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Energy-Efficient Retrofitting Strategies for Research Laboratory Buildings: Case Study at the University of Utah.

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Abstract

This research study examined building performance and retrofitting strategies for reducing energy consumption in existing research laboratories. Research laboratory buildings are one of the most energy-intensive building typologies due to their high energy demands, complex building systems, and significant loads for mechanical cooling and ventilation. Retrofitting may extend buildings' lifespan and improve their performance, energy consumption, carbon footprint, and occupants' comfort. The study examined an existing research laboratory building at the University of Utah campus, utilizing a combination of research methods, such as archival and observational studies, field measurements, building envelope and HVAC systems assessment, and whole-building energy modeling and simulations. Actual energy consumption data was collected for three years and compared against simulated data. Five different retrofitting options were considered, where four options represented low-impact retrofits (improvements to the building envelope and interior lighting) and one option represented a deep-impact retrofit (improvements to the building envelope, interior lighting, and HVAC systems). These investigated retrofit options were simulated and compared to the building's actual and simulated energy consumption data. The results show that the deep-impact retrofit option would have the highest impact on energy use savings (more than 50% energy savings), while the four low-impact retrofit options would have lower, but comparable results (between 22% and 27% energy savings). Therefore, improvements to the mechanical systems are necessary to significantly reduce energy consumption and the associated carbon footprint of existing research laboratory buildings, besides building envelope and lighting improvements.

Keyword: energy efficiency, retrofits of existing buildings, energy performance, research laboratory buildings, simulations and modeling

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1. INTRODUCTION

Retrofitting existing buildings to improve their energy performance is one of the pressing global challenges since buildings account for more than 40% of global energy consumption. Fossil fuels account for more than 80% of existing buildings' energy consumption, thus significantly contributing to carbon emissions (United Nations, 2017). Rapid and energy-efficient retrofitting of existing buildings is crucial in reducing the energy consumption of the existing building stock to reduce associated carbon emissions. In the United States, 60% of buildings were constructed prior to the adoption of minimal energy performance benchmarks and codes in the 1970's (Laustsen, 2008). Recent research shows that energy use in existing buildings can be significantly reduced through proper retrofitting strategies and that retrofitting is one of the main approaches in realistically reducing a significant percentage of carbon emissions (Ma et al., 2012; Rabani et al., 2017).

Energy-efficiency retrofitting of existing buildings has many challenges and opportunities. The primary challenge is to select energy-efficient measures and strategies that can be implemented within the already existing infrastructure and building systems, and which are also economically feasible. Performance optimization in existing buildings is more complex as additional criteria must be considered, such as capabilities of the existing structural system, implementation of appropriate passive design strategies with existing constraints (building shape and form, building envelope design, daylight, ventilation, etc.), code requirements, potential integration of renewable energy systems, etc. Some additional challenges may include financial limitations and barriers, disruptions of ongoing building operations, and discovering unforeseen site or building conditions that may negatively affect project timelines and budgets. However, the environmental benefits of reusing existing buildings through retrofitting are significant since new building construction requires a higher quantity of resources and new materials, while retrofitted buildings conserve the embodied energy and carbon of the original structure (Aksamija, 2017). Implementing sustainable retrofitting strategies can offer additional benefits, such as improvement of building occupants' comfort and well-being.

It should be noted that energy-efficiency retrofits require improvements of building envelope and building systems to improve energy performance of existing buildings. Renovations that solely focus on improvements to spatial organization, interior design, and other design characteristics without considering building systems (heating, cooling, ventilation, lighting) and building envelope performance are not considered as energy-efficiency retrofits. Moreover, adaptive reuse is a specific type of renovation where the original building's function is modified and adapted for new usage (for example, changing industrial buildings into residential or commercial office buildings into multi-family residential), and may include energy-efficiency measures.

This study focuses on existing research laborabory buildings and examines building performance and retrofitting design strategies for improving energy efficiency. The most pronounced challenge in retrofitting research laboratory buildings is their high energy demand. This is associated with increased ventilation requirements, equipment loads and plug loads, compared to other building types. Another challenge is that not all research laboratory buildings have similar mechanical and operational needs, and retrofitting these types of buildings often requires a case-by-case approach (Milosevic and Aksamija, 2022). In higher-education academic institutions, laboratories may be intended primarily for instruction and low-hazard research and may not have been designed with more sophisticated and demanding mechanical systems associated with commercial and industrial research. Commercial laboratory spaces are highly dependent on the types of research activities and may require very specialized types of spaces (wet labs, clean rooms, vivaria, etc.) and research equipment. It is also necessary to consider the future direction of research and potential interdisciplinary or industrial collaborations the facility may undertake, where upgrading, upsizing, and increasing the mechanical systems' capacity is likely and must be considered. Additionally, due to current code requirements, any alterations may require intensive reconfiguration and resizing of interior spaces and improvements to circulation and egress.

A recent literature review of various research studies on energy-efficient retrofits of existing buildings indicates that the most discussed retrofit strategies include building envelope retrofits (improving thermal insulation), improvements of building and lighting systems, and integration of renewable energy sources (Citadini de Oliveira, 2024). Significant research exists on energy-efficient retrofits of residential buildings (Zhang et al. 2011; Dolsak, 2023; Williams et al. 2024; Amaripadathand Sailor, 2024; Beninca et al. 2023; Kadric et al., 2022; Lyu et al. 2025; Milosevic and Aksamija, 2024) and commercial buildings (Aksamija, 2016; Aksamija, 2017; Hong et al. 2023; Fernandes and Regnier, 2022; Lou et al. 2022; Gucyeter and Gunaydin, 2012). However, research on energy-efficient retrofits of research laboratory buildings is very limited. One study analyzed energy conservation knowledge, and attitudes and behaviors of building occupants in higher-education laboratory buildings (Kaplowitz et al. 2012). The study focused on one academic campus in the U.S. and found that the energy conservation measures depend on social systems and human behaviors. Only one study analyzed retrofitting strategies for an existing research laboratory building in a U.S.-based higher education institution, where actual energy consumption was considered, as well as the impacts of different retrofit design strategies through simulations and modeling (Milosevic and Aksamija, 2022). Another study analyzed energy efficient retrofit of two academic buildings in Italy through simulations and modeling, where one building included laboratory spaces in addition to classroom and office spaces (Sesana et al. 2016). One more study analyzed retrofits of historic buildings in a university campus in China through an urban energy model, where one of the investigated buildings included laboratory spaces and where actual energy consumption was considered in the research (Lin et al. 2023). Therefore, this study addresses an important research gap by focusing on an existing research laboratory building within a higher-education campus in the U.S.

2. METHODOLOGY

2.1 Research Questions and Methods

The aim of this research study was to investigate building performance and energy-efficient retrofit strategies for an existing research laboratory building, located at the University of Utah. The study focused on the following research questions:

• What is the current state of the building, including spatial and programmatic elements, building envelope, and building systems?

• How are different building systems operating and what is the current energy usage?

• How is the building currently performing in terms of energy usage?

• What types of energy-efficient retrofit design strategies (passive and active) can be implemented, and what is their impact on the building's performance?

Research methods included qualitative and quantitative research methods (archival research and observations, simulations and modeling, in-situ measurements, and comparisons between simulated and actual energy consumption data). The case study building was chosen due to the availability of construction documentation, the availability of metered energy consumption data, and the opportunity to install sensors and monitoring equipment within specific laboratory spaces.

The as-built set of construction documents was collected and analyzed, and used to construct a whole-building, 3D BIM model that captured the building's characteristics, geometry, and spatial organization. This 3D BIM model was also used to develop an energy model of the building for import into the IES VE software, where it was geometrically simplified and assigned information pertinent for the building performance analysis, including assignment of exterior and interior wall assemblies, spatial zoning and programming, and occupancies. Energy modeling was conducted, and simulation results were compared against actual energy usage data that was collected from 2020 to 2023. This process and information helped establish the existing state performance baseline and to determine discrepancies between simulated and actual energy usage. Several energy-efficient retrofit strategies were then identified, including four low-impact and one deep retrofit option. These five retrofit options were then simulated to determine impacts on the building performance and compared to the baseline.

Additionally, two laboratory spaces were chosen to install sensors and measurement equipment, where indoor environmental quality (IEQ) parameters (such as interior ambient temperature, indoor relative humidity, and carbon dioxide) were measured for a full year, from August 2023 to September 2024. The results of the IEQ analysis, as well as the potential impacts of retrofit strategies on the improvement of IEQ are discussed in another published study by authors (Milosevic et al., 2024). This paper focuses on energy performance analysis and the potential impacts of varying retrofit strategies on current building performance.

2.2 Overview of the Case Study Building

The investigated building, a Research Laboratory Building, was built in 1994. The building is in a cool and dry climate (Zone 4B). This 12,932 m^2 (139,200 ft^2) five-story building is located within the northeast part of the University of Utah campus, near the main hospital and other buildings associated with health sciences, as shown in Figure 1. The building supports medical and other types of research studies and serves three different Colleges.

The building has a long and narrow floor plan, with a central corridor and vertical circulation shafts placed at each end. The building's long sides face north-east and south-west orientations. A southwest-facing central atrium, located within the middle part of the building, provides additional vertical circulation and visual connection among different floors. In terms of programmatic elements, the building includes laboratory spaces, offices, testing areas and facilities, storage, and support spaces, as seen in Figure 2. This

Figure 1: Location of the Research Laboratory Building within health sciences at the University of Utah.

figure also indicates the locations of the two laboratory spaces where the monitoring and sensing equipment was installed to measure IEQ data. The larger monitored lab is located on the fourth level, while the smaller monitored lab is on the fifth level.

Since its construction in 1994, parts of the Research Laboratory Building have been updated and renovated to improve the spatial organization of certain areas of the building and the functioning of individual laboratory spaces, and to make small upgrades to the building systems. However, these were not full-building renovations, but rather targeted interventions for specific spaces.

The primary structural system is composed of reinforced concrete, where waffle slabs are utilized to maximize spans and minimize vibration. The solid building facades include several exterior wall types, including concrete with metal stud assembly, brick cavity wall with metal stud framing, and brick cavity wall with Concrete Masonry Unit (CMU) backup wall. Glazed facade systems include a curtain wall for the multi-story atrium space and a series of stripped and punched windows, all of which consist of clear, double, air-insulating glazing units (IGUs). Thermal properties of both the solid and glazed facade systems are listed in Table 1. The building's roof system consists of a concrete slab, insulation, and bitumen roofing membrane, and the building's typical floor slabs consist of a concrete slab, vinyl or tiled flooring, and a mix of either exposed or dropped ceilings with acoustic ceiling tiles. Thermal properties of the roof and floor assemblies are also listed in Table 1.

The building systems rely on district-supplied hot and chilled water for heating and cooling. The substation serving the northeast part of the University of Utah campus is located near the Biomedical Polymers Research Building and supplies this building with metered hot water and chilled water. Electricity is provided by three metered sources for the building's electricity needs (two grid-connected substations and one emergency generator), as well as one unmetered source used only for exterior lighting. Natural gas is also metered but it is only used for scientific purposes and experiments. Two metered water lines are also supplied, one for buildings' domestic water use and one for fire suppression. Two main heat exchangers are installed within the building, which supply hot water for its radiant heating system and multiple reheat coils. Six smaller heat exchangers are used for multiple preheat coils, domestic hot water, and industrial hot water. Five air-handling units are serving the building for its heating, cooling, and ventilation needs.

3. RESULTS

3.1 Actual Energy Consumption and Benchmarking

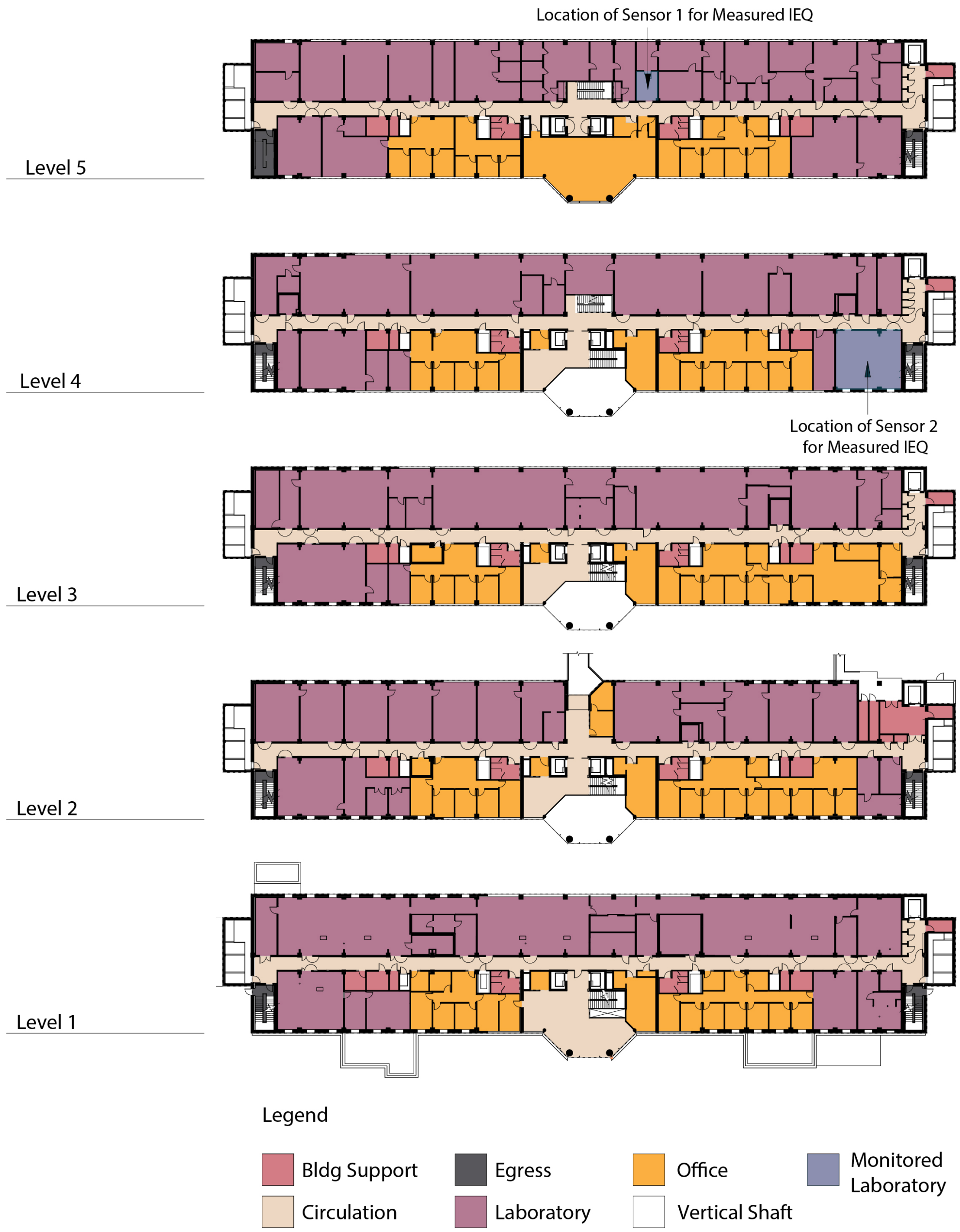

Figure 2: Floor plans of the Research Laboratory Building, indicating spatial organization, programming, circulation, and location of monitored lab spaces.

Building Enclosure System	System Description	Material Components	Overall R-value m²-°K/W (h-ft2-°F/ Btu)	Overall R-value ASHRAE Standard 90.1-2022 Minimum1 m²-°K/W (h-ft²-°F/Btu)	Overall Surface Area m² (ft²)
Exterior wall type 1	Concrete with metal stud framing	406 mm (16 in.) concrete; 76 mm (3 in.) metal stud framing with batt insulation within the cavity; 16 mm (5/8 in.) gypsum board interior finish	2.17 (12.3)	3.35 (19.0)	2,651 (28,539)
Exterior wall type 2	Brick cavity wall with metal stud framing	102 mm (4 in.) brick; 44 mm (1-3/4 in.) air cavity; 16 mm (5/8 in.) exterior sheathing; 76 mm (3 in.) metal stud framing with batt insulation within the cavity; 16 mm (5/8 in.) gypsum board interior finish	2.24 (12.7)	3.35 (19.0)	1,253 (13,483)
Exterior wall type 3	Brick cavity wall with CMU	102 mm (4 in.) brick; 44 mm (1-3/4 in.) air cavity; 152 mm (6 in.) CMU	1.20 (6.8)	2.01 (11.4)	989 (10,648)
Fenestration	Thermally broken, uncoated double air insulating IGU	6 mm (1/4 in.) clear glass; 13 mm (1/2 in.) air; 6 mm (1/4 in.) clear glass	0.51 (2.9) *Overall U-factor equivalent	0.49 (2.8)* *Overall U-factor equivalent maximum value	1,367 (14,717)
Roof	Concrete deck with insulation	Bitumen roofing membrane; 102 mm (4 in.) rigid insulation; 120 mm (4-3/4 in.) reinforced concrete slab	1.41 (8.0)	5.28 (30.0)	1,820 (19,585)
Intermediate Floors	Reinforced concrete with vinyl or tile flooring and recessed acoustic tile ceiling	10 mm (3/8 in.) flooring finish; 50 mm (2 in.) expanded polystyrene insulation; 120 mm (4-3/4 in.) reinforced concrete slab; recessed ceiling with 16 mm (5/8 in.) acoustic tile	2.01 (11.4)	2.57 (14.6)	7,322 (78,814)
Ground Floor	Reinforced concrete with vinyl or tile flooring	10 mm (3/8 in.) flooring finish; 50 mm (2 in.) expanded polystyrene insulation; 4 3/4 in. (0.12 m) 120 mm (4-3/4 in.) reinforced concrete slab; Waterproofing	1.57 (8.9)	2.64 (15.0)	2,334 (25,123)

Table 1: Thermal properties of the Biomedical Polymers Research Building's current building enclosure systems and performance benchmarks according to the ASHRAE Standard 90.1-2022 [25].

Energy consumption data was collected by the Facilities Department at the University of Utah and provided for the purposes of this study. As described previously, metered campus-supplied hot and chilled water is used for heating and cooling systems, while electricity is utilized for fans, lighting, equipment, plug loads, etc. Natural gas is also metered, but it is only used for scientific experiments, thus the overall use of gas is less than 0.1% of the overall energy consumption.

The actual monthly energy consumption data was collected for the period from January 2020 to September 2023. The data includes natural gas and electricity consumption, as well as hot and chilled water. However, sub-meters are not installed in the building, therefore granular metered data for electricity use (equipment, lighting, and plug loads) is not available. Table 2 summarizes source Energy Usage Intensity (EUI) for years 2020, 2021, and 2022 (2023 is not included since full-year data was not available at the time of the study). It should be noted that the energy consumption for the analyzed period has been decreasing, ranging from 523 kBtu/ft²/yr in 2020 to 463 kBtu/ft²/yr in 2022.

Year	Actual source EUI (kWh/m²/yr)	Actual source EUI (kBtu/ft²/yr)
2020	1,659	526
2021	1,615	512
2022	1,460	463

Table 2: Actual source EUI for three years from 2020 to 2022.

The national median source EUI for laboratory buildings is 1,003 kWh/m²/yr (318 kBtu/ft²/yr), calculated based on the reference buildings contained in the Commercial Buildings Energy Consumption Survey database (Environmental Protection Agency, 2023). However, the range varies widely, as indicated in Figure 3, which shows data for laboratory buildings contained in the Laboratory Benchmarking Tool (International Institute for Sustainable Laboratories, n.d.). This database includes almost 1,500 research laboratory buildings, of which more than half are higher-educations labs (628 out of 1446 buildings). The figure indicates the number of buildings that fall within specified EUI ranges, from 158 to 2,996 kWh/m²/yr (50 to 950 kBtu/ft²/yr). Most buildings (84%) utilize less than 1,577 kWh/m²/yr (500 kBtu/ft²/yr), but there are some laboratory buildings that have much higher energy consumption. The benchmarking tool does not identify specific buildings, their location, systems, but rather provides aggregated data for peer comparison. Higher energy consumption could be associated with higher energy demand, inefficient systems, building envelope, climatic factors, etc. Figure 3 also indicates the actual annual EUI for the Research Laboratory Building (years 2020, 2021, and 2023) in comparison to other laboratory buildings contained in the database. Figure 4 shows the Research Laboratory Building's EUI in comparison to laboratory buildings with district heating and cooling systems. Here, 76% of buildings utilize less than 1,577 kWh/m²/yr (500 kBtu/ft²/yr), while the remaining 24% of buildings fall within the 1,577 to 2,996 kWh/m²/yr (500 to 950 kBtu/ft²/yr) range. Therefore, the case study building is not a high-performing laboratory building, and there are opportunities for energy savings through energy-efficient retrofit measures.

3.2 Actual Monthly Normalized Energy Consumption

Figure 5 shows the actual monthly energy usage for the three years that the full-year data was collected (2020, 2021, and 2022). The prevailing energy usage is associated with district hot water use, utilized by the heating system and steam for laboratory use. As previously discussed, sub-metered data is not available, but climate data was analyzed to determine heating-degree days and cooling-degree days for this location. Heating loads would be present from January to May and September to December, thus the assumption is that the usage for other months is associated with laboratory equipment and not the heating systems.

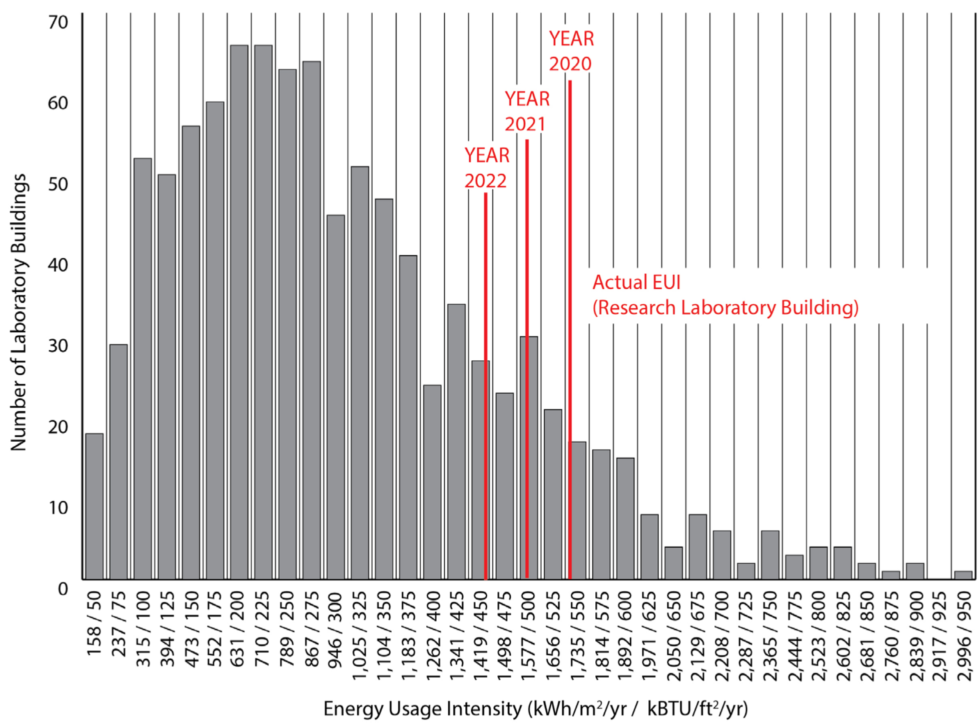

Figure 3: Comparison of actual EUI for the case study building to peer buildings contained in the Laboratory Benchmarking Tool (International Institute for Sustainable Laboratories, (n.d.)).

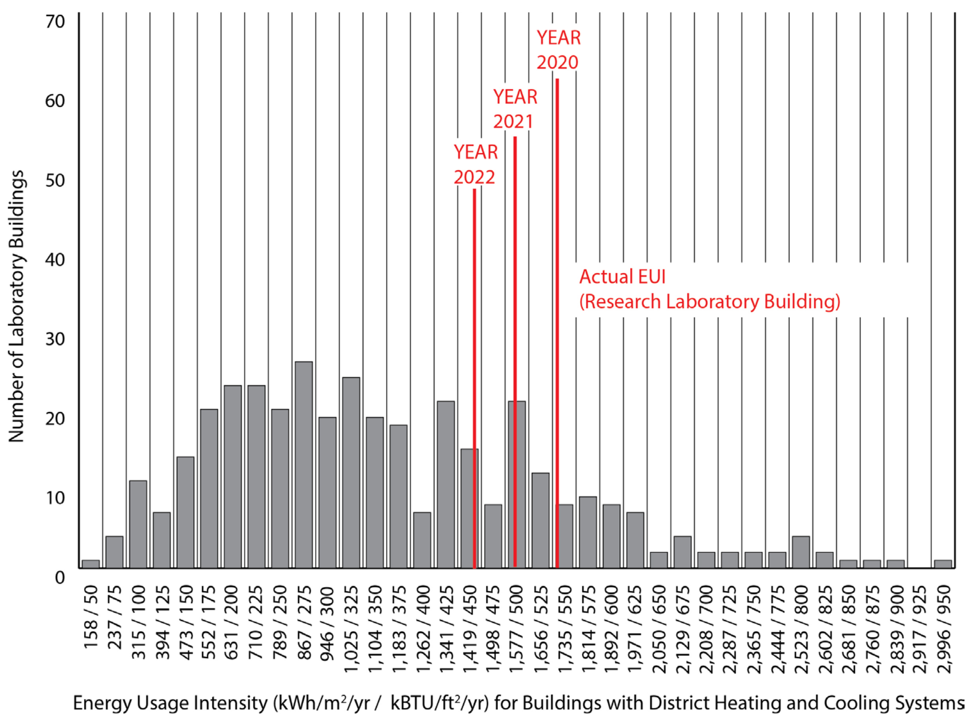

Figure 4: Comparison of actual EUI for the case study building to peer buildings that rely on district heating and cooling.

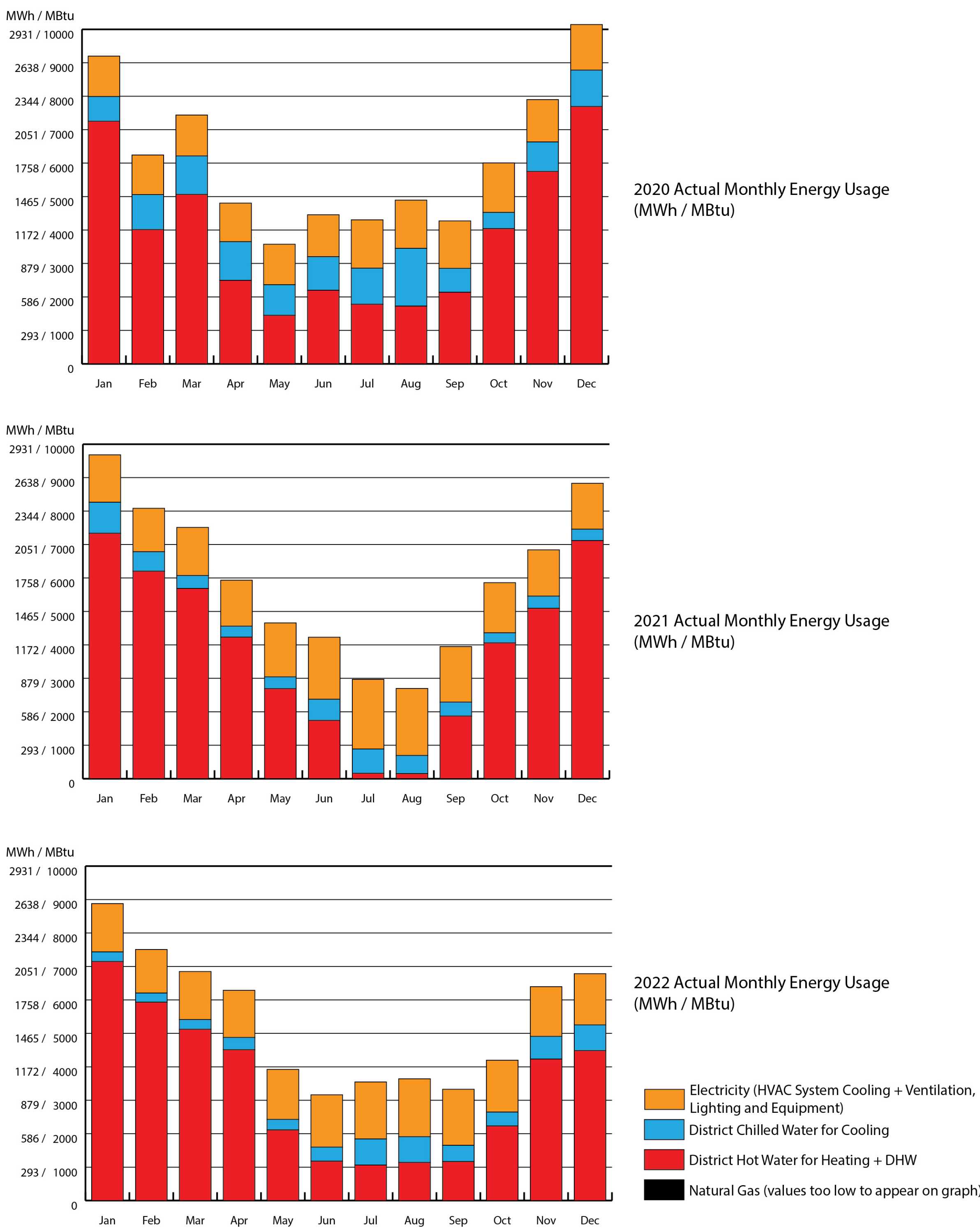

Figure 5: Actual monthly energy usage for the case study building (years 2020-2023).

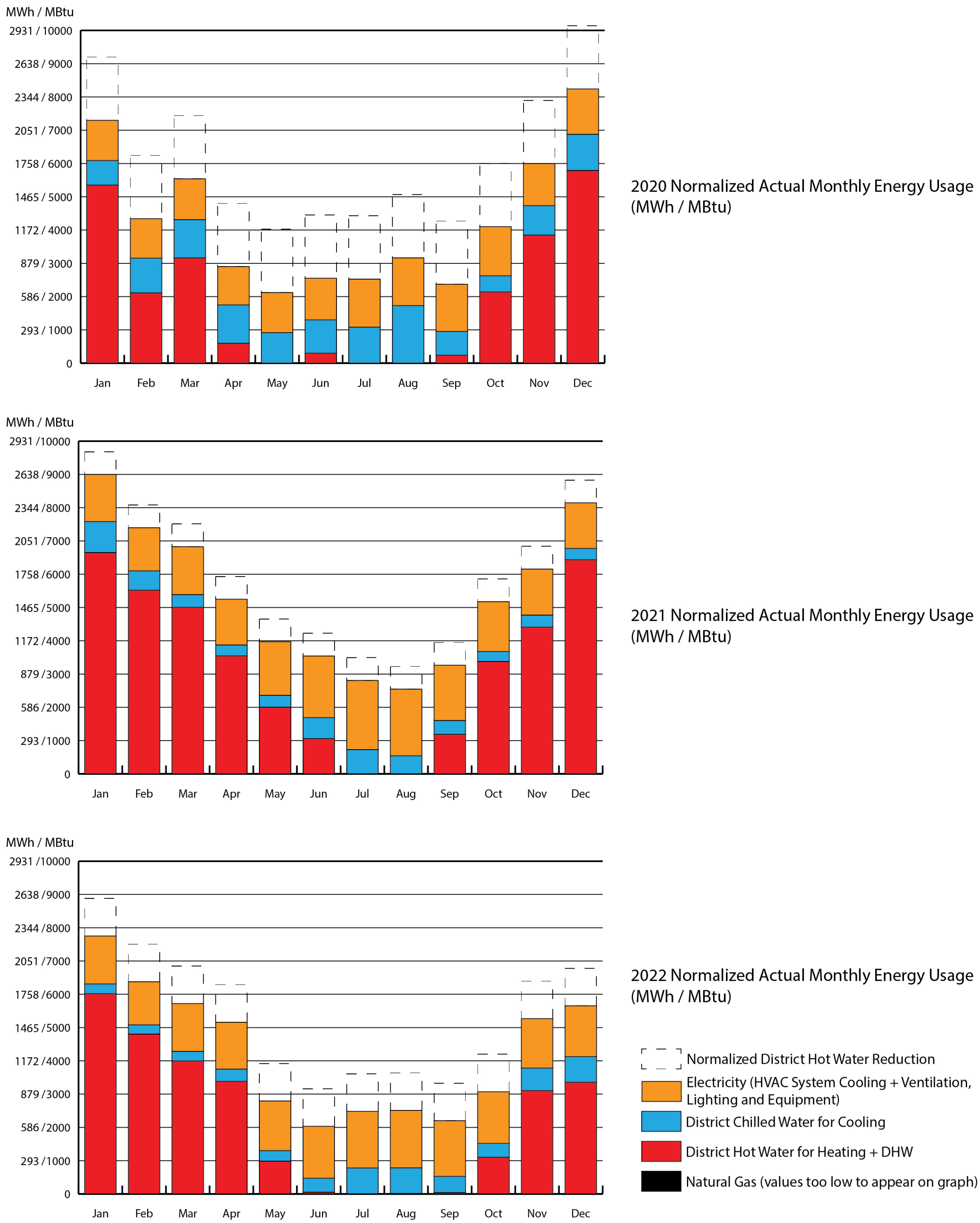

Figure 6: Normalized monthly energy usage for the case study building (years 2020-2023).

Average district hot water usage for the summer months (June, July, and August) of each year was normalized as the typical monthly hot water usage. Then, these values were subtracted from all the months in each year to separate the district hot water distribution between functions of hot water use and heating. Figure 6 illustrates the normalized energy usage for the case study building for each of the four years. Table 3 presents the normalized EUIs for the years 2020, 2021 and 2022.

Figure 7 shows the average normalized monthly energy consumption data for the three full years, which was used for further investigation of energy-efficient retrofit design strategies, and comparison between simulated and actual energy usage data. Electricity usage is the second highest contributor to the building's energy consumption, and it is relatively constant throughout the year (utilized for artificial lighting, fans, plug loads, and other types of electrical equipment), with slight increases in the summer months, most likely due to higher loads associated with fans and ventilation equipment. Surprisingly, energy usage associated with cooling for the Research Laboratory Building is the least contributing factor to its overall energy consumption, which is atypical for laboratory buildings since these types of buildings are internally load-dominated and tend to have high cooling loads. Therefore, specific retrofit strategies for research laboratory buildings must be investigated on a case-by-case basis, since original design strategies, spatial organization, building systems, and actual performance vary greatly between different buildings and climates.

Year	Normalized source EUI (kWh/m²/yr)	Normalized source EUI (kBtu/ft²/yr)
2020	1,156	367
2021	1,451	460
2022	1,154	366
3-year average (normalized)	1,255	398

Table 3: Normalized source EUI for three years from 2020 to 2022 and 3-year average.

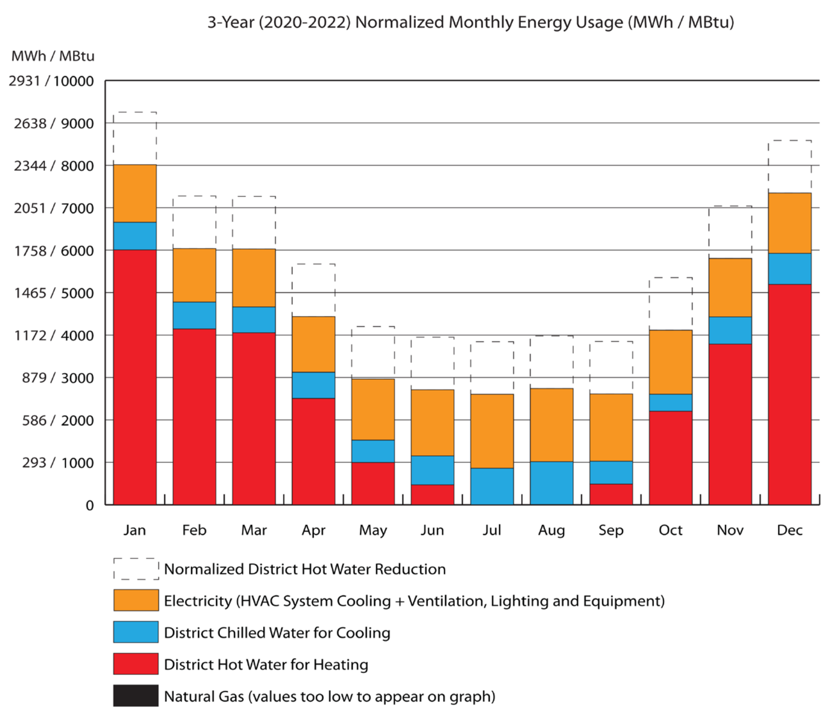

Figure 7: Average 3-year normalized actual monthly energy usage data for the case study building.

3.3 Simulated vs. Actual Energy Consumption

Whole building energy simulations were performed in the IES VE software program, where the first set of simulations represented the current building, its characteristics, building systems, materials, occupancy schedule, etc. The climate data file considered 10-year average weather data. Figure 8 shows simulated results for monthly energy usage. Comparison to actual energy consumption data indicated that electricity loads are comparable, while the monthly heating and cooling loads are not. Simulated results indicated much higher cooling loads during the summer months (June, July, August, and September) than the actual loads. This could be associated with the building not being heavily utilized during the summer since faculty and students are typically on summer break. Moreover, actual heating loads during winter, spring, and fall are much higher than the simulated results, which could be attributed to the building being primarily used according to the 9-month academic calendar. Actual heating loads are much higher than simulated for the months of January to April, as well as October to December. However, Table 4 shows a comparison of EUI values (simulated vs. actual), as well as a comparison to the national median. The simulated EUI is smaller than the normalized actual EUI, averaged over the three years of collected data. Further simulations investigated the impacts of five energy-efficient retrofit options, considering improvements to the building enclosure, lighting systems, and HVAC systems.

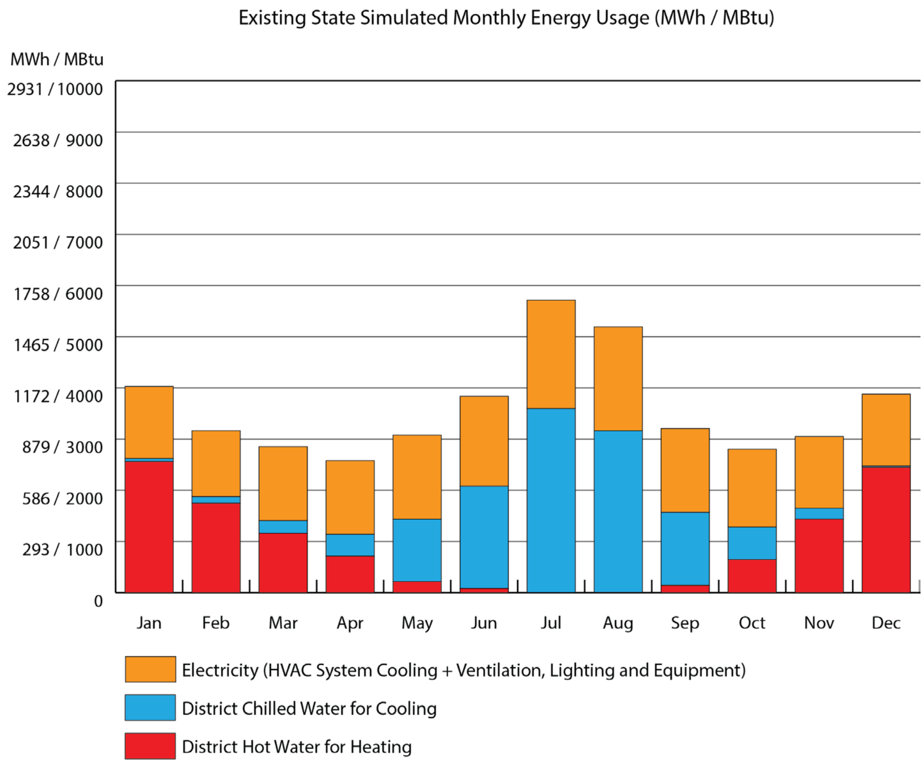

Figure 8: Simulated monthly energy usage for the existing state case study building (considering 10-year average climate data).

Years	Source EUI (kWh/m²/yr)	Source EUI (kBtu/ft²/yr)
10-year climate data average (simulated)	1,069	339
Typical year (simulated)	1,195	379
3-year (2020-2022) normalized average (actual)	1,255	398
U.S. National Median	1,003	318

Table 4: Comparison of simulated vs actual source EUI, and the U.S. national median.

3.4 Impacts of Retrofit Design Strategies on Building Performance

Five different retrofit options were considered, four representing low-impact retrofit design strategies (improvements to the building envelope and interior lighting) and one representing deep-impact retrofit design strategies (improvements to the building envelope, interior lighting, and mechanical systems) as follows:

- Low Impact Retrofit Option 1: Rainscreen facade with double, low-e Insulated Glazing Unit (IGU), and reduced Lighting Power Density (LPD)

- Low Impact Retrofit Option 2: Rainscreen facade with triple, low-e IGU, and reduced LPD

- Low Impact Retrofit Option 3: Exterior Insulation and Finish System (EIFS) facade with double, low-e IGU, and reduced LPD

- Low Impact Retrofit Option 4: EIFS facade with triple, low-e IGU, and reduced LPD and

- Deep Impact Retrofit Option 5: EIFS facade with triple, low-e IGU, reduced LPD, and geo-exchange heating/cooling.

Figure 9 shows the existing exterior walls, as well as retrofit options for exterior wall assemblies. Baseline simulations considered current building characteristics, with the properties of exterior wall systems and roofing listed in Table 1, district-supplied hot and chilled water used for heating, DHW, and cooling, LPD values as listed in Table 5 (based on the ASHRAE Standard 90.1-2022). Table 5 also lists reduced LPD values considered for all retrofit options. Tables 6 to 10 summarize inputs for building enclosure and building systems considered for the different retrofit options.

Results indicate that the deep retrofit design option would have the largest impact on reducing energy consumption, as seen in Table 11. This option would reduce more than half of the building’s energy consumption (compared to either simulated baseline or actual EUI). In terms of low-impact design options, option 4 would have the highest impact on energy savings (around 27% compared to the actual EUI). Comparing all low-impact design options, variations in energy improvements are relatively small between the four options, ranging from around 22% for option 1 (lowest energy savings), 24% for option 3, 26% for option 2, and 27% for option 4. Therefore, significant energy savings cannot be achieved without improving mechanical systems. Improvements to the building envelope and lighting system reduce energy consumption, but retrofitting existing mechanical systems significantly improves the building's performanceResults indicate that the deep retrofit design option would have the largest impact on reducing energy consumption, as seen in Table 11. This option would reduce more than half of the building’s energy consumption (compared to either simulated baseline or actual EUI). In terms of low-impact design options, option 4 would have the highest impact on energy savings (around 27% compared to the actual EUI). Comparing all low-impact design options, variations in energy improvements are relatively small between the four options, ranging from around 22% for option 1 (lowest energy savings), 24% for option 3, 26% for option 2, and 27% for option 4. Therefore, significant energy savings cannot be achieved without improving mechanical systems. Improvements to the building envelope and lighting system reduce energy consumption, but retrofitting existing mechanical systems significantly improves the building's performance.

Figure 10 compares the simulated monthly energy usage breakdown for the baseline model, as well as different retrofit design options. It is evident that improvements to the lighting system and reduction in LPD reduce electricity consumption. The electricity portion of the graphs shows loads for the lighting system, equipment loads, fans, and pumps. Detailed data showed slight variations for these other types of loads besides the lighting system for different retrofit options. However, an improved lighting system would have the largest impact on the reduction of electricity. In terms of heating and cooling loads, there are very slight variations among the different low impact retrofit options but comparing the results to the baseline indicates reductions for monthly heating and cooling loads. The deep retrofit option would result in significant reductions for heating and cooling loads, as well as smaller reductions in electricity loads. Therefore, the deep retrofit option is the best strategy for improving the energy efficiency of this existing research laboratory building.

Figure 11 shows carbon dioxide emissions associatd with the baseline model and different retrofit design options, indicating calculated emissions associated with the operation of building systems, interior lighting, and equipment. It is evident that the deep retrofit option would significantly reduce carbon emissions associated with building operations. Moreover, building systems are the largest contributor to carbon emissions, while lighting systems and equipment are smaller contributors. Low impact retrofit strategies would reduce operational carbon emissions but deep retrofit with improved mechanical systems would be the best option for significantly reducing operational carbon emissions.

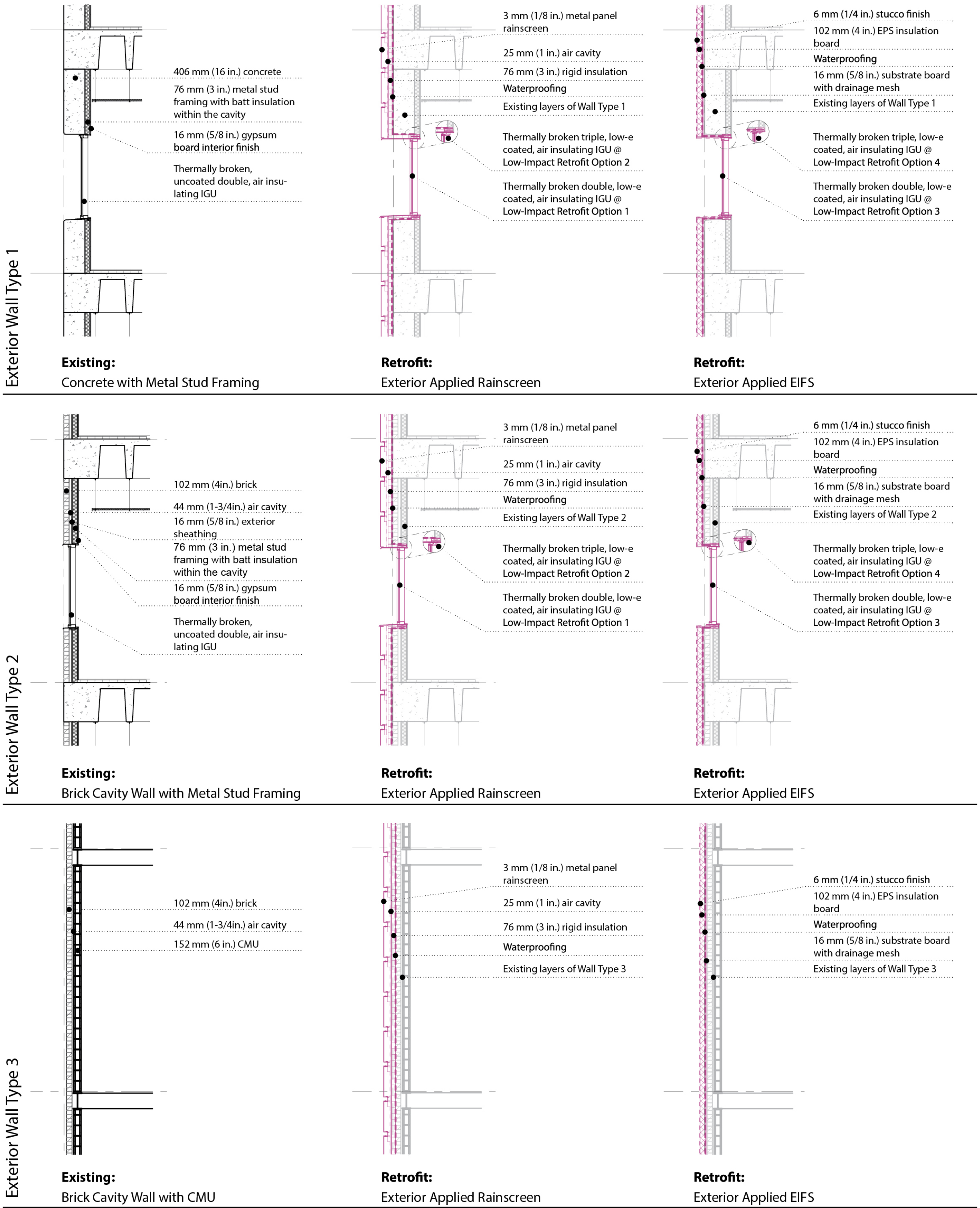

Figure 9: Sections of existing exterior walls and considered retrofit options for all simulations.

Space type	Baseline LPD W/m² (W/ft²)	Retrofit LPD W/m² (W/ft²)	Operation Profile
Circulation	8.61 (0.80)	4.74 (0.44)	On Continuously
Lobby	8.61 (0.80)	6.89 (0.64)	On Continuously
Atrium	6.46 (0.60)	5.49 (0.51)	On Continuously
Laboratory	15.07 (1.40)	11.30 (1.05)	ASHRAE 8am-6pm
Office	15.07 (1.40)	6.03 (0.56)	ASHRAE 8am-6pm
Restrooms	9.69 (0.90)	7.97 (0.74)	On Continuously
Active storage	8.61 (0.80)	3.77 (0.35)	ASHRAE 8am-6pm
Inactive storage	3.23 (0.30)	3.23 (0.30)	ASHRAE 8am-6pm
Electrical/mechanical space	16.15 (1.50)	7.64 (0.71)	ASHRAE 8am-6pm
Stairs	6.46 (0.60)	5.06 (0.47)	On Continuously

Table 5: Interior Lighting Power Density (LPD) values for the baseline and retrofit design options of the Research Laboratory Building.

System	Description	Material components and systems	Overall R value m²-°K/W (h-ft²-°F/Btu)
Rainscreen	Exterior applied rainscreen over Exterior wall 1	3 mm (1/8 in.) metal panel rain-screen; 25 mm (1 in.) air cavity; 76 mm (3 in.) rigid insulation; waterproofing; existing layers of Exterior wall 1	3.33 (18.9)
Rainscreen	Exterior applied rainscreen over Exterior wall 2	3 mm (1/8 in.) metal panel rain-screen; 25 mm (1 in.) air cavity; 76 mm (3 in.) rigid insulation; waterproofing; existing layers of Exterior wall 2	3.86 (21.9)
Rainscreen	Exterior applied rainscreen over Exterior wall 3	3 mm (1/8 in.) metal panel rain-screen; 25 mm (1 in.) air cavity; 76 mm (3 in.) rigid insulation; waterproofing; existing layers of Exterior wall 3	2.97 (16.9)
Fenestration	Thermally broken, double, low-e air IGU	6 mm (1/4 in.) clear glass with low-e coating on surface #2; 13 mm (1/2 in.) air; 6 mm (1/4 in.) clear glass	0.74 (4.2)
Roof	Concrete deck with improved insulation	Waterproofing; 50mm (2 in.) lightweight concrete; 102 mm (4 in.) dense EPS slab insula-tion; existing 120 mm (4-3/4 in.) reinforced concrete slab	4.26 (24.2)
Ground Floor	Reinforced concrete with insula-tion and new flooring tile	Waterproofing; existing 120 mm (4-3/4 in.) reinforced concrete slab; 102 mm (4 in.) dense EPS slab insulation; 13 mm (1/2 in.) flooring substrate and tile	4.17 (23.7)
HVAC System	Existing heating, cooling, and ventilation system	District-supplied hot and chilled water for heating, DHW, and cooling	/

Table 6: Simulation inputs for building enclosure and HVAC systems (Low-Impact Retrofit Option 1).

System	Description	Material components and systems	Overall R value m²-°K/W (h-ft²-°F/Btu)
Rainscreen	Exterior applied rainscreen over Exterior wall 1	3 mm (1/8 in.) metal panel rain-screen; 25 mm (1 in.) air cavity; 76 mm (3 in.) rigid insulation; waterproofing; existing layers of Exterior wall 1	3.33 (18.9)
Rainscreen	Exterior applied rainscreen over Exterior wall 2	3 mm (1/8 in.) metal panel rain-screen; 25 mm (1 in.) air cavity; 76 mm (3 in.) rigid insulation; waterproofing; existing layers of Exterior wall 2	3.86 (21.9)
Rainscreen	Exterior applied rainscreen over Exterior wall 3	3 mm (1/8 in.) metal panel rain-screen; 25 mm (1 in.) air cavity; 76 mm (3 in.) rigid insulation; waterproofing; existing layers of Exterior wall 3	2.97 (16.9)
Fenestration	Thermally broken, triple, low-e air IGU	6 mm (1/4 in.) clear glass with low-e coating on surface #2; 13 mm (1/2 in.) air; 6 mm (1/4 in.) clear glass with low-e coating on surface #4; 13 mm (1/2 in.) air; 6 mm (1/4 in.) clear glass	1.27 (7.2)
Roof	Concrete deck with improved insulation	Waterproofing; 50mm (2 in.) lightweight concrete; 102 mm (4 in.) dense EPS slab insula-tion; existing 120 mm (4-3/4 in.) reinforced concrete slab	4.26 (24.2)
Ground Floor	Reinforced concrete with insula-tion and new flooring tile	Waterproofing; existing 120 mm (4-3/4 in.) reinforced concrete slab; 102 mm (4 in.) dense EPS slab insulation; 13 mm (1/2 in.) flooring substrate and tile	4.17 (23.7)
HVAC System	Existing heating, cooling, and ventilation system	District-supplied hot and chilled water for heating, DHW, and cooling	/

Table 7: Simulation inputs for building enclosure and HVAC systems (Low-Impact Retrofit Option 2).

System	Description	Material components and systems	Overall R value m²-°K/W (h-ft²-°F/Btu)
EIFS	Exterior applied EIFS over Exterior wall 1	6 mm (1/4 in.) stucco finish;102 mm (4 in.) EPS insulation board; waterproofing; 16 mm (5/8 in.) substrate board with drainage mesh; existing layers of Exterior wall 1	5.60 (31.8)
EIFS	Exterior applied EIFS over Exterior wall 2	6 mm (1/4 in.) stucco finish; 102 mm (4 in.) EPS insulation board; waterproofing; 16 mm (5/8 in.) substrate board with drainage mesh; existing layers of Exterior wall 2	6.13 (34.8)
EIFS	Exterior applied EIFS over Exterior wall 3	6 mm (1/4 in.) stucco finish; 102 mm (4 in.) EPS insulation board; waterproofing; 16 mm (5/8 in.) substrate board with drainage mesh; existing layers of Exterior wall 3	5.25 (29.8)
Fenestration	Thermally broken, double, low-e air IGU	6 mm (1/4 in.) clear glass with low-e coating on surface #2; 13 mm (1/2 in.) air; 6 mm (1/4 in.) clear glass	0.74 (4.2)
Roof	Concrete deck with improved insulation	Waterproofing; 50mm (2 in.) lightweight concrete; 102 mm (4 in.) dense EPS slab insulation; existing 120 mm (4-3/4 in.) reinforced concrete slab	4.26 (24.2)
Ground Floor	Reinforced concrete with insulation and new flooring tile	Waterproofing; existing 120 mm (4-3/4 in.) reinforced concrete slab; 102 mm (4 in.) dense EPS slab insulation; 13 mm (1/2 in.) flooring substrate and tile	4.17 (23.7)
HVAC System	Existing heating, cooling, and ventilation system	District-supplied hot and chilled water for heating, DHW, and cooling	/

Table 8: Simulation inputs for building enclosure and HVAC systems (Low-Impact Retrofit Option 3).

System	Description	Material components and systems	Overall R value m²-°K/W (h-ft²-°F/Btu)
EIFS	Exterior applied EIFS over Exterior wall 1	6 mm (1/4 in.) stucco finish;102 mm (4 in.) EPS insulation board; waterproofing; 16 mm (5/8 in.) substrate board with drainage mesh; existing layers of Exterior wall 1	5.60 (31.8)
EIFS	Exterior applied EIFS over Exterior wall 2	6 mm (1/4 in.) stucco finish;102 mm (4 in.) EPS insulation board; waterproofing; 16 mm (5/8 in.) substrate board with drainage mesh; existing layers of Exterior wall 2	6.13 (34.8)
EIFS	Exterior applied EIFS over Exterior wall 3	6 mm (1/4 in.) stucco finish; 102 mm (4 in.) EPS insulation board; waterproofing; 16 mm (5/8 in.) substrate board with drainage mesh;existing layers of Exterior wall 3	5.25 (29.8)
Fenestration	Thermally broken, triple, low-e air IGU	6 mm (1/4 in.) clear glass with low-e coating on surface #2; 13 mm (1/2 in.) air; 6 mm (1/4 in.) clear glass with low-e coating on surface #4; 13 mm (1/2 in.) air; 6 mm (1/4 in.) clear glass	1.27 (7.2)
Roof	Concrete deck with improved insulation	Waterproofing; 50mm (2 in.) lightweight concrete; 102 mm (4 in.) dense EPS slab insulation; existing 120 mm (4-3/4 in.) reinforced concrete slab	4.26 (24.2)
Ground Floor	Reinforced concrete with insulation and new flooring tile	Waterproofing; existing 120 mm (4-3/4 in.) reinforced concrete slab; 102 mm (4 in.) dense EPS slab insulation; 13 mm (1/2 in.) flooring substrate and tile	4.17 (23.7)
HVAC System	Existing heating, cooling, and ventilation system	District-supplied hot and chilled water for heating, DHW, and cooling	/

Table 9: Simulation inputs for building enclosure and HVAC systems (Low-Impact Retrofit Option 4).

System	Description	Material components and systems	Overall R value m²-°K/W (h-ft²-°F/Btu)
EIFS	Exterior applied EIFS over Exterior wall 1	6 mm (1/4 in.) stucco finish; 102 mm (4 in.) EPS insulation board; waterproofing; 16 mm (5/8 in.) substrate board with drainage mesh;existing layers of Exterior wall 1	5.60 (31.8)
EIFS	Exterior applied EIFS over Exterior wall 2	6 mm (1/4 in.) stucco finish; 102 mm (4 in.) EPS insulation board; waterproofing; 16 mm (5/8 in.) substrate board with drainage mesh; existing layers of Exterior wall 2	6.13 (34.8)
EIFS	Exterior applied EIFS over Exterior wall 3	6 mm (1/4 in.) stucco finish; 102 mm (4 in.) EPS insulation board; waterproofing; 16 mm (5/8 in.) substrate board with drainage mesh; existing layers of Exterior wall 3	5.25 (29.8)
Fenestration	Thermally broken, triple, low-e air IGU	6 mm (1/4 in.) clear glass with low-e coating on surface #2; 13 mm (1/2 in.) air; 6 mm (1/4 in.) clear glass with low-e coating on surface #4; 13 mm (1/2 in.) air; 6 mm (1/4 in.) clear glass	1.27 (7.2)
Roof	Concrete deck with improved insulation	Waterproofing; 50mm (2 in.) lightweight concrete; 102 mm (4 in.) dense EPS slab insulation; existing 120 mm (4-3/4 in.) reinforced concrete slab	4.26 (24.2)
Ground Floor	Reinforced concrete with insulation and new flooring tile	Waterproofing; existing 120 mm (4-3/4 in.) reinforced concrete slab; 102 mm (4 in.) dense EPS slab insulation; 13 mm (1/2 in.) flooring substrate and tile	4.17 (23.7)
HVAC System	Geo-exchange heating and cooling system with mechanical ventilation	Geo-exchange heating and cooling with central outside air ventilation, supplementary solar heating system for DHW.	/

Table 10: Simulation inputs for building enclosure and HVAC systems (Deep-Impact Retrofit Option 5).

	Source EUI kWh/m²/yr (kBtu/ft²/yr)	Improvement percentage (%) compared to the existing state (simulated)	Improvement percentage (%) compared to the existing state (actual)
Baseline: Typical year (simulated)	1,195 (379)	/	5.0
Baseline: 3-year (2020-2022) normalized average (actual)	1,255 (398)	-5.0	/
Low Impact 1: Insulated rainscreen with double, low-e air IGU, and reduced LPD	975 (309)	18.5	22.4
Low Impact 2: Insulated rainscreen with triple, low-e air IGU, and reduced LPD	934 (296)	21.9	25.6
Low Impact 3: EIFS with double, low-e air IGU, and reduced LPD	952 (302)	20.3	24.1

Table 11: Summary results showing impacts of different retrofit design options on EUI.

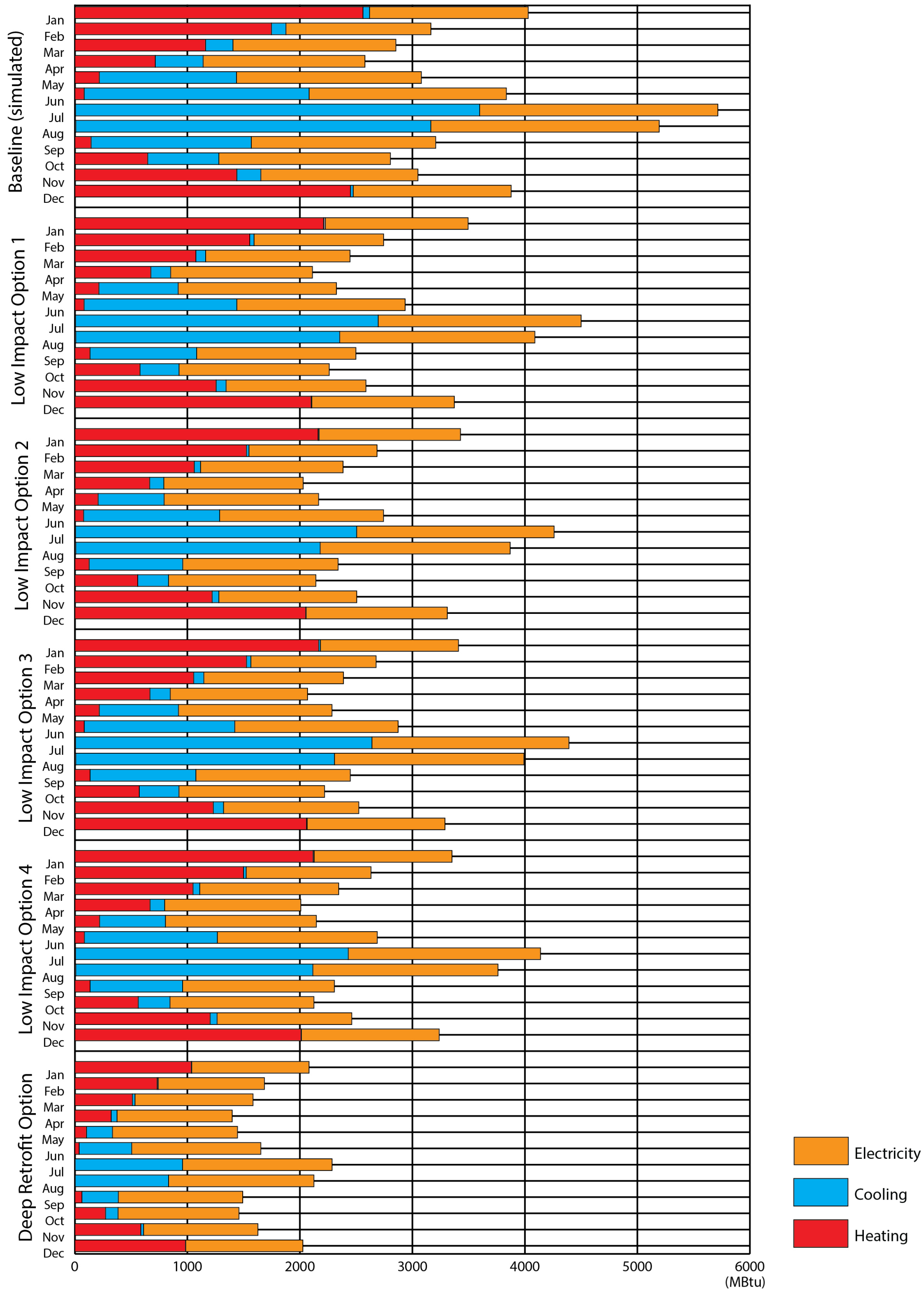

Figure 10: Simulated monthly energy usage for the baseline and different retrofit options.

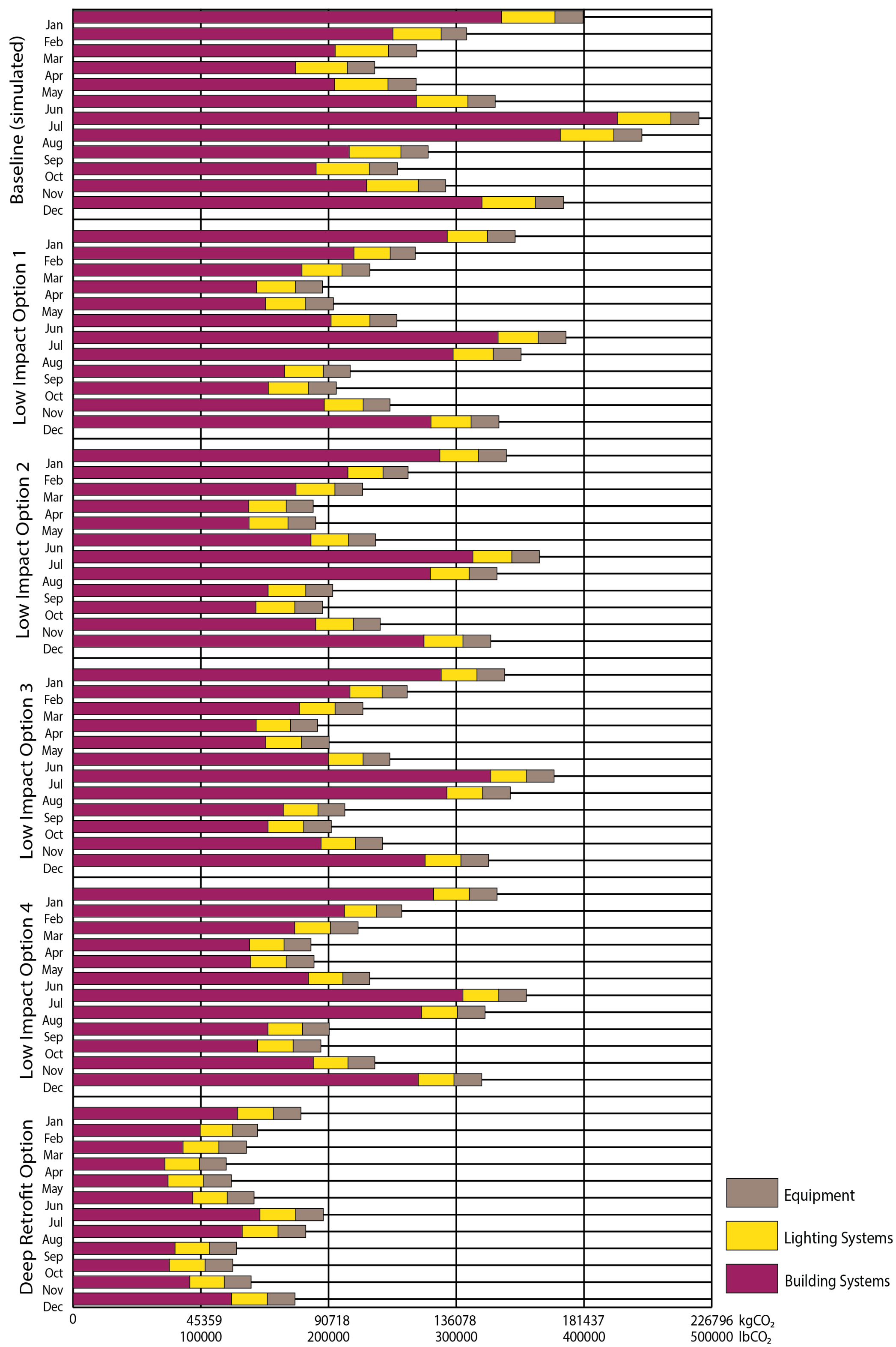

Figure 11: Calculated operational monthly carbon dioxide emissions for the baseline and different retrofit options (associated with building systems, lighting, and equipment).

4. CONCLUSIONS

This research study investigated building performance and energy-efficient retrofit strategies for an existing research laboratory building at the University of Utah. The study first analyzed the current characteristics of this building, including spatial and programmatic elements, building envelope, and building systems, as well as current energy usage. Then, the study considered five different retrofit options, where four options would entail low-impact retrofits (improvements to the building envelope and the interior lighting system), and one option would entail deep retrofits (improvements to the building envelope, interior lighting system, and mechanical systems). The research methodology included qualitative and quantitative methods, including archival research and observations, simulations and modeling, in-situ measurements of indoor environmental quality (reported in other publications), and comparisons between simulated and actual energy consumption data. Simulations were utilized to quantify the impacts of different retrofit options.

Research results showed that the low impact retrofit strategies would improve the energy efficiency of this existing building (between 22 and 27% compared to the actual energy consumption data). Meanwhile, the deep retrofit option would save 54% of energy. The results also indicate that deep retrofit would significantly reduce operational carbon emissions. Therefore, improvements to the mechanical systems, besides building envelope and lighting, are necessary to maximize energy savings of existing research laboratory buildings and reduce their carbon footprint. The study did not consider detailed financial and cost implications of different retrofit options. Future research will capture these aspects. However, it must be noted that low impact retrofit strategies are less costly than deep retrofits. Moreover, existing higher education buildings in the U.S. typically utilize centrally- or district-supplied hot and chilled water for heating and cooling systems, and deep-impact retrofits may consider decoupling existing buildings from the central infrastructure and installing new, energy-efficient building-scale systems. Higher education institutions that are developing decarbonization plans, aiming to eliminate reliance on fossil fuels and reduce carbon emissions, must consider methods for improving energy efficiency of existing buildings, as well as infrastructure developments, utilization of renewable energy sources, and planning strategies that are balancing district-wide supply vs. building-scale building systems. This research study is particularly useful for understanding the performance of existing research laboratory buildings, as one of the most energy-intensive building types, and the impacts of energy-efficient retrofit strategies on building performance.

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