Demonstration and Validation of a Virtual Energy Audit Tool for DoD Buildings

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14. ABSTRACT
Electricity consumption has been in the spotlight as part of the battle for sustainability resulting in legislative measures to try and reduce the amount of energy used. EISA 432 and the Energy Act of 2020 are two examples that require federal facilities to investigate buildings and find saving opportunities through energy audits. EDIFES solves this problem by providing fully virtual audits. Only five inputs are needed (15-minute interval electricity consumption, location, square footage, number of stories, and building end use) to produce complete energy audits. The virtual audit is automated, making them inexpensive and the small number of inputs allows a large number of buildings to be entered quickly. During this project, EDIFES performed energy audits on hundreds of buildings to ensure proper functionality and workflow. Over 250 DoD buildings received energy audits that then had their results posted to an interactive dashboard with portfolio rankings. Several validation methods were employed. All confirmed that EDIFES's methods worked as expected and with a high degree of accuracy.

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ABSTRACT

INTRODUCTION AND OBJECTIVES

Electricity consumption has been in the spotlight as part of the battle for sustainability resulting in legislative measures to try and reduce the amount of energy used. EISA 432 and the Energy Act of 2020 are two examples that require federal facilities to investigate buildings and find saving opportunities through energy audits. Every four years, all federal buildings must undergo at least one energy audit. Typically, this involves a walk-through of a building with various measurements being taken. Physical energy audits are labor and time-intensive making them very expensive, especially when they are needed for every federal facility.

Energy modeling software programs have been created as a cost-effective alternative to physical audits. They do not always require a team to physically assess a building but often need hundreds of inputs to work accurately. On a building-to-building basis this may work, but at larger installations providing those inputs becomes impractical. EDIFES solves this problem by providing fully virtual audits. Only five inputs are needed (15-minute interval electricity consumption, location, square footage, number of stories, and building end use) to produce complete energy audits. The virtual audit is automated, making them inexpensive and the small number of inputs allows a large number of buildings to be entered quickly.

During this project, EDIFES performed energy audits on hundreds of buildings to ensure proper functionality and workflow. Over 250 DoD buildings received energy audits that then had their results posted to an interactive dashboard with portfolio rankings. Validation was performed on EDIFES to confirm that energy savings predictions were accurate. Several validation methods were employed. All confirmed that EDIFES's methods worked as expected and with a high degree of accuracy.

TECHNOLOGY DESCRIPTION

EDIFES is a cloud computing application that performs virtual energy audits with time-series 15-minute interval electricity meter data. Statistical and machine learning analysis of time-series energy data allows for a building's loads to be disaggregated and subsequently potential savings calculated. These statistical and machine learning algorithms are the core of EDIFES, running as a server application in our private cloud environment (CRADLE). The results from the analysis provide energy managers insights into each of their building's behaviors, quantifiable savings, and suggested methods to achieve said savings. The portfolio of buildings is also ranked by total potential savings so that capital expenses for retrofits or other changes can be prioritized and implemented effectively.

PERFORMANCE AND COST ASSESSMENT

EDIFES markers all exceed the Pareto Principle meaning that there is less than 20% error on at least 80% of buildings. The software was validated in several different ways to prove its effectiveness on a wide range of buildings. This allows for potential energy savings to be accurately determined for most buildings. Potential savings are quantified as an annual savings value which allows customers

to easily weigh the value of capital improvements and system behavioral changes.

EDIFES 2.0 is commercially available with virtual energy audits costing $500-$1500 per building with volume discounts and annual subscription programs available. This saves time and money in walk-through audits. Expensive detailed walk-through audits can then be targeted at buildings with big savings opportunities if desired.

IMPLEMENTATION ISSUES

The largest barrier to the demonstration of EDIFES was the lack of access to data. Advanced meter data was very difficult to obtain even with central storage repositories such as MDMS and NavFac. Most DoD building data used was only made available during the last year of the project and limited commercial data had to be leveraged.

PUBLICATIONS

Publications include a patent, multiple theses, and several ESTCP/ARPA-E related posters and presentations. A full list can be found in Chapter 9.

EXECUTIVE SUMMARY

INTRODUCTION

In the US, approximately 40% of electricity consumption can be attributed to buildings. [1] Strategies to reduce energy waste have the potential to save money for building owners and increase sustainable practices. To encourage this, regulations such as EISA 432 and the Energy Act of 2020 require that federal buildings take measures to identify and implement energy conservation opportunities. [2, 3] This includes energy audits of every federally owned building each four-year cycle.

Physical walk-throughs that can include extensive testing and imaging are currently the only method to fulfill mandatory audit requirements. Each audit requires a team of people days to weeks to complete, leading to high costs, especially for larger building portfolios. Walk-through audits also provide differing feedback that is highly dependent on the company performing the audit. [4] This is expensive and time-consuming for federal facilities and yields inconsistent recommendations for energy managers.

Energy models are not a new approach and may seem appealing due to the lower cost and deeper insights they may provide. Unfortunately, these models typically require detailed data that must be assembled and input for each building. While this may work on an individual building level, it becomes impractical or impossible for energy managers who have large building portfolios.

EDIFES (Energy Diagnostics Investigator for Efficiency Savings - pronounced ‘edifice’) is a virtual energy audit software that transforms minimal inputs into actionable capital and behavior changes. 15-minute interval electricity consumption data, square footage, number of floors, location (e.g. zip code), and building end-use are all that is needed to find insights into energy savings. ”Big Data” analysis via distributed cloud computing techniques makes EDIFES cheap, simple, and fast while still providing valuable information about a building’s energy use. Energy audits for large swathes of buildings can be performed overnight for a small fraction of the cost it would take to perform physical audits. With the DoD managing over 300,000 buildings — all requiring EISA 432 compliance — EDIFES becomes an attractive alternative to traditional audits. [5]

OBJECTIVES

The primary objectives of this project were to demonstrate and validate EDIFES as a virtual energy audit tool. This involved the following:

1. Using the EDIFES portfolio screening tool to produce a prioritized list of buildings with the highest energy savings opportunities and an interactive visualization of results.

2. Simply and quickly identifying and quantifying energy and cost savings opportunities in these buildings at the onset (i.e. the audit) and throughout (i.e. for continuous commissioning) the project.

3. Validating the EDIFES prediction of savings through sensor validation (e.g. EDIFES outputs

fall within ±20% of actual values for measured equipment), validation with base energy managers (e.g. yes/no validation), or population validation (e.g. CBECS Dataset)

4. Attracting new partnerships with DoD organizations and other end-users, accelerating the path to commercialization.

Items 1, 2, and 4 involved interacting with DoD energy managers, retrieving building data, and then performing virtual audits. The audits were posted to a secure dashboard where energy managers could view insights into their buildings as well as a list of their buildings prioritized based on potential savings. The ease of use in both submitting batches of data and accessing results in our interactive dashboard demonstrated that EDIFES is an effective tool.

In addition to generally functioning as an auditing tool, EDIFES's results must be accurate. EDIFES identifies savings by first disaggregating various loads (e.g. exterior lighting, heating, cooling, etc.) and then calculating how consumption would be reduced if certain actions were taken. Since the saving insights are dependent on the accuracy of the load disaggregation markers, they need to be validated. Multiple methods were employed to quantify the accuracy of EDIFES including ground truth validation against submeter data, population studies, and comparison to energy modeling audit results. EDIFES needed to meet an 80/20 (Pareto Principle) benchmark: accuracy must be within 20% on 80% of buildings.

TECHNOLOGY DESCRIPTION

EDIFES is a cloud computing platform that uses statistical and machine learning analysis on electricity consumption time series data. Unlike other energy modeling software programs that are downloaded to a local machine by a customer, EDIFES runs as a server application in our private cloud environment, Common Research Analytics and Data Lifecycle Environment (CRADLE). This provides many benefits including faster computing and less work for energy managers since EDIFES is updated and maintained by our team. CRADLE is a hybrid Hadoop-HPC infrastructure utilizing HDFS as the distributed filing system, Spark for large-scale data analysis, and high-performance CPU and GPU nodes. The interactive dashboard is hosted on Amazon Web Services (AWS) to allow energy managers to access their private portfolio results in any common internet browser at any time. Data for analysis is easy to ingest to our server via another client-side dashboard.

Without physical audits, sub-metering, or lengthy questionnaires, EDIFES can provide insight into a facility's energy efficiency and quantify specific opportunities for energy savings. At the core of the EDIFES application lie building markers, which are generated to diagnose building efficiency and forecast energy conservation. To date, we have developed building marker functions capable of identifying components such as heating/cooling system turn-on and off time, heating/cooling turn-on wattage, heating type, cooling type, baseload, plug load, exterior/sensored lighting and schedule, effective R-value, etc. The whole process is automatically operated on CRADLE through the EDIFES pipeline as shown in Figure 1 The EDIFES building markers are used to diagnose building efficiency opportunities. When combined in a "Big Data" approach with the analysis of thousands of buildings, screening of a portfolio for comparison of relative consumption to similar buildings is enabled.

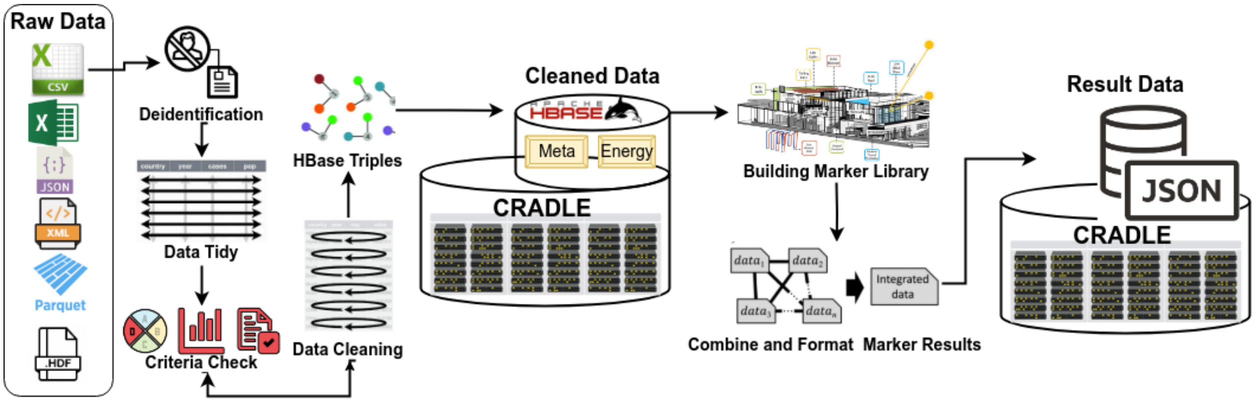


Figure 1: The EDIFES Pipeline.

PERFORMANCE ASSESSMENT

EDIFES met or exceeded all performance objectives, including demonstrating it as a viable virtual energy audit tool and validating the accuracy of the markers. DoD, commercial, and synthetic building data were used to accomplish the demonstration and validation of EDIFES.

331 virtual energy audits on 257 unique DoD buildings were performed. All audits had results posted to the front-end dashboard and credentials provided to energy managers to view results. This well exceeded the initial goal of 250 DoD audits. The locations of all buildings that have been audited by EDIFES are shown in Figure 2.

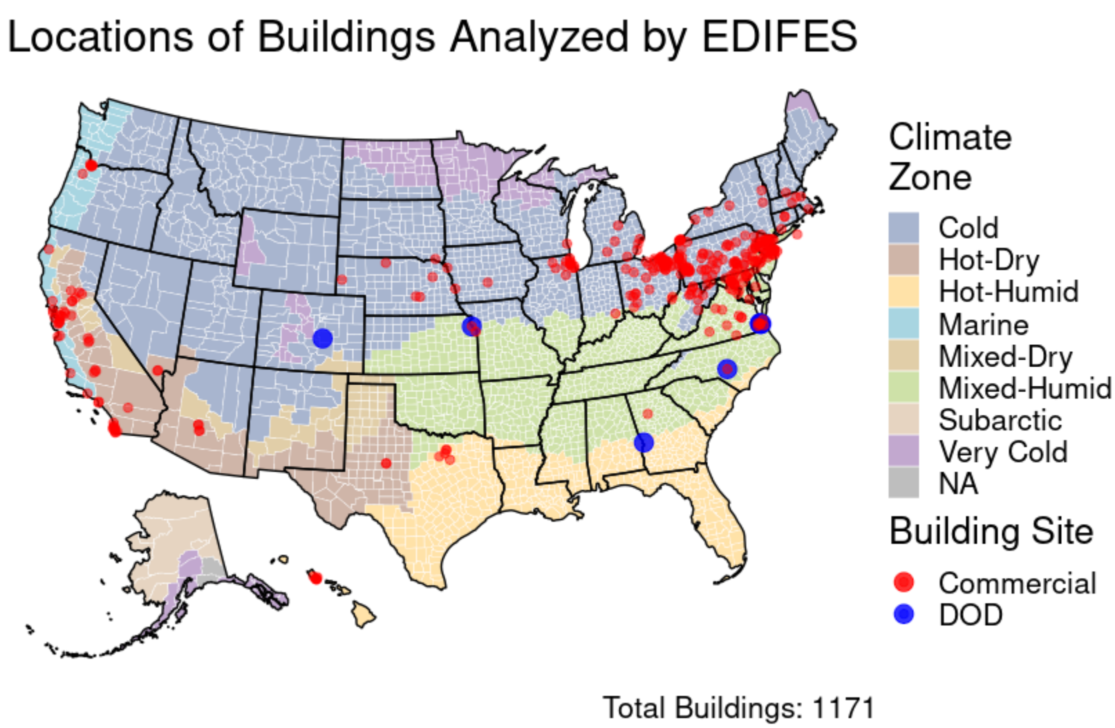


Figure 2: Locations of buildings that have been audited using EDIFES.

While submeter data was scarce, some ground truth validation was able to be performed on 24/7 gas stations and a dining hall/common area on the CWRU campus. The four gas stations all had their heating and cooling loads monitored along with whole building electricity consumption. This allowed for a side-by-side comparison of EDIFES's predicted heating and cooling loads to the true values of the buildings. The four buildings all had errors of less than 11% with a mean error of 6.3%. A comparison of the EDIFES predicted heating and cooling to the actual submeter data can be seen in Figure 3. One gas station also had submeter data for the exterior lighting load. EDIFES's prediction was within 4% of the submeter data.

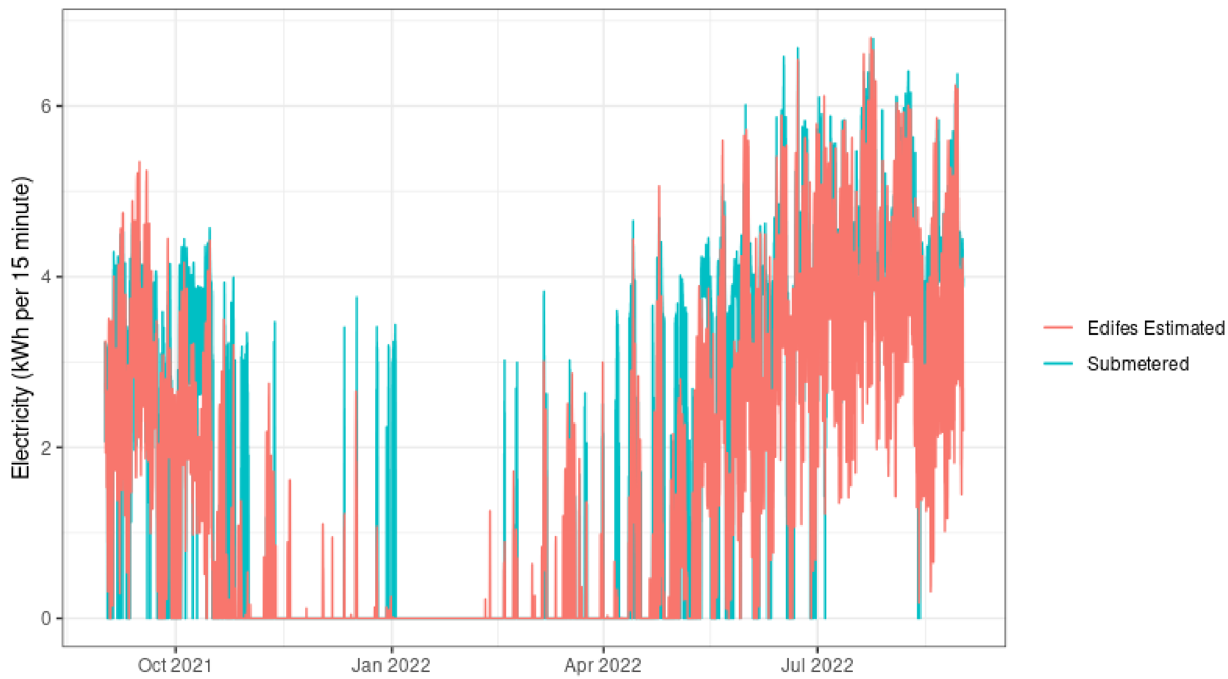


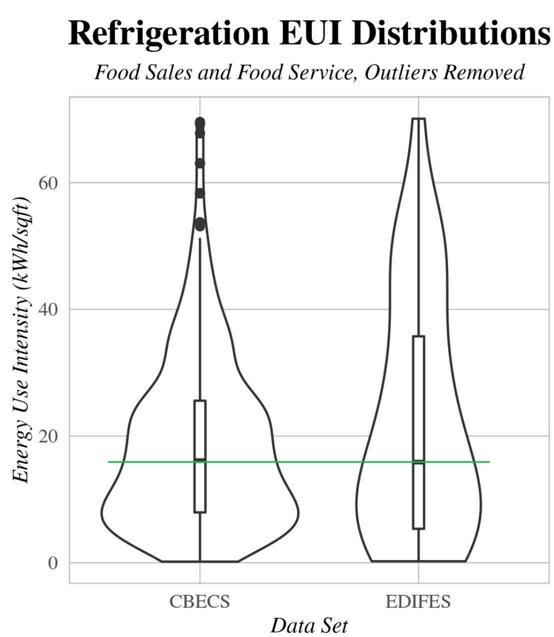
Figure 3: Time series of building 100 comparing EDIFES and submetered heating and cooling load across one year.

The CWRU dining and common area building was used to validate the refrigeration markers. Plug-in refrigeration appliances had submeter data collected. The larger walk-in cooler and freezer needed to have load estimated using a black box physics model due to safety concerns related to data collection. EDIFES's refrigeration load prediction was found to be within 5.88% of the submeter plus modeled load. The margin of error on the model was calculated and, in case of the largest error, EDIFES's prediction would still be within 7% of the submeter plus modeled value.

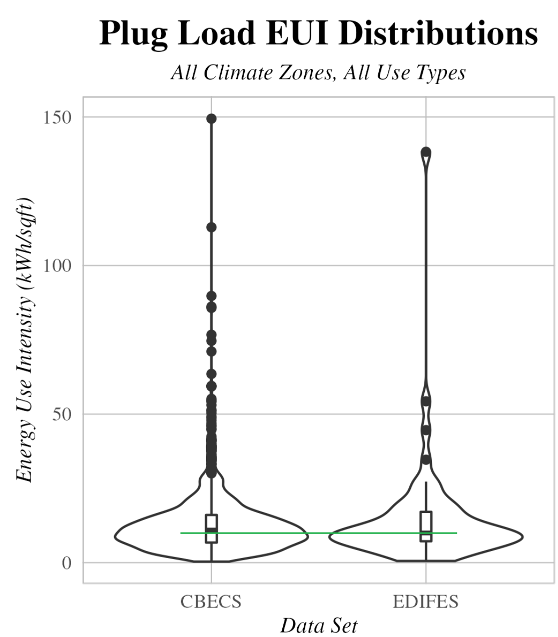
ComStock, a set of synthetic building data, was used to confirm the findings from the gas station exterior lighting validation. Out of 2716 buildings tested, EDIFES had a less than 20% error or correctly determined the building had little to no exterior lighting on 91.8% of buildings. Of the 132 buildings with high exterior lighting load, the mean error was 4.9% and only six were wrongly identified to have insignificant exterior lighting load.

A smaller batch of ComStock data was also used for validation of the heating type and cooling load. 1211 non-electrically heated (e.g. natural gas) buildings were run through the heating type marker, with EDIFES accurately identifying the heating type on 97% of them. The cooling load for ten office buildings was estimated, and EDIFES had a mean error of 9.7% when compared to the synthetic submeter data.

Since submeter data was in short supply, population studies supplemented the validation. Commercial Buildings Energy Consumption Survey (CBECS) is a survey of commercial buildings across the US that has been performed every six years beginning in 1979. [6] Randomly selected buildings have energy consumption recorded including total building consumption, heating and cooling, ventilation, etc. for the entire year, which are reported as energy use intensity (EUI) values. The EUIs are the loads/subloads divided by the building area, which gives a consumption value normalized for the size of the building. CBECS population distribution data for different loads was compared to the EDIFES total dataset using a Wilcoxon Rank-Sum Test. The p-values from this comparison would indicate how similar the distributions are, with a higher p-value (closer to 1) indicating a higher similarity. Alternatively, a p-value less than 0.05 would mean that the populations are unlikely to be the same. The distributions for the refrigeration and plug load were compared, with the p-values being 0.977 and 0.530 respectively. [7, 6] These distributions are visible in Figure 4. These distributions have very similar averages and spread. The HVAC loads were first sorted by heating type and then distributions were compared. While the district and electrically heated and cooled buildings had p-values of 0.677 and 0.524 respectively, the values for the non-electric heating and electric cooling buildings and electric heating and non-electric cooling buildings were much lower. [8] This is partially due to the inclusion of buildings that had "indeterminate" results being included in these groups. Non-electric cooling (e.g. district) is unusual and EDIFES has been noted to have higher errors on such buildings.



(a) Refrigeration



(b) Plug load

Figure 4: EUI distributions for CBECS and EDIFES predictions.

Qualitative validation from DoD site/energy managers was also completed. EDIFES predictions of heating/cooling type, presence of exterior lighting, relative cooling load, building shell ”leakiness,” and HVAC schedule times for 17 buildings were sent to energy managers for feedback. These high-level evaluations, while not the most accurate measure, were able to give a good indication of EDIFES’s results. Of the 92 results that we received feedback for, EDIFES had agreement with 80% of them. This confirms that EDIFES is a good indication of building behavior.

Outside of this project, EDIFES’s portfolio ranking of 12 retail buildings was compared to those of an energy modeling audit. The eight buildings with the highest potential for savings identified by the energy modeling process were the same as the ones identified by EDIFES. While the rankings themselves did not match exactly, EDIFES was able to provide a very similar result with only a fraction of the time and money needed for the energy modeling.

COST ASSESSMENT

The cost to run EDIFES on a single building ranges from approximately $500-$1500 per building (assuming data is readily accessible via the customer). This cost is significantly less than a physical energy audit, which can run $10,000 - $20,000 per building.

IMPLEMENTATION ISSUES

Initial agreements with DoD partners suggested that building electricity time series data was stored and readily available. These partners would also have allowed the EDIFES team to submeter some buildings as part of the demonstration. Unfortunately, it was found that historical data had been deleted and advanced metering discontinued after the project had begun. Getting data from other sites was very difficult and the only submeter data directly collected by the EDIFES team was at the CWRU site. Other challenges included hourly data or data with durations less than a year which is too sporadic for EDIFES to accurately predict savings. Despite these challenges, demonstration and validation were able to be completed.

Contents

List of Tables

List of Figures

1.0 INTRODUCTION

1.1 BACKGROUND

Energy is an ever-important issue capturing the attention of all major countries. A massive consumer of energy is the building sector where there is a significant opportunity to reduce energy waste. The United States uses approximately 100 quads of energy each year, of which about 40% is attributed to building uses such as heating, cooling, lighting, and electronics. [1] Considering the long lifetimes and slow replacement rates of buildings, energy retrofits are necessary to appreciably reduce energy consumption in existing building stock. These retrofits are typically identified and quantified in terms of cost and payback time through conventional energy audits or building information modeling.

Conventional audits entail a physical walk-through of a building, which can include performing leak tests, infrared imaging, blower door tests, equipment sub-metering, extensive sensoring, and more. Therefore, these audits require a team of individuals to survey an entire building, can result in high costs, and can take days to weeks to perform. Further, studies have found that the recommendations from these audits can vary drastically between energy audit companies. [4] Considering the time, cost, and variability in energy recommendations, building managers frequently question the economic benefit and ultimately may refrain from mobilizing their company to conduct conventional energy audits.

Building information modeling is another approach to quantify and understand a building's energy profile. With building information modeling, one can gain an even deeper understanding of a building's retrofit potential. These physics-based models, such as EnergyPlus, BLAST, DOE-2.1E, TRNSYS-TUD, and ESP-r among others, can assess energy efficiency opportunities but require thousands of inputs. [9] These models are often time-consuming and cumbersome, requiring substantial calibration to historical consumption data through various refinement parameters. These models are delivered as traditional shrink-wrap software, or referred to as on-premise software. The software is bought, installed, configured, and operated on the user's hardware. It requires the user to manage the software, including installation, operation, maintenance, and updates. This leads to increased complexity and operational costs, creating barriers to large-scale building energy performance measurement.

The Memorandum on Utilities Meter Policy that was issued by the U.S. Assistant Secretary of Defense on 1/14/2021 gives guidelines for metering energy usage at Department of Defense (DoD) installations. [10] The memorandum specifies that at least 60% of energy usage must be captured by metering or some other means. Consequently, more advanced meters were installed and additional time-series building electrical meter data were collected. For example, the Army developed the Meter Data Management System (MDMS) to track meter data from advanced utility meters in a central database through a secure network[11]. The Navy also worked on generating its own Advanced Metering Infrastructure[12]. Metering alone is not sufficient, and the ability to easily transform raw utility meter data into actionable insights is currently limited. The virtual energy audit tool EDIFES (Energy Diagnostics Investigator for Efficiency Savings - pronounced 'edifice') addresses this need. EDIFES, developed by Edifice Analytics Inc. (EA) and built on the innovations achieved under an earlier ARPA-E award (DE-AR0000668), only requires five pieces of information to provide insight into a facility's energy efficiency and quantify specific opportunities for energy savings: 14 months of whole building 15-minute interval electricity data from the utility or building meter, square footage, number of floors, location (e.g., zip code), and building end-use (e.g., office space or barracks). Instead of developing a traditional shrink-wrap software that only works on personal computers, we developed EDIFES as a cloud computing application, or software as a service (SaaS) application, to meet the emergence of utility meter "Big Data". The data analytic computation is performed on our private computational cloud called CRADLE and dashboard reports are delivered to energy managers through an internet browser. [13] By taking advantage of cloud computing and distributed computing techniques, EDIFES can audit 1000+ buildings overnight. EDIFES also provides a portfolio screening tool to produce a list of buildings prioritized by the highest energy savings opportunities to help energy managers focus capital investments for retrofit. DoD manages over 300,000 buildings (largely small to medium-sized) throughout the United States with annual expenditures of $3.7 billion on facility energy consumption. [5] Therefore, an inexpensive, easy-to-implement solution to diagnose building energy efficiency opportunities and prioritize capital investments to improve building energy performance is highly desirable.

1.2 OBJECTIVE OF THE DEMONSTRATION

The primary objective of this project was to demonstrate and validate the EDIFES tool on a population of 250+ DoD buildings, which requires:

1. Using the EDIFES portfolio screening tool to produce a prioritized list of buildings with the highest energy saving opportunities and an interactive visualization of results.

2. Simply and quickly identifying and quantifying energy and cost savings opportunities in these buildings at the onset (i.e. the audit) and throughout (i.e. for continuous commissioning) the project.

3. Validating the EDIFES prediction of savings either through sensor validation (e.g. EDIFES outputs fall within ±20% of actual values for measured equipment), validation with base energy managers (e.g. yes/no validation), or population validation (e.g. CBECS Dataset)

4. Attracting new partnerships with DoD organizations and other end-users, accelerating the path to commercialization.

1.3 REGULATORY DRIVERS

The implementation of the Energy Independence and Security Act of 2007 (EISA 432) includes mandatory reporting of energy efficiency measures in federal buildings. [2] This involves reporting energy consumption, project measures, and follow-up results for buildings at federal facilities. The main driver for using EDIFES is the requirement for energy consumption evaluations at said facilities. Of the total portfolio of federal buildings, 25% of buildings must undergo an energy evaluation annually such that all buildings are evaluated every four years. As part of this evaluation, each building is required to have recommissioning measures identified. Traditionally this involves a 4-8 hour walk-through in addition to other data collection efforts to determine if the building is a good candidate for a detailed evaluation to reveal potential savings opportunities. If chosen for detailed evaluation, a 1-4 day data collection project will be conducted to find ways to optimize energy use and/or identify where retrofits have the opportunity to reduce consumption. While EISA 432 had not been strictly enforced, the Energy Act of 2020 promises measures to ensure compliance. [3]

These processes are labor intensive making them expensive to complete, especially at facilities with large portfolios. In contrast, EDIFES is quick to implement and — more importantly — a fraction of the cost of physical energy audits. Energy managers simply need to upload data and enter the zip code, square footage, number of stories, and building end use to receive a comprehensive report that fulfills the requirements set by EISA 432. The buildings within a portfolio are also ranked by total potential savings so that detailed physical evaluations can be easily targeted. Through this process, EDIFES makes EISA 432 compliance faster, cheaper, and easier for energy managers.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY OVERVIEW

EDIFES is a cloud computing application that performs virtual energy audits with 15-minute interval electricity meter time-series data. Analogous to a mapping of the human genome, EDIFES maps a building's "DNA" through a rigorous statistical and machine learning analysis of time series energy data streams in comparison to the other buildings in our study population. These statistical and machine learning algorithms are the core of EDIFES, running as a server application in our private cloud environment (CRADLE). CRADLE is a hybrid Hadoop-HPC infrastructure containing a well-known distributed file system – HDFS, state-of-art large-scale data processing tool – Spark, and high-performance CPU and GPU nodes, and is the back-end of the EDIFES application. We built our interactive visualization dashboard (the front-end) as a Node.js application on AWS, that delivers the virtual energy audit results to energy managers through an internet browser. Energy managers can access building energy performance results and portfolios via the internet from anywhere, for as long as they need. The users can also ingest data to the server through the client-side dashboard. The following section will introduce the back-end, cloud computing environment, and the cybersecurity setup. Then we will present the front-end and dashboard. At the end of this section, the EDIFES algorithms will be covered.

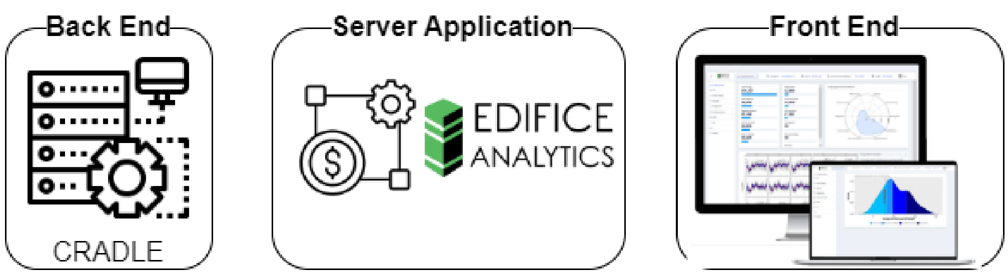


Figure 2.1: The structure of EDIFES — a cloud computing application.

2.2 TECHNOLOGY DEVELOPMENT

CLOUD COMPUTING ENVIRONMENT & CYBERSECURITY SETUP

The cloud computing infrastructure and framework for EDIFES is called the Common Research Analytics and Data Lifecycle Environment (CRADLE) platform (Figure. 2.2) at CWRU, developed by PI French. CRADLE integrates Hadoop clusters and HPC infrastructure into a hybrid framework optimized to leverage the combination of Big Data with Machine Learning to analyze building data at new magnitudes of scale. Hadoop combined with Spark manages vast data stores and distributed preprocessing. HPC systems provide high-performing CPU/GPU nodes that enable compute-intensive simulation, modeling, and machine learning jobs. More details about CRADLE, such as layer-by-layer containerized environment, machine learning toolbox, and benchmarking performance have been presented and discussed in this paper: [13]. Currently, CRADLE contains three Hadoop clusters (CRADLE 3.1, CRADLE 3.2, and CRADLE 3.3) with a storage capacity of 2.5 Petabytes. This architecture has been successfully employed for multiple DOE SETO, NETL, ARPA-E (EDIFES), and industry-funded research projects.

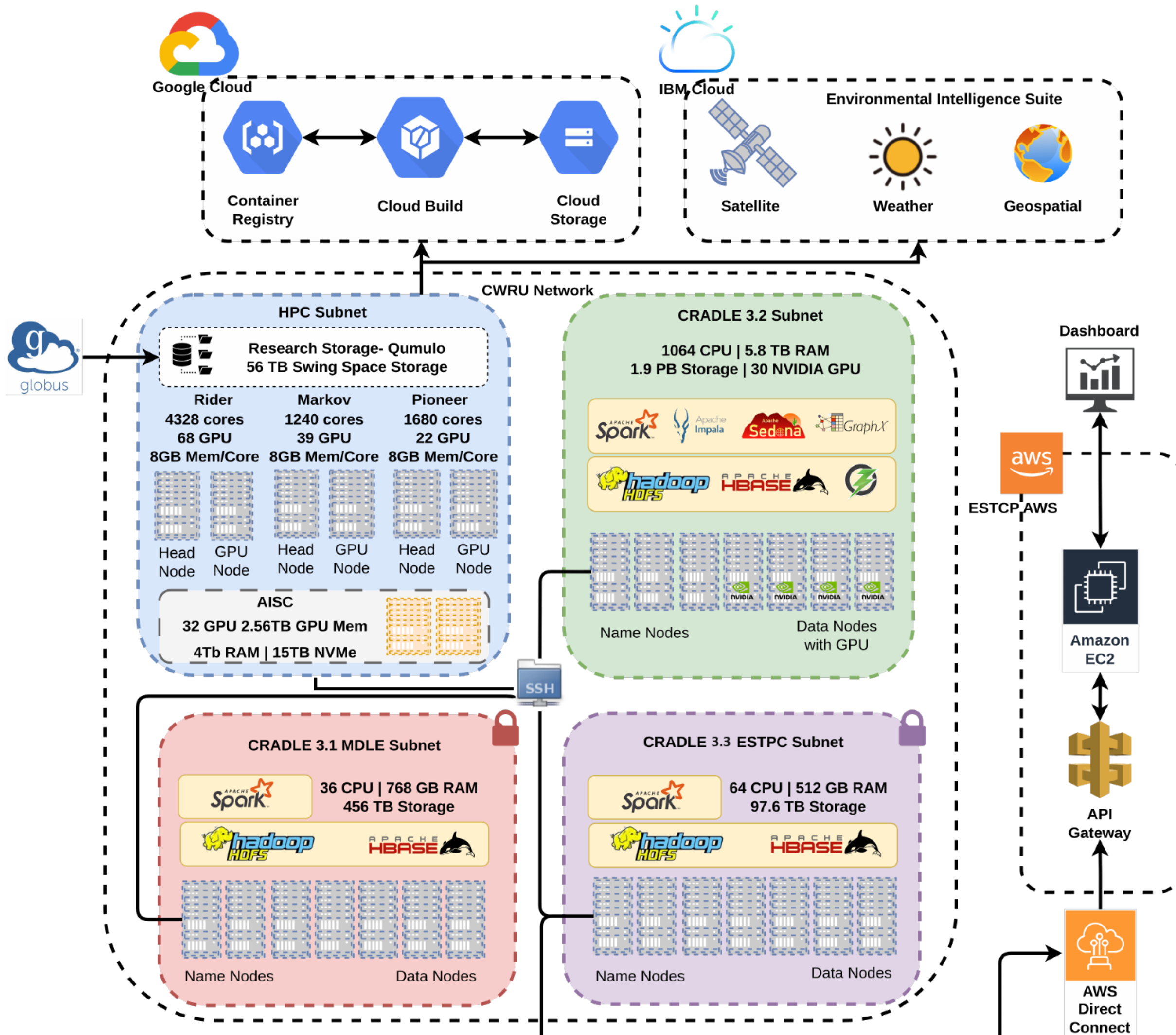


Figure 2.2: The hybrid Hadoop-HPC architecture of CRADLE — the cloud computing environment for EDIFES.

This project is the only project that utilizes the CRADLE 3.3 cluster. CRADLE 3.3 contains 64 CPUs, 512 GB RAM, and 97.6 TB storage, as shown in Figure 2.2. CRADLE 3.3 has the most strict cybersecurity setup illustrated by Figure 2.3. First, CRADLE 3.3, which is built on the Ubuntu singularity container, provides complete control over the EDIFES runtime environment and enables security scans to identify vulnerabilities. Second, CRADLE 3.3 offers disc encryption and Secure Shell Protocol (SSH) tunneling to ensure a secure connection with other clusters. Third, Apache Arrow is widely used in CRADLE interface tools to avoid disk i/o operation during data transfer processes to gain better performance and security. Fourth, we have leveraged university single-sign-on (SSO) systems combined with Kerberos (a network authentication protocol) and Apache Ranger (a centralized policy management software) to enhance the access control of CRADLE 3.3. For an extra level of cybersecurity protection, all members of Edifice Analytics (EA) are following the recommended security protocols, having installed Symantec Endpoint Protection and enabled full disk encryption on their personal computers. Furthermore, software like Nagios is used to monitor all virtual machines. Cloudera Manager was adopted to monitor the health of the Hadoop cluster. Audited AWS Architecture is utilized to enable security settings in the dashboard. This architecture has passed external cyber security audits through PMC Group, LLC, and meets the requirements of the DOD DFARS 7012 Cyber Risk Management Plan And NIST SP 800-171. [14, 15] The DoD CUI Self-Attestation Letter for declaration of conformity is attached in Appendix 2: Self-Attestation Declaration of Cybersecurity Regulation Conformity.

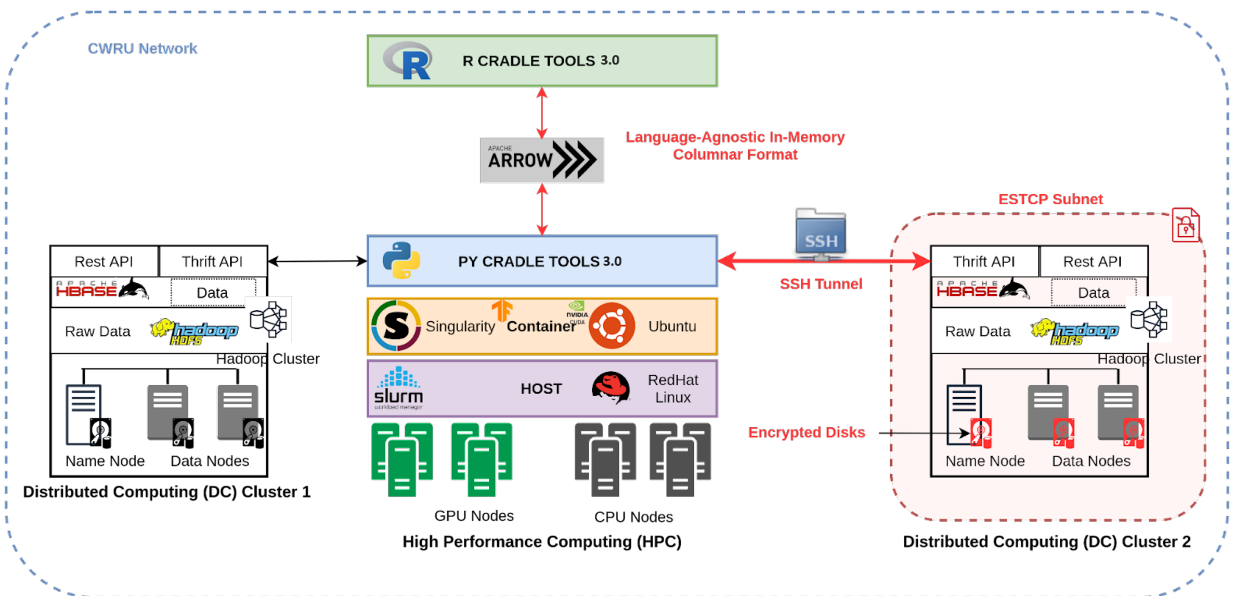


Figure 2.3: CRADLE 3.3 meets the DOD DFARS 7012 Cyber Risk Management Plan and NIST SP 800-171.

INTERACTIVE VISUALIZATION DASHBOARD

An interactive visualization dashboard contains five types of pages: homepage (savings overview), specific building marker energy conservation measures (ECMs), EUI benchmarking, data quality, and data upload. The following section will introduce these five types of pages and then discuss the front end architecture.

Homepage: Figure 2.3 presents an example of the homepage of EDIFES dashboard reports. The header contains basic building information: building name (a drop-down list), location, square footage, annual consumption, and building use type. The main body of the homepage is the savings overview (at the top) and energy pattern snapshot (at the bottom). In the savings overview area, the ECMs of the current building are summarized as a bar plot and arranged from the highest to the lowest in the radar chart.

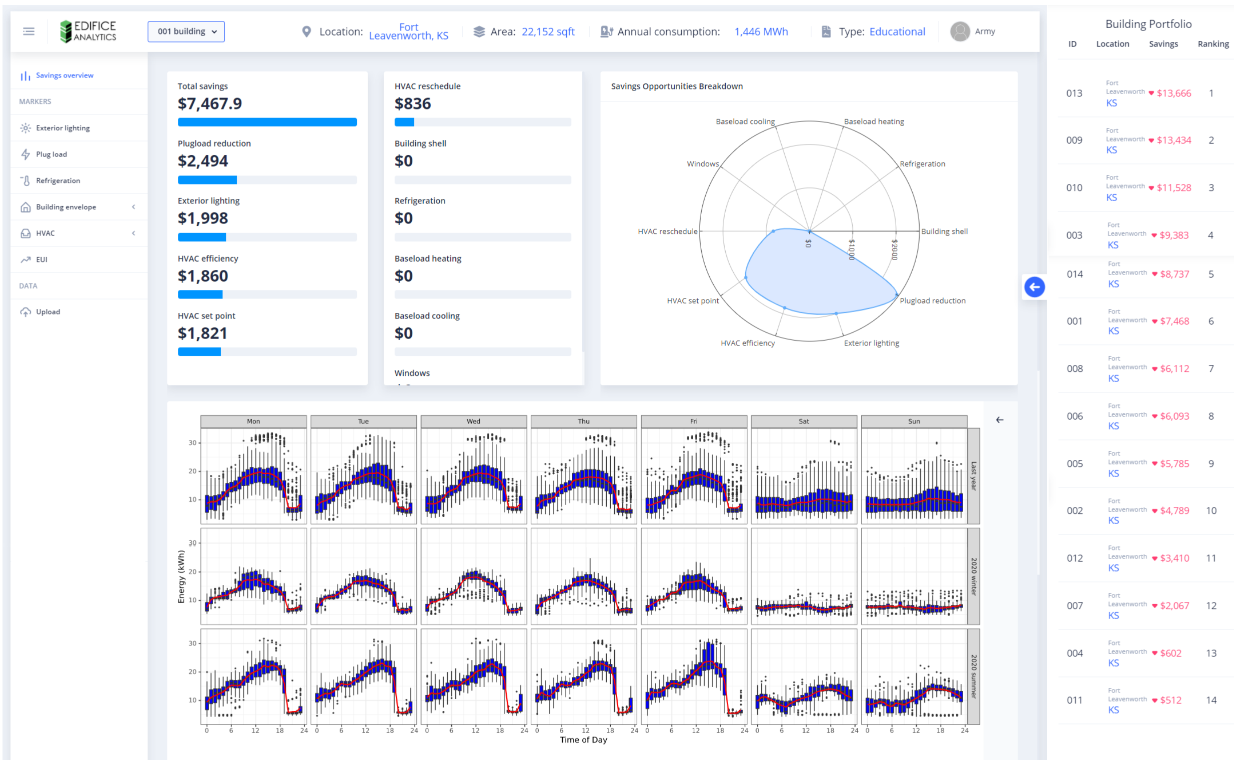


Figure 2.4: An example of the homepage of EDIFES's interactive visualization dashboard.

The energy pattern snapshot is a highlight on the homepage. The plot allows a quick first glance at the schedule of the building and energy consumption variation weekly and seasonally. The blue boxes with vertical lines are boxplots of 15-minute interval electricity data grouped hourly, which shows not only the range but also the distribution of 15-minute energy consumption in that hour. In these boxplots, dots above or below vertical lines represent outliers, that are unusually large or small energy consumption data points. The red line traces the median of 15-minute energy consumption throughout the day. The daily energy usage pattern and base-to-peak ratio can be observed through these boxplots in each cell. Similar cells span horizontally in seven columns, which illustrate energy usage patterns over seven days a week. This allows for easy comparison of weekday to weekend consumption behavior. The cells are spread vertically over three rows so that energy consumption differences between winter and summer are apparent. The portfolio ranking lists the buildings with the largest energy savings potential and is located on the right side. Currently, we only present portfolio screening based on the total saving opportunity. The next generation of the dashboard will include an interactive portfolio screening tool that will allow ranking buildings based on each component such as heating and cooling, refrigeration, insulation, etc. The navigation bar on the left provides the results for every marker. Details about ECMs for specific markers can be found there.

Currently, ECMs are provided for exterior/sensored lighting, plug load, refrigeration, building shell insulation and windows insulation (these two are under the building envelope category), HVAC efficiency savings, HVAC reschedule savings, HVAC setpoint setback savings, and baseload savings (these four are under the HVAC category), and Energy Use Intensity (EUI) benchmarking.

Building Marker ECM Page: An example of the exterior/sensored lighting page is shown in Figure 2.5. It consists of a potential savings bar plot (top left), description (top right), and time series plot (bottom). The exterior/sensored lighting marker identifies if the building has lighting (e.g. in a parking lot) with daylight sensors or a schedule following sunrise/sunset. EDIFES cannot determine the exact type of lighting at the facility but helps by quantifying savings potential if available. The dashboard reports three options for annual paybacks through the bar plot: paybacks of 10%, 20%, and 30% reduction of exterior lighting energy consumption. The suggested solutions to achieve the reductions are listed in the description. The time series plot visualizes the annual energy consumption in kWh. The time interval of the plot can be set to hourly, daily, or monthly. The plot displays the actual energy consumption and also the annual reduction in energy consumption for the recommended adjustment detailed in the bar chart.

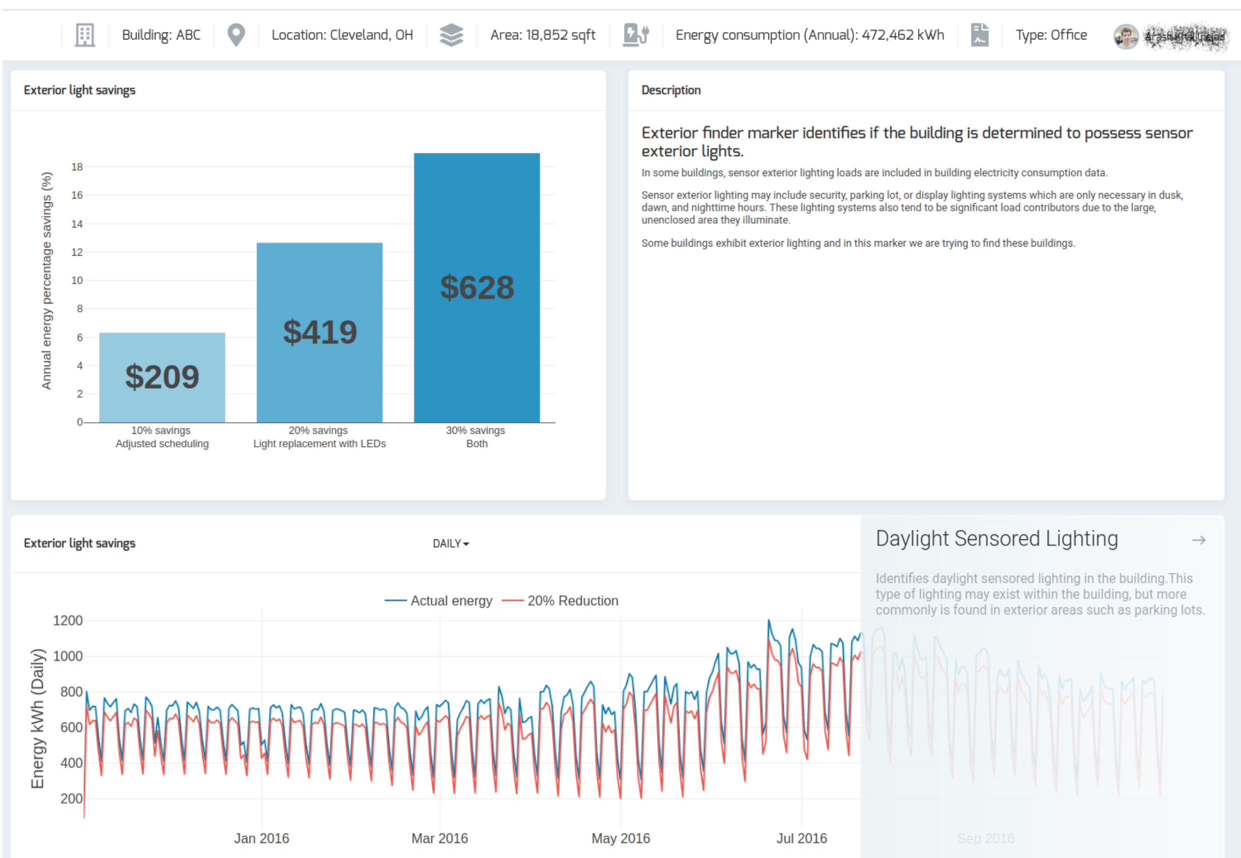


Figure 2.5: An example exterior/sensored lighting ECM page.

EUI Benchmarking Page: To inform energy managers or building owners of a building's relative energy performance, EDIFES also provides EUI benchmarking. The benchmarking was designed to compare the site EUI of electricity consumption of a single building to similar buildings from a hybrid dataset. The dataset we use for benchmarking is a combination of the 2012 Commercial Buildings Energy Consumption Survey (CBECS) dataset and the EDIFES dataset. The CBECS dataset, a large and trustworthy dataset, is a randomly sampled representative survey of all commercial buildings across the United States, which contains more than 6,000 buildings. [6] The EDIFES dataset also holds data of 1,000+ commercial buildings from across the United States. The "similar buildings" are defined as buildings in the hybrid dataset that have the same usage type (e.g. Office or Retail), in the same climate zone, and have the same heating and cooling type. The EUI of the audited building is plotted on the distribution of EUIs of similar buildings. The four quartiles of EUI distribution are shown with the higher EUIs being darker in color. The position of the EUI of the audited building is highlighted as a vertical line. The user can then compare their building's consumption per square foot to similar buildings.

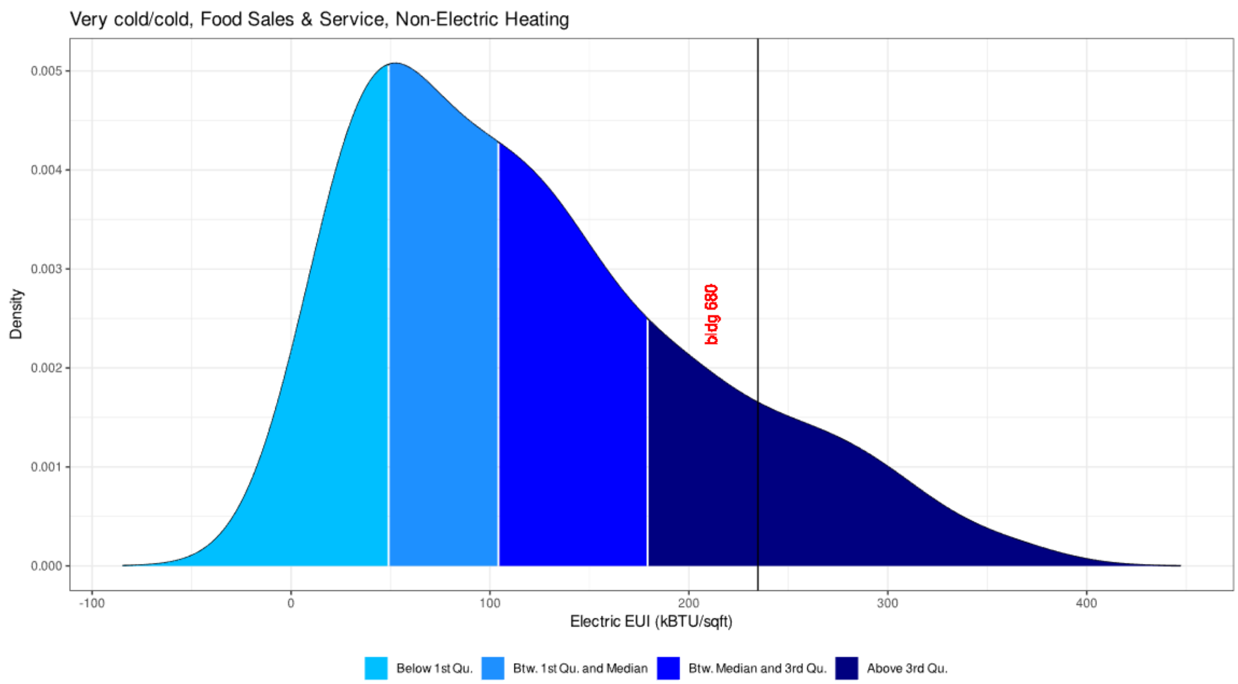


Figure 2.6: An example of the EUI benchmarking page.

Data Quality Page: Real world data are not perfect. They are usually messy, heterogeneous, and subject to various measurement errors and missing values. As a data-driven application, the accuracy of EDIFES is highly dependent on the quality of inputted data. Thus, the data quality grading criteria were built for EDIFES to assess data integrity and suitability and to categorize and tag data accordingly. This will help reduce technological uncertainty, minimize human errors in data recording and delivery, and ensure quality development of the EDIFES tool. Some datasets may be discarded for various reasons including low-quality data, significant anomalies, large amount of missing information, or building type/use/characteristics of low statistical significance. A summary of data quality grading criteria is shown in Table 2.1.

Table 2.1: Data quality grading criteria.

	Anomalies (%)	Missing + Zeros (%)	Largest Missing Chunk (Days)
A	$< 5\%$	$< 10\%$	< 5 days
B	$5\% - 7\%$	$10\% - 15\%$	$5 - 7$ days
C	$7\% - 10\%$	$15\% - 20\%$	$7 - 10$ days
D	$> 10\%$	$> 20\%$	> 10 days

Note that detected missing and zero energy points are imputed in the data prepossessing phase, as discussed in the following subsection. The data quality page reports the data quality grade before the data cleaning process to inform data owners about the raw data quality. The data quality page consists of the final grade (A to D) on the top, a list of detailed data quality parameters on the left, and a line charts that are used to highlight missing values of the data on the right. The data quality parameters listed on the data quality page include:

- *Time interval*: the time interval of the time series data such as 15-minute interval or 1-hour interval
- *Provided start day*: the first day of the data the user provided
- *Provided end day*: the last day of the data the user provided. Site managers can know the length of the data when they look at the provided start and end day
- *Analyzed start day*: the first day used in EDIFES's analysis
- *Analyzed end day*: the last day used for EDIFES's analysis. Site managers can know the time frame their results represent
- *Largest gap (days)*: a series of continuous missing values is called a gap. The number of days in the largest gap can tell site managers the longest interval that the meter is not working
- *Number of gaps*: the number of missing regions in the data
- *Missing data %*: percentage of missing data
- *Data with zeros %*: percentage of zeros (usually due to meter malfunction)
- *Anomalous data %*: percentage of anomalous data

Line charts are used to visualize raw data values. Blue lines represent the value of energy data on each timestamp. Red lines highlight the missing region of the data. The distribution of missing values, outliers, and general data patterns are easy to see from this plot.

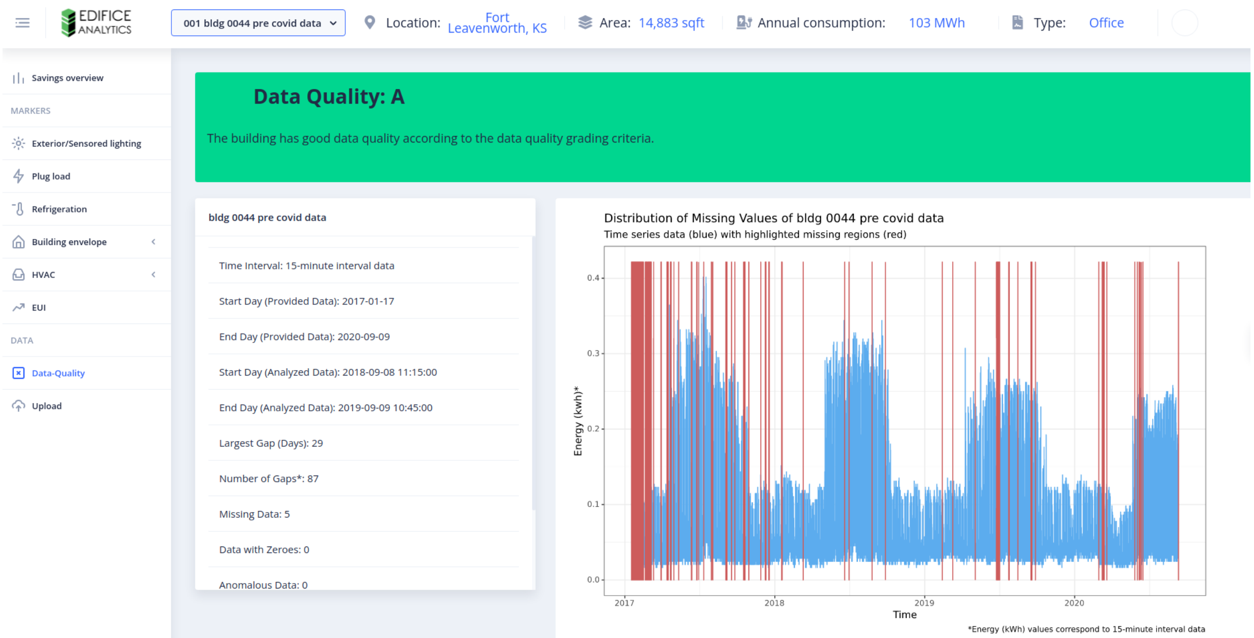


Figure 2.7: An example data quality page.

Data Upload Page: The data upload page allows the user to ingest the data to the back-end server. There are two modes of upload: single-building data upload (Figure 2.8) and batch upload (Figure 2.9). In the single building data upload mode, the user can ingest data of a building by filling out all required meta information and submitting 15-minute interval electricity meter data. In the multi-building upload mode, the user should download the template first to ensure consistency between metadata and time series data. Then, the template can be filled out and a data file for each building can be uploaded.

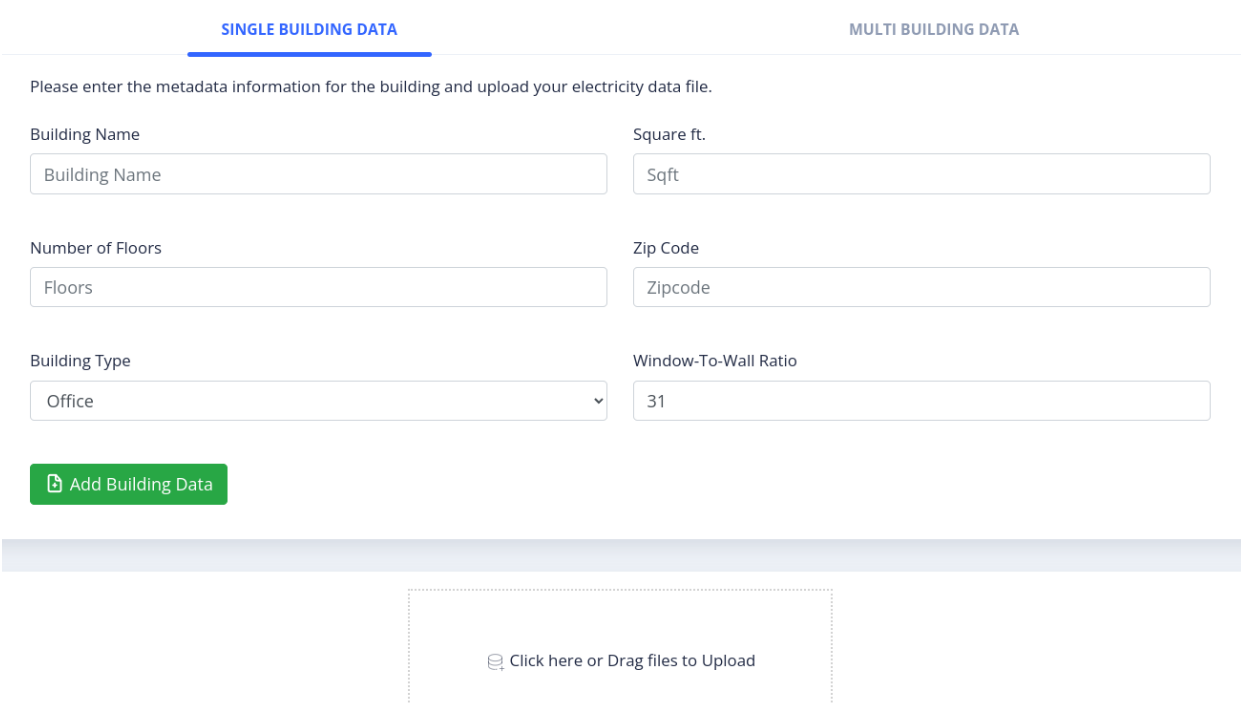


Figure 2.8: The single building data upload page.

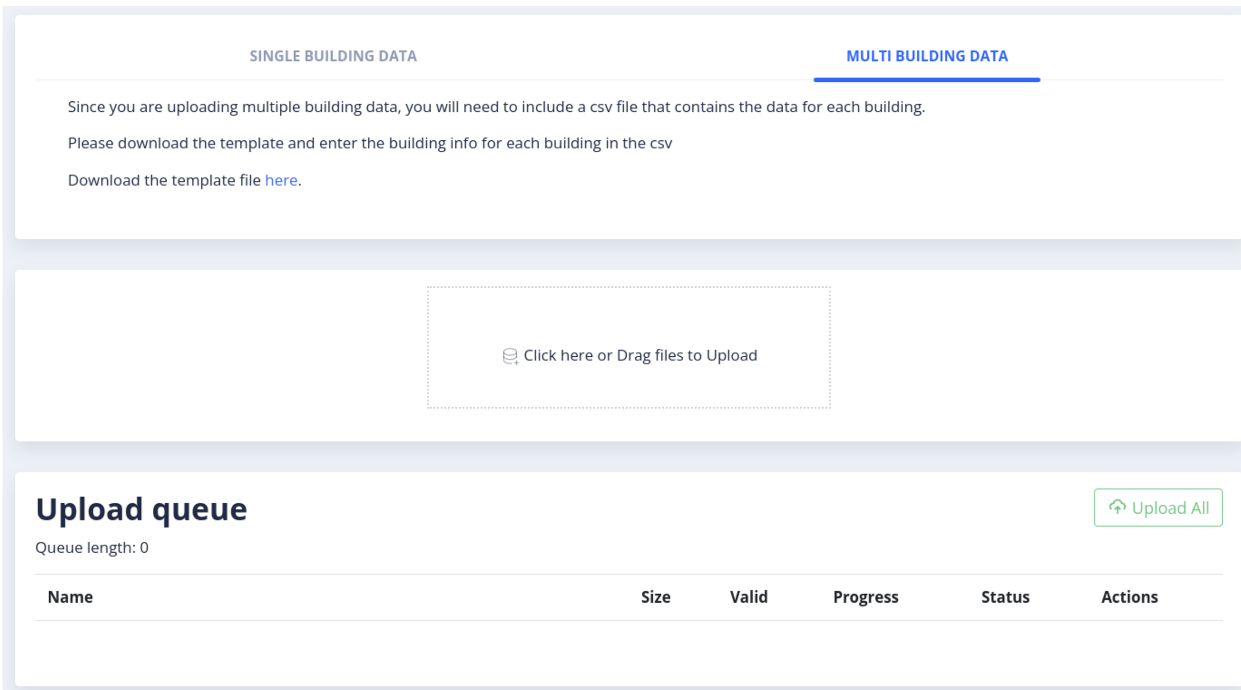


Figure 2.9: The multiple building data upload page.

EDIFES API Architecture: For the front end of EDIFES, AWS was selected based on ease of use, security, scalability, and cost-effectiveness. The EDIFES API architecture is illustrated in Figure 2.10. First, each marker output is converted into JSON format and saved in HBase. All the data and databases are preserved inside the virtual private network (VPN) protected by CWRU, and only use HBase Rest API Gateway to exchange data with outside networks. Second, AWS Direct Connect enables data exchange between AWS and back-end CRADLE. Inside the AWS virtual private cloud (VPC), Amazon API Gateway is used to handle API requests from browsers, and Amazon CloudWatch is used to monitor the application. To improve data security, access control is implemented by token-based API authentication. Authorized users can get an access token by entering their username and password, and then retrieve data by passing the token to the API. The data collection is inaccessible without the token. Finally, the dashboard calls the API to visualize the outputs or upload data.

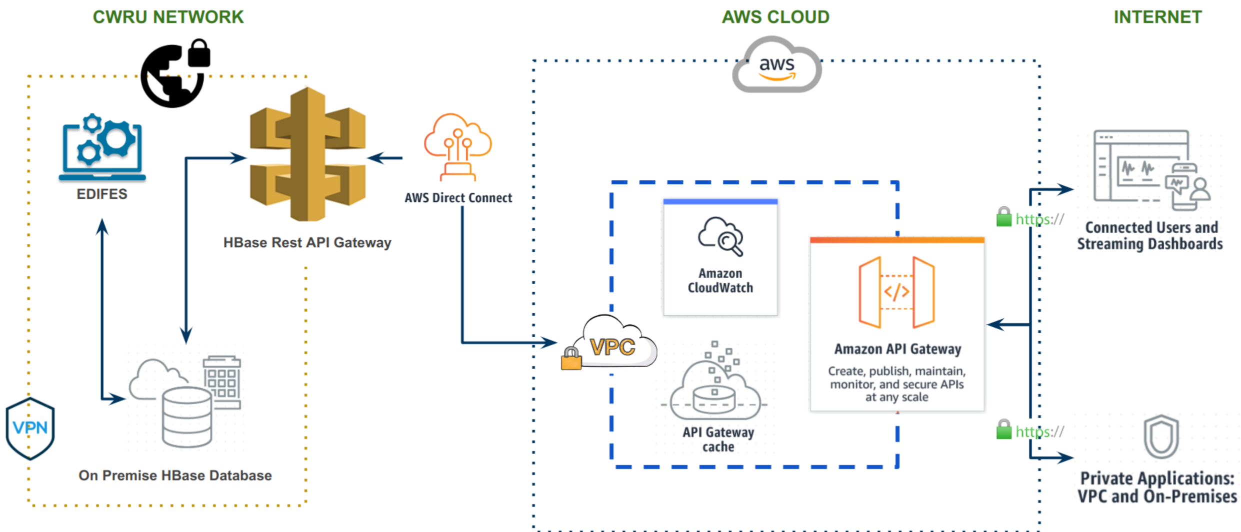


Figure 2.10: EDIFES API Architecture.

EDIFES ALGORITHMS AND PIPELINE

As the core of the EDIFES application, building markers are generated to diagnose building efficiency and forecast energy conservation. The whole process is automatically operated on CRADLE through the EDIFES pipeline. This technique was successfully patented: [16]. In this subsection, we will first introduce the requirements of input datasets. Then, the building marker library will be discussed, followed by the portfolio screening feature based on “Big Data”. The EDIFES pipeline is covered at the end.

Datasets & Data Ingestion: EDIFES requires at least 14 months of time-series utility data associated with temporal energy consumption as the basis for its analysis. The predictive insights improve with shorter time intervals in the time series; for example, 5 or 15-minute interval data is preferred over hourly interval data, while daily or monthly aggregated data time series have little relevant information. Currently, the widely installed advanced meter infrastructure units typically report electricity data in 15-minute intervals. Other building metadata such as location, square footage, number of floors, and building use type are also important for the analysis (as requested in the data upload page shown in Figure 2.8). Building square footage and number of floors are required to understand the thermal management characteristics of a building. These values enable cross-sectional studies, such as comparing multiple buildings in a location or across climate zones on a per-square-foot basis, as illustrated in the EUI benchmarking page in Figure 2.6. Compared with other studies in the field for virtual building audits, EDIFES leverages weather data combined with time-series electricity data for statistical and machine learning analysis. [17, 18, 19] EDIFES is, therefore, able to provide richer building energy marker libraries and enhance the ability for building efficiency diagnostics and energy conservation prognostics. The weather data is supplied by EDIFES, available from sources such as National Oceanic and Atmospheric Administration (NOAA) and satellite-based weather providers such as SolarGIS. [20, 21].

Building Energy Marker Library: Buildings are complex systems where various components interact together and affect overall energy efficiency performance. The building system has multiple critical elements including envelope, lighting, heating and cooling system, electronics, etc. Different components are constructed differently, dominated by different physical rules, and operate differently; no one simple code can work on all components. For this reason, we have generated 30+ building markers and 100+ auxiliary functions that characterize the energy usage and efficiency of target components and built the building marker library. To date, we have developed building marker functions capable of identifying components such as heating/cooling system turn-on and off time, heating/cooling turn-on wattage, heating type, cooling type, baseload, plug load, exterior/sensored lighting and schedule, effective R-value, etc. For example, as shown in Figure 2.11, the exterior lighting load is detected by monitoring the electricity variations during the time of sunrise/set, since an exterior lighting schedule is similar to sunrise and sunset times.

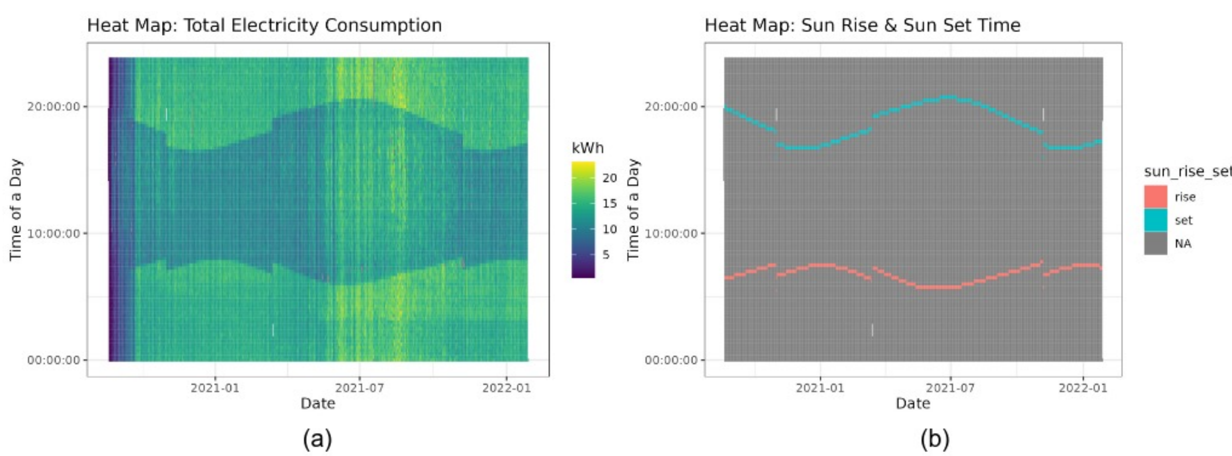


Figure 2.11: Exterior lighting schedules can be ”seen” as periodic lines in this plotting of heat map of energy consumption, and is very similar to the time of sunrise/set.

We can disaggregate the exterior lighting load from the total load by isolating and then comparing and contrasting portions of the data when exterior lighting is on or off, and associating that data with an understanding of when HVAC conditions (i.e. temperature and solar insolation) are changing or steady. We have been successful in accomplishing this type of disaggregation with high confidence in office buildings. [22] Again, the disaggregation can be accomplished using only utility data at the whole building level — additional sensors or non-intrusive load monitoring are NOT required.

These building markers are used to diagnose building efficiency issues, enable the screening of a portfolio of buildings, and conduct a population comparison across similar building types.

Portfolio Screening and Population Comparisons: The EDIFES building markers are used to diagnose building efficiency opportunities, and when combined in a "Big Data" approach with the analysis of thousands of buildings, they enable us to expect behaviors of different building types. From there, we can determine how these buildings behave across different climate zones. This provides the basis for quantitative screening of building portfolios and enables cross-sectional studies. Portfolio analysis, utilizing our full suite of building markers and our thousands of previously analyzed buildings, enables us to quickly rank-order buildings in a portfolio for the best energy savings, considering both operational changes (such as setpoint setback) and capital improvement changes.

An example of HVAC Setpoint Setback savings and HVAC rescheduling savings of 432 building portfolios is shown in Figure 2.12. These buildings come from five different building types (Figure 2.12(a)) and are distributed across the United States predominantly in the North East and California (Figure 2.12(b)). The HVAC Setpoint Setback savings are achieved by changing the temperature setpoint of the building's HVAC system during unoccupied hours. The densities of buildings that can achieve savings of different amounts are shown in 2.12(c)). For Food Sales buildings, these savings are normally distributed and are on the order of 1.55% of energy used. Whereas for Office buildings, the median savings is 1.83%. Office buildings exhibit a bimodal distribution with one subgroup of these buildings showing a 3% energy savings opportunity. Obviously, by prioritizing these 3% savings, office buildings will have a better return on investment (ROI).

Similarly, if we consider the HVAC rescheduling building marker for this building portfolio, we get the results shown in Figure 2.12(d). In this case, we illustrate the potential savings for a total shift of one hour of the HVAC turn-on and turn-off times (in reality, the savings for many different rescheduling times are calculated). Here we see the industrial building types are normally distributed, while food sales show a bimodal density. Office, educational, and retail buildings show a broad range of savings opportunities. This illustrates the utility of the EDIFES portfolio analysis approach since we can prioritize from the building population how to achieve the largest savings for a given investment.

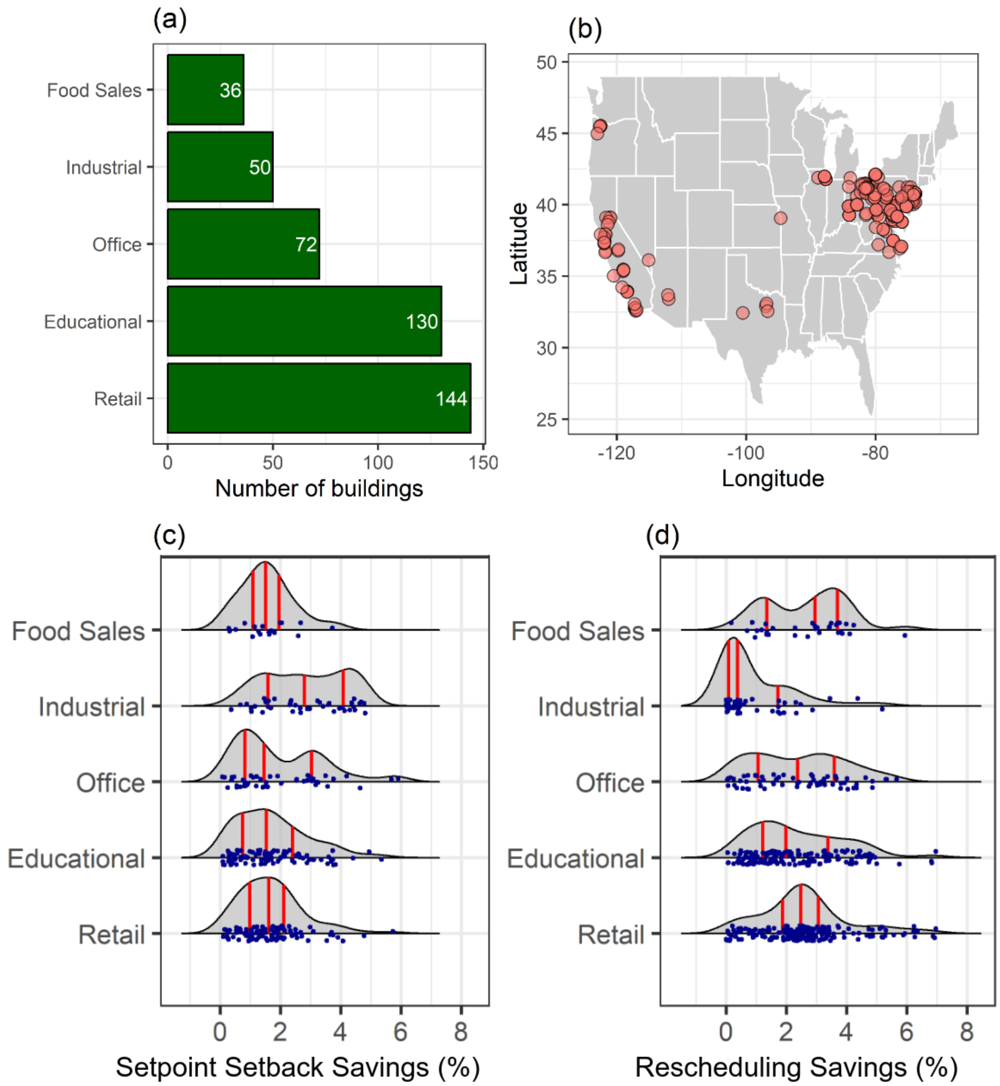


Figure 2.12: Building type, location and two energy savings markers for a population of 432 buildings. (a) Breakdown of the buildings by types. (b) Locations of the buildings. (c) Setpoint setback savings by building type for cooling during unoccupied times. (d) HVAC rescheduling savings by building type. In c, d, the density of buildings for a given savings value is shown, along with the actual building results (blue dots), 1st quartile, 2nd quartile (median), and 3rd quartile (red lines).

EDIFES Pipeline: To reduce labor, achieve scalability, and enhance analytical capability, EDIFES developed the data pipeline in which advanced meter data is ingested, analyzed, and results ported to our database. The data pipeline is a series of data processing steps in which each step delivers an output that is the input to the next step. Independent steps may be run in parallel thus enabling the batch processing to achieve scalability and cost efficiency. In the EDIFES data pipeline, as shown in Figure 2.13, the raw data from various data sources undergoes several data processing and flows into the database as cleaned data. The data processes to clean the raw data include:

- **Deidentification:** Due to privacy and security concerns, the data are de-identified with random alphanumeric names.
- **Data Tidying:** Map the meaning of a dataset to its structure. In tidy data: every column is a variable, and every row is an observation.
- **Criteria Check:** Grade the quality of raw data based on self-developed data quality grading criteria to make sure no "bad" data are used for the virtual energy audit.
- **Data Cleaning:** Detect and impute missing values, anomalous data, and zeros. Cleaned data will be graded again to check if it passes the criteria or not.
- **HBase Triples:** Assign a columnkey and rowkey to each value (build a triple) for the ingestion into HBase.

These cleaning processes ensure that the data stored in the database for analysis is clean, consistent, and reliable. The pipeline automates the process of detecting and correcting errors, which not only maintains the integrity of the data but also safeguards virtual energy audits from making misguided decisions based on faulty data. After cleaned data are available in CRADLE, the building markers are run on the cleaned data. Then, the results from each marker are collected, assembled, and formatted into the final JSON format that is ready for the EDIFES API call. For more details on the EDIFES pipeline, please refer to this paper: [23].

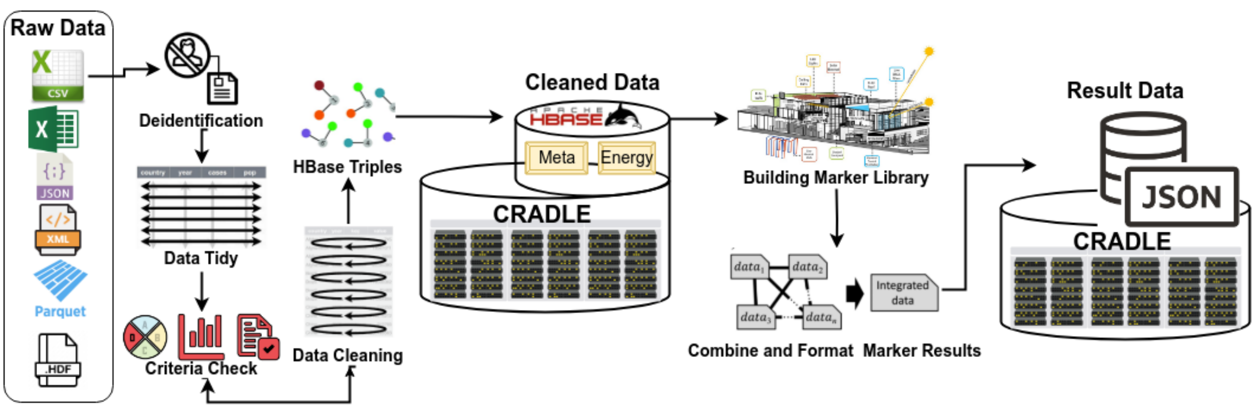


Figure 2.13: The EDIFES Pipeline.

SOFTWARE INTEGRATION (OUTSIDE THIS PROJECT)

Energy Act of 2020 and EISA 432 requires mandatory reports of energy efficiency measures in federal buildings. As a virtual energy audit tool, EDIFES can reduce the need for walk-through audits and speed up the process of energy efficiency measures. There are other popular tools in the Federal market for building energy efficiency, such as Compliance Tracking System (CTS) to submit reports, Energy Star Portfolio Manager to benchmark energy usage, and BuildingSync Schema used to communicate with other tools. In order to better satisfy the Federal market, EDIFES established connection to those commonly used tools aiming to make it easier for users in the Federal market utilizing these tools, as shown in figure 2.14. For example, we enabled EDIFES to "speak" the standardized BuildingSync schema[24]. BuildingSync is developed by DOE FEMP as a common schema for energy audit data that can be utilized by different software and databases. Currently EDIFES can output files in the JSON format using BuildingSync schema, or ingest files (accommodated outputs originating from other tools) if it is in BuildingSync schema format.

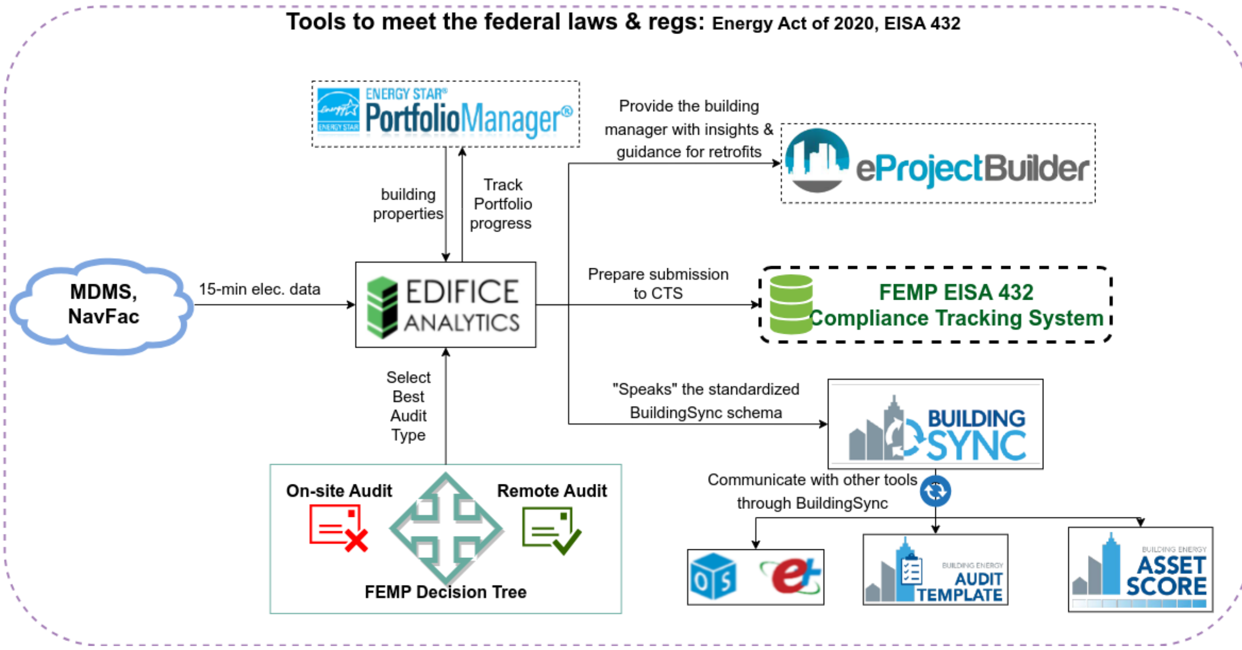
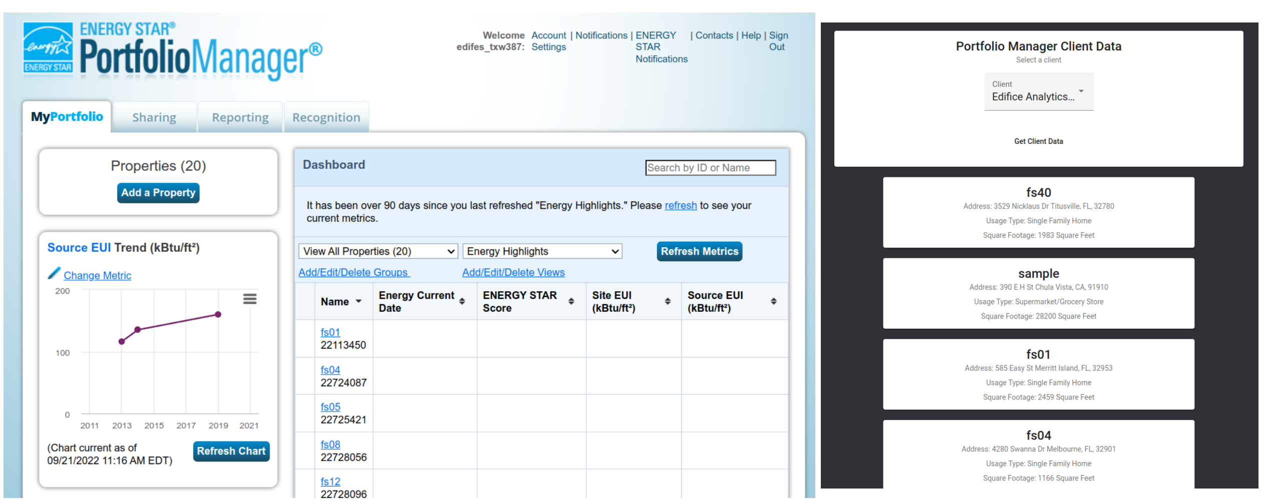


Figure 2.14: EDIFES is well integrated with other tools in the field for easy use.

EDIFES also created API connection with Energy Star Portfolio Manager[25]. Energy Star Portfolio Manager are widely used by energy managers to save information, to track monthly energy usage and to do benchmarking for a portfolio of buildings. Now users can share building information with EDIFES directly through Energy Star Portfolio Manager with few button clicks and our API can get the information we need for the analysis, as shown in figure 2.15.



(a) Portfolio Manager dashboard example

(b) Visualization of retrieved data

Figure 2.15: API Connection with Energy Star Portfolio Manager

We are working on generating connection with CTS to simplify the reporting process for energy managers through the CTS platform. It is envisaged that once FEMP Facility Evaluation (Audit) Decision Tree[26] determines remote audit is the best option to meet agencies' auditing goals, EDIFES will connect MDMS[11] or NAVFAC[12] to get 15-minute interval utility data and then perform virtual energy audit and prepare submission to CTS as shown in figure 2.14. This software integration project is funded by Ohio Department of Development's Third Frontier Commission.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

ADVANTAGES

EDIFES provides a substantial benefit over traditional energy audits in terms of both costs and speed. The labor costs associated with physical energy audits are exorbitant and unnecessary on the majority of buildings. Physical audits from different companies also tend to provide different recommendations, making it unclear where capital should be focused. [4] A virtual energy audit requires less effort to complete and provides insights as accurate and useful as a basic physical audit at a fraction of the cost.

Other virtual energy audit/modeling tools have been developed, however, they often require a lengthy questionnaire to be completed before the audit/modeling can be performed. While this is feasible for audits on an individual building-by-building basis, it becomes cumbersome or impossible when audits are needed on a portfolio of buildings such as required for EISA 432 compliance. EDIFES only requires four inputs other than the electricity consumption data: zip code, end-use, square footage, and number of stories. Large groups of buildings are quick to enter with results being returned overnight. This makes EDIFES the easiest and fastest way to perform an energy audit.

LIMITATIONS

While EDIFES's markers, which identify energy loads, characteristics, and savings opportunities, work well in the majority of cases, some limitations were identified during testing. Across our dataset, we found that >80% of the buildings fell within ±20% of the metered or measured loads. With the buildings that were not validated to the acceptable level, anomalous data and/or inconsistent inputs were largely the reason. EDIFES has been upgraded to include message warnings if results demonstrate low confidence. EDIFES was also limited by the buildings we had access to validate on, which could cause the engine to be less accurate on populations not well-represented during validation. Excluding synthetic data, EDIFES only had validation data and building data from a limited population. Audits were performed on buildings from across the US but were concentrated on the West Coast and Northeast. Validation data was even harder to come by, making it difficult to fully represent the US commercial building population. Buildings from the northwest, central, and Gulf Coast portions of the US are underrepresented. The behavior of systems in these buildings could be slightly different from expected based on our sample. However, the largest and most impactful loads, heating and cooling, are relatively consistent in profile when comparing climate zones of similar seasonality. Seasonality is the major driver for heating and cooling load profiles so buildings in climate zones not yet analyzed should have the same accuracy proven in our validation. Even more, since HVAC can be a large fraction of a building's load, facilities with district/central energy systems are challenging to analyze, and accuracy may be compromised. As a result, the energy savings from these buildings are largely not reported on the dashboard. EDIFES also needs 14 months of 15-minute (or shorter) interval electricity consumption data. Some buildings only had access to hourly data or do not have long enough periods recorded which may not provide EDIFES enough resolution to disaggregate a building's loads appropriately.

3.0 PERFORMANCE OBJECTIVES

3.1 SUMMARY OF PERFORMANCE OBJECTIVES

To recapitulate previous chapters briefly, EDIFES is an inexpensive ”Big Data” analytics tool to identify and quantify energy and cost savings opportunities and produces a portfolio prioritized list of buildings. To successfully demonstrate and validate EDIFES, five main performance metrics were tracked:

- EDIFES’s ability successfully generate energy and cost savings opportunity dashboards and the portfolio screening list on hundreds of buildings
- EDIFES’s outputs validated against ground truth quantitative measurements
- EDIFES outputs validated against ground truth qualitative measurements
- End-use EUIs validated against Commercial Buildings Energy Consumption Survey (CBECS) datasets
- EDIFES audit rankings validated against an energy modeling portfolio ranking (this was performed outside of this project)

A summary of performance objectives is shown in Table 3.1.

Table 3.1: Performance objectives for the EDIFES demonstration.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives				
PO1. Virtual Energy Audits	Audits performed	15-minute interval data ($>$ 14 months)	$>$ 250 Buildings	**Passed** 331 Buildings
PO2. Ground truth validation	End-use equipment annual consumption comparison	15-minute interval submetering data of 5 buildings	EDIFES output within ±20% actual values for measured equipment	**Passed**
PO3.Validation using CBECS Dataset	p-value from Wilcoxon Rank-Sum Test	EUI of end-use equipment for 6,000+ buildings across U.S.	p-value $>$ 0.05	**Passed**
Qualitative Performance Objectives				
PO4. Validation with site managers	Yes / no validation	Feedback from energy managers	Site managers should agree with virtual energy audit results	**Passed** Site managers agree with over 80% of results
PO5. Commercial customer validation	Portfolio ranking	Energy modeling audit portfolio results	Portfolio ranking should be similar to EDIFES audit ranking	**Passed** (outside of ESTCP scope)

3.2 PERFORMANCE OBJECTIVE DESCRIPTION

PO1. VIRTUAL ENERGY AUDITS

Purpose and Relevance: The first objective of this project was to demonstrate the EDIFS tool on a population of 250+ DoD buildings and produce an interactive visualization of audit results. Then, the EDIFES portfolio screening tool was utilized to generate a prioritized list of buildings with the highest energy savings opportunities. This objective first tested the capability of the EDIFES platform to store and process large amounts of data. It then illustrated the intelligent decision-making ability of EDIFES to help energy managers prioritize buildings for equipment replacement/upgrade, operational changes, and retrofits.

Metric: The number of EDIFES dashboard reports generated. Each output included at least 10 energy savings markers per dashboard and a comparison of buildings in the portfolio.

Data: 15-minute interval meter readings of electricity that last at least 14 months and four pieces of basic information about buildings: 1. square footage, 2. number of floors, 3. location (e.g. zip code, latitude and longitude), 4. building use type (e.g. office or retail).

Analytical Methodology: The EDIFES technology has been fully discussed in the previous section.

Success Criteria: EDIFES dashboard reports generated for at least 250 buildings.

PO2. GROUND TRUTH VALIDATION

Purpose and Relevance: To compare the modeling results of each marker with the submeter data of the corresponding equipment. If the modeling results match the submeter data, it would give a high level of confidence in EDIFES's analysis.

Metric: The difference between end-use equipment consumption predictions from EDIFES's model and ground truth submeter data.

Data: Submetered data of equipment (e.g. HVAC, refrigerator, exterior lighting) during the same time range as the whole building electricity meter data.

Analytical Methodology: Sensors were installed on 5 buildings to measure HVAC, refrigeration, and exterior lighting consumption. During the same time range, meters also collected the 15-minute interval electricity data for the whole building to conduct the EDIFES analysis. Then, the modeling results from EDIFES were compared with the measured data to assess the accuracy of EDIFES's analysis.

Success Criteria: EDIFES output should fall within ±20% range of actual values from measured equipment on at least 4 buildings, resulting in at least 4 case studies to demonstrate.

PO3. VALIDATION USING CBECS DATASET

Purpose and Relevance: EDIFES has analyzed 1000+ buildings that contain most commonly encountered building types (e.g. office, education, retail, food service, health care) and over 7 different ASHRAE climate zones. It is impossible to submeter all of these buildings to validate the energy saving markers of EDIFES. Thus, EUI distribution comparisons with the CBECS dataset were conducted to obtain another form of validation. The CBECS dataset is a sampled representative survey of all commercial buildings across the United States. If most end-use equipment EUIs (e.g. refrigeration EUI) determined by EDIFES fall within the range of EUIs provided by the CBECS dataset, then this provides further confidence that EDIFES produces results that are comparable to real-world operational characteristics.

Metric: The p-value from a Wilcoxon Rank-Sum Test.

Data: CBECS dataset which contains the EUIs for end-use equipment for 6,000+ buildings across the U.S.

Analytical Methodology: The Wilcoxon Rank-Sum Rest was used to compare the distribution of EDIFES end-use EUIs and CBECS end-use EUIs. The Wilcoxon Rank-Sum Test is a non-parametric version of the two-sample t-test that allows for the analysis of datasets that are non-normally distributed. The null hypothesis of this test is no difference in building distributions. This is only rejected if the $p\text{-value} < 0.05$.

Success Criteria: $p\text{-value} > 0.05$

PO4. VALIDATION WITH SITE MANAGERS

Purpose and Relevance: Determine the extent to which the dashboard reports meet the needs of base energy managers. Additionally, use knowledge from site managers to qualitatively validate various EDIFES markers.

Metric: Yes/no validation

Data: Information accessed and provided by the building/energy manager.

Analytical Methodology: Review with base energy managers on at least 10 buildings. Base energy managers should confirm (yes/no validation): 1. general pattern of energy usage snapshot appears correct, 2. presence of exterior or daylight sensored lighting, 3. cooling load is "high consumption", "median consumption" or "low consumption", 4. building is either "tight" or "leaky", 5. HVAC turn-off/on time of the building.

Success Criteria: At least 10 buildings are accurately identified via yes/no criteria.

PO5. COMMERCIAL CUSTOMER VALIDATION

Purpose and Relevance: Assessment of the EDIFES portfolio screening results based on a study for which EnergyPlus modeling was used to produce portfolio rankings.

Metric: Portfolio ranking of buildings with the highest energy savings opportunities.

Data: Portfolio ranking conducted by an energy modeling audit.

Analytical Methodology: The analytical methodology was straightforward, requiring only a comparison of two portfolio ranking results.

Success Criteria: Physical audit with energy modeling portfolio ranking should be similar to EDIFES audit ranking.

4.0 FACILITY/SITE DESCRIPTION

4.1 DOD BUILDINGS

ARMY

Advanced meter data was pulled from the following facilities:

Table 4.1: Locations of Army buildings used in the demonstration.

Facility	Location	Number of Buildings
Fort Carson (from MDMS)	Colorado	214
Fort Leavenworth	Kansas	25
Fort Liberty	North Carolina	16
Fort Moore	Georgia	10

NAVY

We received electricity consumption from seven buildings located at the Norfolk Naval Station in Virginia. The electricity consumption data is advanced meter data from NAVFAC.

4.2 COMMERCIAL BUILDINGS

GAS STATION CHAIN

We received building data from a large 24/7 gas station chain in the US. All four of these buildings had their heating and cooling loads submetered and one building was fully submetered. As such, these buildings were used in ground truth validation for several markers.

CASE WESTERN RESERVE UNIVERSITY

Carlton Commons, a mixed dining hall and common area building on the CWRU campus, had its total electricity consumption monitored for three years. Submeter data were collected from plug-in refrigerators and refrigerated vending machines for 11-35 days depending on the appliance. This data was primarily collected and used for validating the refrigeration markers.

COMSTOCK

A relatively new dataset from NREL, ComStock provides synthetically generated load profiles for commercial buildings across the US. It has a variety of building types and locations with detailed metadata and synthetic submeter time series data. ComStock has been compared and validated against real commercial submeter data. [27] While the submeter data they used for validation is not available to the public, it can be assumed that ComStock's synthetic submeter data is representative of a real commercial building. Certain loads such as refrigeration are hard to model and therefore their time series data does not match real behaviors. Heating and cooling loads closely resemble those seen in real buildings and thus are appropriate for validation.

COMMERCIAL BUILDINGS ENERGY CONSUMPTION SURVEY (CBECS)
CBECS is a survey of commercial buildings in the US that has been performed every six years beginning in 1979. [6] Buildings are randomly selected to represent the total commercial population of the US, both in terms of geography and building type. These buildings then have the total energy consumption recorded including total building consumption, heating and cooling, ventilation, etc. for the entire year. Metadata for each building is also recorded. While time series submeter data are not available for ground truth validation, population comparisons between the results of EDIFES buildings and CBECS were performed.

RETAIL BUILDING PORTFOLIO (OUTSIDE ESTCP PROJECT SCOPE)
Beyond the work done during the ESTCP project, virtual energy audits were performed on 12 retail stores located in California. These buildings had previously undergone an extensive modeling effort by RMI to determine savings using EnergyPlus. [28, 9] The building energy consumption and portfolio results from the energy modeling audit were received.

4.3 FACILITY/SITE LOCATION AND OPERATIONS

The datasets include buildings from across the US with a large variety of operational characteristics. These include commercial and DoD buildings with a variety of use types. Generally, the distribution of end uses is skewed toward office and educational buildings which matches the US population. While some DoD buildings had specialized behaviors (e.g. aircraft hangers, vehicle maintenance bays) that did not match any other commercial datasets we used, the vast majority have standard uses.

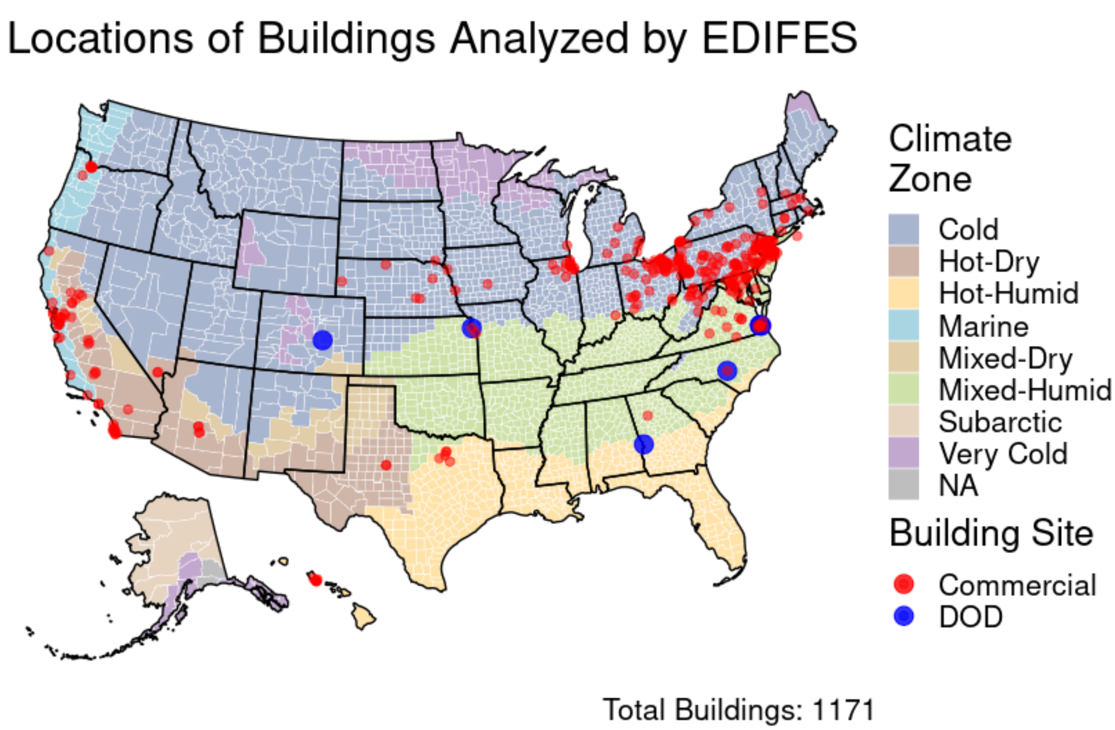


Figure 4.1: Locations of all buildings that have been audited using EDIFES, including those not a part of this project.

4.4 FACILITY/SITE CONDITIONS

One significant event that impacted our analysis was the behavioral changes in energy consumption due to COVID-19. For energy data overlapping the global pandemic, there was a clear shift in energy consumption near the onset. A behavioral change point analysis (BCPA) marker was originally developed to identify building retrofits that reduced energy consumption. This marker was created to allow for verification of the predicted savings from EDIFES by identifying anomalous behavior before analysis. When this marker was used on the Fort Carson data, change points were identified within a few months of March 2020, which is when stay-at-home orders began going into effect. Our analysis revealed that an abrupt plan to send employees to work from home appears similar to how a retrofit or equipment replacement might behave. To improve the accuracy of our analysis, some buildings with data from this period were split into pre-COVID and post-COVID data sets.

5.0 TEST DESIGN

5.1 CONCEPTUAL TEST DESIGN

The technology demonstration was completed over four general phases. Data collection began at the start of the project which then allowed for virtual energy audits to be performed. Results were displayed on a secure dashboard and shared with energy managers for feedback. Multiple methods of validation were used to improve marker performance and increase the accuracy of audits. After validation was complete, EDIFES 2.0 was built for commercial release.

While these phases were broadly followed, difficulties in collecting data caused the testing and development steps to be repeated multiple times. As data became available, EDIFES was tested and validated against both the new and existing datasets.

As the project came to an end and validation was finished, EDIFES was updated to reduce runtime and streamline functionality. Internal documentation of all markers was also completed. Then, the EDIFES 2.0 software package was commercially released.

5.2 BASELINE CHARACTERIZATION

Unlike traditional demonstrations that measure performance before and after the technology is implemented, EDIFES is a retroactive analytic tool. EDIFES identifies potential savings and fulfills mandatory audit requirements rather than directly reducing energy consumption. In-depth baseline characterization of current audit costs and durations was deemed unnecessary as an EDIFES virtual energy audit is significantly less expensive and faster to perform. Instead, emphasis was placed on validating the accuracy of markers within EDIFES.

The baselines for marker accuracy are the true load or ground truth values. The true load values can be recorded as submeter data which, in theory, measures specific building loads with 100% accuracy. This type of end-use comparison is significantly easier to quantify than trying to compare to a traditional audit, which is not perfectly accurate unless a building is completely submetered. Unfortunately, submeter data was even harder to obtain than advanced meter data, forcing our approach to validation to employ a variety of other methods as described in Chapter 6.

To confirm that the potential savings calculated by EDIFES are accurate, we also attempted to identify buildings that had undergone retrofits. For this purpose, one year of data before and after the retrofit can be analyzed to confirm that EDIFES correctly predicted the savings. However, this test was unable to be implemented; a building that had undergone a known retrofit could not be identified by our partners, let alone one with two years of meter data.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

Chapter 2 describes the computing infrastructure and techniques needed for EDIFES. Besides this, no other technology components were used for this demonstration save for the submeter data loggers indicated in section 5.5.

5.4 OPERATIONAL TESTING

Based on the nature of the demonstration, the lack of data, and COVID-19, the operational phases were not as linear as planned. The overarching timeline was as follows:

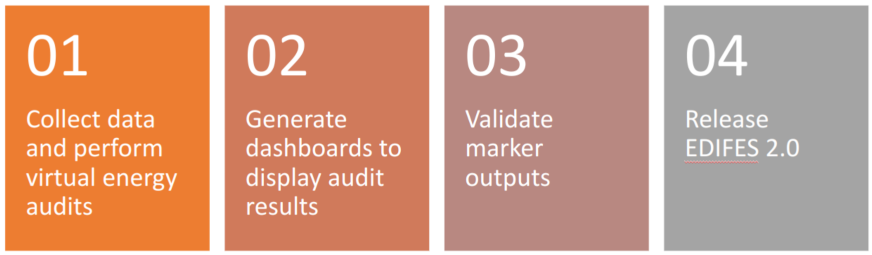


Figure 5.1: The overarching timeline.

The data collection phase was a major barrier that resulted in small batches of data being collected and then validation performed periodically throughout the entire project. While this was inconvenient, EDIFES can quickly analyze large batches of buildings. This shortens the testing timeline and allows for quick and continual revisions. The smaller phases of development during the project were as follows:

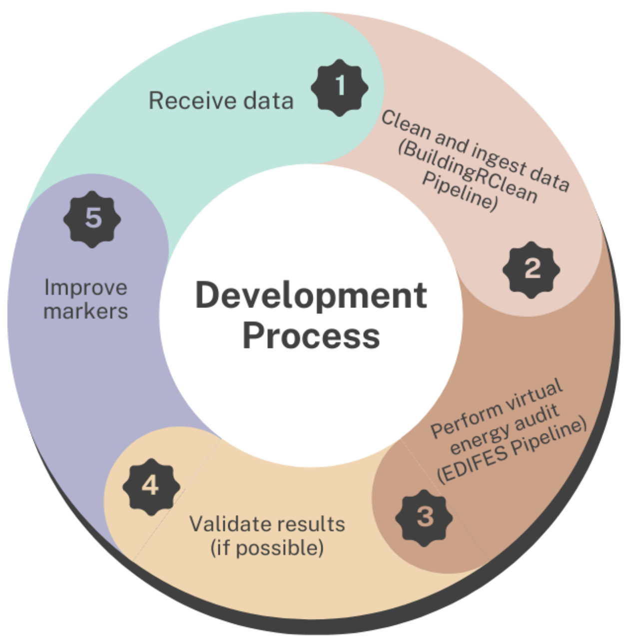


Figure 5.2: The phases of development during the project.

As each dataset became available, the above steps were taken, essentially creating multiple small demonstrations on several sites. This is reflected in our performance objectives as well as performance assessments. These are broken down by dataset and what validation was able to be completed on each. Sites were not limited to an individual phase but instead had their results updated and reevaluated as EDIFES was refined.

5.5 SAMPLING PROTOCOL

Most data were shared/downloaded directly in a spreadsheet or CSV format. Data were cleaned and missing values were interpolated if the gaps were not significant. If data had intervals shorter than 15 minutes, intervals were combined and converted into 15-minute observations. Advanced meters used by buildings were not installed by EDIFES and were assumed to be properly calibrated or consistently inaccurate. While this could affect the magnitude of predicted savings, it should not significantly change EDIFES's relative savings if a meter was consistently under/over measuring load.

Connecting EDIFES to MDMS smoothed the process of retrieving data from Army buildings. This gave access to the necessary meta and consumption data which was most helpful for the large Fort Carson portfolio.

The only case where the EDIFES team was able to set up submeters and collect data was at Carlton Commons. A HOBO UX120-018 Plug Load Data Logger was rotated through different refrigeration appliances to collect data. Further details on the data logger are discussed in Appendix 4: HOBO UX120-018 Data Logger. The meter measures and records the power and energy consumption of 120V plug loads. Two plug load devices were deployed in Carlton Commons to compare to associated EDIFES outputs. No wiring is required, and months of data were recorded, stored, and transferred using the USB interface. Data collected was in one-minute intervals which was later converted to 15-minute interval data to match the ingested building electricity consumption. Meters were first installed in January of 2022 and moved to new appliances every few weeks. The durations of the loads measured are described in Table 5.1.

Table 5.1: Recording times of refrigeration appliances at Carlton Commons.

Appliance	Recording Start	Recording End	Timespan (days)
Arctic Air AR49E	1/19/2022	2/24/2022	35
Atosa MSF8301GR	1/19/2022	2/24/2022	35
True TWT-36	2/24/2022	3/17/2022	21
Crane BevMax4	2/24/2022	3/17/2022	21
Snack Vending Machine	3/17/2022	3/28/2022	11

5.6 SAMPLING RESULTS

Building timeseries data from sites was obtained in a variety of time intervals. Those under 15 minutes could be combined or recalculated into 15-minute intervals for analysis. Hourly data was found to be too sporadic to perform analysis with. Based on the zip code provided in a building's metadata, weather data including insolation and temperature could be retrieved for the same period. The electricity consumption data given by an energy manager paired with the weather data allows for EDIFES to complete its analysis. Other values such as the number of floors and square footage are used namely for estimating savings related to the building envelope. The validation methods and results from the collected data are located in Chapter 6.

6.0 PERFORMANCE ASSESSMENT

6.1 VIRTUAL ENERGY AUDITS

To confirm that EDIFES is functional and able to provide valuable insights, virtual energy audits were performed on a large number of buildings. The goal to run audits on at least 250 buildings was well exceeded. During this, 331 virtual energy audits were completed on a total of 257 DoD buildings. At some facilities, the time series data was split into pre and post-COVID-19 data allowing there to be more audits than buildings. The results of these audits were posted on our dashboard with access given to the energy manager of the respective portfolio.

In addition to DoD buildings, virtual energy audits were also performed on 840 commercial buildings (some commercial customer audits were outside the scope of the ESTCP project). A few of these buildings also came with submeter data or energy modeling audit portfolio rankings that allowed for further validation. ComStock provided another source of commercial data that allowed for audits on synthetic commercial building data. A further 3774 synthetic buildings from the ComStock dataset had virtual energy audits performed.

For each of these audits, EDIFES is capable of producing a building assessment report for a customer's portfolio. The overview report gives a summary of the portfolio results and a separate report containing detailed audit results for each building is also generated. An example overview and building assessment report can be found in Appendix 3: Example Building Assessment Report.

6.2 GROUND TRUTH VALIDATION

GAS STATION SUBMETER DATA

Submeter data for the heating and cooling loads were available for four 24/7 gas stations. EDIFES first disaggregates the heating and cooling load from the overall building consumption before calculating savings. To confirm that EDIFES is correctly calculating the heating and cooling load, the predicted load can be compared to the actual load. The results of EDIFES prediction versus the true values from the submeter data are shown in Table 6.1.

Table 6.1: Results of heating and cooling markers from gas station ground truth validation.

Building ID	Heating and Cooling Load			Exterior Lighting Load		
	Predicted (kWh)	Actual (kWh)	% Difference	Predicted (kWh)	Actual (kWh)	% Difference
100	51600	57959	-11%	48484	50400	-4%
101	42165	40530	4%	N/A	N/A	N/A
102	39291	40225	-2%	N/A	N/A	N/A
103	111044	102727	8%	N/A	N/A	N/A

In all four buildings, EDIFES had less than 11% error with a mean of 6.3%. The heating and cooling markers accurately predict the heating and cooling loads of buildings which can then be translated into potential savings. Figure 6.1 shows the predicted and submetered values for heating and cooling loads across one full year for building 100.

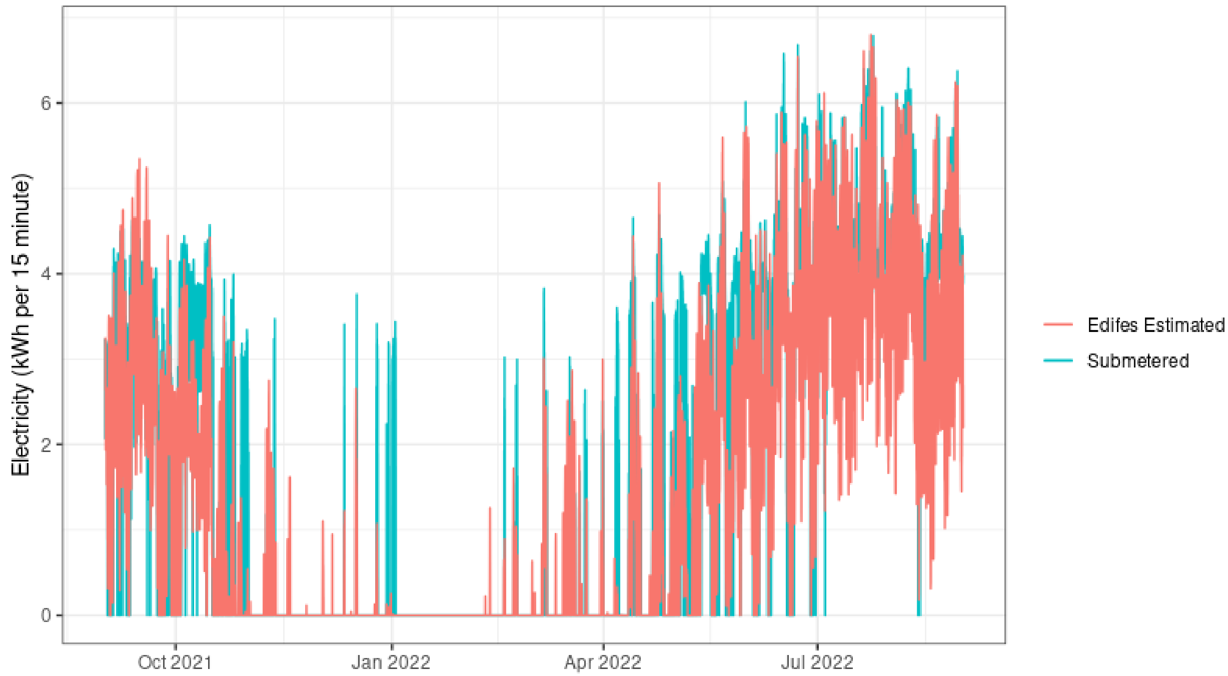


Figure 6.1: Time series of building 100 comparing EDIFES and submetered heating and cooling load across one year.

Exterior lighting submeter data were also available for one of these buildings. The exterior lighting marker predicted an annual load of 48484 kWh with the actual value being 50400 kWh. This is a discrepancy of 4%, well within our targets. Since there is only one building with exterior lighting data available, additional testing was performed using the ComStock dataset. Those results are discussed below.

CWRU SUBMETER DATA

To validate the refrigeration markers, a mixed dining hall and common area building on the CWRU campus had its whole building's electricity consumption collected. Submeter data from refrigerators, freezers, and cooled vending machines were also collected. A walk-in cooler and freezer could not be safely monitored while the kitchen was in use, so a black box physics model was created to predict energy consumption instead.

After performing a virtual energy audit on the whole building, the results of the refrigeration markers can be compared to the submeter plus black box model. EDIFES predicted an average daily load of 283.6 kWh for all the refrigeration appliances in the building. After combining the submeter and black box model results, the average daily load was found to be 300.36 kWh. The percent error is -5.88%, well under our 20% standard. While the black box model is not perfect, its uncertainty was calculated to be 4.8 kWh for the daily average load. Even in the worst case where the model underpredicts by 4.8 kWh, the error is still only -7.0%.

6.3 VALIDATION USING COMSTOCK DATASETS

EXTERIOR LIGHTING

Out of the 3774 total ComStock buildings, 2716 had a regular or no exterior lighting schedule. The buildings removed had lighting schedules that turned on at irregular times or had abnormal load profiles which are thought to be artifacts of their synthetic nature. A summary of the exterior lighting marker results for these buildings is in Table 6.2.

Table 6.2: Results of improved exterior lighting (EL) markers on the ComStock dataset. Red values indicate buildings where the markers incorrectly identified the presence of lighting or had large errors.

		EL >10% (filtered for bad schedule)		5% < EL < 10% (filtered for bad schedule)	EL < 5%	Total
		Large EL (>$50 savings)	Small EL (<$50 savings)			
Total Buildings		132	21	350	2213	2716
Flagged as having EL	Error <20%	**124**	**0**	**61**	**0**	**185**
	Error >20%	**2**	**0**	**91**	**125**	**218**
Flagged as having insubstantial EL/savings		**6**	**21**	**198**	**2088**	**2307, 6**
Total Percent Error		**6.1%**	**0%**	**26%**	**5.6%**	**8.2%**

Note that these markers are only for exterior lighting that follows a sunrise/set schedule or are sensored. EDIFES defines any exterior lighting load that would have predicted savings of less than $50 or that is less than 10% of the building's total load to be insubstantial. When the savings or the proportion of the total load are that small, the savings for the building are relatively minor. On buildings with insubstantial lighting, EDIFES was considered to have worked successfully if it flagged the building as having insignificant exterior lighting load/savings or if it calculated the lighting load within 20% accuracy. For buildings with large exterior lighting loads, EDIFES was only considered successful if the error was less than 20%. After running these buildings through the exterior lighting markers, it was found that they were within 20% accurate or correctly identified that a building had insubstantial exterior lighting on 91.8% of buildings. Furthermore, of the 132 buildings that have large exterior lighting loads, only six were incorrectly identified as having insubstantial exterior lighting loads. The remaining 126 buildings had a mean error of 4.9% and a median error of -1%. The error distribution of these 126 buildings is shown in Figure 6.2 and gives a better sense of the marker accuracy. For the vast majority of buildings, the predictions are within a few percent of the true value.

The exterior lighting markers work well on buildings with large exterior lighting loads (over 10%

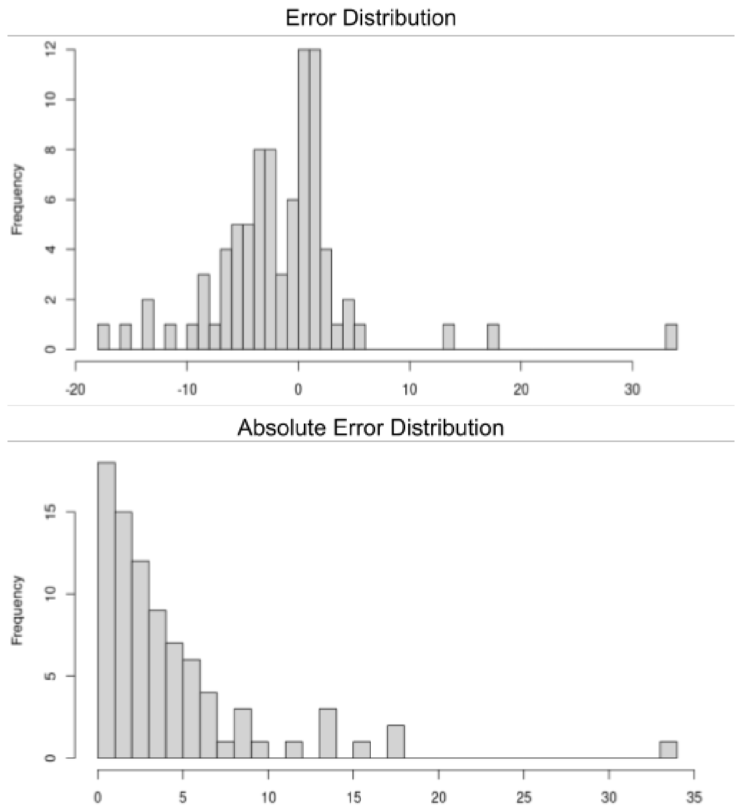


Figure 6.2: Error distribution for the new exterior lighting markers on the ComStock dataset.

of the total load) and with buildings without significant exterior lighting loads (less than 5% of the total load), but struggles with buildings between these thresholds. The markers were only accurate on 74% of buildings with exterior lighting loads between 5-10% of the total load. Since the exterior lighting marker looks for consistent load increases/decreases around sunset/rise, a synthetic building that has an HVAC or fan cycle close to sunrise/set can easily be misidentified instead. Part of this may be because the building is synthetic, meaning that the HVAC and fan cycles are extremely consistent in size and timing and hide small exterior lighting loads. Real building data would likely have more variation in load around these times making it less likely for HVAC to be identified as exterior lighting. The markers tended to work more accurately on buildings with larger exterior lighting loads and the 10% of total building load is an arbitrary threshold from testing. This threshold value optimized the sensitivity and specificity of the markers.

HEATING AND COOLING

Initial validation attempts were also performed on a subset of buildings for the heating type marker. The heating type marker determines what type of heating and cooling a building uses. Electrically based (e.g. electric resistance, heat pump) and non-electric (e.g. natural gas furnace) heating systems have different behaviors that influence savings predictions. Similarly, a building that has traditional air conditioning (electrical cooling) will behave differently than one that is chilled by water pipes from a district system. The heating type was predicted for 1211 non-electrically heated buildings. It was correctly identified on 97% of buildings

Additionally, cooling load for 10 office buildings was predicted. The office building analysis follows the same methodology as used on the gas stations, but only for the cooling load. The predicted load had a mean error of 9.7% when compared to the synthetic submeter data. Figure 6.3 has the EDIFES predicted cooling load compared to the actual synthetic submeter data for one office building.

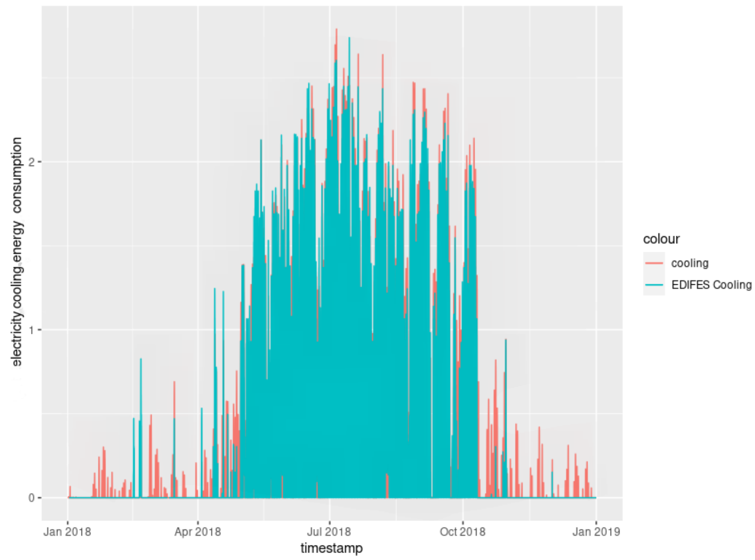
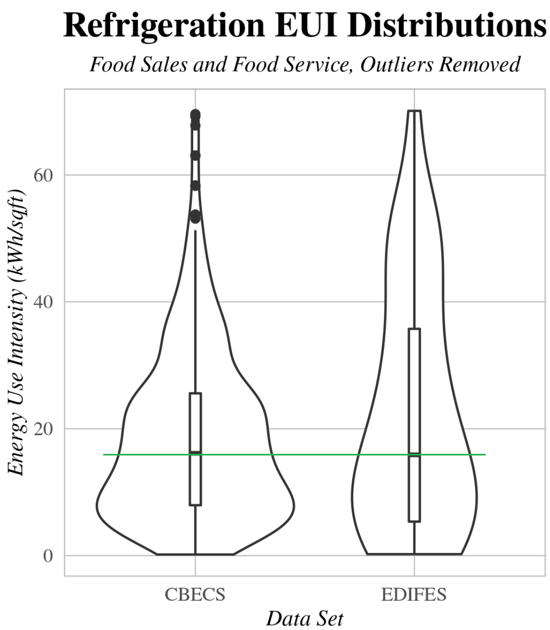


Figure 6.3: Predicted cooling load from an office building in the ComStock dataset.

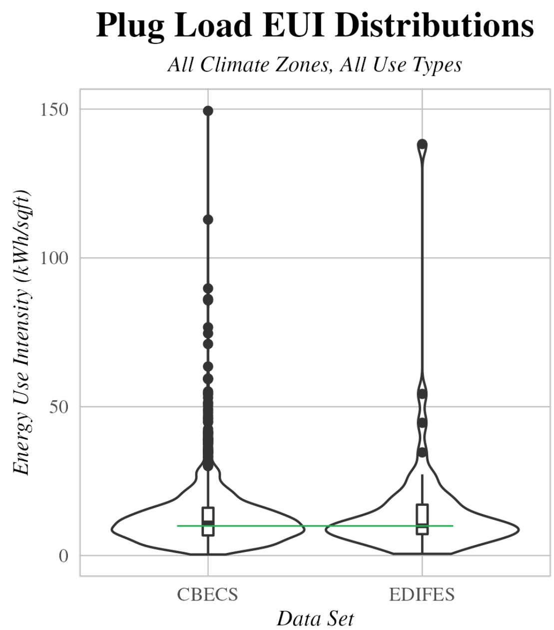
6.4 VALIDATION USING THE CBECS DATASETS

CBECS provides energy use intensity (EUI) values for a variety of load categories. These values provide a sample representative of the US population that can be compared to the EDIFES population. The EDIFES population includes all buildings that have undergone an energy audit, including DoD and all commercial buildings. If EDIFES is predicting loads accurately, the EUI distributions for loads of the EDIFES population should be similar to the CBECS population. After subsetting the CBECS data to the same climate zones represented in the EDIFES dataset, a Wilcoxon Rank-Sum Test was performed to compare the population distributions. The test quantifies how similar the distributions are; the higher the p-value (the closer to 1), the more similar the population distributions are, and the more likely that EDIFES's results are accurate. If the p-value is 0.05 or lower, then there is at least a 95% confidence that the populations are not the same. While the distributions are not expected to be identical given the much smaller sample size of EDIFES, the means and distributions should be similar.

Figure 6.4a shows the refrigeration population distributions while Figure 6.4b shows the the plug load distributions. The p-values for the refrigeration and plug load comparisons are 0.977 and 0.530 respectively. In both cases, the p-value is relatively large indicating that the population distributions are similar. This is reflected in the violin plots which both show that EDIFES has a similar average and spread as CBECS.



(a) Refrigeration



(b) Plug load

Figure 6.4: EUI distributions for CBECS and EDIFES predictions.

The same process was repeated for the HVAC loads after the buildings were sorted by heating type. Figure 6.5 compares HVAC EUIs from the CBECS distribution for each heating type as well as the distributions predicted by EDIFES. Note that the heating types and EUIs in the EDIFES distributions are both predictions. Ventilation loads are not included in these EUI values and are considered a separate load.

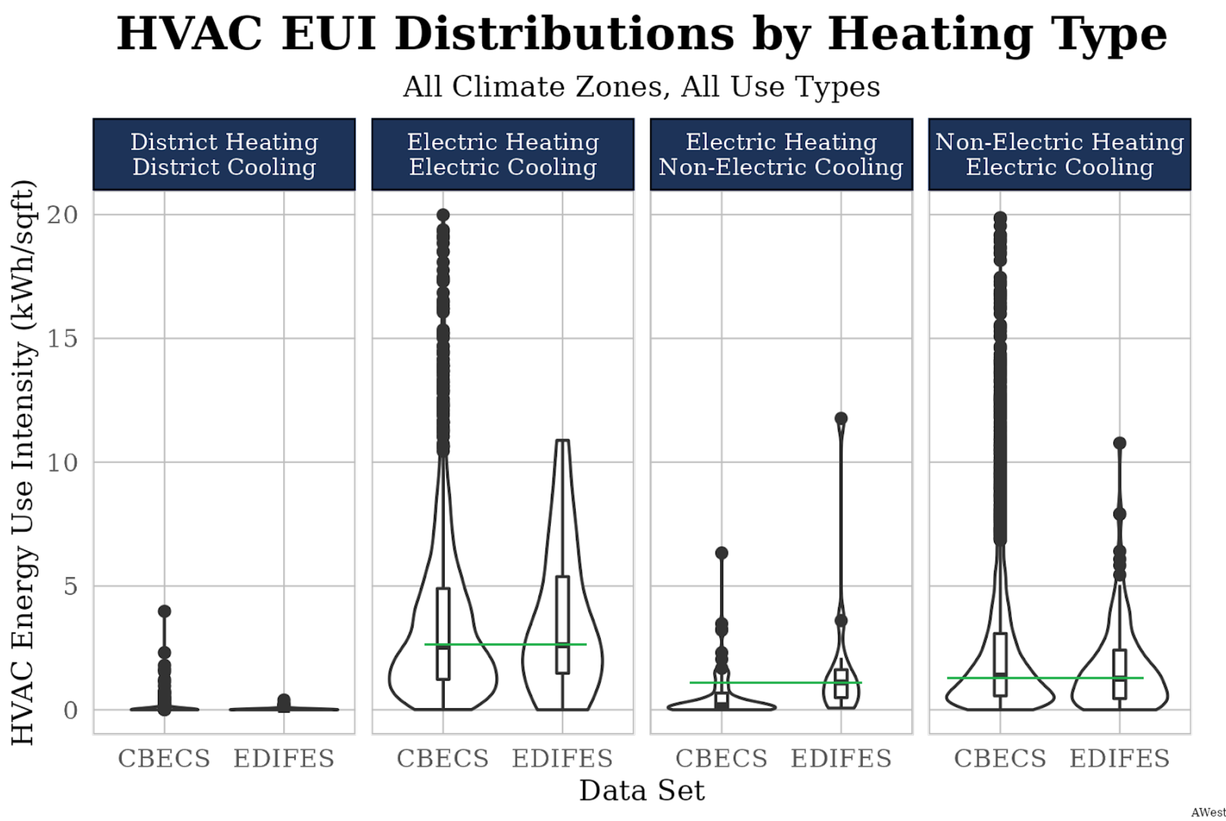


Figure 6.5: HVAC (heating and cooling) EUI distributions for CBECS and EDIFES predictions sorted by heating and cooling type

The p-values for each heating and cooling are summarized in Table 6.3. The p-values are low for the electric heating non-electric cooling and non-electric heating electric cooling categories. One cause of this is that buildings identified as ”indeterminate” heating/cooling were put into their respective ”non-electric” categories. This was noted to lower the p-values. Non-electric cooling is also unusual, has a small group size, and found to be associated with other abnormal behaviors. Buildings with a substantial proportion of cooling from district cooling systems lead EDIFES to over/under predict in other markers and is a noted limitation.

The non-electric heating electric cooling is the largest category and thus the most important. The p-value is slightly lowered by the indeterminate heating buildings, but the larger impact is from the shape of the distributions. While CBECS and EDIFES has similar means, EDIFES has far few outliers. Since the test used compares the two distributions, the long tail of outliers can significantly affect the results. The CBECS population has over 20 times more buildings than EDIFES for this category which would increase the chances of outliers being present. It is likely that as the EDIFES population grows, more buildings with unusually high HVAC EUIs will be recorded, and the p-value will increase.

Table 6.3: Results of population comparisons between CBECS and EDIFES for HVAC EUIs.

Heating Type	District Heating District Cooling	Electric Heating Electric Cooling	Electric Heating Non-Electric Cooling	Non-Electric Heating Electric Cooling
p-value	0.677	0.524	0.043	0.064

6.5 VALIDATION WITH SITE MANAGERS

Validation for buildings without submeter data can be performed by comparing EDIFES results to known building behavior. EDIFES results were compared to feedback from energy managers for 17 buildings and the validation results are shown in Table 6.4. While these are qualitative and thus prone to interpretation, the categories were made as simple as possible to reduce the impact of differences in definition. Even so, categories such as HVAC schedule are hard to verify. A building's HVAC schedule may be set to reach the desired setpoint at a particular time, but the actual heating/cooling system may begin earlier. This leads to discrepancies between the scheduled and true turn-on times. Similarly, it is hard for an energy manager to tell what qualifies as significant exterior lighting or leaky vs. tight building shell without having them evaluated. Even with these inherent problems, there is agreement on 80% of the 92 results that feedback provided.

Table 6.4: Qualitative agreement of EDIFES predictions vs various actual building characteristics as validated by the building/energy manager.

Buildin ID	Predicted heating type	Presence of exterior lighting	Predicted cooling load - general low/med/hi qualitative agreement	Building shell - predicted leaky or tight	Predicted HVAC Schedule	
					On*	Off
196	Electric Heating and Electric Cooling - agreed	Yes - disagreed	219 MWh - agreed	Leaky - agreed	7:00:00 AM - agreed	8:45:00 PM - agreed
285	Mixed Heating and Electric Cooling - agreed	No - agreed	22 MWh - agreed	Leaky - agreed	4:00:00 AM - agreed	7:00:00 PM - agreed
315	Non-Electric Heating and Electric Cooling - agreed	Unknown	39 MWh - agreed	Leaky - agreed	4:30:00 AM - disagreed	7:30:00 PM - agreed
318	Non-Electric Heating and Electric Cooling - agreed	Unknown	197 MWh - agreed	Leaky - agreed	3:45:00 AM - agreed	5:30:00 PM - agreed

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Table 6.4: Qualitative agreement of EDIFES predictions vs various actual building characteristics as validated by the building/energy manager. (Continued)

429	Non-Electric Heating and Electric Cooling - agreed	No - disagreed	104 MWh - agreed	Leaky - agreed	6:00:00 AM - unknown	9:30:00 PM - unknown
664	Non-Electric Heating and Electric Cooling - agreed	No - agreed	243 MWh - agreed	Leaky - agreed	6:00:00 AM - agreed	9:00:00 PM - agreed
077	Non-Electric Heating and Electric Cooling - agreed	Yes - disagreed	98 MWh - agreed	Leaky - agreed	4:00:00 AM - agreed	6:30:00 PM - agreed
225	Electric Heating and Electric Cooling - disagreed	No - agreed	157 MWh - agreed	Leaky - disagreed	4:30:00 AM - agreed	6:30:00 PM - agreed
427	Electric Heating and Electric Cooling - agreed	No - agreed	67 MWh - agreed	Tight - disagreed	5:30:00 AM - agreed	6:30:00 PM - agreed
465	Non-Electric Heating and Electric Cooling - agreed	No - agreed	100 MWh - agreed	Leaky - agreed	6:30:00 AM - no schedule	9:30:00 PM - no schedule
467	Non-Electric Heating and Electric Cooling - agreed	No - agreed	84 MWh - agreed	Leaky - agreed	3:30:00 AM - no schedule	6:30:00 PM - no schedule
699	Non-Electric Heating and Electric Cooling - agreed	No - agreed	39 MWh - agreed	Tight - agreed	5:0:00 AM - agreed	8:30:00 PM - agreed
13571	Non-Electric Heating and Electric Cooling - disagreed	No - agreed	19 MWh - agreed	Tight - disagreed	7:30:00 AM - disagreed	9:30:00 PM - agreed
21133	Electric Heating and Electric Cooling - agreed	No - agreed	78 MWh - agreed	Leaky - agreed	6:45:00 AM - disagreed	9:00:00 PM - disagreed

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Table 6.4: Qualitative agreement of EDIFES predictions vs various actual building characteristics as validated by the building/energy manager. (Continued)

402	Electric Heating and Electric Cooling - disagreed	Yes - agreed	198 MWh - agreed	Leaky - agreed	No pattern - disagreed	No pattern - disagreed
M4861	Non-Electric Heating and Electric Cooling - agreed	Yes - agreed	300 MWh - agreed	Leaky - disagreed	6:30:00 AM - unknown	9:30:00 PM - unknown
P3262	Non-Electric Heating and Electric Cooling - agreed	No - agreed	29 MWh - agreed	Leaky - agreed	5:45:00 AM - disagreed	9:00:00 PM - disagreed

6.6 COMMERCIAL CUSTOMER VALIDATION (OUTSIDE THIS PROJECT)

A retail chain had energy modeling audits using EnergyPlus performed by the Rocky Mountain Institute on a set of 12 buildings. [9, 28] The process was time-consuming and expensive to complete. The 12 buildings had virtual energy audits completed with EDIFES and then were ranked based on potential annual savings. If EDIFES is accurate, it should yield similar portfolio rankings to those produced by the more detailed energy modeling. EDIFES's rankings selected the same top eight buildings as the energy modeling as shown in Table 6.5 While the rankings are not an exact match, they are similar and require only a fraction of the time, money, and effort needed for the energy modeling audit.

Table 6.5: EDIFES portfolio rankings compared to energy modeling audit results.

Location	EDIFES Annual Savings	Edifice Analytics Ranking	Energy Modeling Audit Ranking
Dublin, CA	$11,855	1	2
Fresno, CA	$8,715	2	5
Marina, CA	$8,600	3	4
San Jose, CA	$7,485	4	1
Corte Madera, CA	$7,300	5	3
Chula Vista, CA	$5,061	6	8
Salem, OR	$4,659	7	7
Brentwood, CA	$3,246	8	6

7.0 COST ASSESSMENT

To better take advantage of the cost efficiency of cloud computing, EDIFES adopts pay-as-you-use payment model to determine the price. In the pay-as-you-use payment model, users only pay for utilized resources, rather than provisioning a chunk of resources that may or may not be used. Thus users only pay when they have a building to audit. The cost to run the EDIFES analysis on a single building ranges from approximately $500-$1500 per building (assuming data is readily accessible via the customer). For some buildings, EDIFES may flag a potential anomaly, which may require a data or building scientist to review the outputs, leading to costs at the higher end of the range. Consulting services to interpret results and provide additional recommendations also are available to the customer for an additional fee.

7.1 COST MODEL

In contrast to traditional packaged software that requires users to install, configure, and operate, EDIFES is a server-side application that is installed and operated in our CRADLE platform. Edifice Analytics Inc. is responsible for the operation and maintenance of the EDIFES and CRADLE platforms. It eliminates hardware capital investment cost, installation cost, and operational cost on the DoD side. Also, the users do not need to purchase a software license to utilize EDIFES. Based on a pay-as-you-use model, users are charged on the number of buildings that are audited. The summary of the cost associated with the implementation of EDIFES is included in Table 7.1.

Table 7.1: Cost Model for EDIFES.

Cost Element	Description of Cost Element	Estimated Costs
Hardware capital and life-time costs	No additional hardware is required for the use of the EDIFES tool. Users can access the dashboard reports through a web browser.	$ 0.00
Installation costs	No hardware or software are needed for users to install	$0.00
Consumables	There are no consumables associated with the EDIFES tool	$ 0.00
Virtual Energy Audit	The cost to run the EDIFES analysis	$500-1500 per building
Other services/support	Consulting services to interpret results and provide additional recommendations	$300-600 per building
Operator training	EDIFES is designed for ease of use and dashboard is user-friendly. No specific training is needed to use EDIFES.	$ 0.00

7.2 COST DRIVERS

The largest cost drivers for EDIFES are the operation and maintenance of compute, network, and storage resources in the CRADLE platform. It includes normal operation and lifetime of CPUs and GPUs, quarterly maintenance of the CRADLE platform, a Cloudera license fee for the Hadoop/Spark system, and the debugging and upgrading of EDIFES algorithms.

7.3 COST ANALYSIS AND COMPARISON

The economic benefit in terms of simple payback and savings-to-investment ratio cannot be calculated for the EDIFES solution in the same way such an analysis (i.e. the NIST BLCC process) is conducted for other energy savings solutions. As described above, the pricing to use EDIFES on a building may range from $500-$1500 per building, leading to insight into the potential for energy savings. This cost may be seen as a temporary investment rather than a true cost due to the ultimate payback from implementing one or more no-cost (e.g., rescheduling) energy savings recommendations. If there is already a capital improvement plan to replace aging, inefficient equipment or to overhaul the lighting, then EDIFES is an extremely cost-effective way to ensure appropriate decision-making. Therefore, the payback can be immediate since it is cheaper than physical audits and confirms choices ahead of an investment.

8.0 IMPLEMENTATION ISSUES

8.1 CYBERSECURITY REGULATIONS

With DoD customers, data and results must be stored in systems that meet the DOD DFARS 7012 Cyber Risk Management Plan. Protecting controlled unclassified information in nonfederal systems requires NIST SP 800-171 compliance to ensure adequate cybersecurity. The EDIFES systems were audited by PMC Group, LLC, an external reviewer, and confirmed to meet the aforementioned standards. A letter of self-attestation stating that EDIFES systems meet NIST SP 800-171 is located in Appendix 2: Self-Attestation Declaration of Cybersecurity Regulation Conformity. A few attempts to collect data early on were hindered over concerns that EDIFES did not operate in a secure environment despite meeting the above regulations.

8.2 DATA COLLECTION

The largest hurdle of the project was getting data. The original designated partner site for this project was believed to have 15-minute interval data from smart meters from 1000+ buildings. That data was found to be no longer available shortly after the project began, leaving no buildings for analysis and no potential site to collect submeter data from. While replacement sites were found, similar circumstances led to those collaborations being canceled. Other issues included:

- Deleted historical data
- Unusable data
- Duration of only 4-5 months
- Hourly data
- Lack of response/interest

Initial expectations and promises were that there would be access to data from over five times as many DoD buildings than were received. Collecting extensive submeter data from a demonstration site that was anticipated for validation was also not possible.

9.0 KEY ADDITIONAL PROJECT RESULTS

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- Kamath, Shreyas Mandar. "Energy use intensities across building use types and climate zones using the CBECS dataset." Diss. Case Western Reserve University, 2020.
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APPENDICES

11.1 APPENDIX 1: POINTS OF CONTACT

<table>
<tr><th>Point of Contact</th><th>Organization</th><th>Position</th><th>Contact Information</th><th>Role in Project</th></tr>
<tr><td>David Gordon</td><td>Edifice Analytics Inc.</td><td>CEO</td><td>(216) 334-6565
dave@edificeanalytics.com</td><td>Co-Principal Investigator</td></tr>
<tr><td rowspan="2">Dr. Roger French</td><td>CWRU</td><td>Kyocera Professor, SDLE Director</td><td rowspan="2">(216) 368-3655
roger.french@case.edu</td><td rowspan="2">Principal Investigator</td></tr>
<tr><td>Edifice Analytics Inc.</td><td>CTO</td></tr>
<tr><td rowspan="2">Dr. Alexis Abramson</td><td>Dartmouth College</td><td>Dean of Engineering</td><td rowspan="2">(603) 646-2238
Alexis.R.Abramson@dartmouth.edu</td><td rowspan="2">Co-Principal Investigator</td></tr>
<tr><td>Edifice Analytics Inc.</td><td>Senior Technical Advisor</td></tr>
</table>

11.2 APPENDIX 2: SELF-ATTESTATION DECLARATION OF CYBERSECURITY REGULATION CONFORMITY

CASE WESTERN RESERVE UNIVERSITY EST. 1826

think beyond the possible™

January 14, 2020

Re: DoD CUI SELF-ATTESTATION LETTER DECLARATION OF CONFORMITY

Dear Sir or Madam

Case Western Reserve University ESTCP Project has reviewed *NIST Special Publication 800-171* and based on the evidence provided in the supporting documents attached, has determined that Edifice Analytics, Inc corporate IT systems meet the DoD DFARS 7012 Cyber Risk Management Plan (CRMP) requirements. The following documents are included in Edifice Analytics, Inc CRMP:

- *Corporate Risk Management Plans*
- *Corporate All-Hazards Risk Management Plan*
- *Corporate All-Hazards Risk Management Plan Excel Scoring Matrix*
- *DoD DFARS Controlled Unclassified Information 2015*
- *Information System Policies and Procedures*
    - o *Acceptable Encryption*
    - o *Account Management*
    - o *Audit Policy*
    - o *Awareness and Training*
    - o *Configuration Management*
    - o *Email Policy*
    - o *Information Sensitivity*
    - o *Password Construction*
    - o *Password Protection*
    - o *Penetration Testing*
    - o *Remote Access*
    - o *Software Installation*
    - o *Vulnerability Management*
    - o *Wireless Communication*
    - o *Wireless Communication Standard*

- *Workstation Security*
- *Roles and Responsibilities*
- *Information Security Program Management*
- *Corporate Information Systems Plans and Procedures (ISPP)*
- *Corporate System Security Plan (SSP)*
- *Corporate Plan Of Action and Milestones (POAM)*
- *Corporate Information Systems Contingency Plan / CONOPS (ISCP)*
- *Corporate Event/Incident Communication Plan (EICP)*
- *Corporate Event/Incident Response Plan (EIRP)*
- *Corporate Security Audit Plan (SAP)*
- *Corporate Security Monthly Audit Report (SMAR)*
- *US-CERT Federal Incident Notification Guidelines*
- *USCYBERCOM Incident Reporting Form*
- *DIBNet Incident Reporting Form*
- *Insurance Incident Reporting Form*
- *Client Contracts and POC's*

The control frequency criteria as noted in Edifice Analytics, Inc *System Security Plan* have been met and attestation information has been summarized.

Declaration

I hereby declare Edifice Analytics, Inc system complies with the Requirements of NIST SP 800-171 listed above. This declaration is based on the Documents of Evidence listed above.

Regards,

Roger H French

Digitally signed by Roger H French
Date: 2021.01.21 18:03:31 -05'00'

Roger H. French
Kyocera Professor, Case School of Engineering
Case Western Reserve University
Phone: (302) 468-6667
Email: rxf131@case.edu

11.3 APPENDIX 3: EXAMPLE BUILDING ASSESSMENT REPORT

EDIFICE ANALYTICS

Portfolio Overview

We analyzed your electricity usage based on the information you provided us. We determined that your portfolio of buildings has a potential annual savings of **$1,403,000**. The following information contains an overview of your portfolio, including a portfolio ranking of the highest buildings with savings opportunities along with any data quality issues the EDIFES team has faced.

Building name	Location	Square Footage	# Meters	Climate Zone (ASHRAE)	Ranking in Portfolio (1=largest savings)	Savings opportunity ($)	Comments
1	City, State	87,000	1	4A	1	$757,000	
2	City, State	83,000	3	4A	2	$250,000	
3	City, State	55,000	1	4A	3	$155,000	
4	City, State	72,000	2	4A	4	$133,000	
5	City, State	44,000	1	4A	5	$108,000	
6	City, State	66,000	2	4A	-	-	Inadequate meter data
7	City, State	17,000	1	4A	-	-	Inadequate meter data

April 5, 2023 1
EDIFES Version 1.1.6

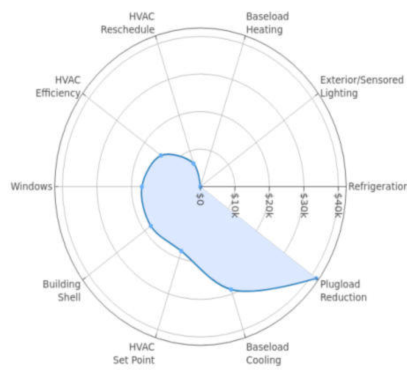
Building Assessment Report

Name: bldg 5
Rate: $0.0759/kWh

Location:	Area:	Annual Consumption:	Use Type:
City, State	44,000 sq.ft.	12,000 MWh	Other

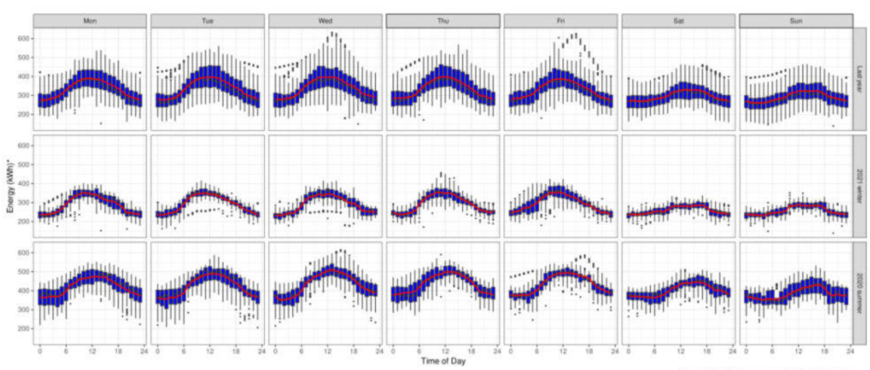
Savings Overview

We analyzed your electricity usage based on the information you provided us. We determined that your building has an annual potential savings of **$108,000.**



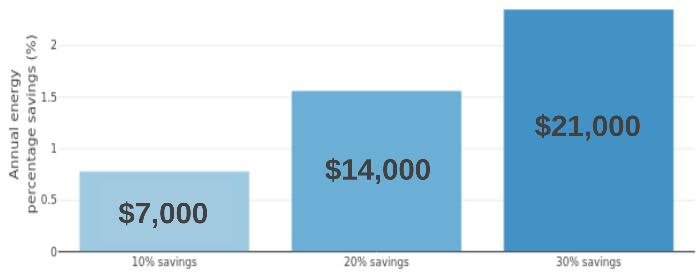
Energy Pattern Snapshot

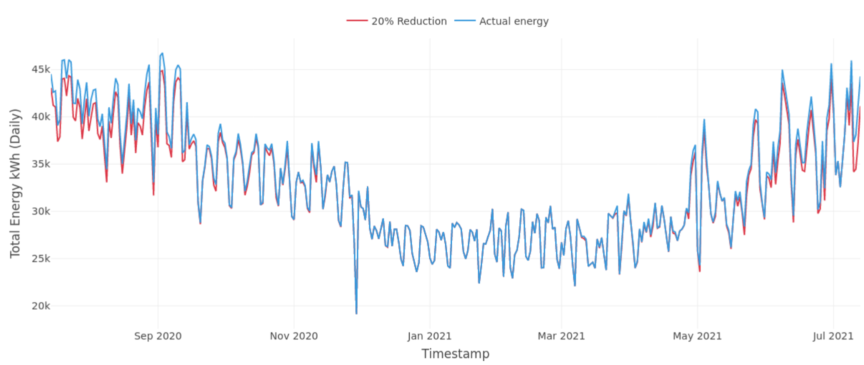
This energy pattern snapshot gives a quick view into the energy consumption of the building. The blue vertical boxes show the distribution (middle 50% variability) of energy consumption for the given hour. The whiskers indicate typical range of consumption.



HVAC Efficiency Savings

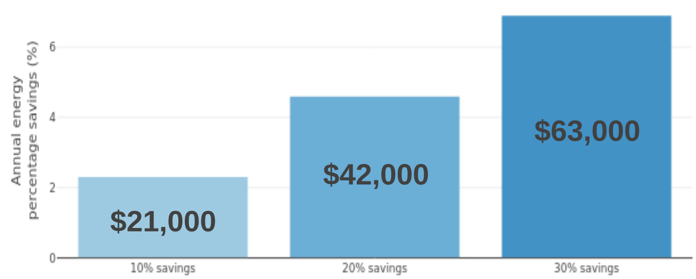
- Quantifies savings potential, if available, for replacing the electrically-driven HVAC equipment with a more efficient system
- Cannot determine the exact type of HVAC equipment, but can estimate the total heating and cooling load
- To achieve the potential savings from replacing HVAC, other clients have replaced their HVAC with a system that save energy at the percentages given here

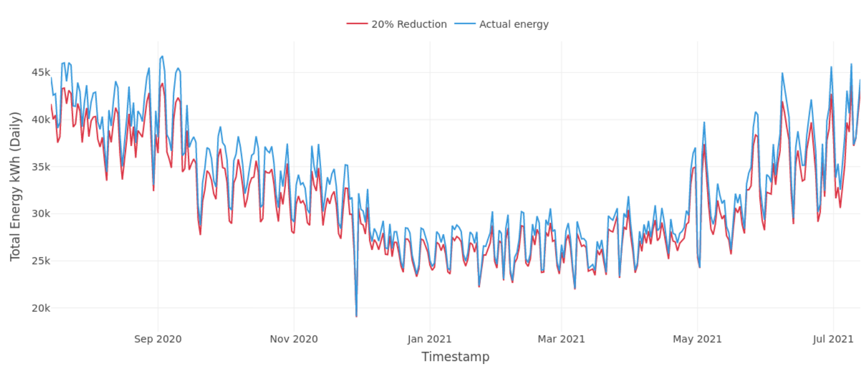




Plug Load Reduction Savings

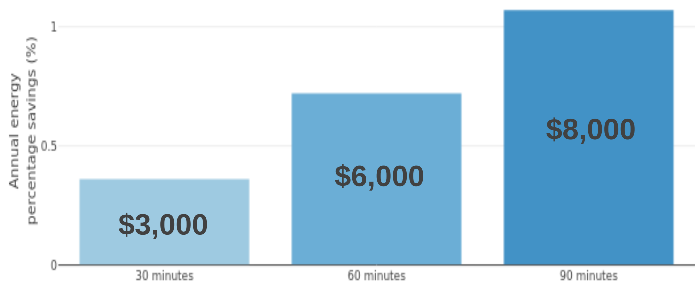
- Quantifies savings potential, if available, for non-HVAC electricity consumption, which includes interior lighting and plug load (e.g. computers, printers, refrigerators, etc.)
- Cannot determine the exact type of plug load equipment installed at the facility without additional sub-metering
- To achieve the potential savings from plug load, other clients have followed these actions:
  - **10-20% savings:**
    - Replace equipment with energy efficient devices
    - Consolidate personal equipment to shared devices
    - Use virtual server software
    - Control scheduling to reduce energy use during unoccupied times (via timers, load-sensing outlets/power strips, in-equipment sensors, etc.)
  - **30% savings:** 2-3 of the above actions

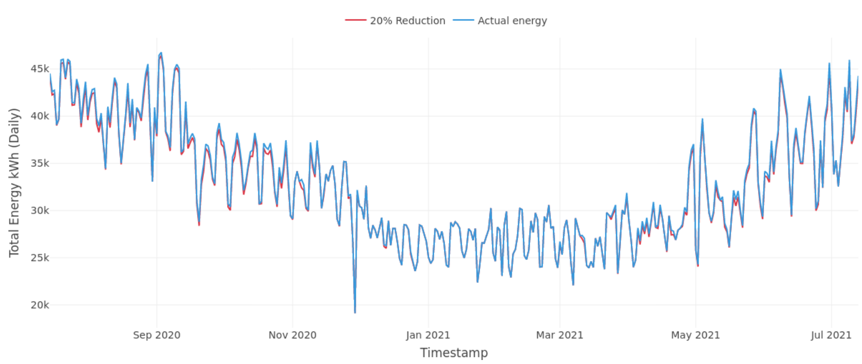




HVAC Reschedule Savings

- Quantifies savings potential, if available, by changing the scheduled HVAC setpoint changes
- The time periods indicated correspond to a change at both occupied and unoccupied modes that occur during a 24 -hour period
- To achieve potential savings, other clients have reprogrammed their thermostats or energy management systems to shift from occupied to unoccupied modes (and vice versa) at the time periods given here





Exterior Lighting Savings

- Quantifies savings potential, if available, for actions related to exterior lighting
- Identifies if the building has exterior lighting (e.g. in a parking lot) operated using daylight sensors or a schedule
- Cannot determine the exact type of lighting installed without additional sub-metering
- To achieve the potential savings from exterior lighting, other clients have followed these actions:
  - **10% savings**: Adjust scheduling of lights to turn on/off later/earlier
  - **20% savings**: Replace high intensity discharge or metal halide lamps with LEDs suitable for exterior lighting applications
  - **30% savings**: Both schedule adjustment and lamp replacement

Exterior or sensored lighting is not detected in this building

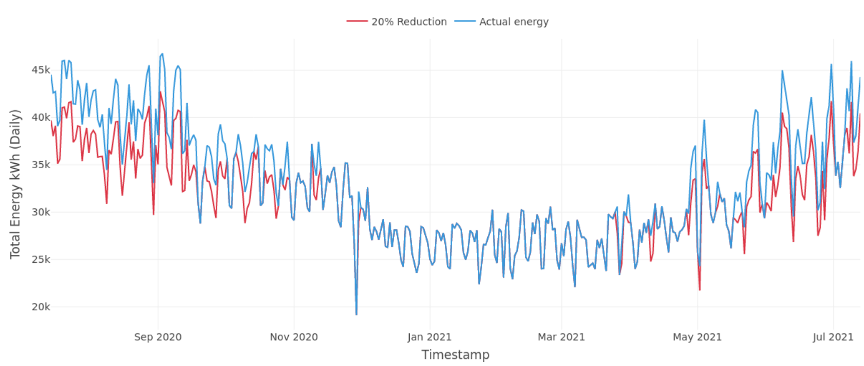
Refrigeration Savings

- Quantifies savings potential, if available, for refrigeration equipment
- Cannot determine the exact type or quantity of refrigerators or ice makers, but can estimate the total refrigeration load
- To achieve the potential savings from refrigeration, other clients have followed these actions:
  - **10% savings:**
    - Clean refrigerator condenser coils 1-2X per year
    - Replace aging seals
    - Set temperature to 35-38F
  - **10-30% savings**: Replace equipment with energy efficient versions (typically, the older the refrigeration unit, the greater the opportunity for savings)

Refrigeration savings are not calculated for this building type

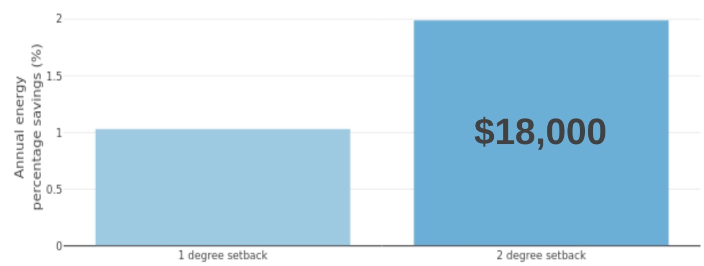
Baseload Cooling Savings

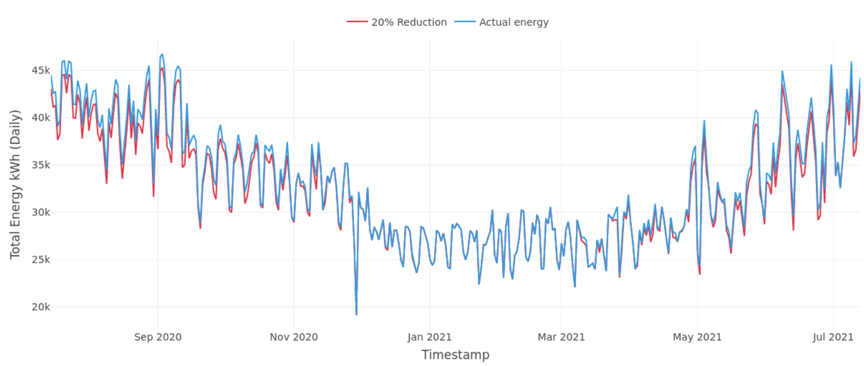
- Quantifies savings potential, if available, by reducing the baseload during unoccupied times
- Uses information about consumption patterns, building size, end usage and climate to devise a target baseload for the building
- Target baseload is always given for the cooling season; a target baseload is given for the heating season if an electric heating system is present
- To achieve potential savings, other clients have followed these actions:
  - To achieve **"best"** savings:
    - All equipment not in use are turned off during unoccupied times
    - HVAC is properly scheduled and setpoints changed up to 5 degrees during unoccupied times
  - To achieve **"better"** savings: As above, but setpoints changed up to 3 degrees during unoccupied times
  - To achieve **"good"** savings: As above, but setpoints changed 1 degree during unoccupied times



HVAC Set Point Savings

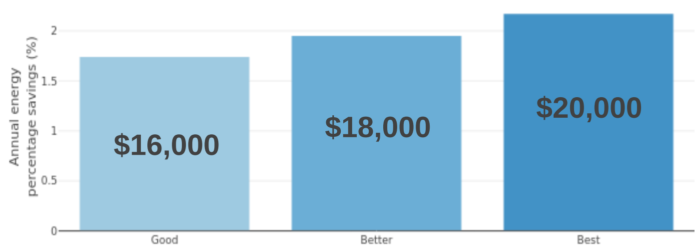
- Quantifies savings potential, if available, for changing the thermostat setpoint by one or two degrees, as indicated
- Savings is quantified for cooling and may be additionally associated with heating if the building is electrically heated; if the building is heated by a fuel, the overall savings will be even greater than indicated
- These setpoint setback savings may overlap with the baseload savings also quantified on the dashboard
- To achieve the potential savings, other clients have changed the setpoints during both occupied and/or unoccupied times

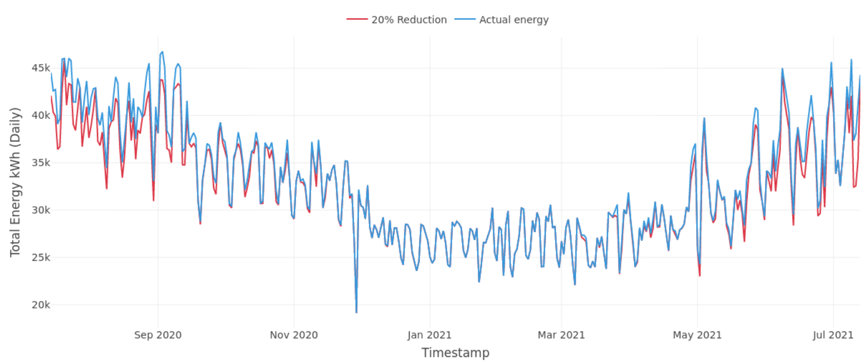




Building Shell Savings

- Quantifies savings potential, if available, from altering the walls or roofs. Determines the effective "R-value" for the building shell, which accounts for heat losses/gains through the building shell via thermal conduction and infiltration.
- Uses information about building size, end usage and climate to devise a target R-value for the building shell
- To achieve the potential savings, other clients have followed these actions:
  - To achieve **"best"** savings, in addition to below:
    - Apply air-sealing, high R-value spray foam insulation
    - Add insulation to increase R-value at roofline
    - Replace Roof
  - To achieve **"better"** savings, in addition to below:
    - Seal cracks and holes in walls, particularly at joints
  - To achieve **"good"** savings, in addition to below:
    - Ensure tight closure of doors





Electric Energy Use Intensity (EUI)

The building category of this building based on CBECS is "Other", and therefore the EUI benchmarking cannot be quantified.

11.4 APPENDIX 4: HOBO UX120-018 DATA LOGGER

For plug load metering, we used the HOBO UX120-018 Plug Load Data Logger (Figure 11.1). The meter measures and records power and energy consumption of 120V plug loads. Multiple plug load meters were deployed in Carlton Commons at CWRU to compare to associated EDIFES outputs. No wiring is required, and months of data can be recorded, stored, and transferred using the USB interface. Note: this meter cannot be connected to wi-fi or cellular systems. The plug load meter simply plugs into a wall outlet, and the equipment (e.g. computer, copier, refrigerator, etc.) is then plugged in directly to the meter.

Figure 11.1: Plug load meter.