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RESEARCH ARTICLE

A Comparison of Programmed Controlled Existing System vs. Electric Resistive Heating for a University Building in Newfoundland

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ABSTRACT

Buildings consume in excess of 30% of the total energy worldwide. In the Canadian context, commercial and institutional buildings contribute to around 14% of the overall energy usage, and space heating emerges as the predominant end-use category, constituting approximately 57% of this consumption. This underscores a considerable potential for energy savings in the realm of building energy consumption. This paper compares the energy consumption for space heating at the Core Science Facility (CSF) of the Memorial University of Newfoundland (MUN), Canada. The analysis contrasts the current system, utilizing hot water from fuel oil-fired boilers, with a proposed system suggesting the replacement of the oil-fired boiler with an electric resistive boiler, by employing a building energy model (BEM) created with the OpenStudio application. The findings indicate that beyond the anticipated enhancements in energy efficiency, a supplementary energy saving of approximately 7% is attainable through the proposed transition. Comparing the simulation outcomes with actual data reveals that the projected consumption from the Building Energy Model (BEM) is lower than the actual figures. This difference is attributed to the model's development, which involved distinct considerations and assumptions compared to the actual conditions such as construction materials, building occupancy, infiltration and exfiltration, interconnected buildings, energy usage by equipment and lighting, HVAC system energy consumption, and transmission losses through piping which can significantly influence the building's energy consumption.

Keywords: Educational Buildings, Energy Plus, OpenStudio, Thermal Modeling.

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1. Introduction

1.1. Energy Consumption in Buildings

Studies show that globally, buildings contribute to in excess of 30% of the total energy consumption [1], [2]. Correspondingly, in Canada, buildings play a substantial role in the country's energy demand, representing about 25% of the total final energy consumption, equivalent to approximately 729.52 Tera-Watt hours (TWh) [3]. Improving the energy efficiency of buildings can play a key role in reducing operational costs and emissions, especially taking into account their lifespan, which at the same time promotes sustainability as well. Although it can be simpler and straightforward to construct new buildings adhering to the latest energy-efficient standards, the existing stock of buildings constitutes the majority of stock and contributes significantly to overall energy consumption. Consequently, enhancing the energy efficiency of existing buildings can have a substantial impact. In Canada, the existing commercial and institutional buildings collectively contributed to around 14% of the total energy consumption in 2020 [4]. Notably, space heating constituted approximately 57% of the total energy consumed within the sector, accounting for approximately 191 TWh [4]. This indicates an opportunity for significant energy savings in the context of building energy consumption.

1.2. Building Energy Systems

Building energy systems (BES) consist of elements responsible for energy consumption within buildings, including physical equipment, machinery, processes, or a combination thereof [5]. BES typically includes heating, ventilation, and air conditioning (HVAC) systems, lighting, insulation, renewable energy sources, and control systems. The design and optimization of BES are crucial for achieving energy efficiency, reducing operational costs, and minimizing environmental impact.

Management of thermal comfort in buildings is fundamental for ensuring the well-being of the occupants while promoting energy efficiency in the building. In order to maintain thermal comfort, it is necessary to introduce or remove a specific amount of energy in the form of either heating or cooling to or from the building space [2]. This energy requirement is predominantly influenced by a number of factors, including but not limited to external weather conditions, such as outside air temperature, relative humidity, and wind characteristics; internal factors, such as occupancy levels, heat and moisture transfer through walls, and leakages to the outside. The accurate calculation of such loads for a building space is critical, as this process significantly influences not only the capital expenditure associated with the design and construction of a building but also the operational expenditure, consequently impacting the overall energy consumption. Moreover, load calculations also have a direct impact on the comfort levels of occupants of the buildings, thereby influencing their productivity.

Building energy modeling and simulation can play a crucial role in the design and optimization of energy-efficient buildings. These tools enable scientists and engineers to evaluate and forecast a building's energy performance across diverse conditions. Building energy models can be classified as either steady-state or dynamic. Steady-state models overlook the transient impact of variables, while dynamic models have the capacity to monitor peak loads and are effective in capturing thermal effects, such as those resulting from setback thermostat strategies [1]. The choice between the two approaches depends on the specific requirements of the analysis. Steady-state models are computationally efficient and suitable for quick assessments where transient effects are less critical. These work well for short-term analyses and initial screening. On the other hand, dynamic models offer a more accurate representation of a building's behavior over time, capturing transient effects, seasonal variations, and interactions among different components. While dynamic simulations are more complex and computationally intensive, they are essential for detailed analyses over a long period.

Amongst many methodologies and approaches used for building energy modeling, one frequently employed methodology is based on physical models, encompassing various approaches such as Computational Fluid Dynamics (CFD), the Zonal approach, and the Multizone or Nodal approach [6]. While regarded as the most comprehensive method, the CFD approach is complex and demands significant time and resources [6], [7]. Conversely, the multi-zone or nodal approach is seen as a relatively simpler method, operating under the assumption that each building zone represents a homogeneous volume characterized by uniform state variables [6]. Nonetheless, this approach can effectively depict the behavior of a multiple-zone building over an extended time frame with minimal computation time. It proves to be especially well-suited for estimating energy consumption and the temporal evolution of space-averaged temperatures within a space [8]. In this study, the Multizone approach is adopted, as it aligns with the methodology employed in commonly used simulation software like EnergyPlus [9], ESP-r [10], TRNSYS [11], and e-QUEST [12]. Introduced in the beginning of 1990s by Bouia and Dalicieux [13] and Wurtz [14], the zonal approach is a way to rapidly detail the indoor environment and to estimate a zone thermal comfort. Practically, it consists in dividing each building zone into several cells, with each cell representing a small part of a zone.

2. Building for the Case Study

This study is focused on the Core Science Facility (CSF) building, encompassing a total floor area of 40,817 square meters (m^2) across five floors. Located on the Memorial University of Newfoundland (MUN) campus in St. John's, Newfoundland, the CSF accommodates teaching rooms, research laboratories, and office spaces exclusively designated for the Department of Electrical and Computer Engineering within the Faculty of Engineering and Applied Science at Memorial University. Furthermore, the building houses many plant and equipment, including the cryogenic facility operated and maintained by the Department of Technical Services [15]. The CSF building is connected to the University Center (UC) building through Wing C in Level 2. CSF building relies on two energy sources: electricity and hot water for space heating, with the hot water sourced from the central heating plant in the university's Utility Annex (UA). The UA produces hot water through boilers fueled by diesel oil #2.

The UA's current setup includes four oil-fired boilers, each having a capacity of 18 MW. A proposal has been put forth to replace one of the oil-fired boilers with two electric resistive boilers, each having a relatively smaller capacity of 15.5 MW. This study aims to assess the impact of substituting the oil-fired boiler with an electric resistive boiler for heating the CSF building.

Figs. 1 and 2 show CSF building and its location on google maps.

Fig. 1. Core science facility building.

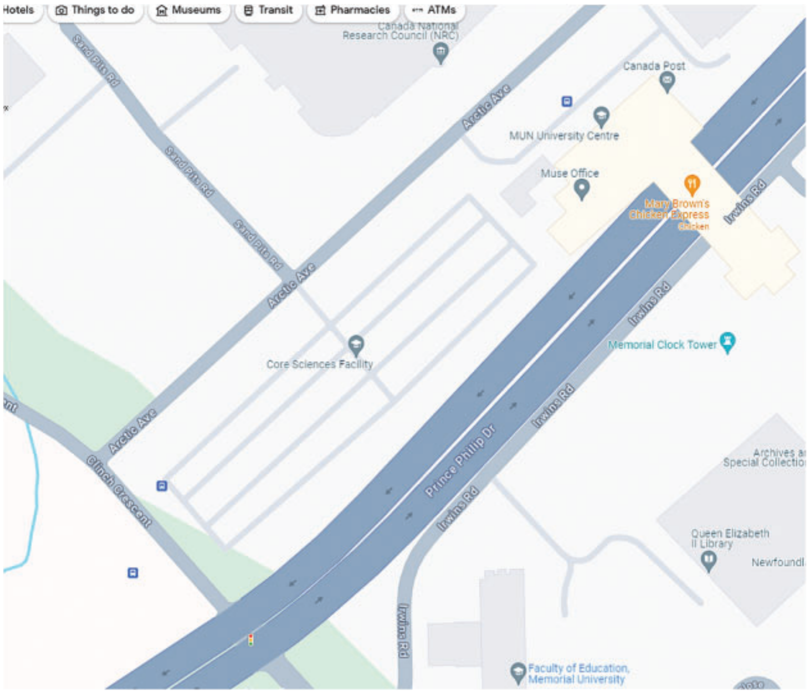


Fig. 2. Orientation of the building [16].

3. Approach and the Development of Building Energy Model

3.1. Selection of Simulation Software

Selecting a robust software tool for Building Energy Modeling (BEM) can serve as the foundation to achieving optimal energy efficiency in construction and retrofitting projects. A good software solution enables the consideration of dynamic conditions, taking into account various factors such as climatic conditions, construction and insulation materials, HVAC systems, and renewable energy integration. This, in turn, can assist with accurate projection of energy consumption patterns, contributing significantly to designing sustainable structures, complying with energy standards, and minimizing environmental impact.

OpenStudio is an open-source BEM software developed in collaboration with a number of institutions, primarily the National Renewable Energy Laboratory (NREL), Department of Energy (DOE), Argonne National Laboratory (ANL), Lawrence Berkely National Laboratory (LBNL), Oak Ridge National Laboratory (ORNL), Pacific Northwest National Laboratories (NPPL), Pennsylvania State University in the United States, and National Resources Canada, that supports whole building energy modeling using EnergyPlus and advanced daylight analysis using Radiance [17], [18]. Apart from functioning as a Software Development Kit (SDK) and a command line interface, OpenStudio is also accessible as a graphical application, which allows users to swiftly generate the necessary building geometries, assign materials, loads, building spaces and thermal zones for EnergyPlus simulations. The OpenStudio SDK can operate across various platforms, such as Windows, Mac, and Linux. It has been effectively utilized by numerous government and private laboratories to develop web and server-based applications [17], [18]. Offering the flexibility to code in multiple programming languages, the OpenStudio SDK provides a versatile platform for creating tools that can cater to a diverse range of end users. In addition to the wide array of data available on the OpenStudio application, it is also supported by the Building Component Library (BCL), which serves as a comprehensive repository of pre-defined building elements and systems, offering users a valuable resource for efficiently constructing energy models. This library encompasses a diverse range of components such as constructions, materials, HVAC systems, and schedules, which can be seamlessly integrated into the energy models, enhancing the accuracy and speed of model development.

Developed in collaboration by the DOE and NREL, EnergyPlus is considered as one of the most powerful tools for simulating building energy performance in various scenarios, including new construction, renovations, and the selection of appropriate building energy systems [9], [19].

While the OpenStudio platform has gained widespread use in BEM, existing literature indicates a limited utilization of this platform for modeling educational or university buildings.

3.2. Use of Standards and Guidelines

There are currently various approaches, guidelines, and standards accessible for the planning, construction, and operation of environmentally sustainable buildings [20], [21]. ASHRAE 189.1-2009, developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), is a standard which has been widely used, that provides total sustainability guidance for designing, building, renovating, and operating high-performance green buildings [22]. The standard encompasses various aspects, including site sustainability, water efficiency, energy efficiency, and indoor environmental quality.

TABLE I: Functionalities of OpenStudio Tabs

Name	Purpose
Site	Specify weather conditions, life cycle costs, and utility expenses.
Schedules	Define schedules that are applied to loads within a building.
Constructions	Specify materials, construction assemblies, and sets.
Loads	Define individual building loads.
Space types	Create space profiles for the building envelop.
Geometry	Define the building exterior and interior geometries.
Building	Assign building level defaults and exterior components.
Spaces	Assign profiles to individual spaces.
Thermal zones	Group spaces into thermal zones and assign zone equipment.
HVAC	Define the heating, cooling, and water systems for the building.
Variables	Specify additional simulation reporting variables as applicable.
Simulation settings	Customize simulation settings.
Measures	Assign OpenStudio and energy plus measure scripts to a workflow.
Run simulations	Perform energy simulation.
Reports	Review simulation results for the energy simulation.

OpenStudio has incorporated ASHRAE 189.1-2009 guidelines into its robust platform for building energy modeling. This alignment provides users the facility to simulate and optimize the energy performance of buildings, ensuring that OpenStudio models adhere to acknowledged sustainability principles, covering a range of aspects including energy efficiency, water conservation, and indoor environmental quality.

4. Methodology

The OpenStudio application features a Graphical User Interface (GUI) that enables users to input or select data from the built-in databases essential for simulations. The GUI has been divided into a number of tabs vertically, organized in accordance with steps commonly used in a BEM workflow. Some of these tabs are broken down into sub tabs horizontally, in the top of each window. Table I (adapted from [18]) provides a concise overview of the main tabs, and Fig. 3 illustrates the home screen of the application.

In the initial tab, "Site," data for weather information and design days (DDY), including the analyzed year, is entered under the sub tab "Weather File and Design Days". Design day information contains extreme climate conditions anticipated for a specific location [18], and these conditions are often employed in sizing HVAC systems, as these systems need to ensure the comfort of the building's occupants under extreme circumstances, including heating, cooling, humidification, and dehumidification conditions. EnergyPlus provides comprehensive weather and design days information for St. John's, Newfoundland, which was utilized for this study [23]. ASHRAE climate zone details can also be entered in the site tab, an

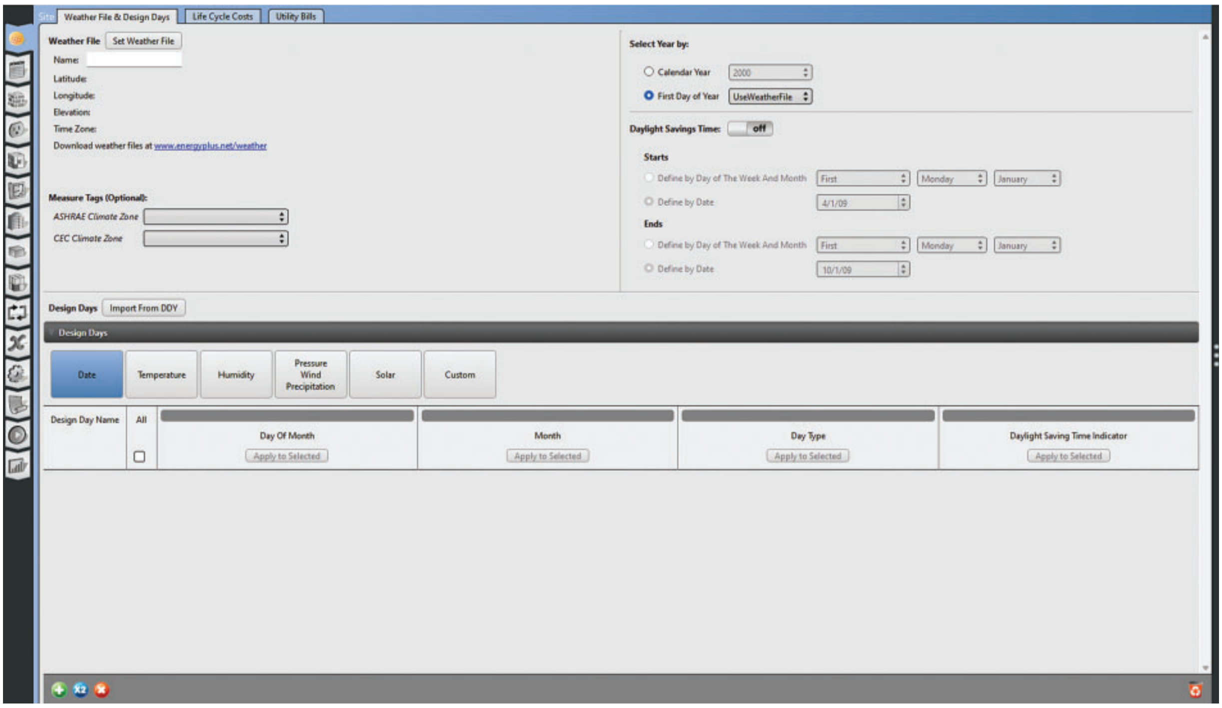


Fig. 3. Home screen of OpenStudio.

option providing an opportunity to enhance the simulation results. Under the Site tab, historical data for utility bills can be inserted under the sub-tab, "Utility Bills." Fig. 4 provides the key information added in the Site tab.

The "Schedules" tab is utilized for incorporating diverse schedules and schedule sets that are relevant to the loads within the building. Schedule Sets, which are combinations of schedules, encompass various parameters such as hours of operation, number of people, people activity, lighting, electric equipment, gas equipment, hot water equipment, steam equipment, and infiltration. It is possible to define multiple schedule sets for different spaces within the building. Schedules are used for defining the timing and intensity of various operations like occupancy, lighting, HVAC systems, and thermostat settings. These schedules outline patterns for the variation of such activities over time. Users have the flexibility to create and customize schedules to simulate real-world scenarios precisely, ensuring that energy models align accurately with the specific requirements and behaviors of the building.

This study required making several assumptions owing to the absence of data on building operations. Essential details such as occupancy patterns, lighting, and equipment loads were not available, primarily because the building is relatively new, and no comprehensive survey has been conducted to date. The dynamics of an educational building can vary significantly throughout the year, and the collection of such data could entail a considerable investment of time, effort, and resources. Conversely, there is also limited literature available on BEM specifically for educational or university buildings, making it challenging to locate reference data. Therefore, occupancy patterns were extrapolated by utilizing predefined schedules in OpenStudio for Office Buildings. This was done, taking into account that a portion of the building functions as office space for faculty staff and students. Given that the lighting in the CSF building operates predominantly throughout the day, common areas were assumed to have continuous lighting, while lighting for laboratories, classrooms, and offices was set to operate during daytime hours. Electrical equipment usage was primarily considered within laboratories and office spaces, following the lighting schedule for the respective space type. Notably, no considerations were made for gas, hot water, or steam equipment in this study. Fig. 5 illustrates the schedule sets utilized and the individual schedules employed within one of the schedule sets. Meanwhile, Table II provides a summary of the system parameters considered in the study.

In the absence of specific information regarding the construction details of the CSF building, including materials, composition, insulation thicknesses, etc., pre-defined construction sets in OpenStudio were utilized. These construction sets comprise materials recommended for a building situated in climate zone 6A, following the ASHRAE standard 189.1-2009. Fig. 6 illustrates the construction sets implemented and the materials selected for the primary building, and Table III summarises the properties of these materials. SHGC and VLT in the table refer to Solar Heat Gain Coefficient and Visible Light Transmission, respectively.

Within the loads category, three load categories; occupancy, lighting, and electrical equipment were considered. Given the absence of actual data, ASHRAE-recommended values for occupancy and electrical equipment for an Office building located in climate zone 4-8, available on OpenStudio, were used for various space types. As for lighting loads, recommended lighting power densities for educational buildings as per the National Energy Code of Canada for Buildings were applied [24].

For this study, the CSF building was categorized into various space types, named as Atrium, Office, Classroom, Corridor, Elevator, Stairs, Laboratory, Equipment Room,

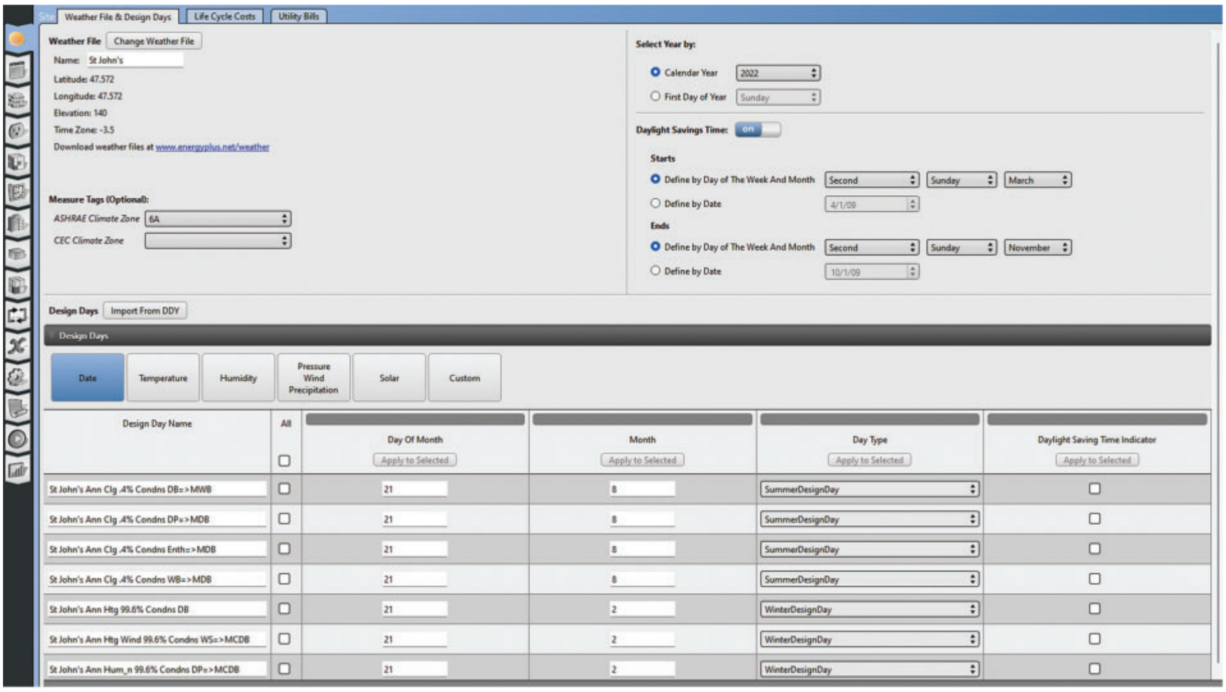


Fig. 4. Information under site.

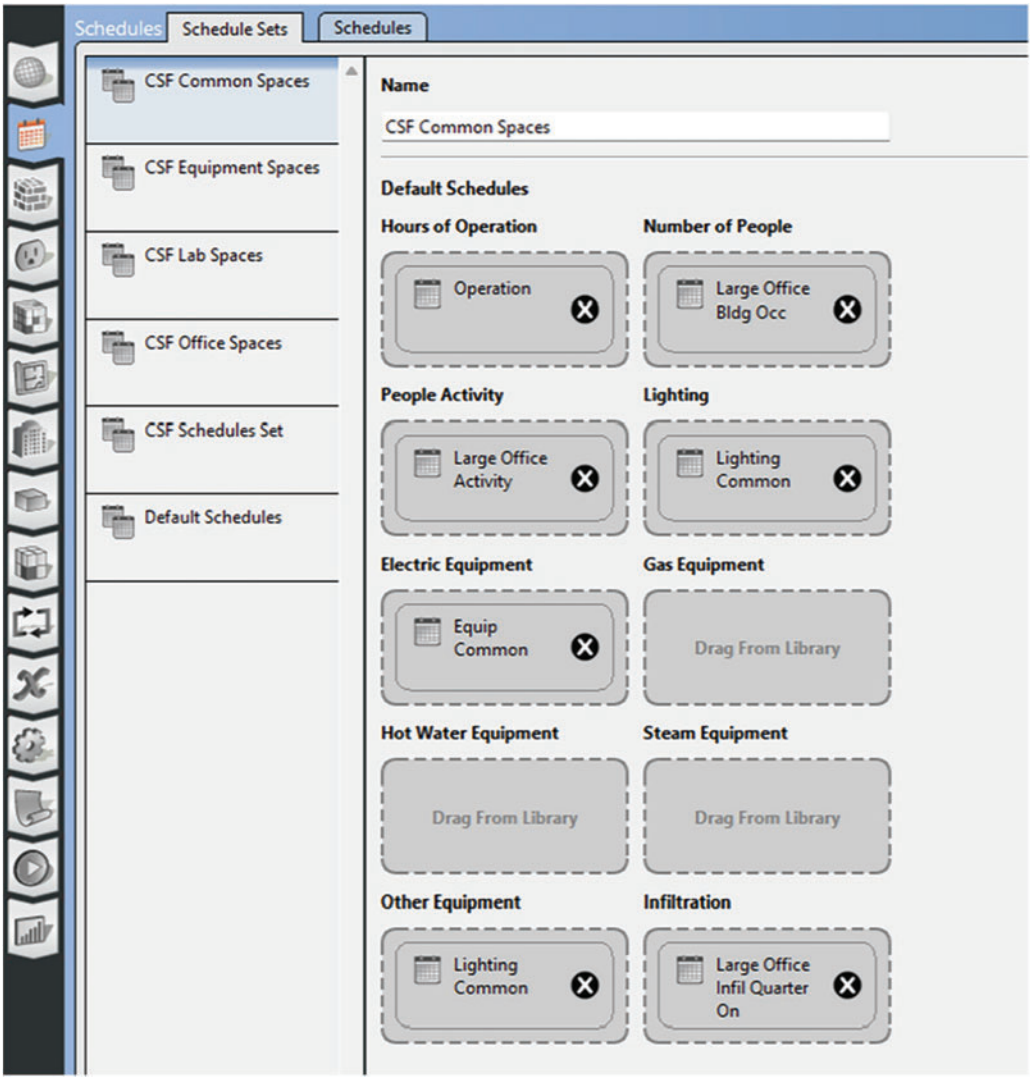


Fig. 5. List of schedule sets.

TABLE II: System Parameters Considered

Parameter	Unit	Value
Thermostat setting-heating	°C	22
Thermostat setting-cooling	°C	26
Relative humidity	%	45
Equipment room thermostat setting for freeze protection	°C	15
Hot water temperature at the inlet of CSF loop	°C	85

and Restroom. The allocation of these space types was completed upon the completion of the building geometry.

Various methods can be employed to create the building geometry in OpenStudio. The OpenStudio Application includes a floor plan editor that facilitates the development of a two-dimensional floor plan for each building story, as shown in Fig. 7. Additionally, OpenStudio offers a plug-in for Trimble SketchUp, enabling the creation of detailed three-dimensional building geometry. It also supports the import of geometry in Green Building Extensible Markup Language (gbXML) format, which can be generated using other third-party Computer-Aided Drafting (CAD) tools that supports the format.

The building geometry for this study was created using the integrated floor plan editor, with the building footprint located using Google Maps. Each floor plan was imported as an image and correctly scaled, forming the foundation for the 2D geometry creation. Subsequently, height was added to each floor plan. While OpenStudio allows for the creation of plenum spaces within individual building spaces, they were omitted in this model to simplify the complexity. Following the completion of building geometry, space types, and thermal zones were assigned to the building envelope. While thermal zoning can be derived based on factors like the location of thermostats, spatial positioning relative to the building facade, and variations in heating and cooling setpoints within spaces, thermal zoning in this study was conducted based on space type, given that heating and cooling setpoint temperatures were considered as constant across the entire building. Fig. 7 illustrates the building geometry when viewed from the North, and a summary of the thermal zone, space type, construction set, and height of building spaces on floor 1.

Within the Facility tab, general details about the building such as the building's orientation, the count of floors, and the nominal height of each floor were added. Some of these details can be modified by the parameters defined in

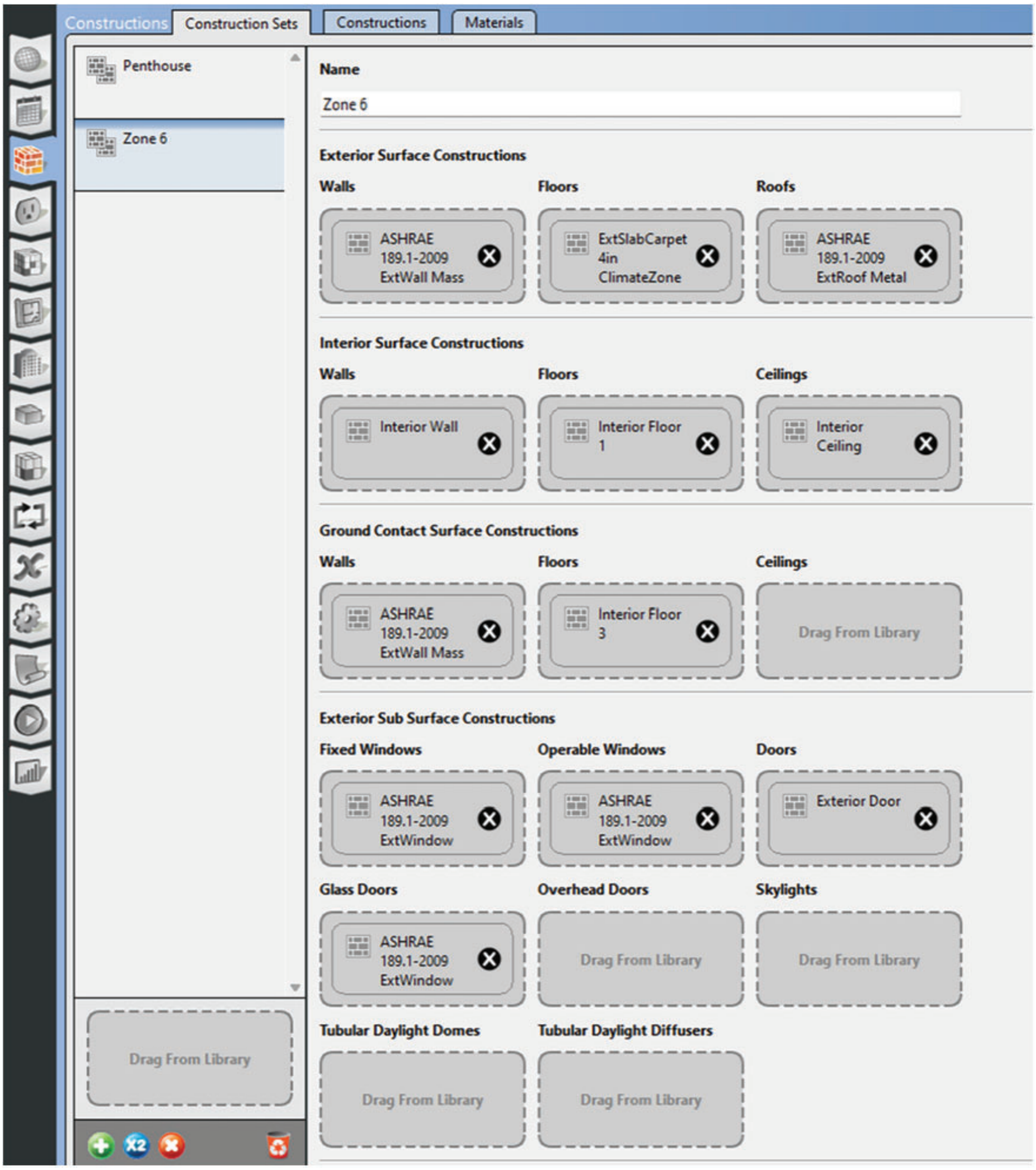


Fig. 6. Construction materials considered for the main building.

TABLE III: Properties of Construction Components

Component	R value	U value	Unit	SHGC	VLT
Main building					
Exterior walls	13.34		ft^2.h.R/Btu		
Roof	30.48		ft^2.h.R/Btu		
All windows and glass doors		0.45	Btu/ft^2.h.R	0.4	0.51
All solid doors		N/A		N/A	N/A
Penthouse (Equipment room in top floor)					
Exterior walls	18.07		ft^2.h.R/Btu		
Roof	30.48		ft^2.h.R/Btu		

the "Geometry" tab, Fig. 8 illustrates the general parameters taken into account in the study.

In the "Spaces" tab, the allocation of default schedule sets and various loads, including lighting, electrical equipment, infiltration, and occupancy, specific to individual spaces, was completed. Then the development of the HVAC system was completed under the HVAC systems. HVAC system modeling in OpenStudio has been streamlined with the integration of the ASHRAE Advanced Energy Design Guides (AEDG) [25]. By using this facility, users can effectively design and simulate energy-efficient HVAC systems for buildings in a number of quick steps. This process encompasses the definition of system types, selection of equipment, and customization of system

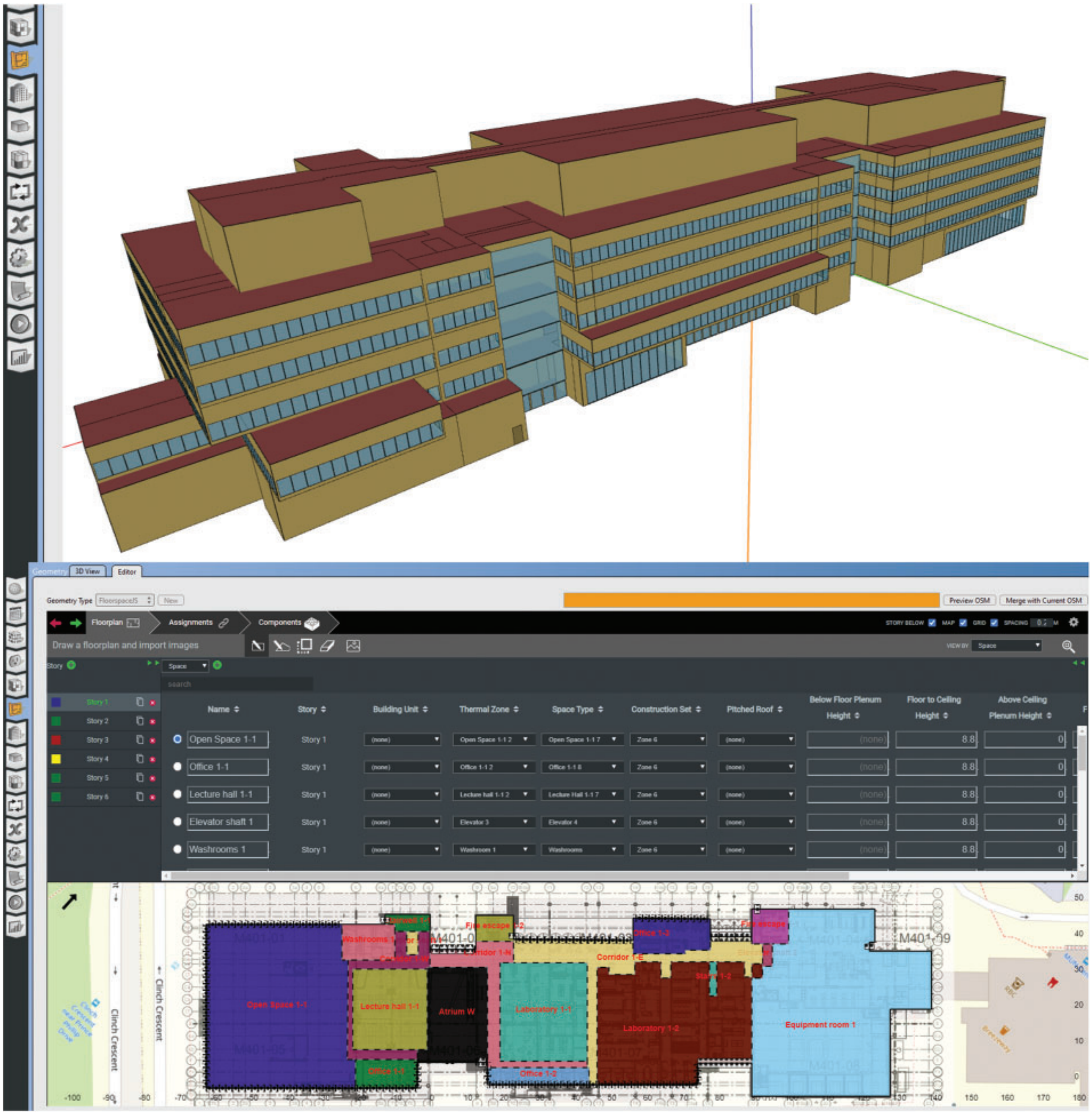


Fig. 7. Completed building geometry of CSF building and the floor plan, space and thermal zone allocation for floor 1.

parameters. The HVAC system for the CSF building was modeled with the inclusion of a hot water loop utilizing a boiler for heating, a chilled water loop with an electric chiller for cooling, and an air loop for each floor of the building. In the initial phase of model development, an oil-fired boiler was chosen to reflect the current scenario, while during the second iteration of the simulation, this was subsequently replaced with an electric boiler. The sizing of the hot water boiler was determined based on the parameters outlined in Table IV, and temperature control parameters were set according to the specifications in Table II. Adiabatic piping was employed for all system loops, assuming negligible heat loss through the transfer lines. Default values were considered for all other system parameters. While Figs. 9–11 illustrate the hot-water loop, chilled water loop, and air loop, respectively, that were taken into account in this study, parameters for hot water loop, chilled water loop and air loop for floor 1 that were automatically sized by OpenStudio are indicated in Table V.

Once the modeling of the HVAC system was completed, system parameters such as cooling thermostat and heating thermostat schedules for individual spaces were added under the Thermal zones tab.

The results from the simulation can be customized using the "Output variables" tab, although no adjustments were made to the settings for this study. To easily identify errors in the models, troubleshooting measures from the Building Component Library (BCL) were implemented under the "Measures" tab. During the initial simulation runs aimed at rectifying model errors, the run period and simulation steps were reduced in the simulation settings to expedite the process and minimize the time required. After rectifying the model errors adequately, the timestep was increased to 4, adhering to the minimum recommended by OpenStudio, and the run period was extended to encompass an entire calendar year.

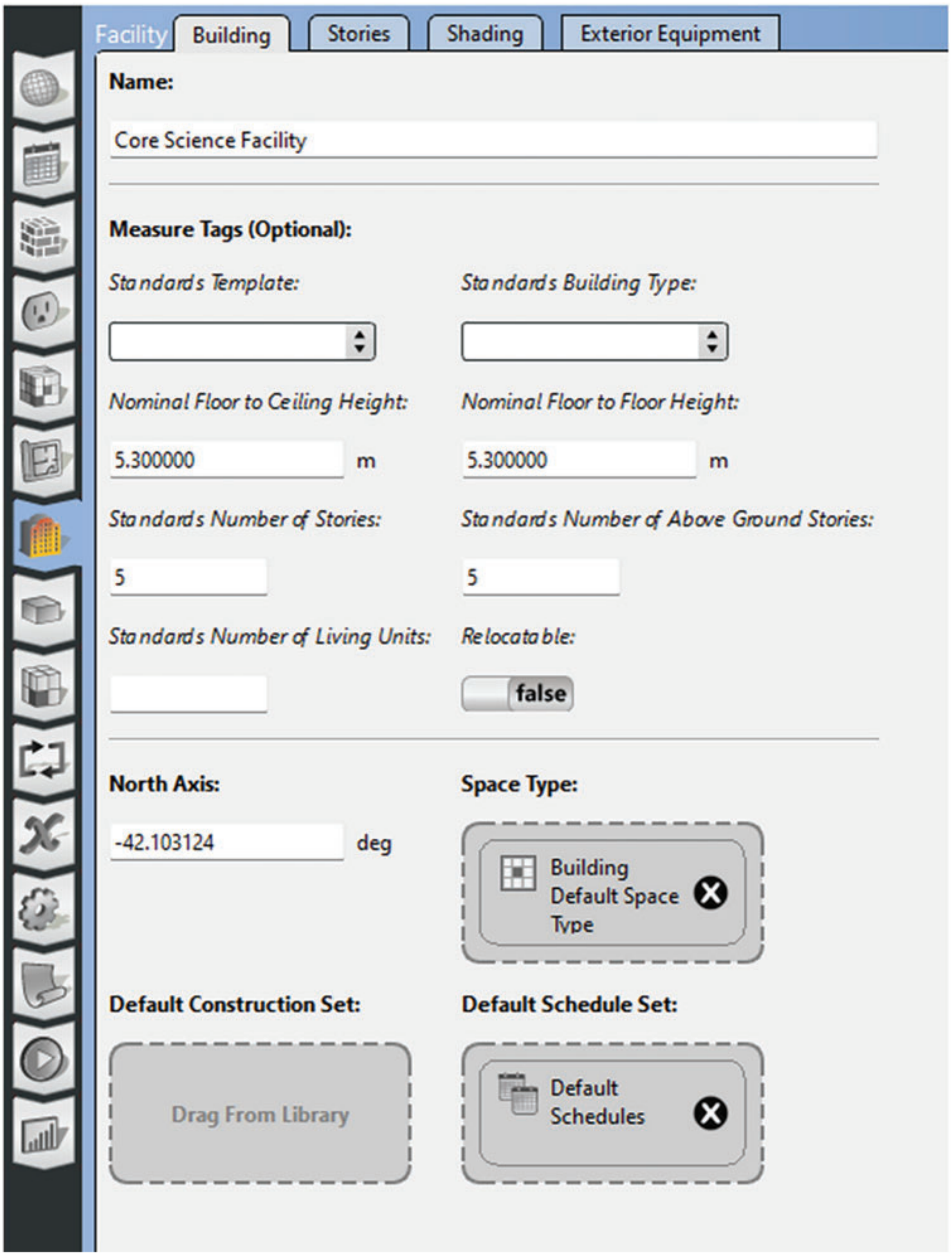


Fig. 8. Information in the facility tab.

TABLE IV: Boiler Parameters for Heating System

Parameter	Unit	For oil fired boiler	For electric resistive boiler
Boiler capacity	Mega-Watt (MW)	18	15.5
Boiler efficiency	%	82	95

5. Results and Discussion

In OpenStudio, the energy consumption simulation results are expressed in Joules (J). The outcomes for the simulation, considering both the existing system and the electric resistive boiler system, are listed in Tables VI and VII, respectively, while the actual consumption data is presented in Table VIII (adapted from [26]).

The actual energy consumption and simulation results can be converted to Giga-Joules (GJ) to facilitate comparison, utilizing the following formulas:

LHV of diesel (MJ/litre) = 38.18

Diesel consumption/January (litres) = 143,447

Energy consumption (heating/Jan) (GJ) = 5,476.81

Electricity consumption/January (kWh) = 938,238

Electricity consumption/ January (GJ) = 3,377.66

Comparisons between the actual and simulation results are presented in Tables IX and X, respectively, for space heating and electricity.

A comparison between the two simulation results is given in Fig. 12.

The graphical representation of energy consumption for space heating and other end uses considering all three scenarios is represented in Fig. 13, above and below,

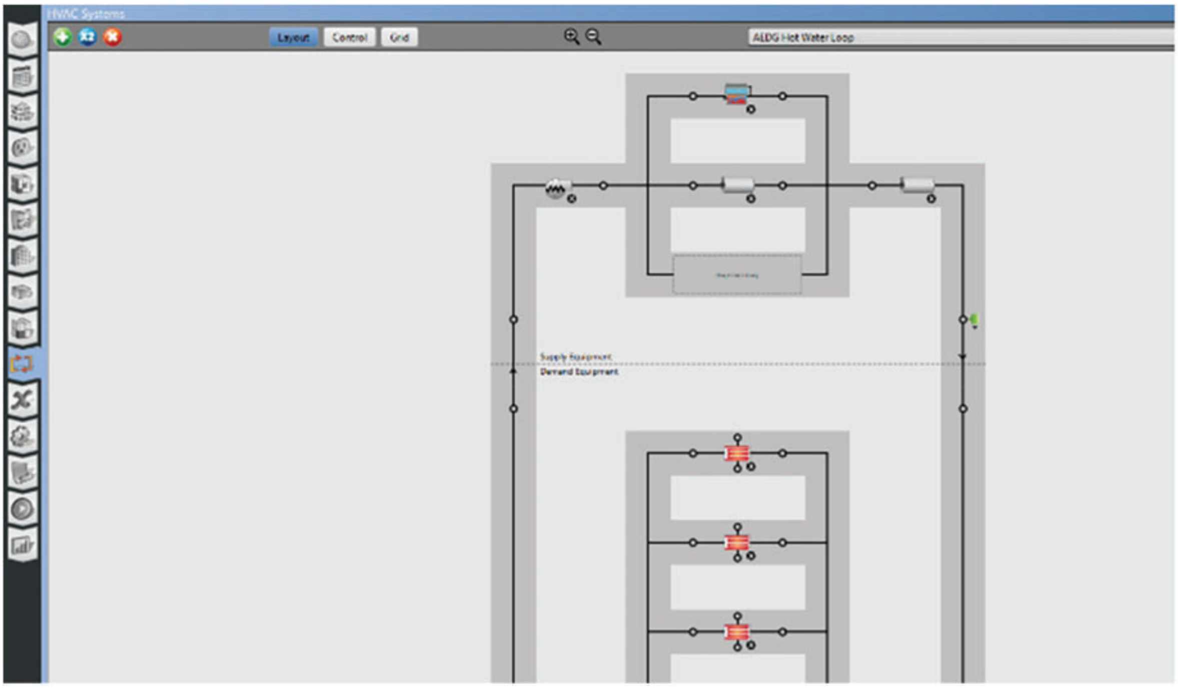


Fig. 9. Hot-water loop (Only a section with key components is shown).

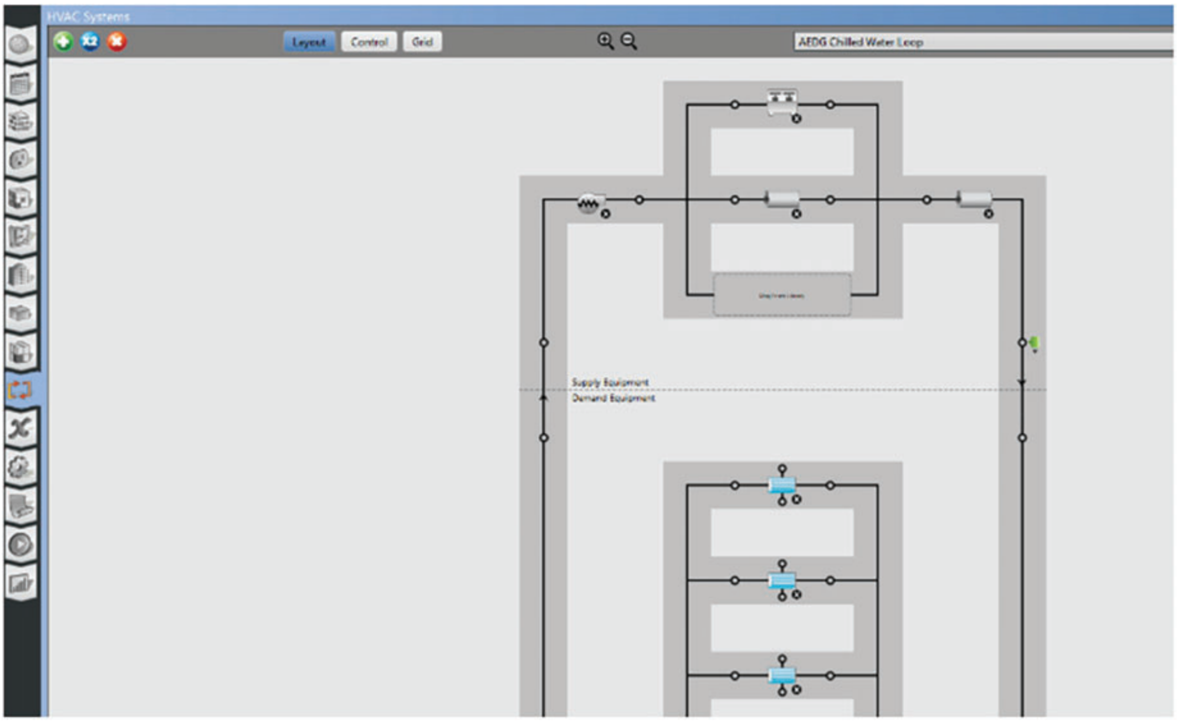


Fig. 10. Chilled-water loop (Only a section with key components is shown).

respectively. While both Figs. 12 and 13 illustrate an identical consumption pattern of electricity in both simulations, Figs. 12 and 13 also reveal a slight difference in energy consumption for space heating under electric resistive heating. Electric resistive heating exhibits approximately 7% less energy consumption, further to the improved efficiency and lower boiler capacity considered for the study.

Electric boilers can modulate their output almost instantaneously in response to fluctuations in temperature or changes in demand for space heating or hot water. This rapid responsiveness allows for precise control, ensuring that the boiler operates at its optimal capacity, neither overproducing nor underproducing heat. In comparison, oil-fired boilers can experience less efficiency during frequent on/off cycling or during periods of low demand, as they may need to cycle on and off to maintain temperature, resulting in a modulation that is less effective than an electric resistive boiler. While this study did not account for dynamic heating loads such as fluctuating occupancy, OpenStudio incorporates passive heating elements such as solar heat gains and radiation from equipment in its simulations. This inclusion allows for the consideration of

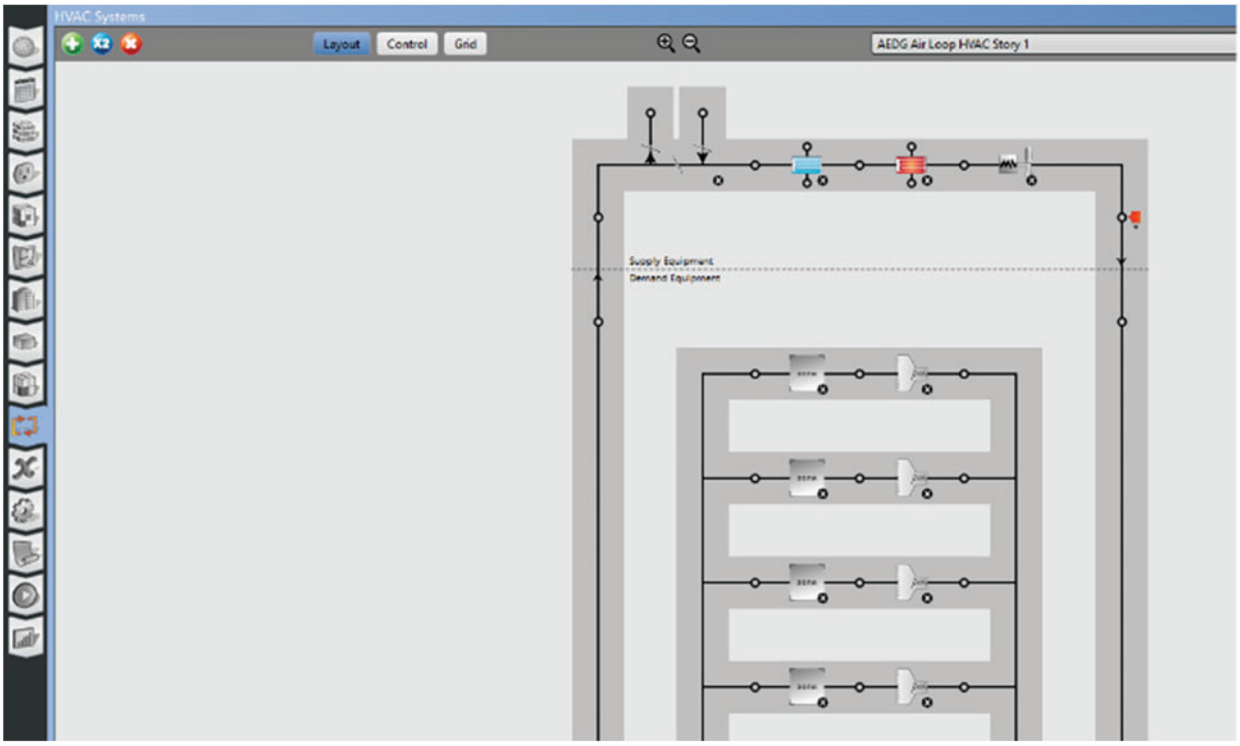


Fig. 11. Air loop for floor 1 (Only a section with key components is shown).

TABLE V: AEDG HVAC System Parameters Auto Sized by OpenStudio

Loop	Parameter description	Unit	System parameter
AEDG chilled water loop	Variable pump water flow rate	gal/min	849.54
	Electric chiller cooling capacity	ton	428.6
	Water flow rate	gal/min	849.54
	Reference COP		2.93
AEDG hot water loop	Variable pump water flow rate	gal/min	425.02
	Water flow rate	gal/min	425.02
Air loop for story 1			
Outdoor air system	Maximum outdoor airflow rate	CFM	21,525
	Minimum outdoor air flow rate	CFM	Auto
Coil cooling: Water	Air flow rate		21,525
	Water flow rate	gal/min	150.31
Coil heating: Water	Heating capacity	Btu/hr	186,371.60
	Water flow rate	gal/min	19.13

dynamic conditions that may impact heating within the modeled environment. Therefore, this difference in energy consumption can be attributed to this inherent distinction between the two technologies.

While the simulation results exhibit a consumption pattern similar to the actual data, there are also some deviations from the energy consumption values calculated using past data. This variance may arise from several disparities between the actual conditions and the OpenStudio model.

In the absence of specific details about the construction materials used in the CSF building, readily available materials optimized for Climate Zone 6 were employed in the OpenStudio model. These materials are designed to perform efficiently in the specified climate conditions. It is important to note that the actual construction materials used in the building may differ, especially in terms of properties such as insulation. Consequently, these discrepancies can influence the energy consumption patterns of the building throughout the year. The utilization of climate-specific materials in the model serves as an approximation, and the actual energy performance may vary based on the real-world construction details. The OpenStudio model also omitted the consideration of internal windows and doors as a simplification measure in the simulation. This resulted in the assumption that all internal surfaces are entirely sealed, whereas, in reality, substantial air leakages can occur through the glass surfaces, seals, and doors, leading to a higher energy consumption.

Furthermore, the second level of the CSF building is linked to the University Center (UC), facilitating substantial airflow between the two structures. The interchange of air between these interconnected buildings can cause heat loss from the CSF building as warm air escapes into the cooler UC. This can produce a comparable impact during the summer season, wherein the influx of warm outdoor air into the CSF building would lead to increased energy consumption for space cooling to lower the temperature of

TABLE VI: Simulation Results (Existing System)

Month	Energy consumption in joules	
	Space heating-fuel oil #2	Electricity
January	3.23E + 12	1.41E + 12
February	2.93E + 12	1.27E + 12
March	2.51E + 12	1.41E + 12
April	1.83E + 12	1.37E + 12
May	1.19E + 12	1.45E + 12
June	4.58E + 11	1.48E + 12
July	1.26E + 11	1.63E + 12
August	1.61E + 11	1.56E + 12
September	5.15E + 11	1.43E + 12
October	1.29E + 12	1.43E + 12
November	2.20E + 12	1.36E + 12
December	3.33E + 12	1.41E + 12
Total	1.98E + 13	1.72E + 13

TABLE VII: Simulation Results (With Electric Resistive Heating)

Month	Energy consumption in joules	
	Space heating-electricity	Other uses-electricity
January	2.99E + 12	1.41E + 12
February	2.88E + 12	1.27E + 12
March	2.32E + 12	1.41E + 12
April	1.64E + 12	1.37E + 12
May	1.04E + 12	1.46E + 12
June	4.00E + 11	1.48E + 12
July	1.49E + 11	1.63E + 12
August	1.46E + 11	1.56E + 12
September	3.73E + 11	1.43E + 12
October	1.04E + 12	1.43E + 12
November	2.23E + 12	1.37E + 12
December	3.06E + 12	1.41E + 12
Total	1.83E + 13	1.72E + 13

TABLE VIII: Actual Energy Consumption

Month	Electricity consumption (kWh)	Oil consumption (liters)
January	938,238	143,447
February	855,079	163,802
March	960,000	151,847
April	932,419	117,433
May	1,001,842	72,558
June	1,116,581	60,246
July	1,239,224	25,221
August	1,301,140	34,303
September	1,151,270	44,295
October	1,096,985	42,079
November	1,047,888	106,251
December	1,065,471	138,628
TOTAL	12,706,138	1,100,109

the building envelope. This heat loss necessitates additional energy consumption, as the heating system in the CSF building must compensate for the dissipated heat. Moreover, the UC features several openings to the outdoors, potentially leading to infiltration and exfiltration, resulting in additional energy losses. Notably, for the simulation in OpenStudio, neither the interconnection nor the heat loss has been taken into account, potentially resulting in an estimated energy consumption that is lower than the actual values.

The CSF building, as well as the UC, accommodates numerous occupants throughout the year. Acknowledging the behavior of occupants is recognized as a pivotal factor contributing to the observed performance gap between actual and simulated energy consumption in buildings [27], [28]. Additionally, fluctuations in occupancy levels within a day influence space heating requirements, introducing

TABLE IX: Comparison of Fuel Consumption for Space Heating

Month	Energy consumption (GJ)		
	Actual	Simulation results (Fuel oil)	Simulation results (Electricity)
January	5476.81	3128.52	2976.22
February	6253.96	2955.37	2918.21
March	5797.52	2490.05	2384.31
April	4483.59	1751.43	1549.46
May	2770.26	1181.74	1074.15
June	2300.19	466.44	321.71
July	962.94	133.75	133.26
August	1309.69	156.07	162.26
September	1691.18	552.97	327.86
October	1606.58	1275.47	991.93
November	4056.66	2261.33	2188.28
December	5292.82	3278.99	3022.45

TABLE X: Comparison of Electricity Consumption (For Purposes Other than Space Heating)

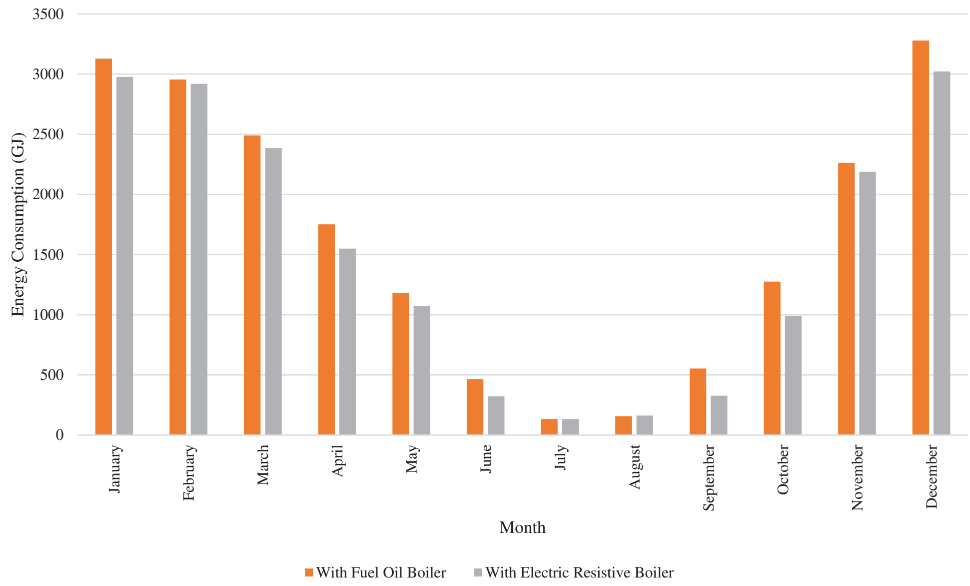
Month	Energy consumption (GJ)		
	Actual	Simulation results (other than for space heating)	
		With space heating using fuel oil	With space heating using electricity
January	3377.66	1410.69	1413.74
February	3078.28	1272.23	1274.51
March	3456.00	1413.63	1414.42
April	3356.71	1371.98	1373.37
May	3606.63	1454.85	1455.86
June	4019.69	1479.04	1479.36
July	4461.21	1625.72	1625.66
August	4684.10	1559.93	1559.89
September	4144.57	1427.71	1427.96
October	3949.15	1429.06	1430.70
November	3772.40	1364.67	1365.58
December	3835.70	1407.47	1409.11

variations in heating needs and potential inefficiencies. Maintaining a comfortable indoor environment involves striking a balance between the heating system and external conditions, and varying occupancy levels can impact the energy consumed for space heating. Thus, it is crucial to consider building occupancy levels in building energy modeling. Occupancy information for CSF building is not currently available, and determining occupancy levels poses significant challenges, especially for buildings with dynamic occupancy patterns like the CSF building. Modeling dynamic occupancy levels is not currently feasible in BEM simulations; therefore, occupancy levels were not factored into this study, which can lead to a disparity in the energy requirements given by the simulation.

The HVAC system modeled in OpenStudio adhered to ASHRAE's Advanced Energy Design Guidelines (AEDG), providing a framework for designing energy-efficient HVAC systems. It is important to note that the actual HVAC system in the CSF building may have a different configuration and potentially lower efficiency, leading to higher energy consumption than indicated by the simulation results.

The energy demand from different equipment utilized across the building was not accessible for this study, posing a challenging task for data compilation. Additionally, the dynamic nature of occupancy levels introduces variations in actual loads and operating times. Consequently, guidelines for electrical equipment usage in an office building situated in climate zones 4-8 were employed for the simulation. This approach may lead to a lower estimated energy consumption value than the actual consumption. The CSF building also accommodates numerous plants and equipment that consume a substantial amount of energy, a factor not taken into account in the simulation. For instance, the ground floor and penthouse, functioning as plant rooms, were modeled as office spaces due to the lack of available data on the actual energy demand from these areas.

The hot water supply and return lines for the CSF building are channelled from the Department of Earth Science building, covering a substantial distance of around 160 meters between the two structures. In the simulation, no consideration was given to any energy loss within this section, as the model employed adiabatic piping with negligible heat losses. This contrasts with real-world conditions where significant losses might occur between the measuring point and the entry points of the pipes into the CSF building.



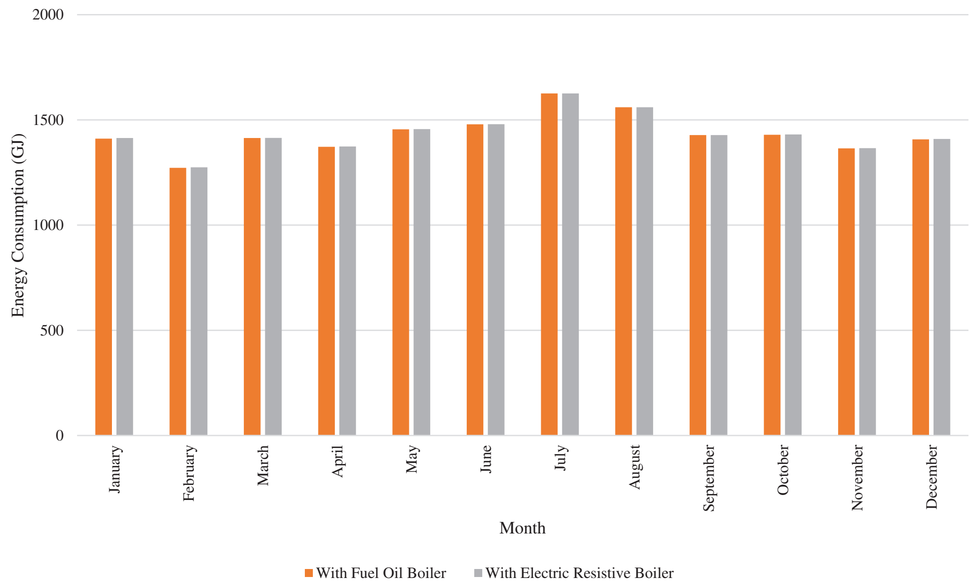


Fig. 12. Comparison of simulation results: energy for space heating (above) and electricity (below).

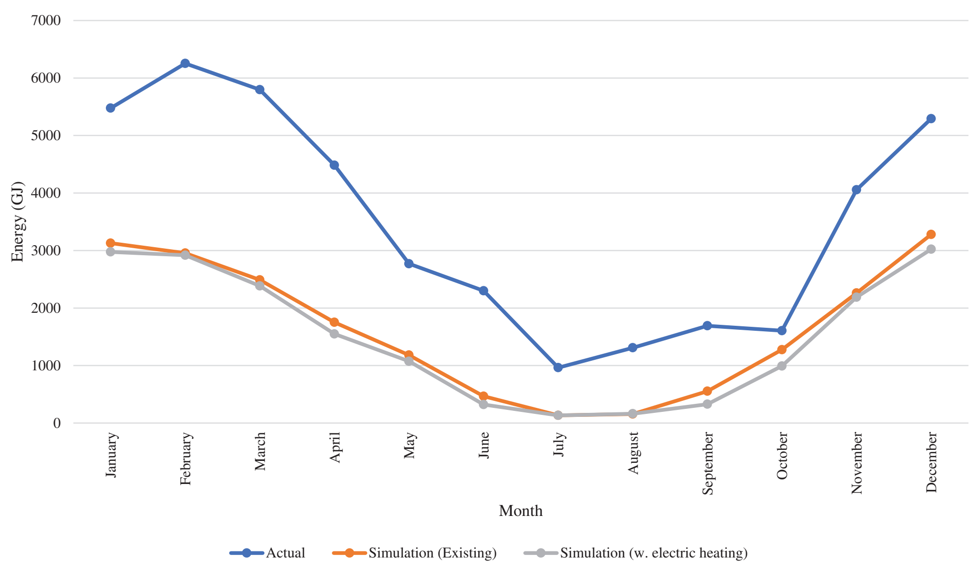


Fig. 13. Continued

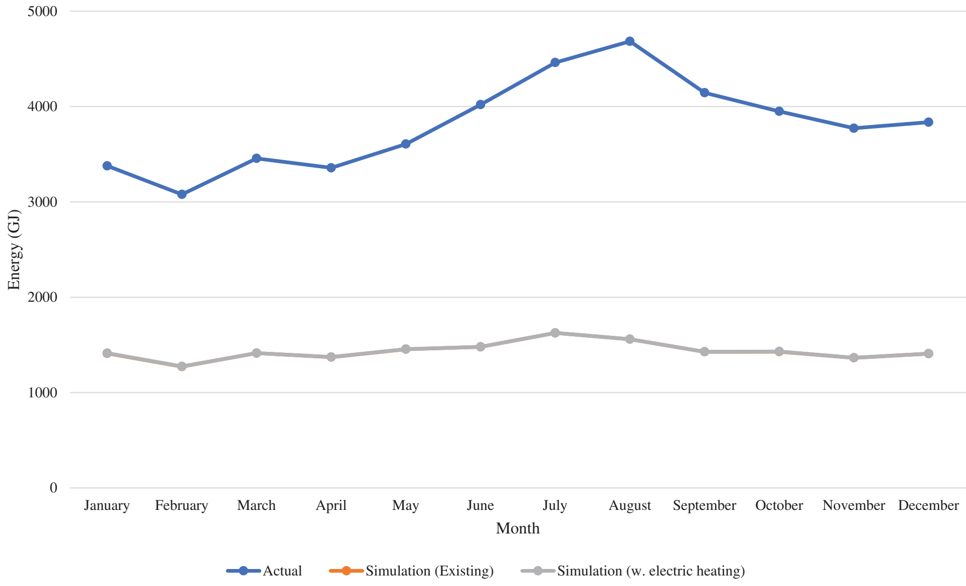


Fig. 13. Comparison of energy consumption for space heating (above) and electricity (below) for other end uses.

6. Conclusions

In this study, a comparative analysis was conducted between the existing space heating system at the CSF building and a proposed electric resistive space heating system using simulations in OpenStudio. The study suggests that, beyond the evident improvement in boiler efficiency, a further reduction in energy consumption, approximately 7%, can be achieved by transitioning to electric resistive heating. Simulated results also indicate that the building's energy consumption pattern closely aligns with actual consumption, although the calculated values are lower than the observed actual consumption. However, it is important to acknowledge that certain assumptions considered in the model development, which can deviate from the actual conditions, such as construction materials, building occupancy, infiltration and exfiltration, interconnected buildings, energy usage by equipment and lighting, HVAC system energy consumption, and transmission losses through piping, can significantly influence energy consumption for space heating and electricity. These unaccounted variables contribute to the higher actual energy consumption of the building. An extensive survey focused on gathering operational data for the building can provide the groundwork for refining both this building energy model and the simulation results.

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Conflict of Interests

The authors declare that they do not have any conflict of interest.

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