

Article

Not peer-reviewed version

Analysis of Energy Efficiency Opportunities for a Public Transportation Maintenance Facility—A Case Study

Jordan Higgins , [Aditya Ramnarayan](#) , Roxana Family , [MICHAEL M OHADI](#) *

Posted Date: 8 March 2024

doi: 10.20944/preprints202403.0496.v1

Keywords: Energy Audit; Energy Modeling; Energy Efficiency; Transportation Maintenance Facility



Preprints.org is a free multidiscipline platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This is an open access article distributed under the Creative Commons Attribution License which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Article

Analysis of Energy Efficiency Opportunities for a Public Transportation Maintenance Facility—A Case Study

Jordan Higgins ¹, Aditya Ramnarayan ¹, Roxana Family ² and Michael Ohadi ^{1,*}

¹ University of Maryland College Park, Center for Environmental Energy Engineering, Smart and Small Thermal Systems Laboratory, 8228 Paint Branch Drive, College Park, MD 20742, USA

² University of Pennsylvania, Department of Materials Engineering, Philadelphia, PA, USA

* Correspondence: ohadi@umd.edu

Abstract: A comprehensive Energy Audit of a Maintenance facility was performed to assess its energy performance and identify scope for improvement. The facility's Energy Use Intensity (EUI) for 2022 was 404 kWh/m² — more than double the Benchmark EUI for Maintenance facilities (151 kWh/m²) recommended by EnergyStar. Furthermore, the Load Factor for 2022 was 0.22, which is lower than the recommended minimum of 0.75 for an efficient building. The audit encompassed an in-depth evaluation of the building's structural and operational characteristics, comprising HVAC systems, lighting, building envelope, and energy-intensive machinery. An energy model of the building was developed to emulate the baseline building energy performance for 2022. Following the energy model's development and validation, an analysis was conducted to identify energy-intensive areas and opportunities for optimization. Energy Efficiency Measures were then formulated, focusing on improving energy efficiency while focusing on energy consumption reduction and GHG emission reduction. Results demonstrated the potential of Energy Audits and Modeling to enable significant reductions in energy consumption and promote sustainable building practices. Among the Energy Efficiency Measures considered, re-sizing and decarbonization of HVAC equipment had the greatest contribution to energy savings, with a 100% decrease in natural gas and 37% decrease in electricity use annually.

Keywords: energy audit; energy modeling; energy efficiency; Transportation Maintenance Facility

1. Introduction

In 2022, U.S. energy consumption peaked at 105 EJ, resulting in a substantial 4.7 Gigatonnes CO₂ of greenhouse gas emissions [1]. In light of the climate change caused by these emissions, the U.S. Department of Energy [2] anticipates the necessity for advanced technologies to facilitate a transition to clean energy by 2050, given projected increases in both population and business activities. The importance of reducing these emissions has also reignited interest in energy efficiency [3], in that alongside advanced technologies, enhanced energy efficiency will also be required to achieve emissions targets.

The building sector consumes nearly 30% of U.S. energy [4]. Buildings are major contributors to energy consumption and greenhouse gas emissions, making their energy efficiency a vital aspect of any sustainability initiative [5]. In response to the energy and climate crisis, Maryland State Governor Wes Moore signed an executive order requiring state-owned facilities to reduce their energy consumption by 20% by 2031 [6]. Furthermore, the Building Energy Performance Standards (BEPS) required by the Maryland Climate Solutions Now Act of 2022 mandates that buildings in Maryland that are 35,000 square feet (~3,252 m²) or larger achieve a 20% reduction in net direct GHG emissions, as compared with 2025 levels, by January 1, 2030, and subsequently net-zero direct GHG emissions by January 1, 2040 [7].

To this end, energy audits and energy-efficient practices have become imperative [8]. Energy audits provide a systematic assessment of a building's energy use and a set of recommendations for enhancing the building's energy efficiency [9]. Energy audits on maintenance buildings are particularly beneficial, as these structures play a crucial role in various industries, housing critical operations that demand optimal energy use for sustainability, cost reduction, and environmental responsibility [10]. These structures house essential equipment, materials, and personnel vital to operations' efficient functioning and upkeep. Maintenance facilities employ and store heavy-duty equipment, including hoists, cranes, presses, lathes, TIG welding, washers, and milling equipment [11]. Regular energy audits can identify energy waste, recommend tailored efficiency measures, and promote sustainable energy usage practices, reducing operational costs and promoting a sustainable future. However, because maintenance facilities vary in operation, the literature on them is limited. This study addresses this gap in knowledge by delving into the importance of energy audits and energy efficiency in maintenance buildings, emphasizing the necessity of this practice for both economic and environmental benefits.

The Maryland Transit Administration (MTA) handles the operation and maintenance of multiple mass transportation methods for the State of Maryland. As part of a larger project, we prioritized the MTA's maintenance facilities for auditing using the ranking software developed by [12], which ranks facilities based on different energy metrics such as EUI, total GHG emissions, and energy-saving potential. We modeled the energy consumption of buildings that were heavy energy consumers to identify the deficiencies contributing to subpar energy performance [13].

This paper focuses on a maintenance facility audited as a part of that project. This facility has an area of 107,000 ft² (~9,941 m²) is located in Baltimore, Maryland and was constructed in 1991. The facility showed a consistently high energy use intensity (EUI) for five consecutive years, with an average of ~410 kWh/m². The facility's energy consumption and performance were evaluated using the following four-step procedure. First, the building's performance was analyzed using energy benchmarks and existing utility bills. Once the bills were analyzed, a walkthrough was done to identify the deficiencies in the building and ways their performance could be optimized for improved energy efficiency. Step three involved modeling the building's energy consumption to simulate the baseline energy performance of the facility. The model was based on the building's original as-built drawings, utility bills, building plug loads, and occupancy schedules. Once the baseline was created and validated, a list of proposed energy efficiency measures (EEMs) was simulated in the energy model. The final step involved documenting the savings in energy, operating costs, and GHG reduction potential that could be achieved by implementing the EEMs. The results show that energy audits of maintenance facilities can produce significant savings. The ramifications of using a four-step approach similar to the one proposed above is the development of a handbook/reference for other facilities that have similar attributes.

2. Methodology

2.1. Building Energy Benchmarking and Utility Bills

Building energy benchmarking involves energy accounting, evaluating opportunities for improvement, and estimating energy and cost savings [14]. By assessing the end-use energy data, facilities' energy performance can be evaluated using predefined benchmarking metrics, such as CBECS benchmarks [15]. Energy benchmarks are quantified using the fundamental metric of the energy use intensity (EUI) measured in kWh/m² (Eq. 1), which measures a facility's overall energy consumption over its gross floor area [16]. The other common energy benchmark, the load factor (Eq. 2), is a value that determines the building's electrical efficiency by comparing the peak demand to the total energy usage in a time frame [17]. As summarized in Table 1, for the maintenance facility, the EUI was ~404 kWh/m², which is almost three times the CBECS benchmark of ~151 kWh/m². Additionally, the load factor was calculated to be 0.22 compared to the recommended minimum of 0.75 for moderately efficient buildings. The high EUI and low LF indicate that the maintenance facility

is not efficiently using its energy resources. Figure 1 shows the energy consumption profile over the last five years.

$$EUI \text{ (Energy Use Intensity)} = \frac{\Sigma(\text{all energy use in a year (electricity, natural gas, etc.)}) [kWh]}{\text{Total Square Footage of facility } [m^2]} \quad (1)$$

$$LF \text{ (Load Factor)} = \frac{\text{Total kWh per period}}{\text{Peak Demand (kW)} \cdot \text{Number of Days} \cdot 24 \text{ hours}} \quad (2)$$

Table 1. Comparison of the maintenance facilities' energy benchmarks against industry standard benchmarks.

Energy Benchmark	Maintenance Facility (2022)	Benchmark
EUI [kWh/m ²]	403.7	151.1
Load Factor	0.22	0.75

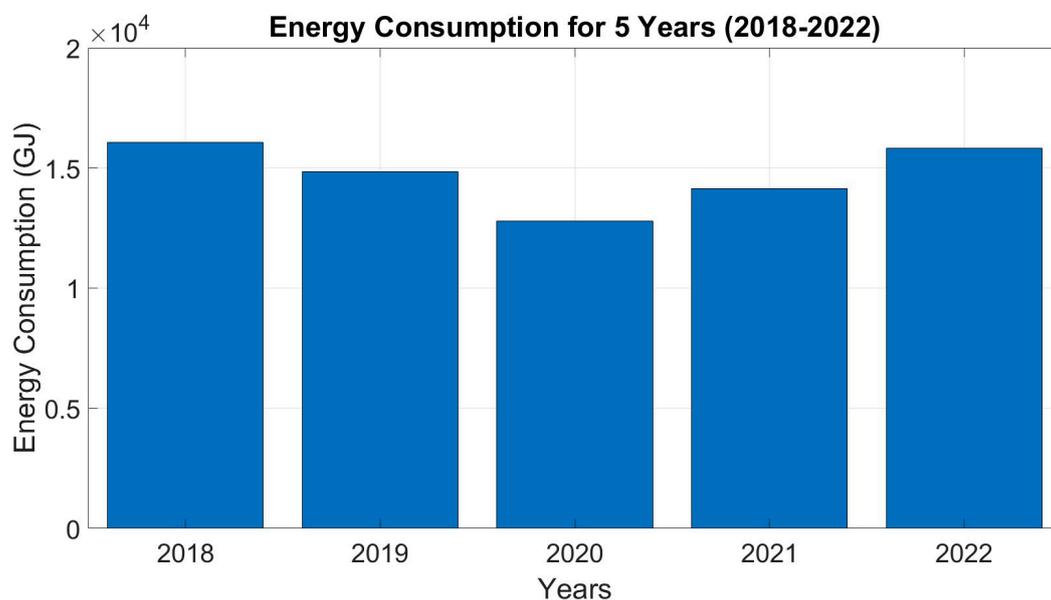


Figure 1. Energy consumption profile for the Maintenance Facility.

2.2. Facility Walkthrough

During a facility walkthrough, notes and pictures are taken of all high-energy-consuming devices/equipment as well as building envelope components. The main considerations for the building envelope are places of infiltration such as windows, doors, garage doors, and other openings. A study by [18] found that infiltration accounted for 6% of total commercial building energy in the U.S. Thus, correcting for infiltration can significantly enhance energy efficiency. The type of materials used and the construction of these features, such as whether windows are single/dual pane or tinted, as well as the number of features present in the building, should be noted during the walkthrough. In addition to the building envelope, high energy-consuming devices such as the HVAC system should be noted. The system's identification plate should be documented for later reference to the system's heating/cooling capacities, power rating, efficiency, and critical information. Other significant energy-consuming devices include plug load equipment for building operation, lighting, and miscellaneous loads found throughout the building's areas. For this information to be useful, the quantities of each device need to be noted, as well as their respective power ratings. Broken devices and equipment should also be considered, as they could lead to less efficient energy consumption. At the end of the walkthrough, the building personnel should be

interviewed to gain their perspective on whether the building is operating according to its intended needs. These personnel can provide information on the actual use of some systems compared to the use initially intended from the as-built drawings. The walkthrough and interview allow for the most up-to-date version of the building to be used in the next steps of energy auditing and modeling. Finally, the information transfer from the walkthrough should be aligned to support the implementation of the building information modeling [19].

2.3. Energy Model Development

Simulation software allows users to customize libraries according to the nature of the building. The process begins with the construction of the building envelope, where users designate the façade, comprising the walls (interior and exterior walls) and any doors or windows, as well as their performance metrics. Improper material selection at this stage can lead to erroneous baseline building values [20]. Next, the building layout is built into the model, creating a full 3D model of the building with rooms, as shown in Figure 2. To create HVAC zones, rooms can be grouped together and later assigned to specific HVAC equipment, as shown in Figure 4. HVAC equipment can be added, with the significant aspects being heating/cooling size, fan size, variable frequency drive (VFD), and type of system. Once the different HVAC equipment at the maintenance facility is entered into the model, it is added to the appropriate zones. Next, based on the zones, users assign the type of area, which incorporates the typical internal plug loads, heating/cooling loads, occupancy, and lighting. The software also considers the building's local weather data to simulate outdoor temperatures and the necessary heating and cooling requirements over the course of a year. The flowchart shown in Figure 3 depicts the process of developing a working energy model.

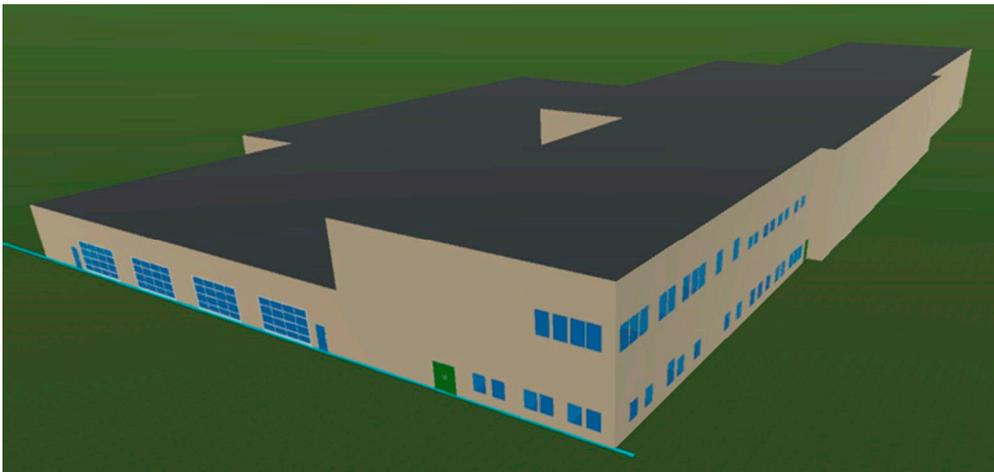


Figure 2. 3D model of the maintenance facility developed within simulation software.

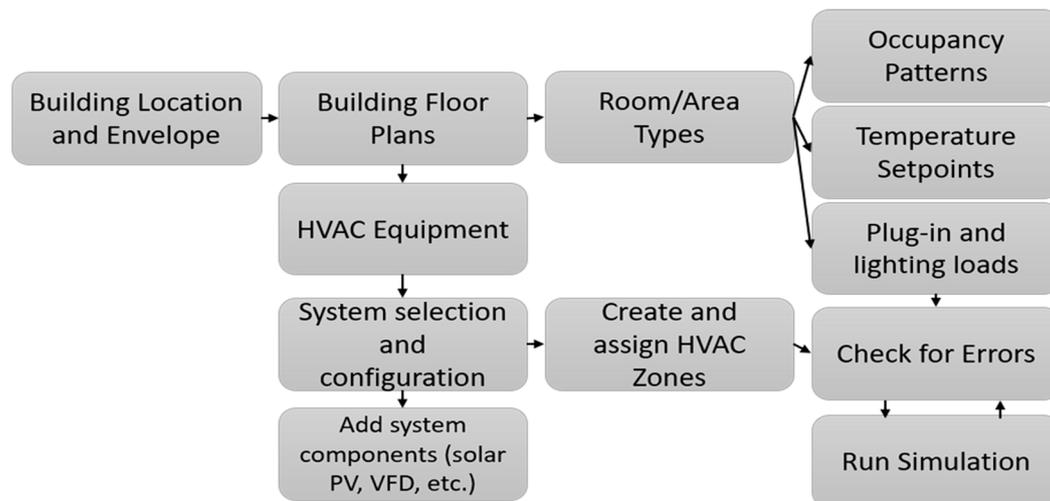


Figure 3. Flow chart of the energy model development.



Figure 4. (a) first and (b) second-floor plan of the maintenance facility in simulation software.

2.4. Identification of Energy-Intensive Areas

Maintenance facilities, depending on their use case and scheduling, can have different energy profiles. In a study by [21], the performance of a railway maintenance facility was optimized by developing the best scheduling policy. By using generic algorithms and industrial simulation software, the facility's performance was significantly improved. However, an optimized scheduling system can't be implemented for the MTA maintenance facility due to its 24/x7 operation schedule. The nature of its operating hours also explains the consistently high EUI for the facility for five consecutive years.

Commercial building energy consumption is divided into four categories: HVAC systems, lighting, equipment (based on building type), and miscellaneous loads [22]. Typically, HVAC systems and lighting comprise 70-75% of a facility's energy consumption [23]. However, these numbers vary based on building type and their use cases. The maintenance facility is a light rail repair facility, having washing bay areas, welding shops, vehicle repair floors, fabricating shops, and a multitude of other light rail repair and maintenance services. This comes with various equipment that can increase the plug load and overall base load of the facility. Based on the plug load inventory provided by the facility manager, some of the most power-intensive equipment in the facility is shown in Table 2.

Table 2. Plug load inventory for the Maintenance Facility.

Plug Load	Quantity	Power Rating (kW)
Car truck hoist	7	22.5
Wheel truing machine	1	64
Lathe motor	2	31.7
Paint booth system	1	79.8
Wheel press	1	43.2
Bridge crane	3	35
Actual press	1	38.2
Train washer equipment	2	54
Air stripper unit	2	43.2

As seen from Table 2, the facility has a significant plug load that can ramp up the energy consumption for the facility. Since this equipment can be complex to model, an overall plug load density (kW/m²) was applied to the areas where the loads are situated. Each piece of equipment was mapped to its location to develop the most accurate model for the facility's baseline performance. Since 85% of the facility comprises maintenance areas, the facility has high ceilings to accommodate the light rail cars. Therefore, running the system fan continuously is suggested, even when the heating or cooling cycles are off [24]. Continuous air circulation aids in mixing cool and warm air and keeps temperatures in rooms with a high ceiling relatively consistent.

Optimization Strategies

As seen in Table 1, the average load factor for the maintenance facility for 2022 was 0.22, leaving tremendous room for improving the facility's electrical efficiency. In a study by [25], the authors studied the effects of varying the plug load schedules using an energy monitoring mobile app, and upon implementation, a net 21% reduction in the plug loads in three buildings was achieved. Because those were plug loads such as computers, coffee machines, and fax machines, their control can be easily achieved using smart power strips [26]. However, this approach is unsuitable for monitoring and controlling the equipment list mentioned in Table 2. Therefore, we recommended a common Energy Conservation Measure (ECM), which involved scheduling high-power-rated devices for night/after hours to avoid the peak demand charges and simultaneously ameliorate the load factor of the facility [27]. This helps reduce the energy demand during peak hours and, consequently, high demand charges. The peak demand charges for maintenance facilities can rise to as high as \$5/kW during peak hours [28].

Once the operation of the plug loads was optimized, we turned to methods for managing the HVAC and lighting for the high ceilings. Providing the desired number of lumens for facilities with large ceilings can be complicated. In a study by [29], the lighting performance of commercially available tubular daylight devices (TDDs) under various conditions was experimentally evaluated. It was found that light levels increased and energy use decreased with solar altitude and TDD diameter. Using a similar approach, we recommended the installation of TDDs to reduce the load of artificial lighting and maximize the benefits of daylight. The specific diameter of the TDDs installed would need to be designed based on the desired lumens for the space [29].

For heating, the maintenance facility mainly uses infrared gas heaters. Infrared gas radiant heaters typically have a higher upfront equipment and installation cost; however, the operating costs

of gas heaters are less than electric heaters owing to the higher energy density of natural gas [30]. While these radiant heaters are economically viable and cheaper to run, they increase on-site CO₂ emissions, increasing their carbon footprint. A study by [31] presents an innovative solution for the heat recovery from the exhaust gasses of ceramic infrared heaters, which allows for environmental benefits and fuel savings in existing buildings heated with radiant heaters with low radiant efficiency. Using a flue gas-water heat exchanger, heat can be extracted from the exhaust gases and transferred to water, which can then be used for domestic hot water (DHW) preparation. The maintenance facility has many infrared radiant gas heaters that could be used for heat recovery for hot water preparation. This use of waste heat would increase fuel savings on the low-efficiency radiant heaters.

2.5. Advantages of Simulation Software

The simulation software offers a high level of customization, which suits the many different types of systems and zones found in the maintenance facility [32]. Additionally, the report generated for the simulation gives insight into the optimum sizing of the HVAC systems, indicating areas where energy needs are not being met and calculating net energy consumption for a fiscal year. The maintenance facility model was generated for the fiscal year 2022, during which data was actively collected and could be compared for accuracy. 2022 is also widely regarded as the “post-COVID” benchmark year [33], thereby giving insight into how the facility fared in its energy consumption pre-, during, and post-COVID-19. The model simulation obtained approximately the same energy usage of natural gas and electricity as the collected data. However, there was a slight overestimation of energy use in the summer months, and in the winter months, an underestimation, as shown in Figure 5.

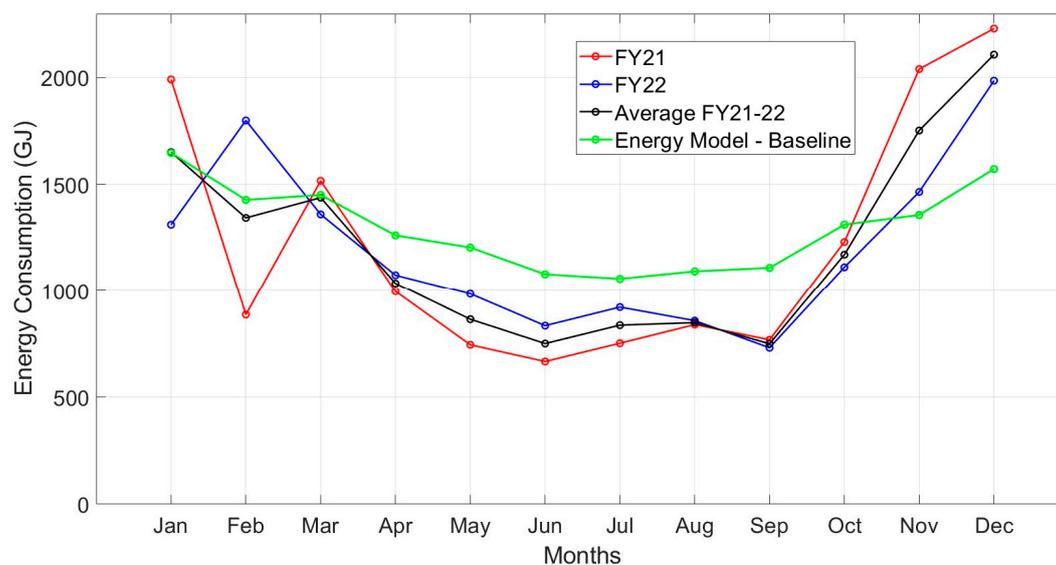


Figure 5. Simulated maintenance facility energy consumption compared to FY2021 and 2022.

Figure 5 shows the ability of the model to predict the baseline of the facility. An energy model should emulate the facility's performance so that it can be used to further analyze the building's energy consumption and develop EEMs. To develop an energy model that replicates the energy performance of a facility, [34] found that the facility's metered energy consumption values need to lie within the metered consumption of the year being simulated (2022), the preceding year (2021) and the average of the two years. Furthermore, ASHRAE Guideline 14-2014 prescribes no more than 15% and 10% deviation in monthly and annual data, respectively [35]. The maintenance facility energy model fell within these tolerance limits, validating the approach and the model's accuracy in replicating the building's energy performance. Thus, the simulated values were close enough to justify the model's use for developing EEMs for the facility and for predicting the energy savings potential across a year.

3. Proposed Energy-Efficiency Measures

A wide range of energy efficiency improvements were identified to ameliorate the facility's subpar energy performance and adhere to the state's energy efficiency [6] and decarbonization [7] goals. A study by [36] evaluated the effect of single-system retrofits versus integrated packages of energy efficiency measures (EEMs) to investigate the overall energy efficiency improvements. Fifteen out of thirty-four case studies implemented single-system retrofits, while the remaining focused on integrated packages. The study found that integrated approaches achieved more than 20% energy savings, while single-system approaches achieved approximately 10% energy savings. This prompted us to evaluate the effect of multiple EEMs on the facility's overall energy efficiency. The proposed EEMs in this section were formulated based on the major deficiencies existing in the facility.

3.1. LED Lighting Upgrades

A combination of compact fluorescent lamps (CFLs), metal halide, high-pressure sodium, and incandescent lamps provides all maintenance facilities lighting. All the lighting fixtures have lower lighting power densities (LPD) than LEDs, requiring higher power to provide the same number of lumens and increasing the facility's energy consumption. Table 3 shows the lighting inventory of the maintenance facility.

Table 3. Lighting Inventory for the maintenance facility.

Lamp type	Number of fixtures
Fluorescent	1,045
Incandescent	4
High-pressure sodium	65
Metal halide	70

A study by [37] performed a life-cycle analysis of LED retrofits replacing traditional artificial lighting in facilities. According to the study, the lifetime of all LED retrofits is longer than the lifetimes of traditional lamps they are replacing. The study found that T8 and T5 fluorescent lamp replacements by LEDs may yield as much as 40–50 % overall savings. For this reason, we modeled the energy savings that could be achieved by replacing the existing lighting with LEDs. In our model, the existing lighting fixtures were replaced with recessed LEDs having wattage based on the lighting power density prescribed by [38].

3.2. Equipment Sizing and Decarbonization

HVAC equipment uses a significant amount of electricity and affects occupant comfort. In recent years, ventilation code requirements have often driven the size of the equipment upward, resulting in mismatched cooling capacities. Oversized cooling equipment experiences shorter run cycles, reducing the ability to dehumidify air and the equipment's life span [39]. The maintenance facility faces a similar plight, with oversized equipment driving up energy consumption and costs. Table 4 shows the existing HVAC equipment in the facility and the amount by which it is oversized.

Table 4. Existing equipment size and amount oversized by.

Equipment	Capacity (kW)	Oversizing (kW)
Unit Heater - 1	5.0	3.3
Unit Heater - 2	8.9	2.9
Unit Heater - 3	5.0	0.4
Unit Heater - 4	8.9	2.9
Unit Heater - 5	5.9	2.9
Unit Heater - 6	29.9	2.3
Unit Heater - 7	10.0	2.3
Heat Pump - 1	6.4	4.5
Heat Pump - 2	6.4	4.5
Heat Pump - 3	11.4	8.2
Heat Pump - 4	4.2	4.0
Heat Pump - 5	3.4	1.6
RTU - 1	57.9	40.6
RTU - 2	71.7	33.9
Heating Ventilator - 1	46.9	0.0
Heating Ventilator - 2	46.9	0.0
Heating Ventilator - 3	46.9	0.0
Heating Ventilator - 4	46.9	0.5
Heating Ventilator - 5	46.9	0.0
Heating Ventilator - 6	27.8	13.5
Heating Ventilator - 7	46.9	38.0

As evident from Table 4, the HVAC systems in the maintenance facility are massively oversized, resulting in egregious energy consumption patterns and significant costs to the facility. Additionally, the heating ventilators and rooftop units (RTUs) use natural gas for heating, increasing the on-site carbon emissions of the facility. With the Environmental Protection Agency (EPA) instituting a penalty on every metric ton of CO₂ emitted annually (\$51/metric ton) [40], facilities need to start looking at their carbon footprint to mitigate the fines that may be imposed on them.

To alleviate the preceding problems, we modeled systems with appropriate HVAC sizing to match the heating and cooling demands of the facility year-round. A 25% margin was added to ensure that the systems are still operational and provide heating and cooling to the facility's occupants in the event of extreme weather conditions [41]. To ensure further the optimal operation

of the systems, we modeled the installation of variable frequency drives (VFDs) on all motors above 5 HP, which was found to be economically feasible and have lower payback periods [42]. VFDs would modulate the operation of the compressors and fans in the HVAC systems based on the occupancy levels and local temperature settings at the zone level from thermostats. Finally, all the HVAC systems were modeled to use electricity as the sole utility for both heating and cooling. This was done to ensure the facility's ambition to adhere to Maryland's net-zero goals. Building decarbonization can transform HVAC systems and, consequently, allow facility managers and building owners to promote more efficient and cleaner operations [43].

3.3. Solar PV Installation

The maintenance facility has an available roof area of ~5,644 m² upon which rooftop solar PV could be installed to replace the facility's grid energy consumption with solar energy. For the developed energy model, the efficiency of the photovoltaic arrays was assumed to be 18%, with an inverter efficiency of 96%. A study by [44] highlighted some of the important tradeoffs between the costs and benefits of installing rooftop solar panels for higher energy generation. One tradeoff they identified was a marginal increase in energy generation compared to the investment to install higher efficiency solar panels. The study further explored the impact of covering the entire roof area and the corresponding increase in the number of photovoltaic arrays required to achieve this; it was found that to provide the last 3% coverage, 20% more panels would be needed, thereby creating a funding burden. From the results of the study, it was concluded that using 50% of the available rooftop area for solar PV would be a good starting point for the facility while maintaining existing rooftop HVAC systems and skylights. The tilt angle for the photovoltaic arrays was set to 30° to match the latitude of the location and harness maximum energy generation potential [44].

3.4. Temperature Setbacks

The maintenance facility has a 24x7 occupancy schedule owing to the maintenance work being carried out in the facility year-round. The existing temperature setpoints for the facility are 75°F (23.9°C) year-round, regardless of the ambient temperature or occupancy levels. A study by [45] revealed that the ambient temperature and occupancy can change the EUI of a facility by 7-15%, making it an attractive opportunity for energy savings. It was thus recommended to use temperature setbacks for the facility to produce extra energy and cost savings. However, upon speaking with the facility managers, it was found that the only spaces with fixed occupancy levels were the offices, while the rest of the spaces were used 24x7, thereby limiting the scope of temperature setbacks. The office spaces in the facility, which account for 15% of the facility's overall square footage, were modeled for temperature setbacks based on ASHRAE recommendations, as seen in Table 5. The occupied temperature setpoint was maintained at 75°F (23.9°C), and the unoccupied temperature setpoint was 85°F (29.4°C) and 65°F (18.3°C) in the summer and winter months, respectively, for the office areas from 9 AM – 5 PM. Over the weekends, the spaces were maintained at the temperature setback setpoints, since there was no occupancy.

Table 5. Temperature setpoints in the office areas during occupied and unoccupied periods.

Months	Occupied temperature setpoint °F (°C)	Temperature setback setpoints °F (°C)
May - September	75 (23.9)	85 (29.4)
October - April	75 (23.9)	65 (18.3)

3.5. Window Replacement

The U-value and solar heat gain coefficient (SHGC) of windows have an enormous impact on buildings' heating and cooling loads. The U-value measures how well a window insulates, while the SHGC measures how much of the sun's heat comes through the window. A study by [46] found that the annual heating and cooling energy demand decreased by 8–17% when the U-value of the windows in a poorly insulated house was enhanced, and that demand decreased by 18–30% when the SHGC was lowered for a well-insulated house with larger windows. Furthermore, for buildings in the north-central climate, it is advised to have double-pane windows having a U-factor lower than 0.3 and an SHGC lower than 0.4 [47]. The maintenance facility has single-pane windows original to the building, far beyond their useful life. For the reasons above, it is recommended to replace the existing windows in the facility with double-pane windows having U-factor ≤ 0.3 and SHGC ≤ 0.4 to reduce the heating and cooling demands of the facility.

4. Results and Discussion

The energy model aims to determine the potential financial savings that could be generated by implementing the recommended EEMs in the maintenance facility. The case studies show that under different scenarios the EEMs can produce substantial energy savings. The results discussed below show the effect that each EEM would have on the overall energy usage of the building and provide explanations and justification for the simulated values.

4.1. LED Lighting Upgrades Savings

The maintenance facility relies on a mixture of light bulbs, including fluorescent, incandescent, high-pressure sodium, and metal halide. Replacing all lighting with LED equivalents was the first EEM suggested for the facility since, as shown in Table 3, many inefficient lighting fixtures currently illuminate the facility, contributing to high energy consumption. Switching the lighting from the current types was modeled using presets that consider the heat transferred to surrounding air, efficiency, and other factors. The user defines inputs including the lighting densities, wattages, and use based on the area type and schedules. The resulting energy savings predicted by the model were a decrease of 54 MWh/year of electricity and an increase of 54 GJ/year of natural gas.

The reason behind the decrease in electricity values is that LEDs operate at least 75% more efficiently than the currently installed bulbs [48]. However, they release less heat during operation, which explains the rise in therms/year: the natural gas must provide more heating in the building during the winter months to supplement the lower heat gain from lighting.

4.2. Decarbonization Savings: Re-Sizing HVAC, VFDs, and Electrification

The model allows users to simulate changes in the energy sources of HVAC systems from electric, gas, and steam to electricity. An example of such a system is depicted in Figure 6. For the various HVAC systems at the maintenance facility, the natural gas components were converted to electrical equivalents, VFDs were applied to any motors over 5 HP, and the HVAC equipment was resized to better match the simulated weather loads. Additionally, it was possible to add VFDs to the configuration with the current components. Finally, another option permits the auto-sizing of HVAC equipment. This auto-sizing feature allows the software to determine the worst-case scenario for heating and cooling based on the geographical zones. By combining these three portions into the decarbonization recommendations, a savings of 62 MWh/year of electricity and 5,034 GJ/year of natural gas could be achieved.

The natural gas usage at the facility was eliminated when the HVAC systems were converted to electrical equivalents. As a result, the electrical usage at the facility will increase. However, adding auto-sizing and VFDs in the same simulation counteracted this increased electricity usage and produced a net decrease in electricity use.

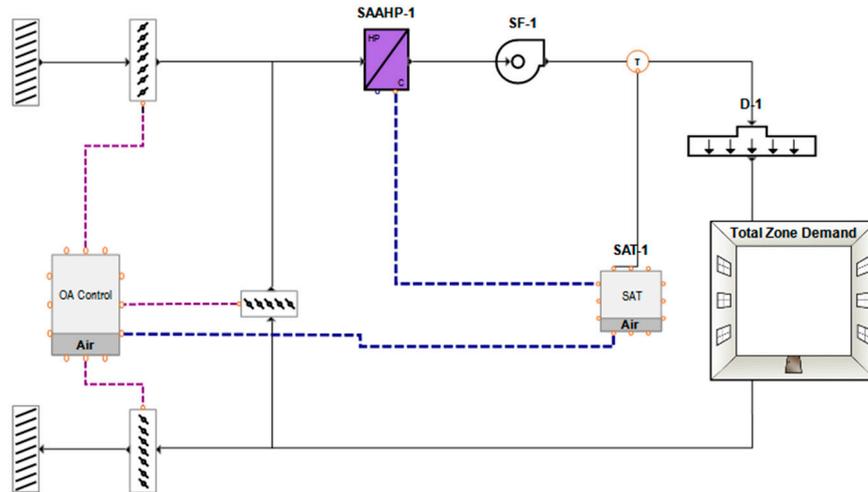


Figure 6. Example HVAC system with configurable components.

4.3. Solar PV Installation

Solar power is intended to supplement the electricity that would be used from the utility supply. A 50% estimation of the total roof area at the maintenance facility was used to determine the useful roof area for installing solar panels. An azimuth angle of 180° and a tilt angle of 30° was the chosen configuration of the solar PV arrays. With the specifications shown below in Figure 7, it is shown that 50 total arrays were needed. The simulated solar array is projected to reduce electricity consumption by 980 MWh/year.

This electricity savings accounts for around 33% of the facility's energy consumption in the base model. The solar panels did not have any energy storage capability in the simulation, so it was assumed that the energy that was produced directly supplemented the energy from utility sources. Installing energy storage equipment could increase the savings potential of the facility by allowing for energy supplementation during fluctuations, such as peak demand [49].



Figure 7. Model view of implemented Solar PV in simulation software.

4.4. Temperature Setbacks

Temperature setbacks at the maintenance facility were recommended for the office area since it operates on a Monday–Friday, 9 AM–5 PM schedule. When the office is unoccupied, the temperature is increased or decreased for energy efficiency. The previous temperature setpoint was 75°F (23.9°C)

year-round for the offices. While that temperature should be maintained when the offices are occupied, the drift point in the winter should be set to 65°F (18.3°C) and 85°F (29.4°C) in the summer. To implement this new schedule into the software, a new occupancy schedule had to be generated based on the typical 9 AM – 5 PM, Monday–Friday work schedule. In the new schedule, during the winter months, the temperature is set to 75°F (23.9°C) when the office area is occupied and drifts to 65°F (18.3°C) when unoccupied. Similarly, for the summer, the temperature when occupied is set to 75°F (23.9°C), and unoccupied drift is 85°F (29.4°C). When building areas are not occupied at all during the day, such as on weekends, the temperature is set to the drift point for the respective season for the full day. When switching from the unoccupied to the occupied temperature set points, the software starts the temperature change an hour before occupants enter the building (8 AM) and change back to the drift temperature an hour after occupants leave (6 PM). This new schedule would result in a decrease in electricity use of 6 MWh/year. Temperature setbacks are an important energy-saving measure in the context of energy efficiency, with savings reaching as high as 30% for heating systems and 23% for cooling systems [50].

4.5. Window Replacement

The maintenance facility features windows in the office area, which is only a fraction of the overall building's square footage. As there have been no window renovations since the original construction of the maintenance facility, it was assumed that the windows are over 30 years old. Given the windows' age, they were assumed to be typical single-pane windows for the Zone 4 climate zone. The recommended replacement windows should fit standards for the North Central Climate Zone with an SHGC \leq 0.40 and U-factor \leq 0.25 [51]. The replacement windows chosen in the model are double-pane tinted windows with an air-filled gap that meets the required SHGC and U-factor values described above. These upgrades to the existing windows would reduce electricity use by 0.5 MWh/year and a natural gas increase of 316 MJ/year. While the savings aren't large, it should also be noted that the facility doesn't have many windows that could benefit from the savings of window retrofits. Moreover, the uncertainty in the estimations makes it difficult to gauge whether a retrofit would be economically viable or suffer from high payback periods [52].

Table 6 highlights the energy and cost savings that could be achieved by implementing the EEMs suggested in this study. The utility savings (\$) were calculated using the standard utility rates obtained from the utility bills of the facility. The rates for electricity and natural gas were \$0.11/kWh and \$0.9/MJ, respectively. With the existing prices, it is no surprise that the facility would be averse to switching to all-electric for its operations, owing to the higher energy density of natural gas/dollar invested [53].

Table 6. Savings from different EEMs.

#	EEM	Energy Consumption		Projected Energy Savings		EEM Energy Savings Percentage		Utility Savings		
		E (MWh/yr)	NG (GJ/yr)	E (MWh/yr)	NG (GJ/yr)	E (%)	NG (%)	E (\$/yr)	NG (\$/yr)	Total (\$/yr)
1	LED lighting upgrade	2,873	5,088	54	-54	1.9	-1	\$5,940	-\$462	\$5,478
2	Solar PV	1,948	5,034	980	0	33	0	\$107,800	\$0	\$107,800
3	Equipment sizing and electrification	2,866	0	62	5,034	2.1	100	\$6,820	\$42,943	\$49,763
4	Window upgrades	2,927	5,034	0.5	-0.3	0	0	\$55	-\$3	\$52
5	Temperature setbacks	2,922	5,034	6	0	1	0	\$660	\$0	\$660
Combined EEMs		1,842	0	1,086	5,034	37	100	\$119,460	\$42,943	\$162,402

Table 7 shows the reduction in GHG emissions that can be achieved by the EEM implementations. Using the coefficients of CO₂ equivalents from the EPA Power Profiler [54], the quantity of GHG emissions quantified in metric tons of CO₂ from electricity was calculated. The CO₂ equivalents for natural gas were obtained from the EPA's Emission Factors Hub [55].

Table 7. GHG reduction from EEMs in metric tons of CO₂.

#	EEM	Projected Energy Savings		Annual GHG Reduction - 2022		
		E (MWh/yr)	NG (GJ/yr)	E (metric tons/yr)	NG (metric tons/yr)	Total (metric tons/yr)
1	LED Lighting Upgrade	54	-54	16	-3	14
2	Solar PV	980	0	299	0	299
3	Equipment sizing and electrification	62	5,034	19	253	272
4	Window upgrades	0.5	-0.3	0	0	0
5	Temperature setbacks	6	0	2	0	2
Combined EEMs		1086	5,034	331	253	584

5. Conclusions

The built environment greatly impacts GHG emissions due to its high energy consumption. Although newly constructed buildings are increasingly being built as net zero facilities, most existing buildings were not built with energy efficiency as a high priority—hence the need to find ways to retrofit existing buildings to achieve global decarbonization and sustainability goals.

The present case study focused on a maintenance facility used by the State of Maryland Mass Transportation Agency. This facility was chosen because the energy performance metrics were below the desired standard benchmark values for comparative facilities. Based on a virtual as well as hands-on energy audit, the recommended EEMs included LED lighting upgrades, installation of solar PVs, appropriate equipment sizing, installation of VFDs, window upgrades, temperature setbacks, and electrification measures. These recommendations are predicted to offer significant energy savings potential, with a net annual reduction of 584 metric tons of CO₂, a decrease of 5,034 GJ of natural gas, and 1,086 MWh of electricity for 2022. The comprehensive energy audit analysis and simulation models were crucial in identifying deficiencies and opportunities to improve the facility's performance. Furthermore, from the energy modeling results, it can be seen that implementing the Energy Efficiency Measures had an attractive cost-saving potential of \$162,402 annually.

The results of this case study show that attractive energy savings can be achieved for a commercial maintenance facility despite having extreme operational schedules. The study also highlights the importance of energy use optimization to enhance building energy efficiency and promote sustainable practices. The outcomes of this study not only contribute to cost and energy savings for the building's occupants but also serve as a blueprint for future energy optimization projects in similar maintenance facilities. The study aims to serve as a guide for measures that can most benefit other similar maintenance facilities.

Author Contributions: Conceptualization, J.H., A.R., R.F., and M.O.; methodology, J.H., A.R.; validation, J.H., A.R., and R.F.; data curation, J.H., and A.R.; resources, J.H., A.R., R.F.; writing—original draft preparation, J.H., A.R.; writing—review and editing, J.H., A.R., R.F., and M.O.; visualization, J.H., A.R.; supervision, J.H., A.R., R.F., and M.O.; project administration, R.F. and M.O.; funding acquisition, M.O. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement: Data is available upon request.

Acknowledgments: The authors would like to thank the Office of Energy Sustainability within the State of Maryland's Department of General Services (DGS) for their support of this project.

Conflicts of interest: The authors declare no conflict of interest.

References

1. EIA. (n.d.-a). Frequently Asked Questions (faqs) - U.S. Energy Information Administration (EIA). Frequently Asked Questions (FAQs) - U.S. Energy Information Administration (EIA). <https://www.eia.gov/tools/faqs/faq.php?id=77&t=11>
2. Cresko, J., Rightor, E., Carpenter, A., Peretti, K., Elliott, N., Nimbalkar, S., ... & Liddell, H. (2022). DOE Industrial Decarbonization Roadmap (No. DOE/EE-2635). USDOE Office of Energy Efficiency and Renewable Energy (EERE).
3. van Bommel, N., & Höffken, J. I. (2023). The urgency of climate action and the aim for justice in energy transitions—dynamics and complexity. *Environmental Innovation and Societal Transitions*, 48, 100763.
4. EIA. (n.d.). *U.S. Energy Information Administration - EIA - independent statistics and analysis*. U.S. energy facts explained - consumption and production - U.S. Energy Information Administration (EIA). <https://www.eia.gov/energyexplained/us-energy-facts/>
5. Allouhi, A., El Fouih, Y., Kousksou, T., Jamil, A., Zeraouli, Y., & Mourad, Y. (2015). Energy consumption and efficiency in buildings: current status and future trends. *Journal of Cleaner production*, 109, 118-130.
6. *Governor Moore Signs executive order doubling Maryland's energy conservation goal through State Government Greenhouse Gas reductions - press releases - news - office of governor Wes Moore*. Governor Moore Signs Executive Order Doubling Maryland's Energy Conservation Goal Through State Government Greenhouse Gas Reductions - Press Releases - News - Office of Governor Wes Moore. (n.d.). <https://governor.maryland.gov/news/press/pages/Governor-Moore-Signs-Executive-Order-Doubling-Maryland%E2%80%99s-Energy-Conservation-Goal.aspx#:~:text=ANNAPOLIS%2C%20MD%20%E2%80%94%20Governor%20Wes%20Moore,a%2020%25%20decrease%20by%202031.>
7. The Maryland Climate Solutions Now Act (2022), Maryland Department of Environment (MDE)
8. Berardi, U. (2015). Building energy consumption in US, EU, and BRIC countries. *Procedia engineering*, 118, 128-136.
9. Deru, M. P., Deru, M. P., & Kelsey, J. (2011). Procedures for commercial building energy audits. *American Society of Heating, Refrigerating, and Air-Conditioning Engineers*.
10. Kontokosta, C. E., Spiegel-Feld, D., & Papadopoulos, S. (2020). The impact of mandatory energy audits on building energy use. *Nature Energy*, 5(4), 309-316.
11. Mangano, G., & De Marco, A. (2014). The role of maintenance and facility management in logistics: a literature review. *Facilities*, 32(5/6), 241-255.
12. Ramnarayan, A., A. Sarmiento, A. Gerami and M. Ohadi. 2023. An energy consumption intensity ranking system for rapid energy efficiency evaluation of a cluster of commercial buildings. *ASHRAE Transactions*, 129(2).
13. Harish, V. S. K. V., & Kumar, A. (2016). A review on modeling and simulation of building energy systems. *Renewable and sustainable energy reviews*, 56, 1272-1292.
14. *Building Energy Use Benchmarking*. Energy.gov. (n.d.). <https://www.energy.gov/scep/slsc/building-energy-use-benchmarking>
15. Scofield, J. H. (2014, August). Energy star building benchmarking scores: good idea, bad science. In *ACEEE Summer Study on Energy Efficiency in Buildings* (pp. 267-82).
16. Vaisi, S., Firouzi, M., & Varmazyari, P. (2023). Energy benchmarking for secondary school buildings, applying the top-down approach. *Energy and Buildings*, 279, 112689. <https://doi.org/10.1016/j.enbuild.2022.112689>
17. Cerna, F. V., Coêlho, J. K., Fantesia, M. P., Naderi, E., Marzband, M., & Contreras, J. (2023). Load Factor Improvement of the Electricity Grid Considering Distributed Energy Resources Operation and Regulation of Peak Load. *Sustainable Cities and Society*, 98, 104802.
18. Lisa C. Ng, W. Stuart Dols, Steven J. Emmerich, Evaluating potential benefits of air barriers in commercial buildings using NIST infiltration correlations in EnergyPlus, *Building and Environment*, Volume 196, 2021, <https://www.sciencedirect.com/science/article/abs/pii/S0360132321001906?via%3Dihub>
19. Atiba, O. E., Efemwenkikie, U. K., Olatunji, R. O., Ohunakin, O. S., Adelekan, D. S., & Oyeleke, O. A. (2019, December). Walk-through energy audit of an institutional building. In *Journal of Physics: Conference Series* (Vol. 1378, No. 3, p. 032051). IOP Publishing.
20. Alzoubi, H. H., & Al-Zoubi, A. H. (2010). Assessment of building façade performance in terms of daylighting and the associated energy consumption in architectural spaces: Vertical and horizontal shading devices for southern exposure facades. *Energy Conversion and Management*, 51(8), 1592-1599.
21. Hani, Y., Amodeo, L., Yalaoui, F., & Chen, H. (2008). Simulation based optimization of a train maintenance facility. *Journal of intelligent manufacturing*, 19(3), 293-300.

22. Pérez-Lombard, L., Ortiz, J., & Pout, C. (2008). A review on buildings energy consumption information. *Energy and buildings*, 40(3), 394-398.
23. Sezgen, O., & Koomey, J. G. (2000). Interactions between lighting and space conditioning energy use in US commercial buildings. *Energy*, 25(8), 793-805.
24. Kim, G., Schaefer, L., Lim, T. S., & Kim, J. T. (2013). Thermal comfort prediction of an underfloor air distribution system in a large indoor environment. *Energy and Buildings*, 64, 323-331.
25. Hafer, M., Howley, W., Chang, M., Ho, K., Tsau, J., & Razavi, H. (2017, November). Occupant engagement leads to substantial energy savings for plug loads. In 2017 IEEE Conference on Technologies for Sustainability (SusTech) (pp. 1-6). IEEE.
26. Nakazawa, F., Soneda, H., Tsuboi, O., Iwakawa, A., Murakami, M., Matsuda, M., & Nagao, N. (2011, July). Smart power strip network and visualization server to motivate energy conservation in office. In 2011 9th IEEE International Conference on Industrial Informatics (pp. 352-357). IEEE.
27. Surai, J., & Surapatana, V. (2014, March). Load factor improvement in industrial sector using load duration curves. In 2014 International Electrical Engineering Congress (iEECON) (pp. 1-4). IEEE.
28. *EnergyCAP*. EnergyCAP Login. (n.d.). <https://my.energycap.com/>
29. Fernandes, L. L., & Regnier, C. M. (2023). Lighting and visual comfort performance of commercially available tubular daylight devices. *Solar Energy*, 251, 420-437.
30. Roth, K., Dieckmann, J., & Brodrick, J. (2007). Infrared radiant heaters. *Ashrae Journal*, 49(6), 72.
31. Dudkiewicz, E., Fidorów-Kaprawy, N., & Szałański, P. (2022). Environmental benefits and energy savings from gas radiant heaters' flue-gas heat recovery. *Sustainability*, 14(13), 8013.
32. Sustar, J. (2020). ASHRAE History of a System: History of Trane's TRACE™ Software. *ASHRAE Transactions*, 126, 640-643.
33. Cortiços, N. D., & Duarte, C. C. (2022). Energy efficiency in large office buildings post-COVID-19 in Europe's top five economies. *Energy for Sustainable Development*, 68, 410-424.
34. (2018). ENERGY MODELING OF MULTI-STORIED RESIDENTIAL BUILDINGS – A MANUAL CALIBRATION.
35. Guideline, A. S. H. R. A. E. (2014). Measurement of energy, demand, and water savings. *ASHRAE guidel*, 4, 1-150.
36. Sherman, R., Naganathan, H., & Parrish, K. (2021). Energy savings results from small commercial building retrofits in the us. *Energies*, 14(19), 6207.
37. Raditschova, J., & Gasparovsky, D. (2018, September). Critical analysis of cost benefits of LED retrofits in indoor lighting. In 2018 VII. Lighting Conference of the Visegrad Countries (Lumen V4) (pp. 1-6). IEEE.
38. ANSI/ASHRAE/IES Standard 90.1-2022, Energy Standard for Sites and Buildings Except Low-Rise Residential Buildings.
39. Gorter, J. L. (2012). HVAC equipment right-sizing: occupant comfort and energy savings potential. *Energy Engineering*, 109(1), 59-75.
40. Sheet, E. F. (2013). Social cost of carbon. *United States Environmental Protection Agency (EPA): Washington, DC, USA*.
41. O'Brien, W., Abdelalim, A., & Gunay, H. B. (2019). Development of an office tenant electricity use model and its application for right-sizing HVAC equipment. *Journal of Building Performance Simulation*, 12(1), 37-55.
42. Aditya, T. (2013). Research to study variable frequency drive and its energy savings. *International Journal of Science and Research (IJSR)*, 2(6), 253-256.
43. RUMSEY, E., Le Garrec, J., & Lévassieur, A. (2021). How Building Decarbonization Can Transform HVAC. *ASHRAE Journal*, 63(9).
44. Zhong, Q., & Tong, D. (2020). Spatial layout optimization for solar photovoltaic (PV) panel installation. *Renewable Energy*, 150, 1-11.
45. Selvacanabady, A., & Judd, K. S. (2017). The Influence of Occupancy on Building Energy Use Intensity and the Utility of an Occupancy-Adjusted Performance Metric. Pacific Northwest National Laboratory.
46. Ahn, B. L., Kim, J. H., Jang, C. Y., Leigh, S. B., & Jeong, H. (2016). Window retrofit strategy for energy saving in existing residences with different thermal characteristics and window sizes. *Building Services Engineering Research and Technology*, 37(1), 18-32.
47. https://www.energystar.gov/products/residential_windows_doors_and_skylights/key_product_criteria
48. *LED lighting*. Energy.gov. (n.d.-b). <https://www.energy.gov/energysaver/led-lighting>
49. https://www.sciencedirect.com/science/article/pii/S0360319916309478?casa_token=ZEtdIKsXPsgAAAAA:AArinc2xlBvwzCp27oBKYPok1tAZpri4bk6OjZsv5DyFFM_aDy-Psj9aph69xO2FIM4e_feUvA
50. Moon, J. W., & Han, S. H. (2011). Thermostat strategies impact on energy consumption in residential buildings. *Energy and Buildings*, 43(2-3), 338-346.
51. [https://www.energystar.gov/sites/default/files/Windows_Doors_and_Skylights_Program_Requirements %20v6.pdf](https://www.energystar.gov/sites/default/files/Windows_Doors_and_Skylights_Program_Requirements%20v6.pdf)

52. Ohlsson, K. A., Nair, G., & Olofsson, T. (2022). Uncertainty in model prediction of energy savings in building retrofits: Case of thermal transmittance of windows. *Renewable and Sustainable Energy Reviews*, 168, 112748.
53. Brehm, P. (2019). Natural gas prices, electric generation investment, and greenhouse gas emissions. *Resource and Energy Economics*, 58, 101106.
54. EPA. (n.d.). Power profiler | US EPA - U.S. Environmental Protection Agency. <https://www.epa.gov/egrid/power-profiler>
55. EPA. (n.d.-a). GHG Emission Factors Hub | US EPA. <https://www.epa.gov/climateleadership/ghg-emission-factors-hub>

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.