/m ² ·K)])	0.258 Btu/h·ft ² ·°F (1.46 W/m ² ·K) (~R-4)	0.135 Btu/h·ft ² ·°F (0.77 W/m ² ·K) (~R-7.4)
Roof Insulation (U-Factor no Film [Btu/h·ft ² ·°F (W/m ² ·K)])	0.085 Btu/h·ft ² ·°F (0.48 W/m ² ·K) (~R-12)	0.83 Btu/h·ft ² ·°F (4.71 W/m ² ·K) (~R-1.21)
Foundation	Basement with Slab on Grade	Slab on Grade
Windows	Window U-Factor: 1.027 Btu/ft ² ·hr·°F (5.83 W/m ² ·K) and SHGC 0.54	Window U-Factor: 1.027 Btu/ft ² ·hr·°F (5.83 W/m ² ·K) and SHGC 0.76
Percentage LED	0%	0%
Lighting Power Density (W/sq.ft)	0.9 W/ft ² (9.69 W/m ²) in meeting areas and 1.4 W/ft ² (15.07 W/m ²) all other areas	1.01 W/ft ² (10.87 W/m ²)
Plug Load (W/sq.ft.)	0.23 W/ft ² (2.48 W/m ²)	0.63 W/ft ² (6.78 W/m ²)
HVAC System (Cooling)	Packaged A/C Unit (Rated COP: 3.27)	Packaged A/C Unit (Rated COP: 2.34)
HVAC System (Heating)	Furnace (Efficiency: 0.78)	Furnace (Efficiency: 0.80)
Water Heating Efficiency (Natural Gas)	0.78	0.80
Floor U factor no film (Btu/h·ft ² ·F [W/m ² ·K])	0.39 Btu/h·ft ² ·°F (2.21 W/m ² ·K) (~R-2.52)	0.057 Btu/h·ft ² ·°F (0.32 W/m ² ·K) (~R-17.5)
Total Site Energy Usage (kBtu [kWh])	836,661 kBtu (245,201 kWh)	577,345 kBtu (169,203 kWh)
Electricity Consumption (kBtu [kWh])	387,370 kBtu (113,527 kWh)	315,278 kBtu (92,399 kWh)
Natural Gas Consumption (kBtu [kWh])	449,291 kBtu (131,674 kWh)	262,066 kBtu (76,804 kWh)
Heating Energy (kBtu [kWh])	294,096 kBtu (86,191 kWh)	703 kBtu (206 kWh)
Cooling Energy (kBtu [kWh])	16,041 kBtu (4701 kWh)	51,913 kBtu (15,214 kWh)
EUI (kBtu/ft ² [kWh/m ²])	66.40 kBtu/ft ² (209.46 kWh/m ²)	104.92 kBtu/ft ² (330.98 kWh/m ²)
EnergyPlus Version	25.1	25.1
EnergyPlus Weather File	USA_CA_San.Francisco.Intl.AP.724940_TMY.epw	USA_CA_San.Diego.722900_TMY2.epw
EnergyPlus Infiltration Rate	0.0984 cfm/ft ² (0.000500 m ³ /s·m ²)	0.1121 cfm/ft ² (0.000569 m ³ /s·m ²)
EnergyPlus Ventilation Rate	14.33 cfm/person (0.00676 m ³ /s·person)	0.0850 cfm/ft ² (0.000432 m ³ /s·m ²)
EnergyPlus HVAC System	Packaged rooftop air conditioner with single-speed DX cooling, gas heating, and constant-volume fan	Packaged rooftop heat pump air loop with single-speed DX cooling, fuel-fired heating coil, and constant-volume fan.
EnergyPlus Heating Setpoint	Uses separate schedules for meeting and office zones; approximately ~69.5–70 °F (20.8–21.1 °C) during conditioned periods and about ~59.6–60 °F (15.3–15.6 °C) during setback periods	70 °F (21.11 °C) during occupied hours. Setback: 60 °F (15.56 °C)
EnergyPlus Cooling Setpoint	Uses separate meeting/office cooling schedules, with occupied/unoccupied setpoints defined by zone schedules	75 °F (23.89 °C) during occupied hours. Setback: 85 °F (29.44 °C)
EnergyPlus HVAC operation	Air loop and coils are set to Always On, while actual heating/cooling operation is governed by thermostat demand	The air loop and associated heating and cooling components use an Always On availability schedule, while actual HVAC operation is determined by the zone thermostat setpoint schedules and resulting heating or cooling demand



(a)



(b)

Figure 7. Monthly (a) electricity and (b) natural gas variations for the prototypical Place of Worship and Office Building.

4.1.1. BETTER

Using the monthly utility data estimated from EnergyPlus simulations of the two prototypical buildings, the BETTER tool was applied to conduct retrofit energy assessments. The BETTER tool developed change point models from the provided utility data, as illustrated in Figure 8 for the Place of Worship and Figure 9 for the Office Building. Based on these models and a comparative analysis with similar buildings available in the BETTER portfolio, the tool estimated the potential energy savings for both buildings, as summarized in Table 5.

Table 5. Summary of output by the BETTER tool for prototypical buildings.

	Prototypical Place of Worship	Prototypical Office Building
Location	San Francisco, CA	San Diego, CA
Facility Type	Place of Worship	Office
BETTER Facility Type	Worship Facility	Office
Fossil Fuel Used	Natural Gas	Natural Gas
EUI (kBtu/ft ² [kWh/m ²])	68 kBtu/ft ² (214.51 kWh/m ²)	104.89 kBtu/ft ² (330.89 kWh/m ²)
Electricity Consumption (kBtu [kWh])	381,411 kBtu (111,781 kWh)	315,312 kBtu (92,409 kWh)
Natural Gas Consumption (kBtu [kWh])	478,883 kBtu (140,347 kWh)	262,131 kBtu (76,823 kWh)
Combined Annual GHG Emissions Intensity (lbCO ₂ e/ft ² [kgCO ₂ e/m ²])	8.84 lbCO ₂ e/ft ² (43.16 kgCO ₂ e/m ²)	13.89 lbCO ₂ e/ft ² (67.82 kgCO ₂ e/m ²)
User Define R2	0.6	0.6
Analyzed R2 for Electricity	0.97	0.87

Table 5. Cont.

	Prototypical Place of Worship	Prototypical Office Building
Analyzed R2 for Fossil Fuel Portfolio included in the BETTER database	0.91 Yes	- Yes
Calculated potential cost savings	\$31,595.88, 70.4%	\$11,636, 47.1%
Calculated potential energy savings (kBtu [kWh])	612,412 kBtu (179,480 kWh), 71.5%	367,184 kBtu (107,611 kWh), 63.6%
Percentage of buildings analyzed building is superior to (Electricity).	<ul style="list-style-type: none"> • Baseload: 0% • Cooling Slope: 83.9% • Cooling Change point: 28.4% 	<ul style="list-style-type: none"> • Baseload: 9.4% • Cooling Slope: 45.6% • Cooling Change point: 68.5%
Percentage of buildings analyzed building is superior to (Fossil Fuel).	<ul style="list-style-type: none"> • Baseload: 0.0% • Heating Slope: 1.8% • Heating Change point: 60.6% 	<ul style="list-style-type: none"> • Baseload: 0.0%
Suggested Retrofit Measures	<ul style="list-style-type: none"> • Reduce Equipment Schedules • Reduce Lighting Load • Reduce Plug Loads • Increase Heating System Efficiency • Upgrade to Sustainable Resources for Water Heating • Upgrade Windows to Reduce Solar Heat Gain • Increase Cooling Setpoints • Add/Fix Economizers 	<ul style="list-style-type: none"> • Reduce Equipment Schedules • Reduce Lighting Load • Reduce Plug Loads • Increase Cooling System Efficiency • Upgrade to Sustainable Resources for Water Heating • Upgrade Windows to Reduce Solar Heat Gain

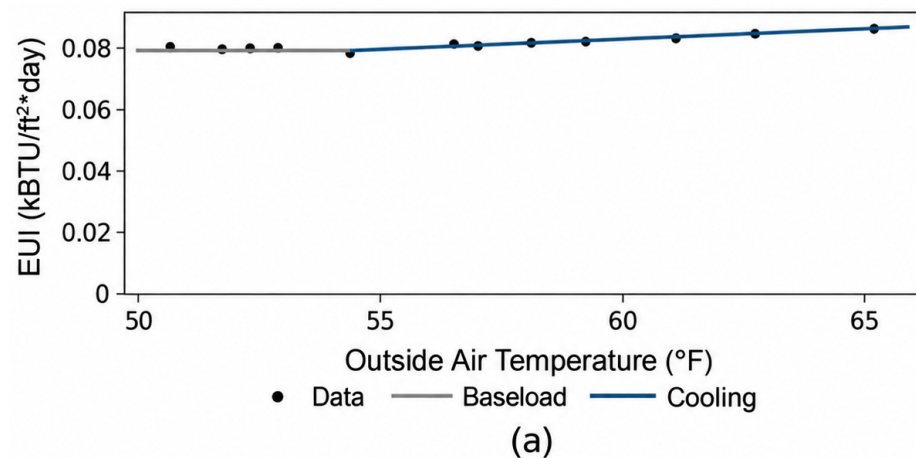
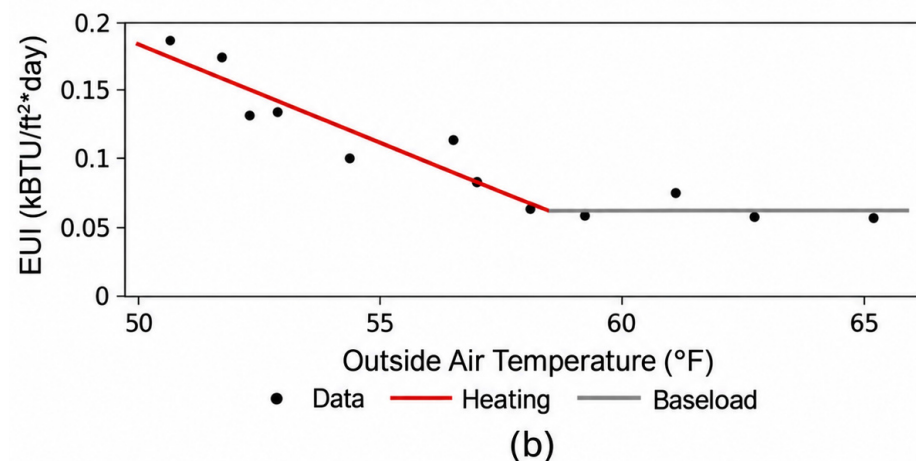


Figure 8. Change point models generated by the BETTER tool for the prototypical Place of Worship (a) cooling and (b) heating energy needs.

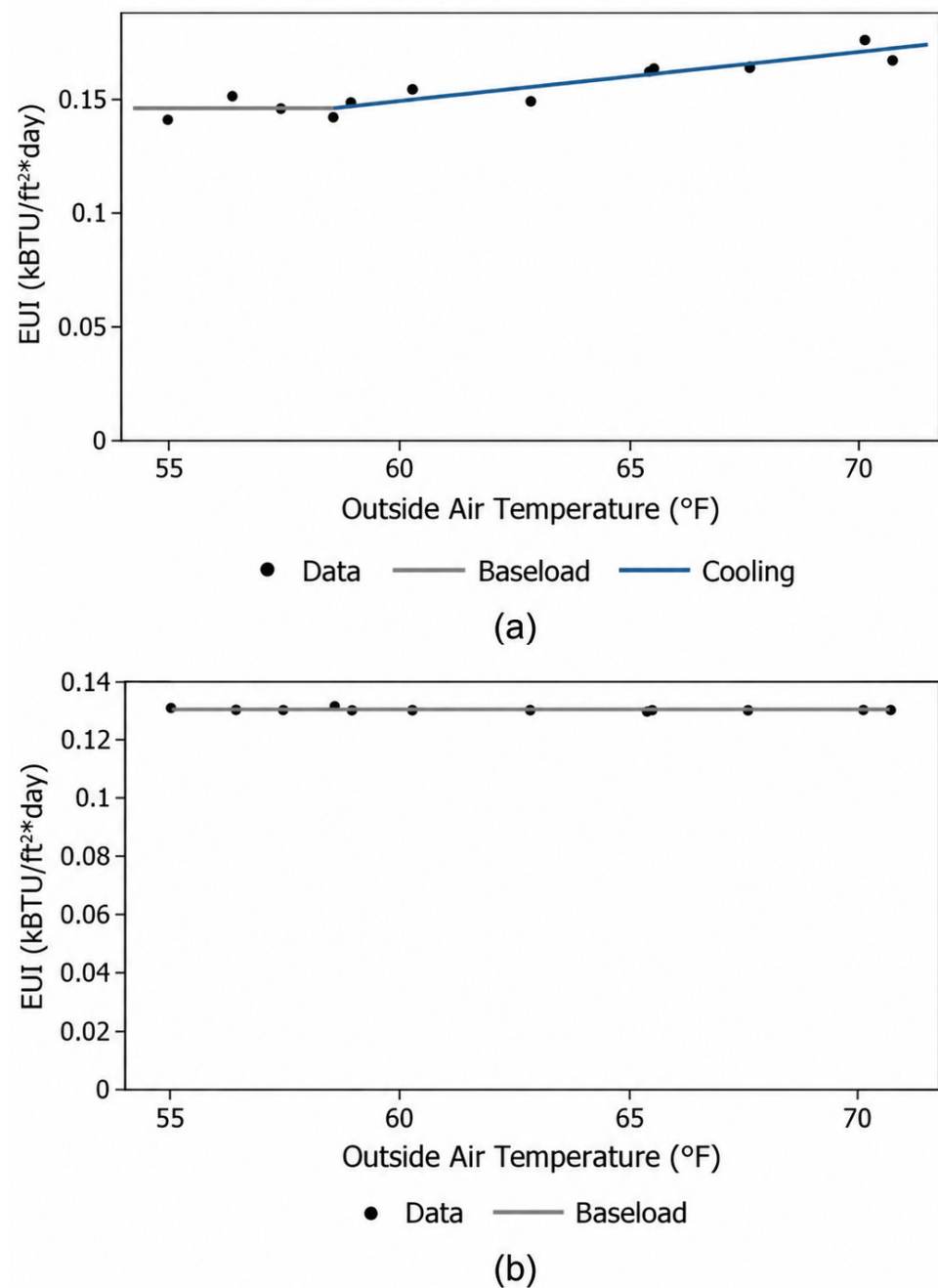


Figure 9. Change point models generated by the BETTER tool for the Office Space (a) cooling and (b) heating energy needs.

4.1.2. Asset Score

Using a simplified geometry, the prototypical Place of Worship was modeled in the Asset Score environment, as illustrated in Figure 10. The building was divided into three thermal zones, with building systems assigned to each zone to reflect the different usage patterns within the building prototype. Overall, the simplified geometry and system configuration for the Place of Worship building in Asset Score were set to approximate the corresponding EnergyPlus representations as closely as possible. In contrast, the prototypical Office Building was modeled in Asset Score as a single block with one thermal zone and one HVAC system, as shown in Figure 11. Compared with the correspondent EnergyPlus model, this representation was substantially more simplified, highlighting the geometric and system-modeling limitations of Asset Score.

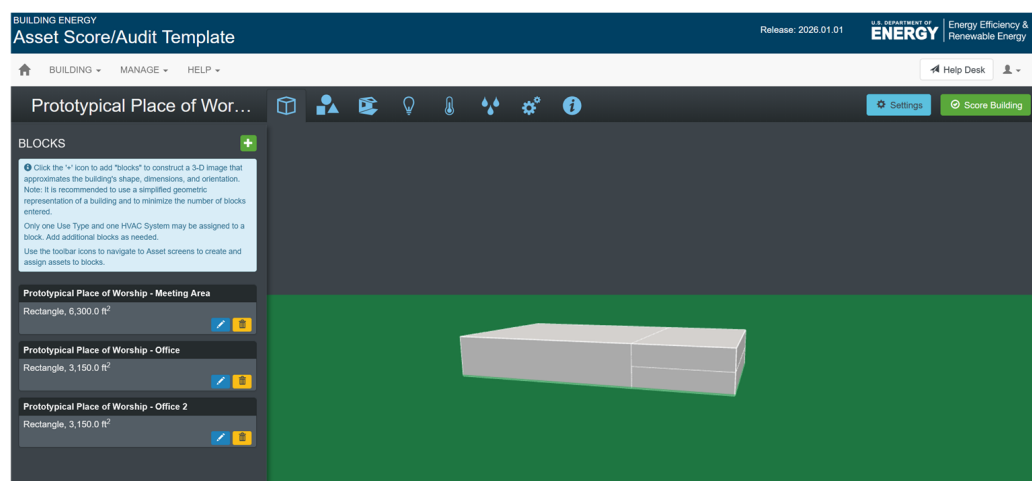


Figure 10. Simplified geometry of the prototypical Place of Worship created for Asset Score.

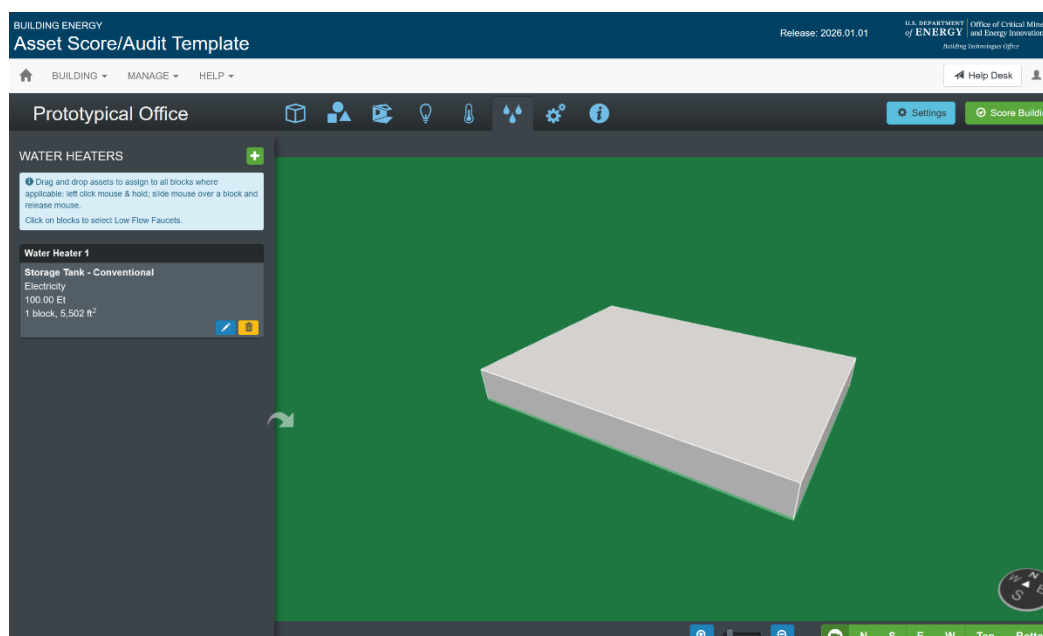
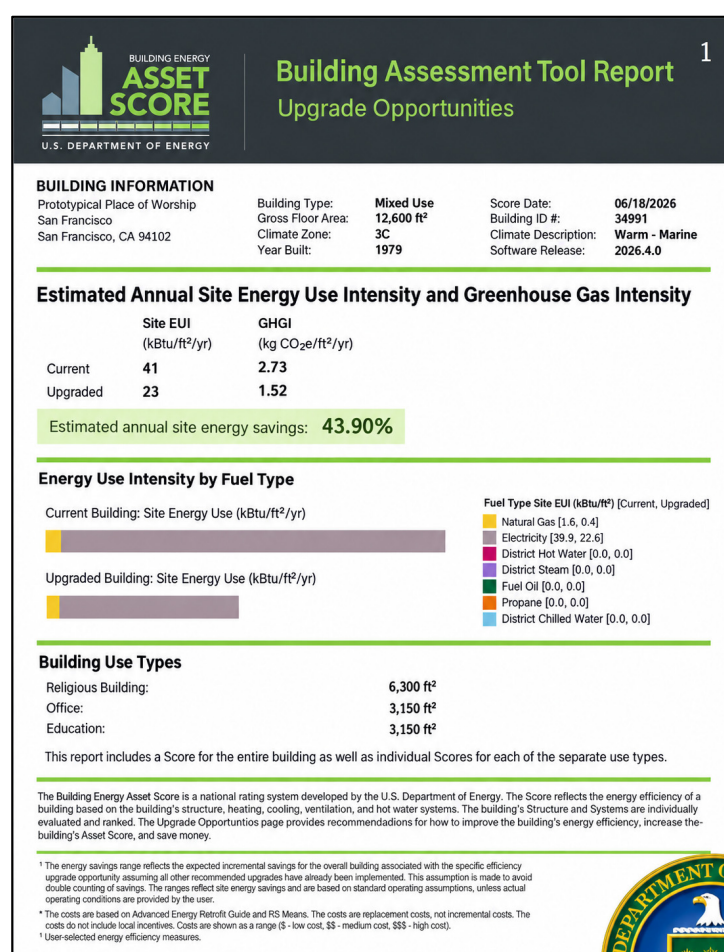


Figure 11. Simplified geometry of the prototypical Office Building created for Asset Score.

Based on the selected space type, Asset Score automatically assigned occupancy assumptions to the building models. Using the specified building type and system characteristics, Asset Score then identified potential retrofit measures for each prototypical building. These recommendations are summarized in Table 6, with representative Asset Score output screens shown in Figure 12 for the Place of Worship and Figure 13 for the Office Building. The potential energy savings associated with the recommended retrofit measures were subsequently evaluated by Asset Score as a combined retrofit package, with the resulting energy savings also reported in Table 6.

Table 6. Summary of the assessment results from Asset Score for the two prototypical buildings.

	Prototypical Place of Worship	Prototypical Office Building
Location	San Francisco, CA	San Diego, CA
Facility Type	Place of Worship	Office
Number of blocks	1	1
Block use type	Religious Building; Office; Education	Office
Estimated annual site energy savings	39.02%	67.21%
Asset Score	7	2
Upgrade Opportunity	<ul style="list-style-type: none"> • Add Roof Insulation • Add a Cool Roof • Add Wall Insulation • Seal Building Envelope • Upgrade to High-performance Windows • Add Occupancy Sensors • Upgrade to LED Fixtures • Replace HVAC with High-performance Packaged Rooftop Heat Pump and a DOAS • Upgrade Heat Pump Hot Water Heater • Add Low Flow Service Hot Water Fixtures 	<ul style="list-style-type: none"> • Seal Building Envelope • Add Roof Insulation • Add a Cool Roof • Add Wall Insulation • Upgrade to High-performance Windows • Add Occupancy Sensors • Upgrade to LED Fixtures for Lighting Fixture • Replace HVAC with High-performance Packaged Rooftop Heat Pump and a DOAS • Add Low Flow Service Hot Water Fixtures • Upgrade Heat Pump Hot Water Heater

**Figure 12.** Summary output screen Asset Score for prototypical Place of Worship.

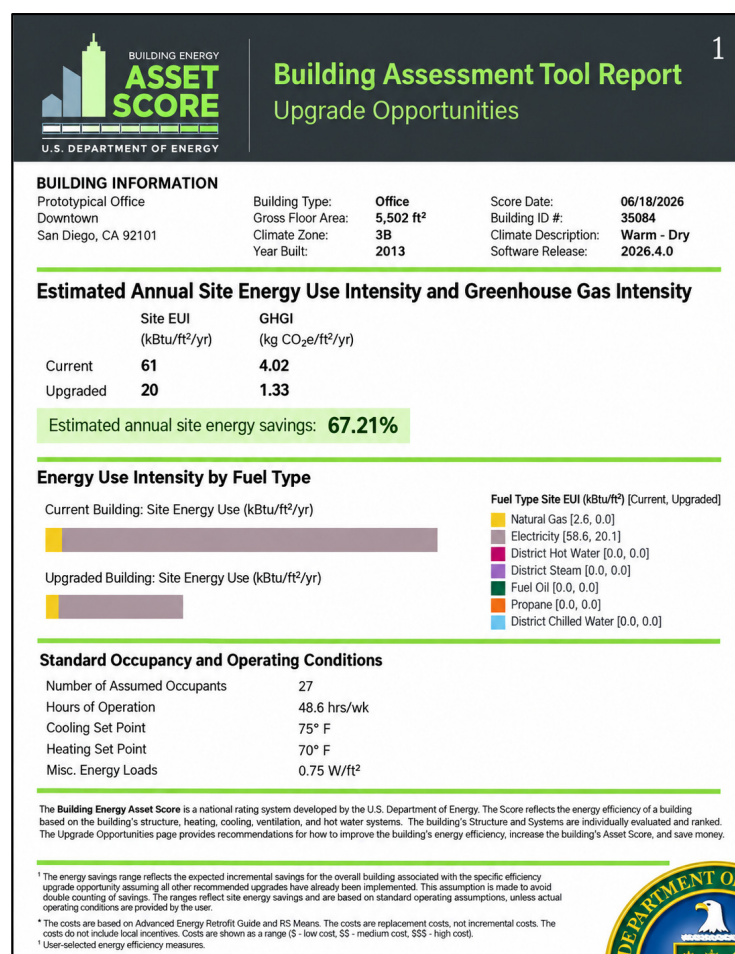


Figure 13. Summary output screen Asset Score for prototypical Office Building.

4.1.3. Commercial Building Energy Saver

In its current version, CBES has a relatively limited scope and set of analysis capabilities. The tool is restricted to office and retail building types located in California; therefore, the Place of Worship was represented using a small office building model for the CBES analysis. In addition, CBES is limited to buildings that use natural gas for heating. Table 7 summarizes the retrofit analysis results obtained from CBES for the two prototypical buildings, while Figures 14 and 15 present the corresponding CBES output screens for the Place of Worship and Office Building, respectively.

Table 7. Summary of the assessment results of Commercial Building Energy Saver for the two prototypical buildings.

	Prototypical Place of Worship	Prototypical Office Building
Location Facility Type	San Francisco, CA Office—small 1 story	San Diego, CA Office—small 1 story
Detailed Retrofit Analysis	<ul style="list-style-type: none"> ECM 1 (3.5%) ECM 10 (7.7%) ECM 12 (−0.6%) ECM 13 (0.4%) ECM 15 (0.5%) ECM 21 (6.4%) ECM 23 (1.0%) ECM 03 (4.2%) ECM 05 (0.4%) 	<ul style="list-style-type: none"> ECM 01 (5.8%) ECM 10 (0.8%) ECM 12 (4.7%) ECM 13 (0.0%) ECM 15 (6.5%) ECM 21 (2.6%) ECM 23 (17.5%) ECM 03 (7.6%) ECM 05 (12.5%)
Single Measure (Energy Saving (%))		

Table 7. Cont.

	Prototypical Place of Worship	Prototypical Office Building
Detailed Retrofit Analysis Package Measure (Energy Saving (%))	<ul style="list-style-type: none"> Package 1 (ECM 5;10;3;21) (19.2%) Package 2 (ECM 12;13;15;23) (1.3%) 	<ul style="list-style-type: none"> Package 1 (ECM 12;03;21) (14.6%) Package 2 (ECM 13;15;23;1;5) (32.6%)
Detailed Retrofit Analysis Package Measure (Energy Cost Savings (\$))	<ul style="list-style-type: none"> Package 1 (ECM 5;10;3;21) (\$5835) Package 2 (ECM 12;13;15;23) (\$1520) 	<ul style="list-style-type: none"> Package 1 (ECM 12;03;21) (\$2354) Package 2 (ECM 13;15;23;1;5) (\$5739)
Detailed Retrofit Analysis Package Measure (Payback (Years))	<ul style="list-style-type: none"> Package 1 (ECM 5;10;3;21) (19.3) Package 2 (ECM 12;13;15;23) (41.5) 	<ul style="list-style-type: none"> Package 1 (ECM 12;03;21) (13.6) Package 2 (ECM 13;15;23;1;5) (9.5)
Detailed Retrofit Analysis Package Measure (Investment Cost (\$))	<ul style="list-style-type: none"> Package 1 (ECM 5;10;3;21) (\$112,742) Package 2 (ECM 12;13;15;23) (\$63,056) 	<ul style="list-style-type: none"> Package 1 (ECM 12;03;21) (\$31,928) Package 2 (ECM 13;15;23;1;5) (\$54,338)

Measure Package

The Deep Energy Retrofit Package were modified.

Please package the measures following these rules:

- (1) A valid package should include at least two measures
- (2) A valid package should not include multiple measures that are of the same type
(E.g., the measure of replace existing lighting with LED upgrade and that with T8 upgrades)

Measure ID	Measure Name	Energy Saving(*)	Payback Years (*)	Package 1	Package 2	Package 3	Package 4
ECM 5	Single zone rooftop unit efficiency ...	-0.04%	85.6	☒	☐	☐	☐
ECM 12	Add Economizer	-0.59%	39.6	☐	☒	☐	☐
ECM 10	Gas Furnace Efficiency Upgrade (AFUE ...	7.71%	18.7	☒	☐	☐	☐
ECM 13	Add Air Sealing to Seal Leaks	-0.43%	2092.8	☐	☒	☐	☐
ECM 3	Replace existing lighting with LED u ...	4.19%	11.3	☒	☐	☐	☐
ECM 15	Use Plug Load Controller (30% effici ...	0.54%	14.7	☐	☒	☐	☐
ECM 21	Apply Wall Insulation (R21)	6.42%	22.7	☒	☐	☐	☐
ECM 23	Replace fixed-window to U-factor (0. ...	0.96%	21.2	☐	☒	☐	☐
ECM 1	Replace existing lighting with T8 up ...	3.55%	3.0	☐	☐	☐	☐

(*): values obtained from single measure simulations

Rename the Measure Package (optional):

Package 1

Package 2

Package 3

Package 4

(Note: Please Update Measure Package Settings before performing Measure Package Analysis)

Update Measure Package Settings

Perform Measure Package Analysis

(a)

Measure Package Analysis Results

Energy metric:

☒ Site Energy
 ☐ Source Energy

Note:

1. Measure ID(s) with (*) mean the runtime option does not meet the investment criteria.

2. The source energy metric can be modified under the "Miscellaneous" tab.

Annual site energy and CO₂ emissions

Package Name	Measure ID(s)	Baseline	Electricity Use (kWh)	Natural Gas Use (therm)	Electricity Demand Charge (\$)	Energy Cost (\$)	CO2 Emission (lbs)
Package 1	ECM 5,10,3,21	80,409	56,039	2,453	0	21,704	39,928
Package 2	ECM 12,13,15,23	79,432	2,936	2,035	0	20,244	39,246

Annual economic analysis

Package Name	Measure ID(s)	Investment Cost (\$)	Payback (Year)	Incentives (\$)	Payback with Incentives (Year)
Package 1	ECM 5,10,3,21	112,742	19.0	0	19.0
Package 2	ECM 12,13,15,23	63,056	41.5	0	41.5

Annual energy and cost saving

Package Name	Measure ID(s)	Energy Cost Savings (\$)	Energy Savings (kWh)	Electricity Cost Savings (\$)	Electricity Savings (kWh)	Natural Gas Cost Savings (\$)	Natural Gas Savings (therm)
Package 1	ECM 5,10,3,21	5,935	24,794	5,779	24,186	156	157
Package 2	ECM 12,13,15,23	1,320	1,931	1,091	6,973	-171	-172

Annual energy and cost saving percentage

Package Name	Measure ID(s)	Energy Cost Savings (%)	Energy Savings (%)	Electricity UsageCost Savings (%)	Natural Gas UsageCost Savings (%)
Package 1	ECM 5,10,3,21	27.3%	18.9%	30.1%	6.4%
Package 2	ECM 12,13,15,23	7.0%	1.9%	8.7%	-7.0%

(b)

Figure 14. Summary output screen from Commercial Building Energy Saver for prototypical Place of Worship (a) Selection of individual retrofit measure to conduct package analysis and (b) Results of selected package analysis.

- (1) A valid package should include at least two measures
 (2) A valid package should not include multiple measures that are of the same type
 (E.g., the measure of replace existing lighting with LED upgrade and that with T8 upgrades)

Measure ID	Measure Name	Energy Saving(*)	Payback Years (*)	Package 1	Package 2	Package 3	Package 4
ECM 12	Add Economizer	4.68%	4.2	☒	☐	☐	☐
ECM 13	Add Air Sealing to Seal Leaks	0.02%	NA	☐	☒	☐	☐
ECM 3	Replace existing lighting with LED u ...	7.62%	12.9	☒	☐	☐	☐
ECM 15	Use Plug Load Controller (30% effici ...	6.47%	4.3	☐	☒	☐	☐
ECM 21	Apply Wall Insulation (R21)	2.6%	55.5	☒	☐	☐	☐
ECM 23	Replace fixed-window to U-factor (0. ...	17.48%	6.2	☐	☒	☐	☐
ECM 1	Replace existing lighting with T8 up ...	5.76%	3.8	☐	☒	☐	☐
ECM 5	Single zone rooftop unit efficiency ...	12.51%	12.0	☐	☒	☐	☐
ECM 10	Gas Furnace Efficiency Upgrade (AFUE ...	0.83%	196.2	☐	☐	☐	☐

(*): values obtained from single measure simulations

Rename the Measure Package (optional):

(a)

Measure Package Analysis Results

Energy metric:

☒ Site Energy

☐ Source Energy

Note:

1. Measure ID(s) with (*) means the retrofit option does not meet the investment criteria.

2. The source energy metric can be modified under the "Miscellaneous" tab.

Annual site energy and CO2 emissions

Package Name	Measure ID(s)	Baseline	Electricity Use (kWh)	Natural Gas Use (therm)	Electricity Demand Charge (\$)	Energy Cost (\$)	CO2 Emission (lbs)
Package 1	ECM 12,3,21	57,361	47,095	249	0	14,321	24,706
Package 2	ECM 13,15,23,1,5	33,182	33,182	333	0	8,582	16,733

Annual economic analysis

Package Name	Measure ID(s)	Investment Cost (\$)	Payback (Year)	Incentives (\$)	Payback with Incentives (Year)
Package 1	ECM 12,3,21	31,928	13.6	0	13.6
Package 2	ECM 13,15,23,1,5	54,338	9.5	0	9.5

Annual energy and cost saving

Package Name	Measure ID(s)	Energy Cost Savings (\$)	Energy Savings (kWh)	Electricity Cost Savings (\$)	Electricity Savings (kWh)	Natural Gas Cost Savings (\$)	Natural Gas Savings (therm)
Package 1	ECM 12,3,21	2,254	10,279	2,387	10,255	-33	-33
Package 2	ECM 13,15,23,1,5	5,779	20,755	5,856	24,179	-117	-118

Annual energy and cost saving percentage

Package Name	Measure ID(s)	Energy Cost Savings (%)	Energy Savings (%)	Electricity UsageCost Savings (%)	Natural Gas UsageCost Savings (%)
Package 1	ECM 12,3,21	8.4%	14.6%	17.9%	-15.4%
Package 2	ECM 13,15,23,1,5	40.1%	32.6%	42.2%	-54.4%

(b)

Figure 15. Summary output screen for Commercial Building Energy Saver for prototypical Office Building. (a) Selection of individual retrofit measure to conduct package analysis and (b) Results of selected package analysis.

4.1.4. SABER

A systematic retrofit analysis was conducted using the SABER tool for both prototypical buildings. First, SABER develops calibrated energy models based on basic building information data as well as the monthly utility data. For the place of worship, the energy model was calibrated with CVRMSE at 3.44% and NMBE at −3.27% for electrical energy consumption and CVRMSE at 7.92% and NMBE at 4.39% for thermal energy consumption as shown in Figure 16. For the office building, the SABER developed model was calibrated with CVRMSE at 4.57% and NMBE at 4.53% for electrical energy consumption and CVRMSE at 3.98% and NMBE at −3.94% for thermal energy consumption as shown in Figure 17. The SABER tool is used to evaluate the potential annual energy savings and simple payback periods for selected energy efficiency measures as listed in Table 8. Finally, the SABER tool is utilized to determine the optimal retrofit package based on life cycle cost analysis as depicted by Figure 18 for the place of worship and Figure 19 for the office building. The results of the optimal retrofit recommendations are summarized in Table 8.

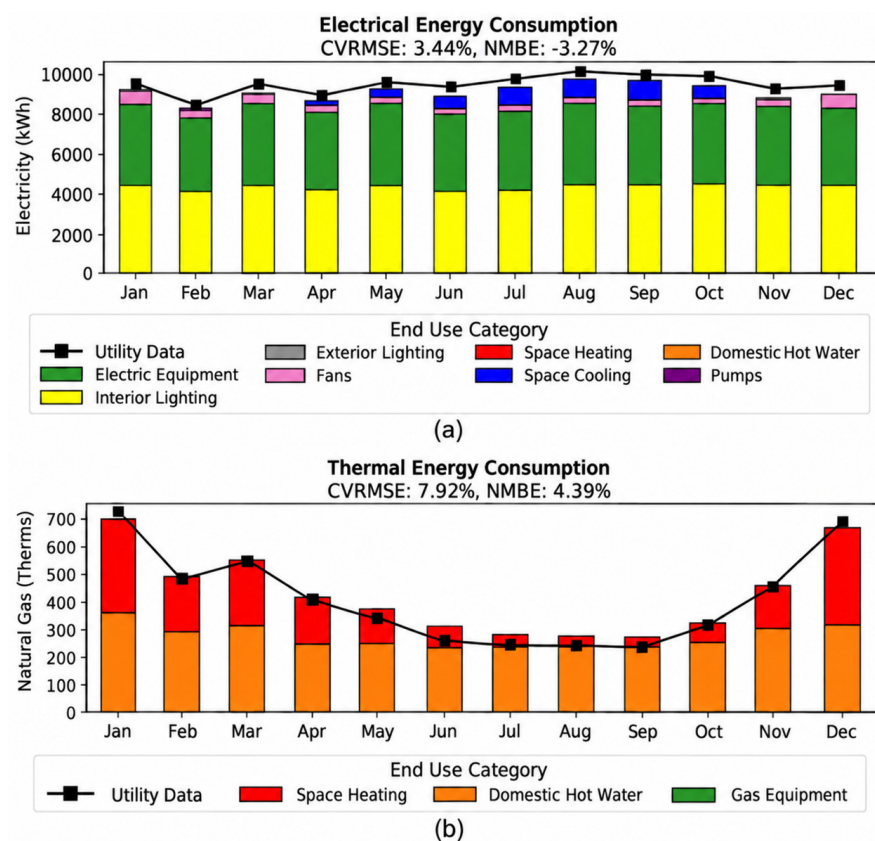


Figure 16. Calibration of the energy model for prototypical Place of Worship (a) electrical and (b) natural gas monthly usage.

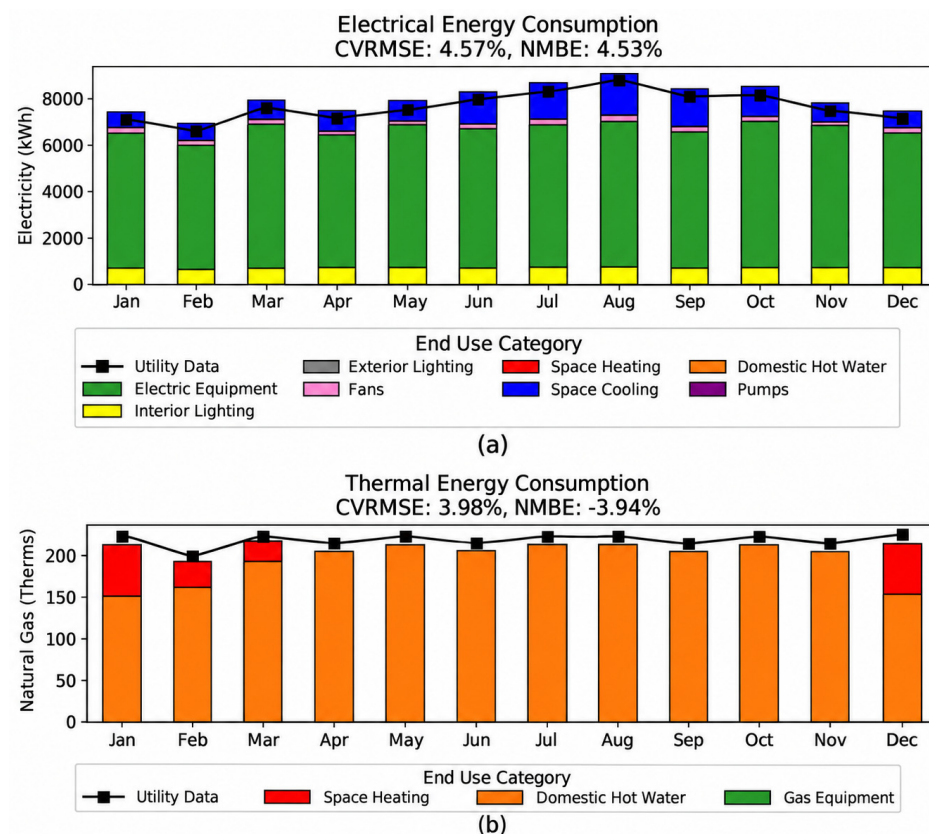
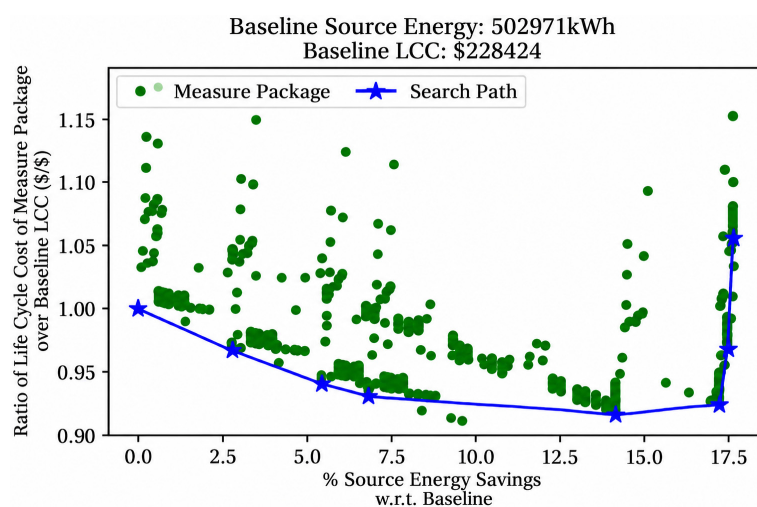


Figure 17. Calibration of the energy model for prototypical Office Space (a) electrical and (b) monthly natural gas usage.

Table 8. Summary of the assessment results from Commercial Building Energy Saver for the prototypical buildings.

	Prototypical Place of Worship	Prototypical Office Building
Location	San Francisco, CA	San Diego, CA
Facility Type	Worship Facility	Office
Individual Measure Analysis	<ul style="list-style-type: none"> EEM 1—Wall Insulation: Uninsulated -> R36 Spray Foam EEM 2—Infiltration: 10 ACH50 -> 2 ACH50 EEM 3—Daylighting Controls: No -> Yes EEM 4—Electrification: Gas Furnace (80% AFUE) -> ASHP (8.8 HSPF) EEM 5—LED: 0% LED—> 100% LED 	<ul style="list-style-type: none"> EEM 1—Wall Insulation: Uninsulated -> R36 Spray Foam EEM 2—Infiltration: 10 ACH50 -> 2 ACH50 EEM 3—Daylighting Controls: No -> Yes EEM 4—Electrification: Gas Furnace (80% AFUE) -> ASHP (8.8 HSPF) EEM 5—LED: 0% LED—> 100% LED
Natural Gas Saving (%)	<ul style="list-style-type: none"> EEM 1—Wall Insulation: 3.2 EEM 2—Infiltration: 32.4 EEM 3—Daylighting Controls: −0.84 EEM 4—Electrification: 36.84 EEM 5—LED: −5.7 	<ul style="list-style-type: none"> EEM 1—Wall Insulation: −0.68 EEM 2—Infiltration: 6.23 EEM 3—Daylighting Controls: −0.05 EEM 4—Electrification: 6.7 EEM 5—LED: −0.4
Electricity Saving (%)	<ul style="list-style-type: none"> EEM 1—Wall Insulation: −0.4 EEM 2—Infiltration: −6 EEM 3—Daylighting Controls: 4.5 EEM 4—Electrification: −13.6 EEM 5—LED: 19.9 	<ul style="list-style-type: none"> EEM 1—Wall Insulation: 1.49 EEM 2—Infiltration: −5.84 EEM 3—Daylighting Controls: 2.45 EEM 4—Electrification: 5.27 EEM 5—LED: 4
Simple Payback Period (Years)	<ul style="list-style-type: none"> EEM 1—Wall Insulation: 543 EEM 2—Infiltration: 27.4 EEM 3—Daylighting Controls: 0.2 EEM 4—Electrification: −5 EEM 5—LED: 0.47 	<ul style="list-style-type: none"> EEM 1—Wall Insulation: −207 EEM 2—Infiltration: −6.9 EEM 3—Daylighting Controls: 0.17 EEM 4—Electrification: 3.47 EEM 5—LED: 1.06
Optimal Package	<ul style="list-style-type: none"> Daylighting Options: No -> Yes Occupancy Sensor: No -> Yes Night Setback: None -> 3.6 °F (2 °C) HVAC: Gas Furnace -> ASHP (19SEER—9.8HSPF) 	<ul style="list-style-type: none"> Daylighting Options: No -> Yes Occupancy Sensor: No -> Yes Night Setback: None -> 18 °F (10 °C) Gas Furnace (AFUE80%) AC (8 SEER) -> ASHP (19SEER—9.8HSPF)
Natural Gas Savings Optimal Package (%)	36.83%	6.7%
Electricity Savings Optimal Package (%)	3%	13.9%
Simple Payback Period (yrs)	10.3	2.02

**Figure 18.** Selection process for optimum package for prototypical Place of Worship.

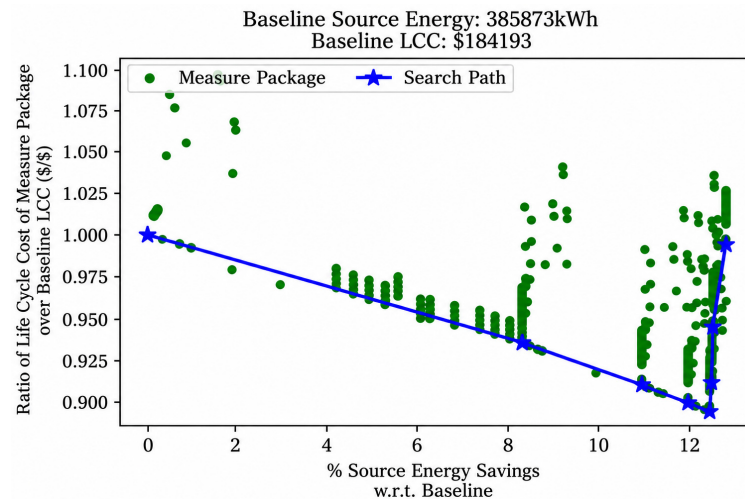


Figure 19. Selection process for optimum package for prototypical Office Building.

4.2. Comparative Assessment of Simplified Retrofit Analysis Tools Against EnergyPlus Simulation

Tables 9 and 10 summarize the comparative results generated by four retrofit analysis tools with the corresponding EnergyPlus simulation results for the two prototypical buildings. Specifically, the annual energy savings associated with individual and packaged retrofit measures are compared with the EnergyPlus results, which are used as the reference for this assessment. In the case of package analysis, all packaged retrofit measures were implemented in the EnergyPlus model to account for interactive effects of different retrofit measures. Table 9 presents the results for the Place of Worship, while Table 10 presents the results for the Office Building. As shown in both tables, BETTER and Asset Score provide only package-level retrofit recommendations, whereas SABER and CBES can evaluate both individual and packaged retrofit measures. In addition, BETTER and Asset Score provide limited details regarding the specific characteristics of the recommended retrofit measures. For example, BETTER may recommend reducing the equipment operating schedule without specifying the revised schedule settings to be implemented. To enable consistent implementation in EnergyPlus and facilitate an objective comparison with the reference results, the retrofit measures recommended by BETTER and Asset Score were mapped to specific EnergyPlus implementation strategies. Additionally, certain retrofit measures recommended by SABER have been modeled with equivalent EnergyPlus modeling inputs to enable consistent evaluation. For example, the installation of occupancy sensors was represented in EnergyPlus by applying an appropriate percentage reduction in lighting power density. Table 11 summarizes the mapping between the retrofit measures recommended by the analysis tools and their corresponding implementation strategies in EnergyPlus.

As indicated by the results presented in Tables 9 and 10, the estimated energy savings and their agreement with EnergyPlus reference predictions vary substantially depending on the retrofit analysis toolkit selected. BETTER consistently overestimates the annual energy savings of the retrofit packages, with differences of 49.5% for the Place of Worship and 34.4% for the Office Building relative to EnergyPlus. Asset Score produces estimates that are generally closer to the EnergyPlus results, with differences of 0.8% for the Place of Worship and 20.3% for the Office Building. The larger discrepancy observed for the Office Building may be partly attributable to the more simplified geometric representation used in Asset Score. CBES also provides energy savings for both individual and packaged retrofit measures that are generally close to the EnergyPlus estimates, with differences ranging from 0.3% to 2.3% for the Place of Worship and from 0% to 16.0% for the Office Building. In contrast, SABER generally underestimates annual energy savings relative to EnergyPlus, with differences ranging from 2.1% to 17.7% for the Place of Worship and from 0.3% to 9.9% for the Office

Building. Overall, these results demonstrate that the accuracy of retrofit energy savings estimates can vary considerably across tools and may also depend on how closely the building geometry, systems, and recommended measures can be represented within each toolkit.

Table 9. Comparison of estimate annual energy savings between simplified retrofit analysis tools and EnergyPlus for the prototypical place of worship.

Toolkit	Measure Evaluation Type	Measure	Action Taken	Toolkit Estimated Energy Saving (Site)	EnergyPlus Estimated Energy Saving (Site)	Difference In Energy Estimate (Site)
BETTER	Package	Reduce Equipment Schedules	Reduced Night Time Electric Equipment Loads by a Factor of 0.1	1.5%	22%	49.5%
		Reduce Lighting Load	80% Reduction			
		Reduce Plug Loads	30% Reduction			
		Increase Heating System Efficiency	Increased to 95%			
		Upgrade to Sustainable Resources for Water Heating	Electric Water Heater with Thermal Efficiency 1			
		Upgrade Windows to Reduce Solar Heat Gain	0.40 SHGC			
		Increase Cooling Setpoints	Increased by 5			
		Add/Fix Economizers	Economizer Added			
Asset Score	Package	Add Roof Insulation	Increased to R30	39.02%	38.18%	0.84%
		Add a Cool Roof	Solar Absorptance Reduced by 30%			
		Add Wall Insulation	Change to R13			
		Seal Building Envelope	Infiltration Reduced by 30%			
		Upgrade to High-performance Windows	0.4 SHGC			
		Add Occupancy Sensors	15% lighting load reduction			
		Upgrade to LED Fixtures	80% Reduction			
		Replace HVAC with High-performance Packaged Rooftop Heat Pump and a DOAS	Replaced with “Dedicated Outdoor Air System (DOAS) with fan coil air-cooled chiller with central air source heat pump”			
		Upgrade Heat Pump Hot Water Heater	Upgraded to “Heat Pump Water Heater”			
		Add Low Flow Service Hot Water Fixtures	Peak flow rate reduced by 30%			
CBES	Individual	ECM1	Reduced Lighting Power Density (LPD) by 40%	3.5%	5%	−1.5%
		ECM 3	Reduced LPD by 50%	4.2%	6%	−1.8%
		ECM 5	Increase COP to 4.10	0.4%	0.08%	0.32%
		ECM 10	Increased AFUE to 95%	7.7%	6.53%	1.17%
		ECM 12	Economizer Added	−0.6%	−0.30%	−0.30%
		ECM 13	Infiltration Reduced by 30%	0.4%	−1.9%	2.30%
		ECM 15	Plug Load Reduced by 30%	0.5%	1.3%	−0.80%
		ECM 21	Wall insulation increased to R21	6.4%	4.5%	1.90%
		ECM 23	Window U-value and SHGC changed to U-0.25 and SHGC-0.18	1%	0.43%	0.57%
	Package 1	ECM 5;10;3;21		19.2%	18.62%	0.58%
	Package 2	ECM 12;13;15;23		1.3%	−0.15%	1.45%

Table 9. Cont.

Toolkit	Measure Evaluation Type	Measure	Action Taken	Toolkit Estimated Energy Saving (Site)	EnergyPlus Estimated Energy Saving (Site)	Difference In Energy Estimate (Site)
SABER	Individual	Wall Insulation	Changed to R36	0.67%	6.79%	−6.12%
		Infiltration	Reduced to 2 ACH50	15.17%	2.88%	12.29%
		Daylighting Controls	Installed Daylight Control	0.42%	2.54%	−2.12%
		Electrification	Installed Air Source Heat Pump	14.51%	27.28%	−12.77%
		Install LED	Reduced by 80%	4.22%	10.62%	−6.40%
	Package	Daylighting Controls	Installed Daylight Control	21.66%	39.31%	−17.65%
		Occupancy Sensor	Reduced LPD by 15%			
		Night Setback	Reduced setpoint by 2 degrees between 10 PM and 6 AM			
		HVAC Upgrade	Installed Air Source Heat Pump			

Table 10. Comparison of estimated annual energy savings between simplified retrofit analysis tools and EnergyPlus for prototypical office building.

Toolkit	Measure Evaluation Type	Measure	Action Taken	Toolkit Estimated Energy Saving (Site)	EnergyPlus Estimated Energy Saving (Site)	Difference In Energy Estimate (Site)
BETTER	Package	Reduce Equipment Schedules	Reduced Nighttime Electric Equipment Loads by a Factor of 0.1	63.6%	29.22%	34.38%
		Reduce Lighting Load	Reduced by 80%			
		Reduce Plug Loads	Reduced by 30%			
		Increase Cooling System Efficiency	Increase the Coefficient of Performance (COP) to 4.0			
		Upgrade to Sustainable Resources for Water Heating	Electric Water Heater with Thermal Efficiency 1			
		Upgrade Windows to Reduce Solar Heat Gain	0.40 SHGC			
Asset Score	Package	Seal Building Envelope	Infiltration Reduced by 30%	67.21%	46.89%	20.31%
		Add Roof Insulation	Increased to R30			
		Add a Cool Roof	Solar Absorptance Reduced by 30%			
		Add Wall Insulation	Change to R13			
		Upgrade to High-performance Windows	0.4 SHGC			
		Add Occupancy Sensors	15% lighting load reduction			
		Upgrade to LED Fixtures for Lighting Fixture	80% Reduction			
		Replace HVAC with High-performance Packaged Rooftop Heat Pump and a DOAS	Replaced with “DOAS with fan coil air-cooled chiller with central air source heat pump”			
		Add Low Flow Service Hot Water Fixtures	Peak flow rate reduced by 30%			
		Upgrade Heat Pump Hot Water Heater	Upgraded to “Heat Pump Water Heater”			

Table 10. Cont.

Toolkit	Measure Evaluation Type	Measure	Action Taken	Toolkit Estimated Energy Saving (Site)	EnergyPlus Estimated Energy Saving (Site)	Difference In Energy Estimate (Site)
CBES	Individual	ECM 1	Reduced LPD by 30%	5.8%	4.52%	1.28
		ECM 3	Reduced LPD by 40%	0.8%	6.03%	−5.23
		ECM 5	Increase COP to 5.15	4.7%	4.8%	−0.10
		ECM 10	Increased AFUE to 95	0.0%	0.00%	0.00
		ECM 12	Economizer Added	6.5%	5.39	1.11
		ECM 13	Infiltration Reduced by 30%	2.6%	0.03	2.57
		ECM 15	Plug Load Reduced by 30%	17.5%	3.78%	13.72
		ECM 21	Wall insulation increased to R21	7.6%	0.45%	7.15
		ECM 23	Window U-value and SHGC changed to U-0.25 and SHGC-0.18	12.5%	6.85%	5.65
	Package 1	ECM (12;03;21)		14.6%	11.15%	3.45
	Package 2	ECM (13;15;23;1;5)		32.6%	16.56%	16.04
SABER	Individual	Wall Insulation	Changed to R36	0.25%	0.53%	−0.28%
		Infiltration	Reduced to 2 ACH50	−0.61%	−0.13%	−0.48%
		Daylighting Controls	Installed Daylight Control	1.36%	4.52%	−3.17%
		Electrification	Replace Gas Furnace with ASHP	5.88%	9.33%	−3.45%
		Install LED	Reduced by 80%	2.13%	12%	−9.87%
	Package	Daylighting Controls	Installed Daylight Control			
		Occupancy Sensor	Reduced LPD by 15%	10.80%	17.60%	−6.8%
		Night Setback	Reduced setpoint by 10 degree between 10 PM and 6 AM			
		HVAC Upgrade	Installed Air Source Heat Pump			

Table 11. Mapping of retrofit measures recommended by selected toolkits to specific EnergyPlus implementation strategies.

Toolkit	Recommended Measure	Equivalent EnergyPlus Implementation
BETTER	Reduce Equipment Schedule	Reduced Night Time Electric Equipment Loads by a Factor of 0.1
BETTER	Reduce Lighting Load	80% Reduction
BETTER	Reduce Plug Loads	30% Reduction
BETTER	Increase Heating System Efficiency	Increased to 95%
BETTER	Increase Cooling System Efficiency	Increase the COP to 4.0
BETTER	Upgrade to Sustainable Resources for Water Heating	Electric Water Heater with Thermal Efficiency 1
BETTER	Upgrade Windows to Reduce Solar Heat Gain	0.40 SHGC
BETTER	Increase Cooling Setpoints	Increased by 5
BETTER	Add Roof Insulation	Increased to R30
BETTER	Add a Cool Roof	Solar Absorptance Reduced by 30%
BETTER	Add Wall Insulation	Change to R13
BETTER	Seal Building Envelope	Infiltration Reduced by 30%
BETTER	Upgrade to High-performance Windows	0.4 SHGC
BETTER, Asset Score, SABER, Asset Score	Add Occupancy Sensors	15% lighting load reduction
Asset Score	Upgrade to LED Fixtures	80% Reduction
Asset Score	Replace HVAC with High-performance Packaged Rooftop Heat Pump and a DOAS	Replaced with “DOAS with fan coil air-cooled chiller with central air source heat pump”
Asset Score	Add Low Flow Service Hot Water Fixtures	Peak flow rate reduced by 30%

5. Applications for Real World Buildings

In this section, the SABER, BETTER, and Asset Score tools are applied to conduct detailed energy assessments for four existing buildings located in different cities across the state of Montana, USA. These buildings were selected since detailed energy audits have been conducted by the authors including access to detailed building specifications and long-term utility data. CBES is excluded from this comparative analysis because the tool is currently limited to buildings located in California. The selected building portfolio consists of two places of worship (churches), one food bank, and one residential building. Table 12 summarizes the key characteristics of the four buildings based on Level II energy audit evaluations, while Figure 20 presents their monthly natural gas and electricity energy use intensities.

Table 12. Summary of main characteristics of four existing buildings evaluated using simplified retrofit analysis tools.

	Facility 1	Facility 2	Facility 3	Facility 4
Location	Helena, MT	Great Falls, MT	Browning, MT	St. Ignatius, MT
Facility Type	Place of Worship	Place of Worship	Food Bank	Residence
Square Footage (sq.ft. (sq. m))	9512 ft ² (883.7 m ²)	22,000 ft ² (2043.9 m ²)	2336 ft ² (217.0 m ²)	1392 ft ² (129.3 m ²)
Built Year	1969	1955	1940	1940
Wall Insulation	R-15 Fiberglass	NA	NA	NA
Roof Insulation	R-49 Fiberglass	NA	NA	NA
Foundation	Basement with Slab on Grade	2/3 crawl space 1/3 basement with boiler room	Slab on Grade	Basement
Windows	Low e double pane medium SHGC air filled insulated	Double-pane	Single and Double Pane	Double Pane
Percentage LED	60%	60%	80%	0%
Lighting Power Density (W/sq.ft)	0.48	0.75	0.69	0.58
Plug Load (W/sq.ft.)	1.74 W/ft ² (18.73 W/m ²)	1.19 W/ft ² (12.81 W/m ²)	12.92 W/ft ² (139.07 W/m ²)	10.30 W/ft ² (110.87 W/m ²)
Total Site Energy Usage (kBtu)	465,860 kBtu (136,530 kWh)	1,570,015 kBtu (460,126 kWh)	358,797 kBtu (105,153 kWh)	81,598 kBtu (23,914 kWh)

Table 13, Table 14, and Table 15 summarize the retrofit analysis results obtained using the BETTER, Asset Score, and SABER tools, respectively, for the four facilities. Specifically, the three tools estimate the energy and cost benefits associated with individual and packaged retrofit measures. Figure 21 shows the results of calibration effort for Facility 1 by SABER. In addition, SABER identifies optimal retrofit packages by minimizing life cycle cost using calibrated energy models, as illustrated in Figure 22 for Facility 1. Specifically, the SABER tool enables identification of an optimal retrofit pathway that progressively reduces energy use while minimizing life cycle cost, as shown in Figure 22 for Facility 1.

Table 13. Summary of the analysis results obtained from the BETTER tool for four existing buildings.

	Facility 1	Facility 2	Facility 3	Facility 4
Location	Helena, MT	Great Falls, MT	Browning, MT	St. Ignatius, MT
Facility Type	Worship Facility	Worship Facility	Food Bank	Parsonage/Residential
BETTER Facility Type	Worship Facility	Worship Facility	N/A	Multifamily Housing
Fossil Fuel Used	Natural Gas	Natural Gas	N/A	N/A
User Define R ²	0.6	0.6	N/A	0.6
Analyzed R ² for Electricity	22.1% (CV(RMSE))	0.79	N/A	0.8
Analyzed R ² for Fossil Fuel	0.9	0.92	N/A	N/A
Portfolio included in the BETTER database	Yes	Yes	N/A	N/A
Calculated potential cost savings	\$1384.10, 17.7%	\$4229.28, 30.7%	N/A	\$1842.39, 57.6%
Calculated potential energy savings	45,264 kBtu (13,265 kWh), 9.7%	503,822 kBtu (147,659 kWh), 33.7%	N/A	45,472 kBtu (13,327 kWh), 63.3%

Table 13. Cont.

	Facility 1	Facility 2	Facility 3	Facility 4
Percentage of buildings analyzed building is superior to (Electricity).	Baseload: 29%	Baseload: 81%	N/A	Baseload: 49%
Percentage of buildings analyzed building is superior to (Fossil Fuel).	Baseload: 65%	Heating Slope: 39%		Heating Slope: 0%
	Heating Slope: 59%	Heating Change point: 28%		Heating Change point: 42%
	Heating Change point: 45%	Baseload: 77%	N/A	N/A
		Heating Slope: 27%		
		Heating Change point: 34%		
Suggested Retrofit Measures	<ul style="list-style-type: none"> Decrease Heating Setpoints. Reduce Equipment Schedules. Reduce Lighting Load. Reduce Plug Loads. 	<ul style="list-style-type: none"> Decrease Heating Setpoints. Reduce Equipment Schedules. Ensure Adequate Ventilation Rate. Decrease Infiltration. Add Wall/Ceiling/Roof Insulation. Upgrade Windows to Improve Thermal Efficiency. Use High Efficiency Heat Pump for Heating. Increase Heating System Efficiency. 	N/A	<ul style="list-style-type: none"> Decrease Heating Setpoints. Reduce Equipment Schedules. Ensure Adequate Ventilation Rate. Decrease Infiltration. Add Wall/Ceiling/Roof Insulation. Upgrade Windows to Improve Thermal Efficiency. Use High Efficiency Heat Pump for Heating. Reduce Lighting Load. Reduce Plug Loads. Increase Heating System Efficiency.

Table 14. Summary of analysis results of the Asset Scire tool for four existing facilities.

	Facility 1	Facility 2	Facility 3	Facility 4
Location	Helena, MT	Great Falls, MT	Browning, MT	St. Ignatius, MT
Facility Type	Worship Facility	Worship Facility	Food Bank	Parsonage/Residential
Number of blocks	4	3	2	1
Block use type	Religious Building, Community Center, Office	Religious Building, Community Center, Office	Office, Retail	Lodging
Estimated annual site energy savings	11.63%	26.32%	31.65%	10.61%
Asset Score	9.5	8.0	6.5	5.0
Upgrade Opportunity	<ul style="list-style-type: none"> Seal Building Envelope to Reduce Air Infiltration. Upgrade to LED Fixtures for Lighting Fixture in Fellowship Hall and Classroom/Office. Replace HVAC with High-performance Packaged Rooftop Heat Pump and a DOAS. Add Low Flow Service Hot Water Fixtures for Fellowship Hall. Upgrade Heat Pump Hot Water Heater for Fellowship Hall. 	<ul style="list-style-type: none"> Add Floor Insulation for Office, Sanctuary, and Basement. Add Roof Insulation for Office. Add Wall Insulation for Office, Community Space, Kitchen, and Sanctuary. Seal Building Envelope to Reduce Air Infiltration. Add Wall Insulation for Basement. Add Floor Insulation for Community Space, and Kitchen. Add Roof Insulation for Sanctuary. Upgrade to LED Fixtures for Office, Community Space, Kitchen, and Basement. Add Occupancy Sensors for Interior Lighting Control. Upgrade to LED Fixtures for Sanctuary. Replace Existing Boiler with High-performance Boiler. 	<ul style="list-style-type: none"> Seal Building Envelope to Reduce Air Infiltration. Upgrade to High-performance Windows for Apartment, Pantry and Office. Add Roof Insulation for Apartment and Pantry. Add Roof Insulation for Office. Add Occupancy Sensors for Interior Lighting Control. Upgrade to LED Fixtures for Office. Add Low Flow Service Hot Water Fixtures. 	<ul style="list-style-type: none"> Seal Building Envelope to Reduce Air Infiltration. Add Roof Insulation. Add Occupancy Sensors for Interior Lighting Control. Upgrade to LED Fixtures. Add Low Flow Service Hot Water Fixtures. Upgrade Heat Pump Hot Water Heater.

Table 15. Summary of results of the retrofit analysis conducted using the SABER tool for four buildings.

	Facility 1	Facility 2	Facility 3	Facility 4
Location Facility Type	Helena, MT Worship Facility	Great Falls, MT Worship Facility	Browning, MT Food Bank	St. Ignatius, MT Parsonage/Residential
Individual Measure Analysis	<ul style="list-style-type: none"> EEM 1—Wall Insulation: R19 Fiberglass -> R36 Spray Foam EEM 2—Infiltration: 10 ACH50 -> 2 ACH50 EEM 3—Daylighting Controls: No -> Yes EEM 4—Electrification: Gas Furnace -> ASHP (8.8 HSPF) EEM 5—LED: 15% LED -> 100% LED 	<ul style="list-style-type: none"> EEM 1—Wall Insulation: R7 Fiberglass -> R36 Spray Foam EEM 2—Infiltration: 10 ACH50 -> 2 ACH50 EEM 3—Daylighting Controls: No -> Yes EEM 4—Electrification: Gas Furnace -> ASHP EEM 5—LED: 10% -> 100% 	<ul style="list-style-type: none"> EEM 1—Wall Insulation: Uninsulated -> R36 Spray Foam EEM 2—Infiltration: 25 ACH50 -> 2 ACH50 EEM 3—Daylighting Controls: No -> Yes EEM 4—Electrification: Gas Furnace -> ASHP EEM 5—LED: 0% -> 100% 	<ul style="list-style-type: none"> EEM 1—Wall Insulation: R7 Fiberglass -> R36 Spray Foam EEM 2—Infiltration: 15 ACH50 -> 2 ACH50 EEM 3—Daylighting Controls: No -> Yes EEM 4—Electrification: Electric Furnace -> ASHP EEM 5—LED: 0% -> 100%
Natural Gas Saving (%)	<ul style="list-style-type: none"> EEM 1—Wall Insulation: 2.8 EEM 2—Infiltration: 77.9 EEM 3—Daylighting Controls: -0.195 EEM 4—Electrification: 94.3 EEM 5—LED: -1.74 	<ul style="list-style-type: none"> EEM 1—Wall Insulation: 1.94 EEM 2—Infiltration: 73 EEM 3—Daylighting Controls: 0 EEM 4—Electrification: 99 EEM 5—LED: -2.1 	<ul style="list-style-type: none"> EEM 1—Wall Insulation: 9.8 EEM 2—Infiltration: 90.4 EEM 3—Daylighting Controls: 2.5 EEM 4—Electrification: 100 EEM 5—LED: -2 	<ul style="list-style-type: none"> EEM 1—Wall Insulation: 0 EEM 2—Infiltration: 0 EEM 3—Daylighting Controls: 0 EEM 4—Electrification: 0 EEM 5—LED: 0
Electricity Saving (%)	<ul style="list-style-type: none"> EEM 1—Wall Insulation: -0.2 EEM 2—Infiltration: -7.5 EEM 3—Daylighting Controls: 1.82 EEM 4—Electrification: -203 EEM 5—LED: 11.6 	<ul style="list-style-type: none"> EEM 1—Wall Insulation: 0.02 EEM 2—Infiltration: 0.27 EEM 3—Daylighting Controls: 0 EEM 4—Electrification: -491 EEM 5—LED: -20.6 	<ul style="list-style-type: none"> EEM 1—Wall Insulation: 0.11 EEM 2—Infiltration: 3 EEM 3—Daylighting Controls: -0.52 EEM 4—Electrification: -99 EEM 5—LED: -6.5 	<ul style="list-style-type: none"> EEM 1—Wall Insulation: 0.84 EEM 2—Infiltration: 57.25 EEM 3—Daylighting Controls: 0 EEM 4—Electrification: 30 EEM 5—LED: 0.38
Simple Payback Period (Years)	<ul style="list-style-type: none"> EEM 1—Wall Insulation: 387 EEM 2—Infiltration: 6.8 EEM 3—Daylighting Controls: 3.8 EEM 4—Electrification: -0.99 EEM 5—LED: 6.3 	<ul style="list-style-type: none"> EEM 1—Wall Insulation: 356 EEM 2—Infiltration: 6 EEM 3—Daylighting Controls: 0 EEM 4—Electrification: -0.2 EEM 5—LED: -8.1 	<ul style="list-style-type: none"> EEM 1—Wall Insulation: 76 EEM 2—Infiltration: 2.64 EEM 3—Daylighting Controls: 0.72 EEM 4—Electrification: -2.76 EEM 5—LED: 3 	<ul style="list-style-type: none"> EEM 1—Wall Insulation: 335 EEM 2—Infiltration: 1.09 EEM 3—Daylighting Controls: 0 EEM 4—Electrification: 2.2 EEM 5—LED: 20
Optimal Package	<ul style="list-style-type: none"> Daylighting Options: No -> Yes Percentage LED: 15% -> 100% Occupancy Sensor: No -> Yes Infiltration: 10 ACH50 -> 3 ACH50 	<ul style="list-style-type: none"> Percentage LED: 15% -> 60% Occupancy Sensor: No -> Yes Night Setback: 14.4 °F (8 °C) -> 18 °F (10 °C) Infiltration: 7 ACH50 -> 2 ACH50 Gas Furnace: 80% AFUE -> 98% AFUE 	<ul style="list-style-type: none"> Daylighting: No -> Yes Percentage LED: 0% -> 100% Occupancy Sensor: No -> Yes Night Setback: 0 °F (0 °C) -> 3.6 °F (2 °C) Infiltration: 25 ACH50 -> 4 ACH50 	<ul style="list-style-type: none"> Percentage LED: 0% -> 100% Occupancy Sensor: No -> Yes Night Setback: 0 °F (0 °C) -> 9 °F (5 °C) Infiltration: 15 ACH50 -> 3 ACH50
Natural Gas Savings Optimal Package (%)	68.4	75.69	82.4	N/A
Electricity Savings Optimal Package (%)	21	27.36	13.1	55.6
Simple Payback Period (yrs)	0.64	0.4	1.3	0.67

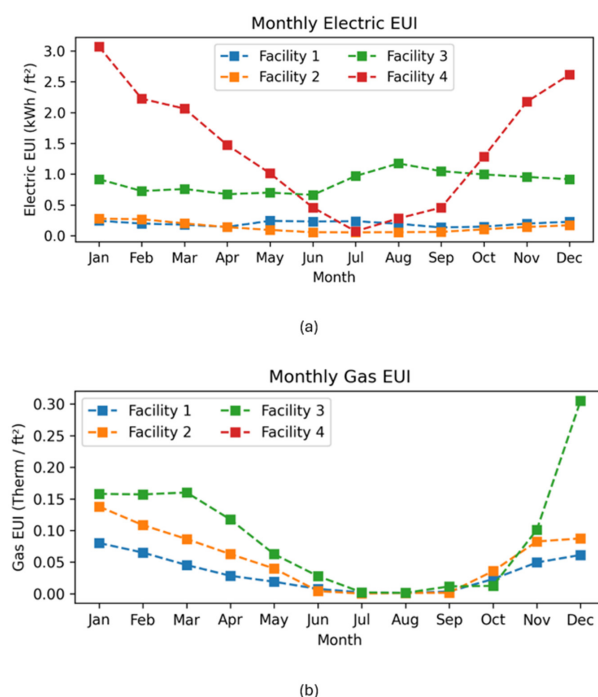


Figure 20. Monthly electricity and gas EUI values for four existing buildings (a) Monthly Electric EUI and (b) Monthly Gas EUI.

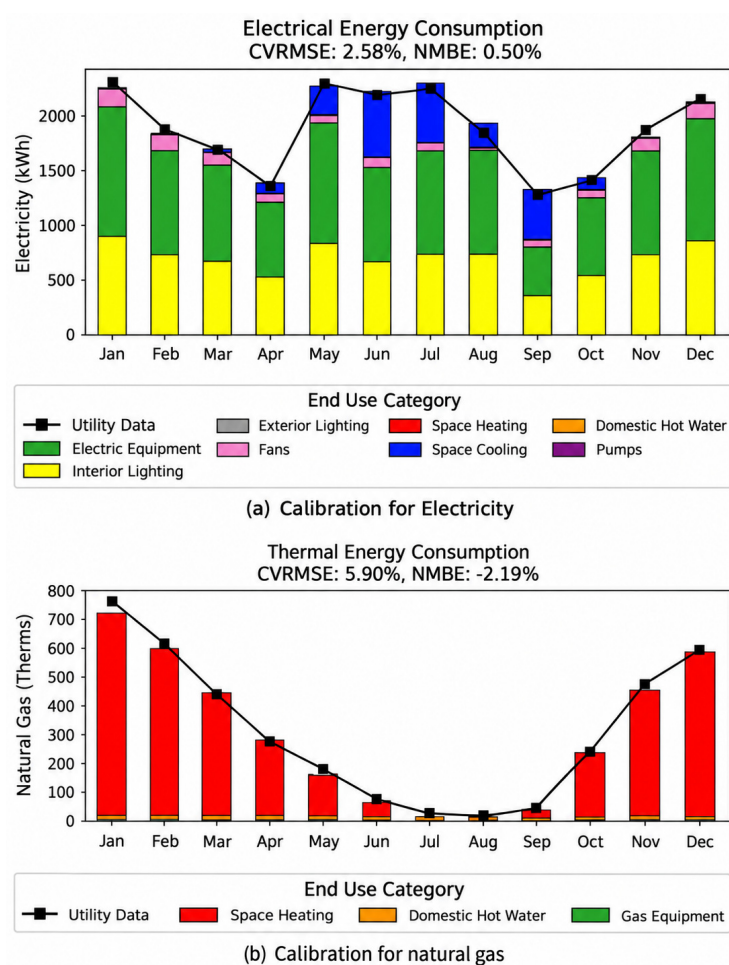


Figure 21. Calibration results of building energy model of Facility 1 conducted using the SABER tool for (a) electricity use and (b) natural gas use.

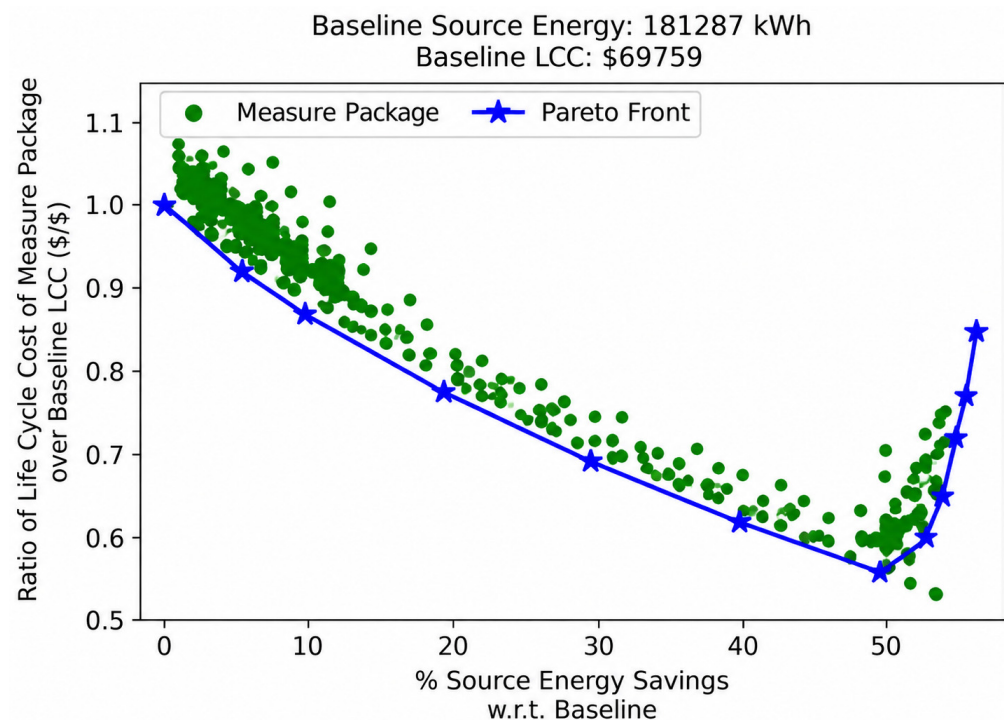


Figure 22. Optimal retrofit path based on minimization of life cycle costs obtained using the SABER tool for Facility 1.

6. Discussion

Based on the assessments conducted for the two prototypical buildings and four existing buildings, the four evaluated tools employ different analytical approaches and selection criteria to identify retrofit measures and estimate their potential energy and cost benefits. The comparative evaluation confirms that the tools vary considerably in their complexity levels, analytical capabilities, input requirements, and accuracy thresholds. Consequently, the suitability of each tool depends on the objectives of the analysis, the types of retrofit measures, and the building information available to the user.

The BETTER tool is most suitable for benchmarking and preliminary retrofit screening because it can evaluate existing buildings using primarily utility-consumption data. However, its recommendations are relatively generalized, and the tool does not provide sufficient information to independently evaluate the energy savings associated with specific retrofit measures for an audited building. Asset Score incorporates physics-based energy modeling and can identify a limited set of potential retrofit measures and evaluate their combined effect on building performance and Asset Score. However, it provides limited capability for quantifying the energy and cost benefits of individual recommended measures. In contrast, CBES and SABER provide more detailed retrofit assessments, including the development of building energy models and evaluation of the energy and cost impacts of individual and packaged retrofit measures. SABER further supports optimization of retrofit packages based on life cycle cost, allowing users to identify retrofit pathways that balance reductions in energy use with long-term economic performance. However, both SABER and CBES tools require more detailed information specific to building geometries, envelope characteristics, and building systems to conduct reliable retrofit assessments.

Based on the comparative results obtained from these retrofit analysis tools, the following guidelines are proposed to support selection of an appropriate tool for different retrofit assessment needs and to highlight the principal limitations that may affect their accuracy and applicability.

6.1. BETTER

The BETTER tool allows users to perform quick energy analysis of their buildings using monthly utility data with limited available building information. The tool is suitable to assess if an existing building can benefit from retrofitting its energy systems. The BETTER tool estimates the potential annual energy savings from a set of generic retrofit measures without considering the actual specifications of the existing building systems. Thus, the BETTER tool is more suitable for preliminary retrofit assessments where information other than utility data is not available.

The main limitations of the BETTER tool include:

1. The tool relies solely on utility data and does not consider the specific characteristics for the building geometry and the energy systems of the evaluated building. Thus, the recommended generic retrofit measures may not be suitable and applicable to the evaluated building.
2. The tool does not perform any cost–benefit analysis for the recommended individual retrofit measures.
3. The tool is more suitable for buildings that are compatible with the data specific to the portfolio of buildings used by the tool. This portfolio can be generated by providing data for to at least 30 different buildings with similar function and climate.
4. The tool results are completely dependent on the quality of utility energy use data and the accuracy of the change point models to fit this data. Any uncertainty with the utility data leads to the inability of the tool to perform any inverse modeling within any acceptable accuracy tolerance level and consequently to provide any retrofit recommendations.

6.2. Asset Score

The Asset Score tool develops energy models of existing buildings using simplified geometry configurations and limited systems. The tool requires basic building specifications including envelope constructions and HVAC systems. However, the developed energy models are not calibrated to match any available measured energy use data. While the tool recommends some potential retrofit measures, it does not allow the evaluation of any user specified retrofit measures. This limits the utility of the tool to undertake any comprehensive retrofit analysis. The accuracy of retrofit evaluation depends highly on how well the building geometries and HVAC system configurations can be defined in Asset Score.

The main limitations of the Asset Score tool consist of:

1. The Asset Score tool limits the number of use types for any evaluated building depending on its total floor area (2 use types for buildings with floor area of less than 5000 ft² (465 m²); 4 use types for buildings with floor area of less than 10,000 ft² (929 m²); and 5 use types for buildings with floor area of less than 50,000 ft² (4645 m²)).
2. The Asset Score uses only simplified geometries to model existing buildings.
3. The tool considers only limited HVAC system types.
4. The tool cannot handle conditioned spaces served by multiple HVAC systems.
5. The tool automatically suggests potential retrofit measures and does not allow the user to propose and evaluate retrofit measures.
6. The tool does not perform any cost–benefit analysis for the recommended retrofit measures.

6.3. CBES

The CBES tool provides the most flexibility in performing energy analysis for existing buildings. Based on available building information, the tool can assess energy and cost benefits of individual and packaged retrofit measures. The analysis is based on a calibrated energy model for the evaluated building. However, the available version of the tool can

be only used for office and retail buildings located in California and can only perform a calibration of the natural gas predictions of the developed building energy models.

Some of the major limitations for the CBES tool include:

1. It is limited to three building types: office, retail, and mixed-use.
2. It is suitable for buildings located only in California.
3. It can evaluate only buildings with floor area above 5000 ft² (465 m²).
4. For performing Load Shape Benchmarking and No- or Low-Cost Improvement Analysis, the tool needs data for outdoor air temperatures, and electricity use.
5. It considers only rectangular shapes to model any building geometry.
6. It is limited to utility bill data specific to electricity and natural gas usage.
7. It does not allow for automated optimal package selection. Users need to manually select the retrofit measures.
8. The calibration algorithm of the tool only applies to predict natural gas usage for space heating.
9. It cannot evaluate buildings with electrical heating.

6.4. SABER

The SABER tool can be used to perform energy and cost–benefit analysis of retrofitting buildings using calibrated energy models. The tool requires basic building information as well as monthly utility data for automatically developing calibrated energy models. Additionally, the tool has the capability to select an optimum retrofit package based on minimizing life cycle costs. The current version of the tool can be used for only residential and small commercial buildings.

The main limitations of the SABER tool are:

1. The current version of the tool is built for residential buildings and small commercial buildings served with one HVAC system type.
2. The tool considers only limited options for HVAC system types.
3. The tool is only capable of evaluating single zone facilities.
4. The tool can only evaluate buildings that utilize electricity and/or natural gas. No other fuel type is considered.

Table 16 provides a summary of input data required, possible applications, and possible improvements for the four evaluated simplified retrofit analysis tools.

Table 16. Summary of input data required, applications, and possible improvements for the evaluated simplified retrofit analysis tools.

		BETTER	Asset Score	CBES	SABER
Input Requirements	Building Envelope		X	X	X
	HVAC System		X	X	X
	Occupancy		X		
	Lighting System		X	X	X
	Electrical Equipment			X	X
	Utility Data	X		X	X
	Percentage Energy Saving	X		X	X
Output Options	EEM Implementation			X	X
	Cost				
	Cost Savings	X		X	X
	Score		X		
Calibration Capabilities	Benchmark	X	X	X	
	Energy Simulation Analysis		X	X	X
	Optimized Retrofit Package Analysis				X

Table 16. *Cont.*

	BETTER	Asset Score	CBES	SABER
Applications	Retrofit Feasibility Study	Retrofit Feasibility Study and EEM Selection	Retrofit Feasibility Study, Detailed impact of retrofit project, and EEM Selection	Detailed impact of retrofit project, and EEM selection
Possible Future Improvements	The tool should consider the current building system of facility to make retrofit recommendation more suitable for the facility	Improvements are required in how HVAC systems are assignment to spaces. Ability to assign multiple HVAC systems to a single space needs to be added	The application of the tool needs to be increased beyond California region	The tool needs to be expanded to include more HVAC System options and building types

7. Conclusions

The main goals of this research are: (1) to comparatively evaluate selected US retrofit analysis toolkits based on their accuracy thresholds, data requirements, analytical capabilities, and user expertise levels, thereby providing guidance for selecting an appropriate toolkit for various retrofit assessment needs; and (2) to assess the practical applicability of the retrofit measures recommended by these toolkits by identifying building-specific, market, demographic, cultural, and infrastructure-related barriers that may influence their actual deployment.

To achieve these aims, the study and the adopted methodology focus on answering the following two research questions:

RQ1: How do the selected retrofit analysis toolkits compare in terms of accuracy, data requirements, analytical capabilities, and the level of user expertise required for their application?

RQ2: What building-specific, market, demographic, cultural, and infrastructure-related factors influence the practical implementation of retrofit measures recommended by these toolkits, and how can these factors inform future toolkit improvements and developments?

The comparative analysis addressed RQ1 by demonstrating that the selected retrofit toolkits differ substantially in their accuracy levels, data requirements, analytical capabilities, and user expertise needs. The results indicate a clear tradeoff between ease of use and analysis complexity. The BETTER tool requires minimal building information and is most appropriate for rapid benchmarking and preliminary screening, but it provides generic package-level recommendations. The analysis results from the BETTER tool were found to exhibit the largest deviations from EnergyPlus predictions. Asset Score provides a more building-specific, physics-based assessment but is constrained by its use of simplified geometries, limited HVAC representations, and sole package-level evaluation of recommended measures. In contrast, CBES and SABER support more detailed analysis using calibrated building energy models to evaluate individual and packaged retrofit measures, although both require more comprehensive building information and greater user expertise. CBES is further restricted by building types, locations, and system configurations, whereas SABER supports life cycle cost optimization and identification of optimal retrofit packages but is currently limited to relatively limited building types and HVAC configurations.

The comparison with EnergyPlus further showed that prediction accuracy varied across tools and building types. BETTER produced the largest discrepancies, overestimating package savings by 49.5% for the Place of Worship and 34.4% for the Office Building. Asset Score differed by 0.8% and 20.3%, respectively, while CBES analysis results differed from

0.3% to 2.3% for the Place of Worship and from 0% to 16.0% for the Office Building. SABER generally underestimated savings, with differences from those estimated by EnergyPlus ranging from 2.1% to 17.7% for the Place of Worship and from 0.3% to 9.9% for the Office Building. These results show that toolkit selection should be guided by the intended level of analysis, available building information, desired accuracy threshold, and user expertise rather than by assuming that one tool is suitable for all retrofit assessments.

The application of three selected retrofit analysis tools on four existing buildings in Montana helped address RQ2 by identifying several practical factors that can limit the implementation of technically attractive retrofit measures. Importantly, these factors were not identified from the modeling results alone. They emerged after the retrofit analysis results and recommended measures were presented to the respective building owners and discussed in the context of actual building operations, local conditions, and implementation feasibility constraints. These discussions revealed that retrofit recommendations should not be based solely on modeled energy and cost savings but should also account for the broader context in which the building operates.

First, energy availability and reliability can directly affect the feasibility of a recommended retrofit measure. For example, SABER indicated that electrification of the building located in Browning, Montana, could reduce energy use. However, after discussing the recommendation with the building owner, complete electrification was considered impractical because of concerns associated with the reliability of the local electricity supply during winter. Loss of power could result in loss of heating, creating potential safety concerns. This indicates that retrofit tools should account for local energy-system reliability when recommending fuel-switching or electrification measures.

Second, local crime and vandalism risks can affect the economic feasibility of certain measures. Owner feedback indicated that installing high-performance windows in areas where break-ins or vandalism are common may require additional protective measures and associated costs. Without such protection strategies, building owners may risk losing the retrofit investment before realizing its expected energy saving benefits. Therefore, local security conditions may need to be considered when estimating the actual implementation costs and associated cost-effectiveness of selected retrofit measures.

Third, the availability of local contractors, installers, and specialized services can strongly influence implementation. Discussions with building owners highlighted that retrofit measures requiring specialized labor or equipment may be difficult or expensive to acquire in rural or remote areas where such services are not readily available. These additional implementation challenges can increase project costs, delay installations, and ultimately lower building-owner confidence in the retrofit recommendations. Retrofit tools could therefore be improved by incorporating information on local service availability or by identifying measures that are more feasible under local market conditions.

The discussions with building owners and managers also demonstrated the importance of identifying low-cost and no-cost measures before recommending more capital-intensive retrofits. Changes in occupant behaviors, heating and cooling setpoints, operating schedules, and corrections of previously deployed retrofit measures can often provide meaningful savings with limited investments. Prioritizing these measures can improve cost-effectiveness and provide more practical options considering financial, market, or infrastructure constraints typically inherent to major retrofit measures.

Finally, occupant behavior must be considered when establishing baseline energy performance. Owner feedback indicated that low utility consumption does not necessarily mean that a building is energy efficient, as occupants may reduce heating or cooling setpoints to save energy at the expense of acceptable thermal comfort levels. If this behavior is not recognized, retrofit tools may underestimate the true energy needs of the building and

establish an inaccurate baseline. Incorporating information on occupant comfort targets, operating practices, and actual space-conditioning behaviors can therefore improve both baseline characterization and retrofit recommendations.

Overall, the findings from the post-analysis discussions with building owners and managers indicate that the practical implementation of retrofit measures is influenced by factors extending beyond modeled building energy performance, including energy reliabilities, local security conditions, service availabilities, implementation costs, occupant behaviors, and the availability of low-cost alternatives. Incorporating these factors into future retrofit analysis tools could improve the real-world applicability of their recommendations by filtering out technically attractive but practically infeasible measures, improving estimates of implementation cost, and prioritizing options that are more likely to be adopted by building owners and managers.

Overall, this study shows that retrofit analysis tools should be selected based on the level of accuracy required, available building information, user expertise available, and intended analysis complexity. The comparative assessment showed that simpler tools such as BETTER are more suitable for preliminary screening, while Asset Score provides an intermediate physics-based assessment and CBES and SABER support more detailed evaluation of individual and packaged retrofit measures, with SABER additionally enabling life cycle cost optimization. However, the comparative analysis results for real-building applications and discussions with building owners and managers demonstrated that technically attractive retrofit measures may still be impractical because of local energy reliability, security concerns, limited access to specialized services, occupant behaviors, and other implementation constraints. These findings highlight the need for future retrofit tools to combine robust energy and economic analysis with practical, location-specific considerations so that recommendations are both technically sound and realistically implementable.

8. Limitation and Future Work

Several limitations should be considered when interpreting the findings of this study. First, the comparative assessment was limited to a small set of readily accessible and freely available retrofit analysis tools. Therefore, the results do not represent the full range of commercial or proprietary retrofit analysis platforms currently available in the US and worldwide. In addition, the accuracy assessment was conducted using only two prototypical buildings with EnergyPlus predictions used as reference metrics. Although this approach enabled a controlled and systematic comparative analysis across all evaluated tools, the reported differences may vary for other building types, HVAC configurations, climates, and operational conditions. The real-building assessments, limited to four facilities in Montana, have allowed to identify some practical implementation barriers of building retrofit projects primarily through discussions with building owners and managers after the recommended retrofit measures were presented. Consequently, the identified practical barriers may not capture the full range of market, demographic, regulatory, or infrastructure conditions encountered in other regions.

Future work should therefore expand the comparative assessment to include a broader range of open-source and commercial retrofit tools, building types, climate zones, HVAC systems, and levels of building complexity. Additional studies should also incorporate measured post-retrofit data to evaluate not only the accuracy of predicted energy savings but also the ability of each toolkit to support measurement and verification after retrofit measure implementation. Such analysis would help distinguish uncertainties associated with the retrofit tool itself from changes caused by occupant behaviors, installation quality levels, operational adjustments, and other real-world factors.

Future retrofit tool development should also place greater emphasis on the practical feasibility of recommended measures. In addition to energy and economic performance, future frameworks could incorporate information related to electricity reliability, availability of qualified contractors and specialized services, local market conditions, security concerns, occupant behaviors, and opportunities for low- and no-cost improvements. Integrating these considerations into the retrofit-selection process could allow tools to prescreen technically attractive but impractical measures, improve estimates of implementation costs and risks, and generate recommendations that are more responsive to local conditions and more likely to be adopted by building owners and managers.

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Conflicts of Interest: The SABER tool evaluated in this study was developed by the authors. In this study, the authors took all necessary steps including comparing results of SABER with Energy-Plus simulation, avoiding comparative analysis between the tools, and avoiding commentary on superiority of any tool, to keep the analysis conducted in this study objective and without bias.

Abbreviations

The following abbreviations are used in this manuscript:

ASHRAE	American Society for Heating, Refrigeration, and Air-Conditioning Engineers
CBES	Commercial Building Energy Saver
DHW	Domestic Hot Water
DOE	Department of Energy
HVAC	Heating, Ventilation, and Air Conditioning
CO	Colorado
MT	Montana
SABER	Simplified and Automated Building Energy Retrofit Analysis Tool
SEER	Seasonal Energy Efficiency Ratio
SHGC	Solar Heat Gain Coefficient
US	United States
CSV	Comma Separated Values
LLM	Large Language Models
PV	Photovoltaic
DSS	Decision Support System
BPS	Building Performance Simulation
BESTAI	Building Energy Simulation and Analysis
BES	Building Energy Simulation

CBEI	Consortium for Building Energy Innovation
VERIFY	Virtual integrated platform on Life cycle Analysis
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
ERDSS	Energy Retrofit Decision Support System
KPI	Key Performance Index
IFC	Industry Foundation Class
BIM	Building Information Modeling
UAV	Unmanned Aerial Vehicle
AI4EF	Artificial Intelligence for Energy Efficiency
EFFESUS	Energy Efficiency for EU Historic Districts' Sustainability
CNZP	Community Annual Net-Zero Planning

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