ABSTRACT

Title of Document: ENERGY ANALYSIS OF A METRO TRANSIT SYSTEM FOR SUSTAINABILITY AND EFFICIENCY IMPROVEMENT

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The industrial sector in the US accounted for 33% of the overall energy consumption and 23% of total GHG Emissions in 2022, necessitating the need for energy efficiency and decarbonization of this sector. This study identifies common opportunities and challenges while performing energy audits for the State of Maryland public transportation maintenance complex and proposes site-specific energy efficiency measures. Utilizing performance indices such as Energy Use Intensity (EUI) and load factor from end-use energy data, as well as walkthrough observations from energy audits, energy efficiency measures specific to each facility were formulated to augment the overall energy performance. Additionally, energy modeling helped pinpoint the additional scope of energy efficiency improvements that could have potential significant energy performance improvements and reduce on-site GHG emissions. Among the energy conservation measures considered, the re-sizing and decarbonization of HVAC equipment has the greatest contribution to energy and GHG savings, with a 100% decrease in natural gas, a

37% decrease in electricity use annually, and net decrease of 272 Mton CO_2. This study aims to highlight the similarities and differences in existing transportation and maintenance facilities and the applicable technology(ies) that could streamline and serve as a guide for energy audits for transportation maintenance facilities by demonstrating the most common energy efficiency measures and subsequent achievable savings for these facilities.

ENERGY ANALYSIS OF A METRO TRANSIT SYSTEM FOR SUSTAINABILITY AND EFFICIENCY IMPROVEMENT

by

Jordan Andrew Higgins

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Dedication

This is dedicated to my parents, Mark and Tina Higgins, for their support and sacrifices allowed me to achieve my life long goals.

Acknowledgments

I thank my Advisor, Dr. Michael Ohadi, for the guidance and assistance in completing this thesis as well as his knowledge in all aspects of my master's program. I am appreciative of being able to have leadership experience and work among different teams in the Smart and Small Thermal Systems Laboratory (S2TS).

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Nomenclature

AHU – Air Handling Unit
ASHRAE – American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BAS – Building Automation System
BTU – British Thermal Unit
CBECS – Commercial Buildings Energy Consumption Survey
CO2 – Carbon Dioxide
DDC – Direct Digital Controls
DGS – Department of General Services
ECM – Energy Conservation Measure
EIA – U.S. Energy Information Administration
EPA – U.S. Environmental Protection Agency
EUI – Energy Usage Intensity
HVAC – Heating, Ventilation, and Air-Conditioning
KW – Kilowatt
KWH – Kilowatt-Hour
S2TS – University of Maryland Smart and Small Thermal Systems Laboratory

Chapter 1: Introduction

1.1 Project Background and Goals

There is a current and evolving energy crisis happening across the globe that is causing energy to be more expensive and less available [1]. This is especially the case in the United States where the average costs of electricity have risen 8% since 2022 [2]. The United States used a total of 12.16 quadrillion BTU (3.56 trillion kWh) of energy in 2021 [3]. The commercial building and residential sector combined for a total of 40% of the U.S.'s total energy consumption [4]. From this, the commercial building sector alone accounted for 35% of the nation's electricity consumption [4]. Efforts are being made by building owners and manufacturers to help counteract the increasing cost and decreasing availability of energy. According to recent EPA reporting, approximately 30% of energy use in buildings is wasted, providing a significant opportunity for energy savings in the commercial building sector [4]. At the same time as the energy crisis is happening, there is also a climate crisis. The climate crisis is a result of rising global temperatures from greenhouse gas production [5]. The rise in temperatures could result in drastic impacts such as mass areas being submerged in water, increased competition for essential resources such as water, food shortages, and socioeconomic tension [5]. The United States is the second-highest emitter of greenhouse gases. As a leading contributor to harmful gasses (primarily carbon dioxide), around 16% of the United States contributions come from commercial buildings [4]. There is a direct correlation between the energy and climate crises; both are the result of inefficient energy systems using inefficient carbon-based fuels. There has been some transition to zero-emissions energy technologies that do not emit greenhouse gasses;

they consist primarily of wind, solar, hydropower, and geothermal, which in total represent only 11% of energy generation in the U.S. [6].

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 [7]. This executive order indicated that there would be 2 million square feet of state buildings audited annually to reduce energy consumption and costs to the taxpayers. These audits were to be provided to the building manager where, to the best of their ability, they would implement the savings (cost) measures identified within the audit. The overall minimum goal of the executive order was a 20% decrease in energy consumption in state buildings by 2029, using each building's 2018 energy consumption data as the baseline. The University of Maryland Smart and Small Thermal Systems Lab (S2TS), a part of the Center for Environmental Energy Engineering (CEEE), is currently working with the Maryland Department of General Services (DGS) to complete these audits in support of the State legislation. The auditing process is supported by Professor Michael Ohadi, Co-Founder of CEEE. He is assisted by a team involving staff research scientist, research engineer, and graduate and undergraduate students. As a part of Year 2 and Year 3, the University of Maryland Audit team's efforts included completing energy efficiency audits for the Maryland Transit Administration (MTA) maintenance facility for Metro, Bus, Light Rail, and MARC Facilities, among other facilities audited. The type of energy audit that has been conducted by the S2TS Lab was an ASHRAE Level 2 audit. According to ASHRAE, level 2 audit should consist of a site-visit walk-through analysis where key personnel are interviewed, utility bills are analyzed, and an energy analysis report is prepared. The specific Level 2 features that are identified by ASHRAE include energy consumption analysis that is broken down by the different end uses to identify the areas with the highest potential for energy savings. Level 2 auditing also calls for a more in-depth interview with the personnel currently using the building to determine if there are any abnormalities or faulty equipment present in the building that may result in inefficient energy use [8].

While performing the energy audits for MTA, a gap in the literature for auditing maintenance facilities was noted. Through research of available resources, the S2TS Team combined and applied practices from other audits of large buildings and applied continuous learning from the challenges that were encountered. From these experiences, many similarities were identified among the maintenance facilities. These similarities allowed the team to streamline the auditing process as the assigned audits and energy efficiency recommendations were completed. Although the actual outcomes of implementing the audit recommendations are not yet available, energy modeling using Trane Trace3 3D Plus was utilized to estimate some of the potential savings of the commonly identified energy conservation measures (ECMs). It is the objective of this paper to present case studies to showcase the different MTA subdivisions that were audited and outline the commonalities that the University of Maryland team identified. This study will then present validated modeling data as a justification of ECM effectiveness and can be used as a validated methodology to assist other entities in completing energy auditing for maintenance facilities in the future.

Chapter 2: Pre-Audit Preparations

2.1 Initial Building Selection

The energy auditing team historically has worked with the State of Maryland to audit many different state organizations. Examples of completed projects include the Maryland School for the Deaf and Maryland Department of Military (DMIL) Readiness Centers. These state organizations were completed within Year 1 and Year 2 of the S2TS effort. The Maryland Transit Administration audits were completed at the end of Year 2 and the beginning of Year 3. Subsections within MTA include MARC, Bus, Light Rail, Metro Maintenance Facilities, and Metro Stations.

The order in which the subsections were audited was by priority from DGS and is listed below:

1. Light Rail
2. Bus Maintenance Buildings
3. Metro Maintenance Buildings
4. Metro Stations
5. MARC Maintenance Buildings

2.2 Building Information

The initial introduction to each building was done with a questionnaire and building equipment spreadsheet. The building questionnaire and spreadsheet were filled out by the building manager. Using the online program called ProjectWise, MTA was able to share the building's questionnaires and Excel sheets supplied by the building managers. The information that was available in the questionnaire included general building information. This included the official building address, main facility uses, as well as name and contact information of the building manager. It also contained more in-depth information such as the current building occupancy schedules, state of equipment, building operational issues, building automation system (BAS), and utility type uses. The Excel sheet contained lists of the building renovations and the date when they occurred, all HVAC equipment, internal plug loads, and the lighting inventory. Using the online software ProjectWise, building managers supplied any available building drawings. The building drawings included the mechanical, structural, and electrical versions from the original construction. The mechanical drawings help to show the installed HVAC equipment and their operation sequence within the facility. The structural drawings are useful in identifying the different areas within the building and confirming the building's square footage. The electrical drawings were used to help identify the current transformers in the facility and the power coming into the facility.

Another software provided is EnergyCAP, which tracks the utility usage of all the Maryland State-owned facilities. The State of Maryland uses this software tool to track, monitor, and quantify different utility usage monthly. This is the way that the different utilities used within a facility are identified and quantified by fiscal year. These values are beneficial to the audit process since one of the main measures used to determine a building's overall energy efficiency is the energy use intensity (EUI). This measure is calculated by adding all the energy used within a fiscal year and dividing it by the total building square footage as shown in Equation (1) below.

$$EUI = \frac{\sum(Oil\ Use + Electricity\ use + Gas\ Use + \cdots)[kWh]}{Total\ square\ footage\ [sq.ft.]} \qquad (1)$$

This value is then compared to a well-known standard produced by EnergyStar, which provides the median EUI of all buildings of similar use in the United States. Under ideal circumstances, the building will, at a minimum, meet the EnergyStar average; but in many cases the goal of an energy usage standard is for the EUI to fall below the minimum EnergyStar value. As the EnergyStar produced reference is the median of all buildings of similar use, 50% use more energy and 50% use less energy. This means that being right at the reference only signifies less energy consumption than 50% of buildings and is not always the most efficient a building could be.

The second measure that EnergyCAP-provided data can be used to calculate is the load factor of a facility, which is a reference to the electrical usage efficiency. The load factor utilizes knowledge of monthly peak demands compared to the total month electricity usage and can be seen in equation (2) below.

$$Load\ Factor\ = \frac{Total\ Consumption\ in\ Billing\ Period}{Peak\ Demand\ X\ Number\ of\ Hours\ in\ Billing\ Period}[kWh] \quad (2)$$

The typical value for a load factor to show electrical usage efficiency is 0.75, however, most modern buildings can operate at a load factor of 0.9.

Chapter 3: Energy Audit Case Studies

3.1 Introduction to the Case Studies

The use of case studies is often the most preferred way to provide an understanding of the different situations that were observed when completing audits across the MTA. There was a case study for each of the sub-organizations within MTA where the differences and similarities can be compared against one another. The choice of using a case study from each sub-organization was completed to provide and illustrate the broadest range of MTA maintenance facility types.

3.2 Framework of Energy Auditing of Commercial Repair Facilities

In order to establish a framework of how energy audits are conducted, multiple studies were reviewed and evaluated for methods of other energy audits (such as the order of steps within the audit and desired outcomes). Then, energy auditing guides for specific building types were sought to determine the gap in literature for special case commercial maintenance facilities, which this thesis hopes to satisfy.

According to Wu from Shanghai University, an energy audit refers to the inspection, verification, and evaluation of how energy is physically and financially used and should be done to strengthen and aid in energy conservation [9]. In order to complete an energy audit from these standards, there needs to be measurements of energy usage, calculations of the energy usage, analysis of the operating efficiency of the building/equipment, calculations of potential energy savings, and some financial cost savings of proposed energy saving measures [9]. Wu continues that an energy auditor should have the ability to interpret the calculations completed to make educated suggestions to achieve maximum energy savings. The outcomes of these audits should provide the audited facility economic and social benefits as well as improved energy efficiency. Wu proposed a simple flow chart of the energy auditing process and the potential outcomes, shown below in figure 1.

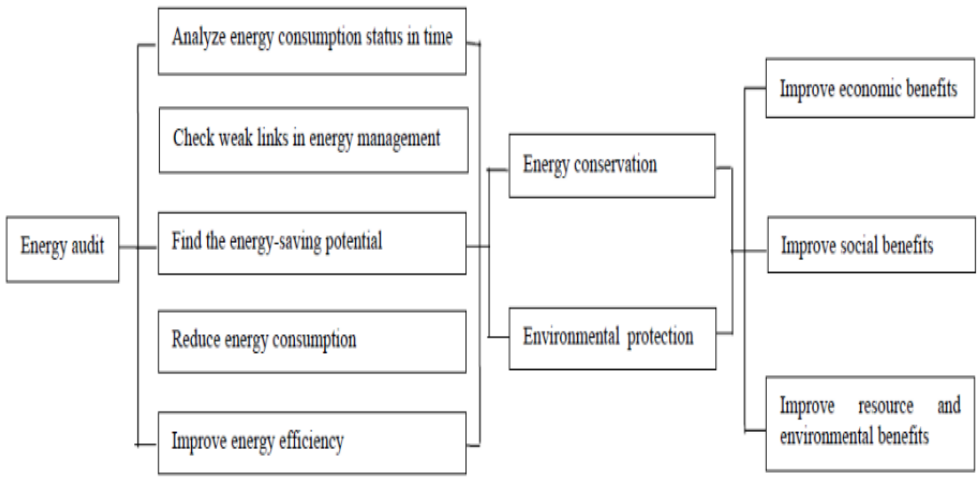


Figure 1: Energy Auditing process flow chart [9].

In a paper produced by Kluczek and Olszewski, there is a slightly different process that is outlined for a sufficient energy audit. In the proposed outline, which is specifically tailored for industrial processes but can be extended and applied to buildings as a general guideline. The first step of their audit process involves a pre-audit questionnaire which includes basic information such as annual billing/costs, building images, energy intensive processes, and general building uses [10]. Next in the process is an initial analysis of the building and processes, which include an initial meeting with the building engineers and a site visit [10]. From this step, there can be further auditing directions where the auditing engineers identify potential energy saving measures and decide on what further data should be reviewed or collected within the building to support their analyses. Once the needed measurements have been determined, the measurements and data collection process can begin. Once the data and measures have been collected and evaluated, the energy analysis and final report can be completed. The report records all energy savings opportunities that were identified and their resulting potential savings. Finally, the last step of energy auditing is the implementation of the energy conservation recommendations, which should align with the ISO 50001 Standard (global energy management systems standard) [10]. The mentioned auditing process by Kluczek and Olszewski is shown in figure 2 below.

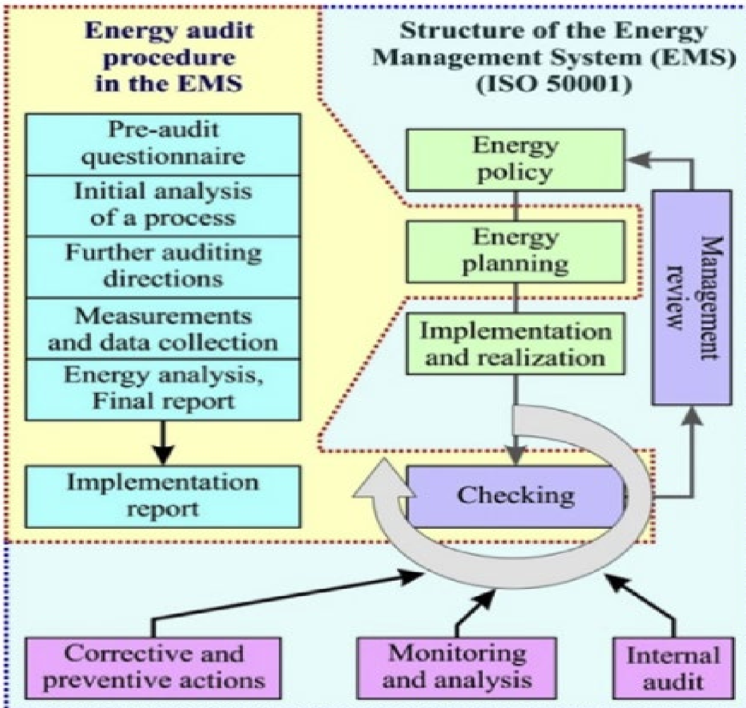


Figure 2: Energy Auditing procedure for industrial processes [10].

The main outcomes set forth by this energy auditing process are energy savings, cost savings, and emission reduction [10].

In the final study that was reviewed, the situational scenario was very similar to the conditions that were observed during the MTA audit conducted by the University of Maryland. The framework that was provided is suggested for programs where Universities or other research institutions provide energy audits to small or medium-sized manufacturers. The primary driver for these energy audits is to present potential opportunities to conserve energy, reduce waste, and improve productivity. In this study, the energy auditors conducted preliminary assessments which consisted of reviewing the facilities' energy consumption; on-site visits where they were able to interview the current building manager and staff; and finally, gathering data such as lighting levels or infiltration. The next step involved the Universities providing their recommendations in a final report. The information included in these reports contained valuable information and data, such as the estimated cost of implementation, the quantity of energy that could be conserved, the estimated reduced annual operating costs, and potential follow-up activities to confirm and validate recommendations following installation and implementation [11].

The takeaways of the studies (e.g., step by step procedure, recommendations, walk-throughs, etc.) were found to be similar to those that were used by the University of Maryland when conducting State energy audits. These similarities in approach and validation provide the justification for our methods and the important premise that the University of Maryland energy audit reports have value once completed. As stated earlier when trying to find an energy auditing guide for commercial maintenance buildings there is a gap in the literature. To fill this void of how-to energy audit commercial maintenance facilities, a comparison of other guides was used to determine methods that are valid and create a unique combination of energy recommendations that can be specifically useful to the commercial maintenance style building.

A common building type with high energy use (and the potential for significant savings) are industrial buildings which have significant literature for energy auditing such as "Industrial Energy Audit Guidebook: Guidelines for Conducting an Energy Audit in Industrial Facilities" by Ali Hasanbeigi and Lynn Price [12]. This guide offers a start to finish plan for energy auditing that includes multiple steps in preparing for auditing, auditing/analysis, post audit, and recommending EEMs for industrial processes. The industrial equipment that this guide covers includes electric motors, compressed air, pumping, fans, lighting, steam, and process heating. When auditing industrial process buildings, these components are the most important, accounting for 81% of energy used in industrial buildings [12]. Thus, prioritizing industrial energy audits towards these large consumers of energy is the most effective method; and while there is significant overlap in equipment used between industrial buildings and transportation maintenance facilities, the limitation of the guide is apparent when comparing use intensity of the equipment in each facility. Transportation maintenance facilities have a lower use intensity in comparison to manufacturing facilities since the processes are maintenance based and mixed with office use portions of the building. Another limitation to the guide produced by Hasanbeigi and Price is that it lacks a case study as a companion to their recommendations (for illustrative purposes). In this paper, a model based on current construction and equipment is provided for one of the maintenance facilities to validate the recommendations.

Another style of energy auditing guide “Energy Efficiency Design Strategies in Office Buildings: A Literature Review" by E. M. Erebor, E. O. Ibem, et. al. provides potential energy savings factors for office style buildings [13]. The factors addressed in the post-construction phase include the installation of occupancy and CO_2 sensors, daylight control mechanisms, and active, real-time data collection of energy use. The use of CO_2 sensors determines when a room needs to have conditioning due to the concentration level of CO_2 detected; thus, reducing energy consumption by only conditioning an unoccupied or slightly occupied area when necessary [13]. Daylight controls, where a sensor determines how much artificial lighting needs to be used in addition to the natural lighting through windows determines the necessary power levels and in turn reduces energy consumption [14]. These types of ECMs are useful for office style areas since there are few other significant operational processes occurring; and typically lighting accounts for 35% of energy consumed in commercial buildings [15]. Although the factors found in these two energy auditing guides are important, they only slightly address HVAC equipment use which can account for 35% of a commercial building's energy use [16]. This paper looks to determine ways to increase the building's HVAC efficiency beyond just the use of the equipment; but also, through the installation of additional equipment such as ERVs or VFDs.

A final energy audit guide that has been created to streamline the energy auditing processes is “Energy Audit of Building Systems: An Engineering Approach, Third Edition” created by Moncef Krarti. This guide provides details for auditing industrial and commercial buildings to include major areas such as the building envelope, electrical systems, HVAC systems, compressed air systems, energy management controls, indoor water management, and new technologies [17]. This guide is effective because it offers a significant analysis of the building operations that can be applicable to commercial buildings independent of the type of use. This is advantageous because in 2012, an estimated 4.5 million commercial buildings in the United States have HVAC systems [18], which as previously mentioned consumes nearly 35% of the buildings energy. This fact alone demonstrates the application and importance of the guide for all versions of public facilities Additionally, this guide provides for analysis of other factors that are common in almost every building including lighting, water, and a building envelope. While this guide provides an effective road map for all energy auditing applications, it is limited in scope and detail for those looking to complete energy audits for maintenance facilities. The recommendations need to be broad enough for all the commercial and industrial buildings. In contrast, the goal of this paper is to create a slightly narrower scope for the mixed-use systems, processes, and building operations that are typical in MTA commercial maintenance style facilities.

Although the energy auditing guides are effective in their respective applications (industrial, offices, and general industrial/commercial buildings), there remains a gap in documentation and research for how to most effectively complete audit commercial maintenance facilities. From the current energy auditing guides that are publicly available and published, there are recommendations for how to lower energy consumed by specific types of equipment, reduce energy consumption in office areas, and general audit guidelines to look for. However, no entity has yet to create a guide for maintenance facilities that details recommendations associated with the building envelope, HVAC system, and other building operations. This paper will aim to take the applicable aspects of each of these guides (as reviewed and evaluated) and combine it with the experience and information that has been gained through the completion of energy audits on maintenance/repair facilities for the State of Maryland.

3.3 Case Study 1: North Avenue Light Rail Maintenance

Figure 3: The street view of the North Avenue Light Rail Maintenance Facility.

3.3.1 Data Collected for Case Study 1: North Avenue Light Rail Maintenance

The North Avenue Light Rail Maintenance facility (North Ave) is primarily used as a maintenance facility for light rail train cars. There are secondary uses for administration in offices within the same building. The maintenance facility is located at 340 W North Ave, Baltimore, MD. The original construction was completed in 1991 and consisted of a two-story building with an overall total area of 107,000 square feet. The maintenance areas are not cooled during the summer but are heated using radiant heat in the winter with a 24/7 occupancy. The office areas are on the central heating and cooling from the building systems with a typical Monday to Friday, 9AM-5PM occupancy. The conditioned areas are set to a year-round 74°F.

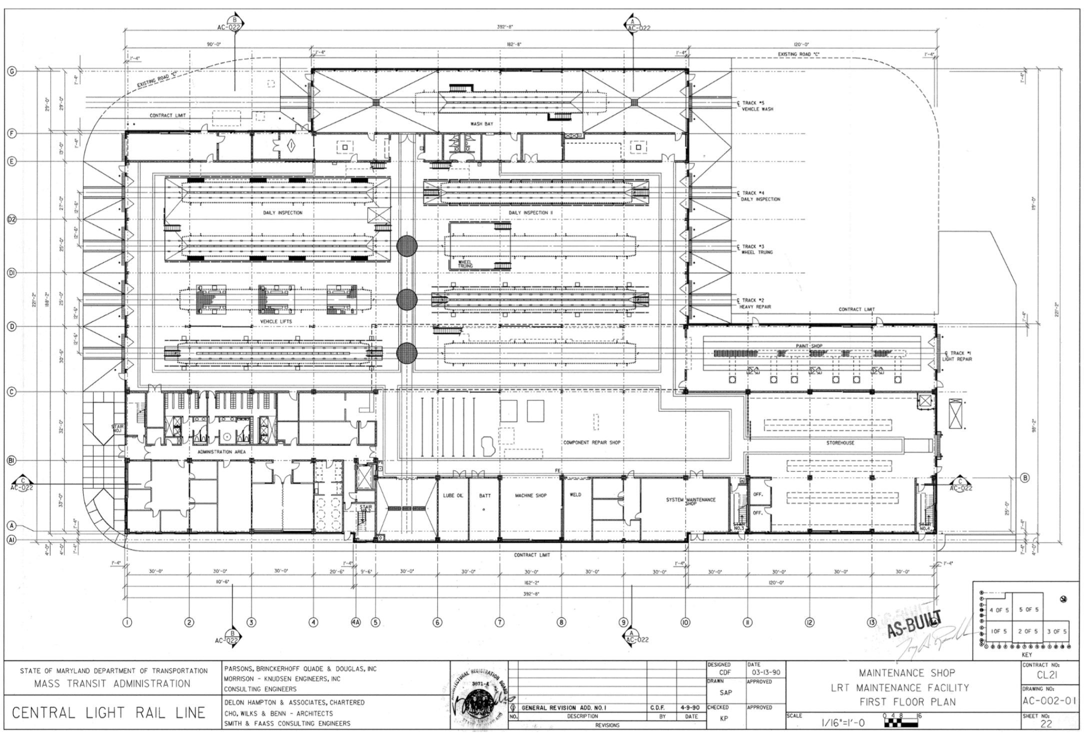


Figure 4: The as-built first-floor plan for North Avenue Facility.

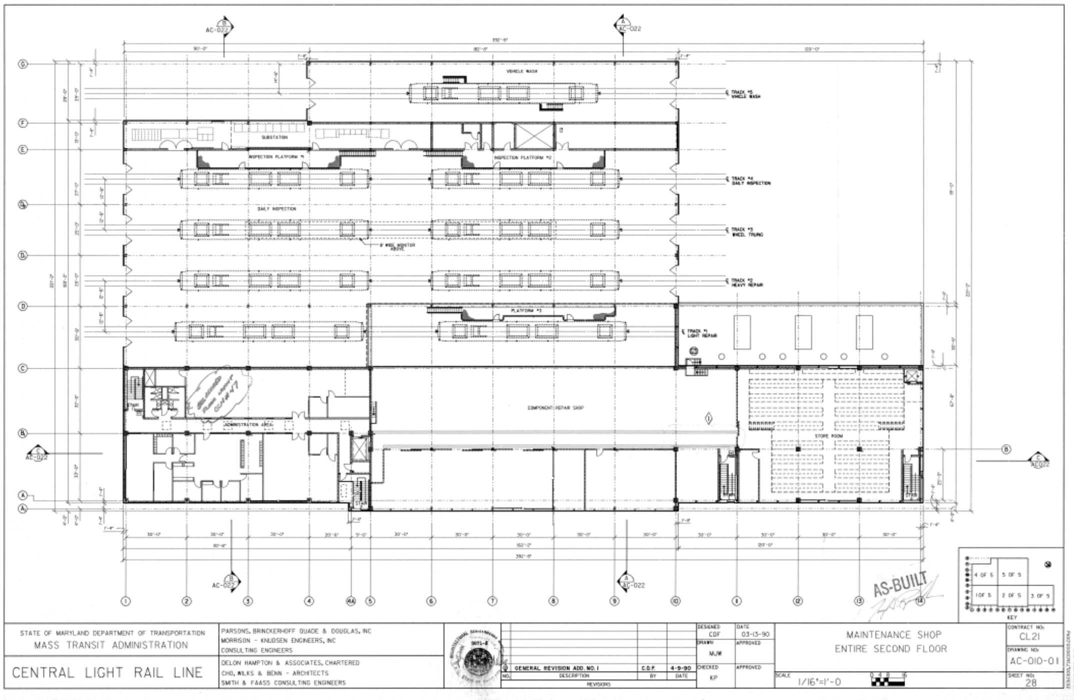


Figure 5: The as-built second-floor plan for North Avenue Facility.

HVAC system: North Avenue Light Rail Maintenance

The current major HVAC systems that are installed in North Avenue include 3 Air Handling Units (AHUs), 5 heat pumps, 6 rooftop units (RTUs), and 6 HVs. There are some additional minor systems within the building that include 15-unit heaters, 11 electric duct heaters, and 50 fans. The current control sequence for the HVAC system is based on the temperature setpoint of 74°F within the building as there are no building automation systems currently installed.

Energy Usage (FY2018): North Avenue Light Rail Maintenance

In FY2018, there were two main energy sources: grid electricity and natural gas. The total energy usage was 2,854,388 kWh of electricity and 50,674 Therms of natural gas. This led to a EUI of 39.71 kWh/ft^2 which is above the EnergyStar reference for "other maintenance facilities" of 14.04 kWh/ft^2. This provides a general sense that the building is not being operated in an energy efficient manner. Additionally, the load factor was calculated for the facility to be 0.22, which is well below the standard of 0.7. This low load factor denotes a large inefficiency in electricity usage.

<u>*3.4 Case Study 2: Bush Bus Maintenance*</u>

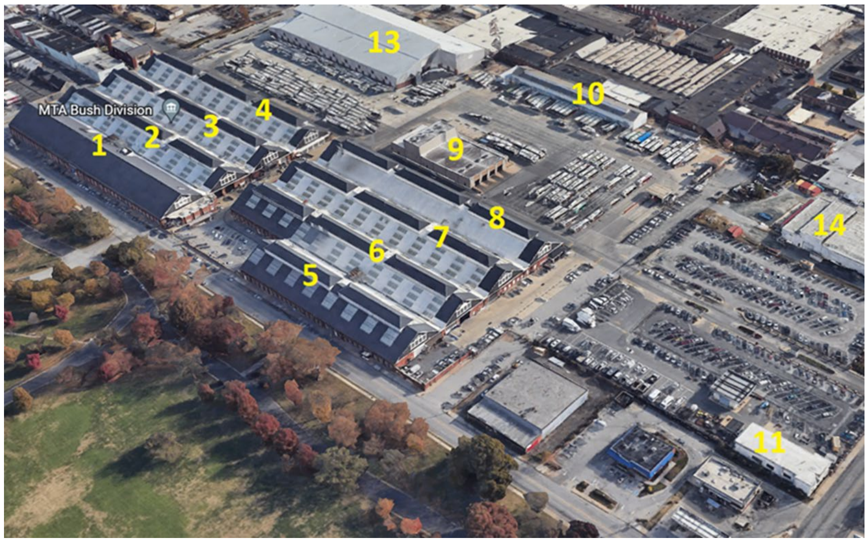


Figure 6: Aerial view of the Bush Bus Maintenance Facility.

3.4.1 Data Collected for Case Study 2: Bush Bus Maintenance

The Bush Facilities' main use is for the maintenance of publicly used buses. There are also secondary uses within the facility that are used for administrative purposes and storage. The facility buildings 1-11 are located at 1515 Washington Blvd, Baltimore, MD 21230. There are two additional buildings; building 13 located at 1300 Bush Street, Baltimore, MD 21230 and building 14 located at 1331 South Monroe Street, Baltimore, MD, 21230. The total combined square footage of these buildings is 624,222 square feet. A summary breakdown of the total square footage and uses of the 13 buildings is shown in table 1 below. The maintenance areas are not connected to the central heating and cooling systems. Instead, they only utilize unit heaters during the winter and fans during the summer. The administrative areas utilize central heating and cooling systems. The storage areas do not have any type of heating or cooling and are only accessed when necessary.

Table 1: Bush Bus Maintenance Facility building information breakdown.

Building No.	Primary Use	Construction Year	Number of floors	Square Footage (sq. ft)
1	Administrative	1903	2 + Attic	15,832
2	Maintenance/Vehicle Acceptance	1903	2 + Attic	78,034
3	Administrative/Training	1903	2 + Attic	11,503
4	Maintenance/Vehicle Recovery	1903	2 + Attic	52,184
5	Maintenance/Truck Shop	1903	2 + Attic	76,179
6	Maintenance/Body Shop	1903	2 + Attic	77,519
7	Maintenance/Brake Shop	1903	2 + Attic	74,139
8	Maintenance/Print Shop	1903	2 + Attic	64,035
9	Maintenance/Wash House	1975	2	35,766
10	Administrative/ Material Storage	1975	2	35,766
11	Maintenance	1974	2	3,859
13	Main Shop	2014	3	64,900
14	Administrative/ Material Management	1950	2	34,506

HVAC System: Bush Bus Maintenance

The buildings within this facility are all near each other and as a result, have some shared systems to provide the heating and cooling to the administrative areas in each. The shared systems are expressed in table 2 below, to show how heating and cooling systems are shared.

Table 2: Bush Bus Building heating and cooling relationships.

Building	Heating Source	Cooling
1	5	2,3
2	5	N/A
3	5	3
4	5	3
5	5	3
6	5	3

Building 1 major equipment includes AHUs, Variable air volume boxes (VAV), unit heaters, and exhaust fans.

Building 2 has chillers, HV units, steam unit heaters, exhaust fans (EFs), high volume low speed (HVLS) fans, heat pumps, and pumps. The HVAC equipment in this facility is operated based on a DDC system by Pritchett Controls. The DDC system in places operates the heating and cooling to maintain a year-round temperature of 75°F in the area it supplies.

The major HVAC equipment in Building 3 includes pumps, cooling towers, and a centrifugal separator. For building 4, major HVAC equipment includes fan cooled VFDs, hot water heaters, air compressors, room heaters, and an air blower motor. Building 5 has major HVAC equipment of pumps, boilers, AHU compressors, heat pumps, hot air blowers, and pumps. Building 6 major equipment is a hot air blower and exhaust fans. Building 7 has MAUs, air compressors, exhaust fans, unit heaters, and an air dryer as its major HVAC equipment. Within Building 8, there are AHUs, exhaust fans, pumps, and a compressor. Building 9 has air blowers and pumps as the HVAC systems. Buildings 10 and 11 have no HVAC equipment in the building according to the data that was provided to us by the facility managers. Building 13 has unit heaters, HV units, exhaust fans, and heat pumps.

Building 14 uses AHUs, an RTU, fans, water heaters, and heat pumps as its major HVAC equipment. The building has morning cool-down and heat-up sequences. There is also temperature set points in place for both occupied and unoccupied conditions. In the winter the unoccupied temperature is 60°F and occupied temperature of 70°F. In the summer the unoccupied temperature is 85°F and occupied temperature of 75°F.

Energy Usage (FY2018): Bush Bus Maintenance

For the Bush Bus Maintenance Facility, there were three sets of meter data provided to the energy audit team, and these were used in the energy calculations for the facility. The sets of meters are Buildings 1-11 grouped together, while Buildings 13 and 14 have individual meters.

For Buildings 1-11, in FY2018, there were two main energy sources: electricity and natural gas. The total energy usage was 5,836,979 kWh of electricity and 153,977 Therms of natural gas. This led to an EUI of 22.3 kWh/ft^2 which is above the EnergyStar reference for other maintenance facilities of 14.04 kWh/ft^2. This gives a general sense that the building is not operating in an energy-efficient way. Second, the load factor was calculated for the facility to be 0.73, which is below the standard of 0.75. The lower load factor denotes potential inefficiencies in electricity usage.

For Buildings 13, in FY2018, there were two main energy sources: electricity and natural gas. The total energy usage was 23,050 kWh of electricity (F1515) and 34,086 (1515) Therms of natural gas. This led to an EUI of 15.74 kWh/ ft^2 which is above the EnergyStar reference for other maintenance facilities of 14.04 kWh/ft^2. This gives a general sense that the building is not operating in an energy-efficient way. Second, the load factor was calculated for the facility to be 0.54, which is well below the standard of 0.75. The low load factor denotes a large inefficiency in electricity usage.

For Buildings 14, in FY2018, there were two main energy sources: electricity and natural gas. The total energy usage was 25,050 kWh of electricity and 34,086 Therms of natural gas. This led to an EUI of 26.74 kWh/ft^2 which is above the EnergyStar reference for other maintenance facilities of 14.04 kWh/ft^2. This gives a general sense that the building is not operating in an energy-efficient way. Second, the load factor was calculated for the facility to be 0.54, which is well below the standard of 0.75. The low load factor denotes a large inefficiency in electricity usage.

3.5 Case Study 3: Old Court Metro Maintenance

Figure 7: Street view of the Old Court Maintenance.

3.5.1 Data Collected for Case Study 3: Old Court Metro Maintenance

The Old Court Metro Maintenance facility building's main use is for the maintenance of publicly used metro cars. Additional areas within the building are used for administrative, storage, and locker rooms. The facility is a single building located at 4380 Old Court Rd, Pikesville, MD 21208 and was constructed in 2006. The total square footage is 36,367 sq. ft. The maintenance areas are not connected to the central heating and cooling systems. Instead, they only utilize unit heaters during the winter and fans during the summer. The administrative areas utilize central heating and cooling systems. The storage areas do not have any type of heating or cooling and are only accessed when necessary.

HVAC System: Old Court Metro Maintenance

The major equipment that is present in the Old Court Facility is 7 RTUs, 11 exhaust fans, 28-unit heaters, 1 HW, and 3 pumps. There is a DDC (Direct Dynamic Control) BAS that is used to control the building's HVAC system based on the two-season occupied and unoccupied setting. When occupied there is a year-round temperature set point is 75 F.

Energy Usage (FY2018): Old Court Metro Maintenance

The Old Court facility has three main sources of energy: natural gas, electricity, and oil. However, the oil data is non-continuous and doesn't follow a pattern of use, so it was omitted for the calculation of our benchmarks. As a result, we consider the two remaining main energy sources: electricity and natural gas. The total energy usage was 742,547 kWh of electricity and 30,350 Therms of natural gas. This led to an EUI of 44.75 kWh/ ft^2 which is above the EnergyStar reference for other maintenance facilities of 14.04 kWh/ft^2. This gives a general sense that the building is not operating in an energy-efficient way. Second, the load factor was calculated for the facility to be 0.74, which is slightly below the standard of 0.75. However, as more modern buildings can operate up to a load factor of 0.9, there is still room for increased electrical efficiency.

3.6 Case Study 4: MARC Riverside Maintenance Facility

Figure 8: Street view of MARC Riverside Maintenance Facility

3.6.1 Data Collected for Case Study 4: MARC Riverside Maintenance Facility

The MARC Riverside Maintenance Facility contains 4 different buildings that utilize shared utility meters. The MARC Maintenance's primary use is the maintenance of MARC public transit cars and administrative purposes. The facility is located at 1600 Ludlow Street, Baltimore, Maryland, and has a total area of 71,547 ft^2. The buildings are denoted as 2,3,4 and 7 since other buildings within the facility were no longer in use or demolished. Buildings 2,3 and 4 were originally built in 1978 while building 7 was built in 2018 and is used exclusively for administration. Similar to the other case studies, the maintenance areas are not connected to the central building HVAC, instead they utilize large ceiling fans and open garage doors in the summer and unit heaters in the winter. The administrative areas are connected to a central HVAC distribution to provide heating in the winter and cooling in the summer.

Table 3: Riverside MARC building square footage and use.

Building	Square Footage	Building Use
2 & 3 (combined)	48,154	Maintenance and Administration
4	14,273	Maintenance
7	9,120	Administration

HVAC System: MARC Riverside Maintenance

The major HVAC equipment in Buildings 2 and 3 are 6 MAUs, 18 coil heaters, 8 water unit heaters, 1 electric water heater, 3 oil pumps, 2 water pumps, and 17 exhaust fans. Building 4 major HVAC equipment includes 9 water unit heaters, a pump, ceiling fan, and 4 exhaust fans. Building 7 has 6 AHUs with condensing units and a single exhaust fan. There is no BAS system that is used at the MARC Riverside facility, however, using the unit heaters the maintenance area has a setpoint of 65°F in the winter. Additionally, the administrative areas have a year-round set point of 75°F.

Energy Usage (FY2018): MARC Riverside Maintenance

The MARC facility utilizes only one source of energy: grid electricity. The facility has previous year data that utilized oil, but this practice was discontinued in 2015. The total usage of electricity for FY2018 was 1,619,544 kWh. Using this value, the calculated EUI was found to be 22.64 kWh/ft^2 which is above the EnergyStar reference for other maintenance facilities of 14.04 kWh/ft^2. The load factor was 0.67 which is slightly below the minimum standard of 0.75 and denotes the potential for electrical efficiency upgrades.

Chapter 4: EEM Application by Case Study

4.1 Energy Efficiency Measures

The results of the completed energy audits were presented as a compiled list of energy efficiency measures (EEMs) that could be implemented to increase the building's overall efficiency. As each building has a different selection of characteristics, there are different variations of EEMs that were recommended to each facility. However, although the selected EEMs may vary, the overall reasons for recommending the EEM are typically the same.

4.1.1 Installation of a Building Automation System (BAS)

The goal of a full BAS is to connect lighting, HVAC, and occupancy schedules. This can be accomplished by setting a sequence of operations that allow for the building to have set startup and shut down sequences for the HVAC equipment. Additional features of a BAS can be added such as smart thermostats which are WIFI compatible and work by connecting real-time weather data with the BAS. A study by Ecobee found their Smart thermostats saved 0.0480 therms/ft^2 (13.3%) at an average temperature of 67.7°F for heating and 0.1808 kWh/ft^2 (14.5%) at an average temperature of 72.3°F for cooling [19]. Another aspect of BAS that can be added are occupancy sensors which could be used to determine when lighting and air conditioning are needed for certain areas. The studies for occupancy sensor savings varied by area of the building, as shown in table 4 below, but for a typically unoccupied building area with lights that operate roughly 8 hours a day the savings can be 0.05 - 0.20 $/sq. ft. [20]. The occupancy sensors would only be applicable to the office areas of these buildings since they operate on the typical 9AM-5PM work schedule, while the maintenance areas are occupied 24/7.

Table 4: EPA predictions for energy savings with occupancy sensors based on space type [20].

Type of Space	U.S. EPA Energy Savings Prediction
Private Offices	13-50%
Conference Rooms	22-65%
Restrooms	30-90%
Corridors	30-80%
Storage Areas	45-80%

The overall potential energy savings of a BAS being installed in a building without any prior automation controls can lead to savings of \$0.20 - 0.40/ft^2 [21].

Case Study 1 Application: North Avenue Light Rail Maintenance

The North Avenue facility doesn't have a BAS system. As a result, the S2TS Team is recommending the installation of occupancy sensors and smart thermostats. Most of the North Avenue facility, 85%, operates as a maintenance facility which only has air conditioning in the winter months to provide heat. As a result, the installation of a full BAS system would be costly and mainly support the office area, a fraction of the remaining 15% area. A full BAS installation would result in a long-term ROI and would not be economically feasible/advantageous for this facility, however, smart thermostats and occupancy sensors are much cheaper and can provide many of the wanted BAS capabilities.

Case Study 2 Application: Bush Bus Maintenance

Since the Bush Bus Facility consists of 13 different buildings, the BAS that has been recommended for each building is slightly different. The typical trend was that for all buildings where the primary use was for administration a full DDC BAS would be most beneficial. In contrast, in buildings with mixed-use between administration and maintenance only occupancy sensors and smart thermostats were recommended. There were also considerations for buildings with very little square footage or little to no available HVAC systems. These buildings did not receive any BAS recommendations since they wouldn't have significant energy or cost savings in comparison to the installed cost; however, it is still recommended to ensure that the temperature set points on smart thermostats were adjusted per season and matched to ASHRAE standards. The breakdown of the recommended levels of BAS are shown below in table 5.

Table 5: Bush Bus BAS recommendations.

Building	Current Controls	Proposed Controls	Functionality
1	-	Smart Thermostats and Occupancy Sensors	Temperature and Lighting controls
2	Chillers controlled with BAS	BAS	Temperature, Lighting, and Humidity Control
3	-	Smart Thermostats and Occupancy Sensors	Temperature and Lighting controls
4	-	Smart Thermostats and Occupancy Sensors	Temperature and Lighting controls
5	-	BAS	Temperature, Lighting, and Humidity Control
6	-	Smart Thermostats and Occupancy Sensors	Temperature and Lighting controls
7	-	BAS	Temperature, Lighting, and Humidity Control
8	DDC Controls	Smart Thermostats	Automated temperature controls over manual control
9	DDC Controls	Smart Thermostats	Automated temperature controls over manual control
10	-	-	-
11	-	-	-
13	-	-	-
14	-	-	-

Case Study 3 Application: Old Court Metro Maintenance

Since the Old Court Metro facility was already operating on a DDC BAS system, it was key to understand what aspects of an updated system would most impact the facility. The study found that the facility did not utilize the Smart thermostats to link outside and indoor conditions as well as occupancy schedules. Additionally, there were no occupancy sensors present in the facility. Thus, the S2TS Team recommendation was to install both smart thermostats and occupancy sensors to enhance the current DDC BAS.

Case Study 4 Application: Riverside MARC Maintenance

The Riverside MARC facility did not have any BAS present in any of the four buildings. For buildings 2, 3, and 7 it was recommended to install full DDC BAS with Smart thermostats and occupancy sensors. This was dictated by the primary administrative use of the buildings as well as the significant HVAC systems present in each. Building 4, had less HVAC equipment as well due to its use being primarily maintenance in nature.

Table 6: Riverside MARC BAS recommendations

Building	Current Controls	Proposed Controls	Functionality
Buildings 2 &3	None	BAS Installation, Smart Thermostats, Occupancy sensors	Integration between lighting, HVAC, and smart thermostats. Automated Temperature and Lighting Controls.
Building 4	None	Smart Thermostats, Occupancy sensors	Automated Temperature and Lighting Controls.
Building 7	None	BAS Installation, Smart Thermostats, Occupancy sensors	Integration between lighting, HVAC, and smart thermostats. Automated Temperature and Lighting Controls.

4.1.2 Plug and Process Load Reduction

Plug and Process Load Reduction are used to reduce the load of plug-in devices in a facility. These plug-in devices include but are not limited to typical office equipment (computers, printers, etc.), vending machines, and refrigerators. Additionally, it considers equipment that can utilize VFDs (variable frequency drives) and devices that may be in use but are past their useful life, thus causing inefficiencies. The recommendations that are provided to reduce smaller plug loads are the use of APS (advanced power strips) which eliminate vampire loads or electrical usage when the equipment is not in use. For APSs, there can be annual savings of 84 kWh/year/strip use in a typical PC environment [22]. Additionally, for other equipment such as refrigerators, there are recommendations given to upgrade EnergyStar certified appliances when the useful life of the current equipment is exhausted. EnergyStar certified equipment such as refrigerators operate at a minimum of

9% more efficiency than the federal standard which leads to direct energy and monetary savings [23]. The application of VFDs is only beneficial to pumps and motors that are above 5 HP since the ROI is only reasonable for higher power equipment. The use of VFDs modulate the amount of power provided to motors or pumps and only supply the maximum level of power when it is needed. By not operating at constant full speed, there can be significant energy savings. An example of this savings results from installing a VFD and decreasing the motors speed by 25%. This reduction will consume nearly 60% less energy [24]. Finally, for equipment that is past its useful service life, the S2TS team has recommended that it be replaced. Once equipment has passed its useful life there are significant inefficiencies which result in increased operational costs.

Case Study 1 Application: North Avenue Light Rail Maintenance

Since the North Avenue facility is partially used for administrative purposes, it is assumed that there is typical office equipment in use such as: computers, printers, fax machines, etc. To capture energy savings at these devices the S2TS Team has recommended the implementation of APS. Additionally installed motors within the facility can benefit from VFD installation, shown in table 7 below.

Table 7: North Avenue Light Rail motors and devices that can benefit from VFDs.

Device	Zone Served	Model Number	Number of units	Power Rating (HP)
Exhaust Fans	Paint Booth	Baldor M3615T	6	5.5
Water Pump	Compressor Room	Baldor M3615T	1	20

Case Study 2 Application: Bush Bus Maintenance

For the Bush Bus Facility, there were buildings that were solely used and mixed-use for administrative purposes. These areas were assumed to have typical office equipment where APS can be utilized. There were also motors identified as which could benefit from VFDs which are given in table 8 below.

Table 8: Bush Bus equipment that could benefit from VFDs.

Building	Device	Model Number	Number of Units	Power Rating (HP)
2	Air Compressor	CBV785286	1	>5
3	Pumps 1-2	B & G SERIES e-1510 4EB Baldor Reliance EM2513T	2	14 15
4	Air Blower Motor	Baldor Reliance EM2531T	1	15
5	Pumps 3-10 AHU Compressor 1-2	Taco FE4008 Taco FE3010 (x2) Carrier 39EH21/50BB028520	1 2 2	20 20 >5
7	Vehicle Exhaust Fans	DSP MONOXIVENT	2	5
9	Air Blower Motors	Marathon Globetrotter VM 215TTDB6026 BB H	4	10
13	Exhaust Fan	Chassis Dyno 134	5	5

Additionally, there are a significant number of appliances present that could be transitioned to the EnergyStar rated equivalents to benefit from their increased efficiency, shown in table 9.

Table 9: Bush Bus appliances that can be replaced with recommended EnergyStar-rated equivalents.

Building	Unit	Number of Units	Power Rating (kW)
1	Vending Machine	2	0.34
	Refrigerator	1	0.78
	Ice Maker	1	0.16
5	Vending Machine	1	1.9
	Window AC Units	2	0.55
	Ice Maker	1	0.16
6	Refrigerator	1	0.8
8	Ice Maker	1	0.2
	Refrigerator	3	0.8
11	Refrigerator	2	0.8
	Portable Cool Unit	2	1.4
13	Washer #1	1	57.4
	Washer #2	1	76
	Refrigerator	3	0.78
	Vending Machine	2	0.4

Since the buildings were originally built from 1903 - 1974 there is equipment still in use that is well past its useful life. These devices are identified with the current age and recommended useful life (in years) below in table 10.

Table 10: Bush Bus equipment that is past their useful life.

Building	Device	Model (Model Year)	Number of Units	Useful Life (Years) [25]	Power Rating (HP)
1	Unit Heaters	VULCAN / MODEL #RC-1200-04 (1996)	1	25	1/10
		VULCAN / MODEL #RC-1200-03 (1996)	1		1/10
		VULCAN / MODEL #W-1080-02 (1996)	1		1/10
		VULCAN / MODEL #HV-118A (1996)	1		1/50
		VULCAN / MODEL #HV-72 (1996)	1		1/30
5	Pump	Taco FE4008 (1996)	1	15-20	15
		Taco FE3010 (1996)	1		15
		Taco FE3010 (1996)	1		20
7	Air Compressor	Sullair LS10 (2002)	2	10-15	30

Case Study 3 Application: Old Court Metro Maintenance

The Old Court facility is partially utilized for administrative purposes which has been assumed to utilize typical office equipment, so APSs are recommended in these areas. The VFD recommendations for this facility are shown in table 11 below.

Table 11: Old Court equipment that could benefit from VFDs.

Building	Device	Model Number	Number of Units	Power Rating (HP)
Old Court Maintenance	Heating Water Pump	Super-E EJMM3218T	3	5

The appliances identified in the Old Court facility that can be replaced with EnergyStar rated equivalents given in table 12.

Table 12: Items that can be replaced with recommended EnergyStar-rated equivalents in the Old Court facility.

Building	Unit	Number of Units	Power Rating (kW)
Old Court Maintenance	Refrigerator	2	0.8
	Vending Machine	2	0.4
	Ice Maker	1	0.2

The original construction of the facility was constructed in 2004 and has equipment in use that is past its useful life and is identified below in table 13.

Table 13: List of equipment that is past its useful life in the Old Court facility.

Building	Device	Model (Model Year)	Current Age	Number of Units	Useful life (Years) [25]	Power Rating
Maintenance	Rooftop AC Unit	57855 RM-007-3-0-AA01-EHN (2004)	18	3	15	18 kW
	Rooftop AC Unit	57856 RM-008-3-0-AA02-EHJ (2004)	18	3	15	13.3 kW
	Rooftop AC Unit	RM-013-3-0-AB-02-EJH (2003-2010)	13-20	1	15	-
	Split system Heat Pump	Mr. Slim (2004)	18	1	15	0.2 kW
	Heat Pump	Marathon Electric UVF 143TTDR6030AA P (1989)	33	2	20	1
	Sump Pump	Hydromatic Pumps S3HX150M4-4 (1986)	36	2	10	1.5

Case Study 4 Application: Riverside MARC Maintenance

For the MARC Riverside Facility, there were buildings that were solely used and mixed use for administrative purposes. These areas were assumed to have typical office equipment where APS can be utilized. There were also motors identified as which could benefit from VFDs which are given in table 14 below.

Table 14: Equipment that could benefit from VFDs in the Riverside Maintenance Facility.

Building	Device	Model Number	Number of Units	Power Rating (HP)
Riverside Maintenance 2 & 3	MAU Motor 1-6	-	6	15
	EF 1 & 2	-	2	5
Riverside Maintenance 4	Circulation Pump	-	1	5

There are a significant number of appliances present in the facility that could be upgraded to EnergyStar equivalents. These appliances are listed below in Table 15.

Table 15: Items that can be replaced with recommended EnergyStar-rated equivalents at the Riverside facility.

Building	Unit	Number of Units	Power Rating (kW)
Riverside 2 & 3	Refrigerator	2	0.8
	Vending Machine	2	0.34
	Window AC Units	14	0.6

The equipment that is past its useful life and may need to be replaced is given in table 16.

Table 16: MARC Riverside equipment that may be past their useful life.

Building	Device	Model (Model Year)	Current Age	Number of Units	Useful life (Years) [25]	Power Rating
Buildings 2 & 3	Boiler	Cleaver Brooks CB100-300 (1980)	42 years	2	25	12,553 MBH
	MAU	-	~30	6	15	17.5 kW
	Coil Heaters (L1-16)	-	~30	16	13	0.9 kW
	Small Water Heaters (T1-4)	-	~30	4	12	0.09 kW
	Large Water Heaters (T5-9)	-	~30	5	12	0.9 kW
	Exhaust Fan	-	~30	2	15	6.3 kW
	Exhaust Fan	-	~30	15	15	0.9 kW
	Coil heaters	-	~30	6	10	0.09 kW
	Coil heaters	-	~30	2	10	0.9 kW
	Water Pumps	-	~30	2	20	41.6 kW
Building 4	Small Coil Heaters	-	~30	6	10	0.09 kW

	Big Coil Heaters	-	~30	3	10	0.9 kW
	Circulation Pump	-	~30	1	20	6.3 kW
	Exhaust Fan	-	~30	4	15	0.9 kW

4.1.3 Energy Recovery Ventilators

Energy Recovery Ventilators (ERVs) can be added to an existing building HVAC system and can contribute to decreasing the energy required to condition cooling and heating air. ERVs accomplish this by directing the exhaust air from a given space into a heat exchanger mixed with outside air that is coming into the system as shown in figure 9. Within the heat exchanger, heat and moisture is transferred from one stream to the other making the outside air closer to the desired indoor environment without any cross contamination [26]. This means that the energy required to finish conditioning the air is less than before the heat exchanger. Implementation of ERVs have a relatively short payback period ranging from 1-3 years depending on the size of the system, the building's geographic location and the remaining useful life of the system (over 20 years) [26]. ERVs have efficiencies ranging from as low as 45% to as high as 65% [26]. ERVs can result in savings as high as 40% of HVAC operating costs [26]. They also assist in shaving the peak electrical demand (kW) and thus improve the load factor of the facility. For a typical office building that uses 10% outside air, ERVs can save $1/CFM/annually [27]. For this reason, we investigate the individual components and HVAC systems at the MTA facilities to determine if they have any energy recovery devices (ERVs, HRVs, or ERWs) present in devices that could benefit. One limitation to this technology is when ductless split systems are being used to cool an indoor environment. Since these devices are connected via the ductwork, they cannot apply to this type of equipment. Additionally, of the three potential options (ERV, HRV, and ERW) the ERV is the only device that can be applied to heating, cooling, as well as sensible and latent heat. This makes it the optimal choice, however, if an HRV or ERW is currently installed and operating then it isn't economically viable to remove and replace with an ERV.

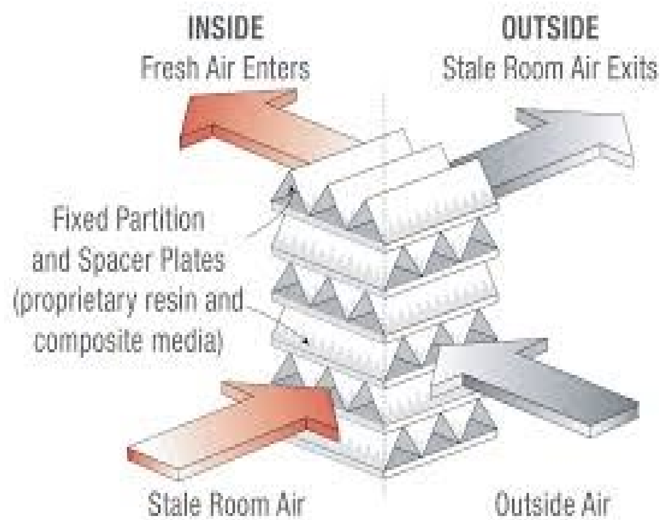


Figure 9: Diagram of crossflow in ERV between stale and outside air.

Case Study 1 Application: North Avenue Light Rail Maintenance

North Avenue utilizes conditioned air for parts of the building including administrative areas. There are AHUs that supply conditioned air to these areas that do not already have ERWs installed in the systems, making them available for ERV installation. The AHUs and their power rating are listed below in table 17.

Table 17: List of equipment at North Avenue that may benefit from ERVs.

Applicable System	Model Number	Number of Units	Power Rating (kW)
AHU 1-6	Carrier 48PMEM24-CB61-A0	1	40.5
	Carrier 48HCDD24ACA6 A0B0A0	1	121
	Carrier 48HCED08A2A6A 0B0A0	1	48.8
	York D1EB036A06B	1	4.6
	York D4CE150A46B	1	28.4
	Carrier 48HJD008631	1	13.7

Case Study 2 Application: Bush Bus Maintenance

The Bush Bus facilities have significant HVAC systems on the premises in order to condition air that is going to the administrative and mixed-use buildings. From this HVAC system we can investigate the individual components at the facility. Some of the currently installed devices have Energy Recovery Wheels (ERWs), so ERVs were not recommended on top of those devices. The remaining large air handling devices that could benefit from ERV installation have been listed below in table 18.

Table 18: List of equipment at Bush Bus that may benefit from ERVs.

Building	Applicable System	Model Number	Number of Units	Power Rating (kW)
1	AHU	YORK MODEL #CSI113	1	7
		YORK MODEL #CSI156	1	11.6
		YORK MODEL #CSI156	1	11.6
		YORK MODEL #CSI158	1	15
		YORK MODEL #CSI74	1	7
		YORK MODEL #CSI113	1	7
		YORK MODEL #CSI74	1	7
		YORK MODEL #CSI113	1	7
2	HV	MCQUAY VISION/CAH050 GHAC	3	12.5

Case Study 3 Application: Old Court Metro Maintenance

The Old Court facility has a completely conditioned second floor as well as some offices on the first floor that are fed conditioned air by the RTUs. These RTUs can benefit from the installation of ERVs since there is no prior installed energy recovery device. The RTUs mentioned and their power rating are given in table 19 below.

Table 19: List of equipment at Old Court that may benefit from ERVs.

Applicable System	Model Number	Number of Units	Power Rating (kW)
RTU 1-7	57855 RM-007-3-0-AA01-EHN	1	18
	RM-013-3-0-AB-02-EJH	1	21.3
	57855 RM-007-3-0-AA01-EHN	1	18
	57856 RM-008-3-0-AA02-EHJ	1	13.3
	57856 RM-008-3-0-AA02-EHJ	1	13.3
	57855 RM-007-3-0-AA01-EHN	1	18
	57856 RM-008-3-0-AA02-EHJ	1	13.3
	57855 RM-007-3-0-AA01-EHN	1	18

Case Study 4 Application: Riverside MARC Maintenance

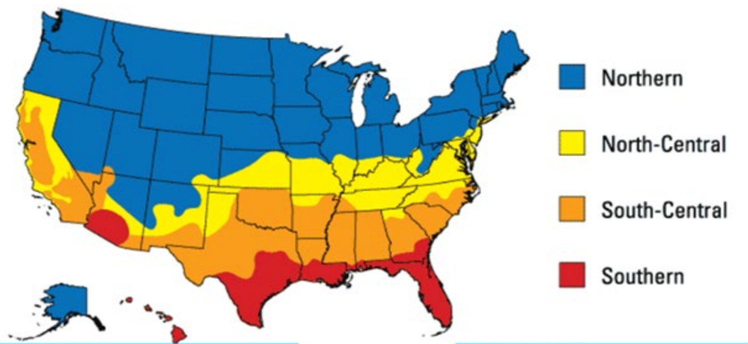
The Riverside buildings 2 & 3 have significant air conditioning in place for the mixed-use facilities. The office and conditioned areas are fed by six MAUs that could benefit from ERVs. Building 4, has no large HVAC devices that are used to condition air, so there are no ERV installation opportunities available. Building 7, is an administrative only building and is conditioned by six AHUs that could also have ERVs used to reduce energy consumption. The equipment for riverside that could benefit from the installation of ERVs is listed below in table 20.

Table 20: List of equipment at Riverside that may benefit from ERVs.

Building	Applicable System	Model Number	Number of Units	Power Rating (kW)
2 & 3	MAU 1 - 6	N/A	6	17.5
7	AHU 1 - 6	(Trane) In: GAM5BOC48 / Out: 4TWR5049E1	3	14.4
		(Trane) In: GAM5BOC48 / Out: 4TWR5049E1	1	14.4
		(Trane) In: GAM5BOC60 / Out: 4TWR5061E1	1	18
		(Trane) In: GAM5BOB30 / Out: 4TWR5030G1	1	10.8
		(Trane) In: GAM5BOC48 / Out: 4TWR5049E1	1	14.4
		(Trane) In: GAM5BOA24 / Out: 4TWR5024G1	1	7.2

4.1.4 Building Envelope Upgrades

Building envelope upgrades refer to the replacement of outdated windows and doors. These building components need to be replaced due to long term break down over time which can increase the amount of infiltration and thermal radiation to the building resulting in an increase in building energy consumption of 20-30% [28]. Windows are designed to last for between 15 to 20 years and replacing them when they are past their useful life can result in significant energy savings [29]. Since the buildings audited as part of this study are located in the North-Central climate zone, it is recommended to install windows with Low-E glass that meet performance criteria certified by the National Fenestration Rating Council (NFRC) [30]: U-factor <= 0.30 BTU/(h·ft²·°F) and Solar Heat Gain Coefficient (SHGC) <= 0.40 (Fig. 26). Modern low-E glass reduces energy use by 30-50%, especially during hot summer months [31].



WINDOWS

CLIMATE ZONE	U-FACTOR[1]	SHGC[2]	
Northern	≤0.27	Any	Prescriptive
	=0.28	≥0.32	Equivalent Energy Performance
	=0.29	≥0.37	
	=0.30	≥0.42	
North Central	≤ 0.30	≤ 0.40	
South Central	≤ 0.30	≤ 0.25	
Southern	≤ 0.40	≤ 0.25	

SKYLIGHTS

CLIMATE ZONE	U-FACTOR[1]	SHGC[2]
Northern	≤ 0.50	Any
North Central	≤ 0.53	≤ 0.35
South Central	≤ 0.53	≤ 0.28
Southern	≤ 0.60	≤ 0.28

Air Leakage ≤ 0.3 cfm/ft2

[1] Btuh ft2·°F
[2] Solar Heat Gain Coefficient

Figure 10: Energy Star qualified windows by climate zones

Replacing existing windows with energy-efficient ones has many benefits such as better insulation which improves temperature control and comfort and reduced carbon footprints. A study by EnergyStar demonstrated that replacing old, single-pane windows with double-pane windows can save between 21% and 31% off heating and cooling costs, respectively [X31]. Energy-efficient windows based on the specifications mentioned above have typical payback periods of ~8 [29] years and useful life of 20-30 years [32].

Case Study 1 Application: North Avenue Light Rail Maintenance

The North Avenue facility was built in 1991 and has no recorded renovations to the windows or doors since its original construction. The windows are assumed to be at least

32 years old, which is past the useful life of windows. The S2TS Team has recommended the installation of dual pane windows with the recommended U-Factor and SHGC for the North-Central Climate Zone.

Case Study 2 Application: Bush Bus Maintenance

Bush Buildings 1-11 were all constructed between the years 1903-1975. The buildings had roof replacements in 2002 and 2009 which involved the replacement of the skylights that were originally installed. However, there are no additional reported window/door replacements. The windows are at least 48 - 120 years old. Building 14 is a similar situation where the building was constructed in 1950 with no recorded window replacements. This puts the windows in building 14 at 73 years old. The windows for this facility are way past their useful life and should be replaced with modern dual-pane windows with the correct U-Factor and SHGC for the North-Central Climate Zone. Building 13 was constructed in 2014, so the windows are only 9 years old and well within their useful age of 20-30 years.

Case Study 3 Application: Old Court Metro Maintenance

The Old Court Facility was constructed in 2006 and has not needed any renovations since the initial construction. The windows are original to the construction and are around 17 years old. However, they are approaching the period when infiltration and thermal radiation may increase and the overall efficiency of these doors and windows deteriorate. As a result, it's recommended that routine inspections of the windows be completed to ensure they are functioning properly. A quick and efficient method is the use of infrared imaging.

Active loss points can be identified using an infrared camera. Infrared cameras detect surface temperatures and can identify areas of heat loss by showing what areas are hotter/colder than the surrounding infrastructure. The best practices for an infrared camera are to be used at night since the building will have returned to ambient temperature from the daytime temperatures, making the loss points easier to identify by the difference in color [33]. In the image below, figure 11, is an example of poor window seams that allow cold air into a structure. This can be seen in the by the dark color rim (indicating cold) in comparison to the warm colored (indicating heat) interior. Although the example used is windows, these loss points can also be found in the walls of a structure. When this happens, typical fixes include expanding foam to fill wall areas that may be missing insulation. The seals around windows may be leaking due to improper installation, extended sun exposure leading to dry rotting or other forms of natural deterioration. In this instance, it is best to replace the caulking of the window to allow for less thermal losses [34].

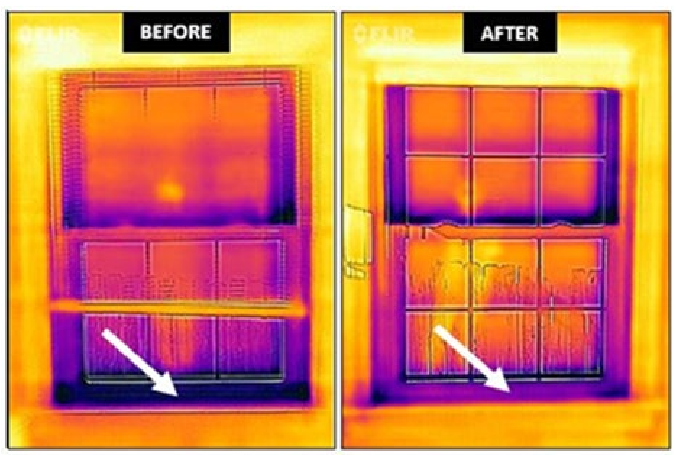


Figure 11: Example of poor window seam using infrared camera [35].

Case Study 4 Application: Riverside MARC Maintenance

Buildings 2, 3, and 4 at the Riverside facility were built in 1978. There are no recorded renovations to the building or window/door upgrades. This means that the windows and doors are at least 45 years old and past their typical useful life of 20-30 years. It was recommended that all the windows that are original to the building's construction be replaced with dual-pane windows having the U-Factor and SHGC for the North-Central Climate Zone. Building 7 was constructed in 2018 and the windows are well within their useful life, so no changes are recommended or contemplated.

4.1.5 Solar Skylights

Solar Skylights capture sunlight by installing a dome on the rooftop of a building and transferring it indoors using a reflective tube. The tube runs from the roof of the building directly to the ceiling of the indoor space. Solar tube skylights are an energy-efficient alternative to artificial lighting as they are autonomous in operation and function even during power outages.

Using Solar Tube Skylights, only require 1.5-2% of the roof area to be penetrated. Solar tube skylights are best used to supply daylight to large open spaces with high and open ceilings. Solar tube skylights also have the advantage of capturing low-angle sunlight during the winter months making them more effective than traditional skylights. An additional benefit of installing solar tube skylights is that they are equipped with remote-controlled dimmers to regulate the amount of daylight it transmits in compliance with ASHRAE Standard 90.1. The dimming controls can also be coupled with a BAS or DDC control system to modulate the level of lighting required within a particular space and move away from manual controls. This can be accomplished while minimizing the impact of infrared heat entering the facility because of the small roof footprint compared to typical skylights [36]. Solar Skylights are a viable option when large spaces such as warehouses and shop floors need to be provided with significant amounts of lighting. The typical payback period for solar tube skylights was found to be similar, around 4 years, when comparing situations with the replacement of typical skylights to solar tube skylights and installing solar tube skylights to a building with no previous skylights [37].

Due to the technology employed by tubular solar skylights in bringing in natural light for daylighting, the Lighting Power Density (LPD) from artificial lighting can be reduced by 1.5 W/sq. ft [38]. Annual energy savings and cooling load reduction attributed to tubular skylights are projected at 7.3 kWh/ft^2-yr. [38].

Case Study 1 Application: North Avenue Light Rail Maintenance

North Avenue Facility has maintenance areas used for light rail trains. These maintenance areas have high ceilings and open areas. This type of indoor environment is where solar tube skylights are most beneficial. For this reason, we are recommending installing solar tube skylights in the maintenance areas of the building.

Case Study 2 Application: Bush Bus Maintenance

At the Bush Bus Facility, many of the buildings either have typical skylights or are not the optimal indoor environment since they are administrative. The remaining buildings that have the right conditions for the installation of solar tube skylights are buildings 9,10, and 13.

Case Study 3 Application: Old Court Metro Maintenance

The Old Court Facility does have the correct style indoor structure with a high ceiling open maintenance area. However, the building is two stories with a second floor directly over the maintenance area. This means that even if there were skylights installed, they would not be able to connect to the interior of the maintenance areas. For this reason, we do not recommend the installation of solar tube skylights.

Case Study 4 Application: Riverside MARC Maintenance

The Riverside Facility building 2, 3, and 4 are used for maintenance of MARC trains. They feature the high ceiling open areas that can benefit the most from the solar tube skylights. Building 7 is used for administration and doesn't feature any large open areas that can use solar skylights.

4.1.6 Lighting Upgrades

The replacement of the existing lighting fixtures with LEDs along with the implementation of lighting controls is imperative since it accounts for 11% building energy consumption [39] and has multiple end-user benefits. Compared to fluorescent, metal halide, high pressure sodium, and incandescent lighting, LED lighting can yield significant energy savings while also reducing the maintenance and labor costs associated with the lighting fixtures [40]. LED light fixtures have longer rated lifespans which would mean fewer costs associated with replacing them. Lighting controls, such as daylight harvesting and dimming, further enhance the energy-saving potential of LED lighting up to 60% of lighting related energy usage depending on the type of space applied [41]. In 2011, there was a lighting study conducted at most of the MTA facilities, however, LEDs were still very expensive at around $20-50 per bulb [42]. As a result, the recommended retrofit was usually CFLs since at the time they were both cost and energy efficient. As technology progressed, LED prices came down in price and are now more cost effective while maintaining the best energy efficiency of lighting all options. In recent years, many of the MTA facilities began replacing light bulbs with LEDs as they break rather than of the same type (CFL, incandescent, metal halide, high pressure sodium). Even still, not all lighting in the MTA facilities has transitioned to energy-efficient LED light bulbs. Therefore, it is recommended to replace all non-LEDs with LEDs which match the existing bulb size/type, fixture styles, and lumens. Occupancy controls and sensors shall then be integrated with LED lights in all applicable spaces. Transitioning towards LEDs could result in significant savings shown in table 21 below based on the typical cost of a kWh in off peak hours from EnergyCAP for each facility. The LED equivalents recommended are based on the lumens produced by the current fixture.

Table 21: non-LED to LED equivalent wattage and associated prices.

Non-LED Lighting Fixture	LED Equivalent replacement	Cost per replacement
32 W T8 Fluorescent	17W LED	$7.00
64 W T8 Fluorescent	24W LED	$7.00
96 W T8 Fluorescent	40W LED	$7.00
128 W T8 Fluorescent	60W LED	$7.00
160 W T8 Fluorescent	75W LED	$7.00
192 W T8 Fluorescent	90W LED	$7.00
224 W T8 Fluorescent	105W LED	$7.00
13W CFL	9W LED	$2.50
18W CFL	12W LED	$3.50
26W CFL	17W LED	$5.50
36 W CFL	20W LED	$7.50
43W CFL	20W LED	$8.00
60W Incandescent	6W LED	$2.50
100 W Incandescent	15W LED	$5.50
250 W High Pressure Sodium	100W LED	$10.50
1000 W High Pressure Sodium	400W LED	$25.00
150W Metal Halide	80W LED	$13.50
175 W Metal Halide	85W LED	$13.50
250 W Metal Halide	100W LED	$10.50
400 W Metal Halide	200W LED	$13.00

Case Study 1 Application: North Avenue Light Rail Maintenance

The North Avenue facility has three different lighting studies completed in 2001, 2011, and 2019. The only noted changes were made in 2019, where a total of 76 fixtures were replaced with LED lighting. There was a remaining inventory of non-LEDs that are listed below in table 22. It is recommended to replace all these remaining lights with LEDs. The energy savings and simple payback has been estimated based on the average cost of 0.082 $/kWh for the baseline year 2018.

Table 22. Recommended LED retrofits, savings potential, and simple payback period for North Avenue.

Current Lighting Fixture	Number of Units / Hours of Operation	Proposed LED Retrofit (W)	Annual Dollar Savings ($/year) [43]	Simple Payback (months) [43]
32 W T8 Fluorescent	6 Units / 24 hours	17 W	$83.31	6
64 W T8 Fluorescent	316 Units / 8 hours	24 W	$3,679.82	7.2
64 W T8 Fluorescent	194 Units / 24 hours	24 W	$6,777.41	2.4
96 W T8 Fluorescent	20 Units / 8 hours	40 W	$330.25	5.1
96 W T8 Fluorescent	102 Units / 24 hours	40 W	$5,052.79	1.7
128 W T8 Fluorescent	89 Units / 8 hours	60 W	$1,817.79	4.1
128 W T8 Fluorescent	82 Units / 24 hours	60 W	$5,024.46	1.4
160 W T8 Fluorescent	4 Units / 24 hours	75 W	$306.37	1.1
192 W T8 Fluorescent	36 Units / 8 hours	90 W	$1,102.93	2.7
192 W T8 Fluorescent	141 Units / 24 hours	90 W	$12,959.42	0.9
224 W T8 Fluorescent	52 Units / 24 hours	105 W	$5,575.93	0.8
36 W CFL	1 Units / 8 hours	20 W	$4.99	18
100 W Incandescent	4 Units / 24 hours	15 W	$243.56	1.1
1000 W High Pressure Sodium	25 Units / 8 hours	400 W	$3,581.76	1.7
250 W High Pressure Sodium	40 Units / 8 hours	100 W	$1,759.83	2.9
175 W Metal Halide	16 Units / 8 hours	85 W	$435.44	6
400 W Metal Halide	52 Units / 8 hours	200 W	$3,163.80	2.6
250 W Metal Halide	2 Units / 8 hours	100 W	$87.99	2.9

Case Study 2 Application: Bush Bus Maintenance

The Bush buildings 1-11 have had two different lighting studies conducted. The first was in 1980 and the second was in 2011. During the 2011 study, 1017 fixtures were assessed, where retrofits were made to utilize higher efficiency ballasts. As a result of the study, no changes were made to existing CFL or LED lighting. Since then, many of the CFLs have been changed to LEDs as they stopped working. Building 13 has no recorded lighting studies completed or inventory that remained non-LED, so it is assumed the lighting was replaced with LEDs over time. Building 14 was also included in the lighting study completed in 2011, which assessed 352 fixtures and replaced some with higher efficiency ballasts, occupancy sensors, and auto-dimming controls. Like buildings 1-11, no CFL or LEDs were recommended to be changed as a result. It is assumed that some of the existing lighting was replaced over time with LEDs as they broke. The remaining non-LED fixtures are listed in table 23 below. The savings potential and simple payback were calculated using the average cost of 0.081 $/kWh from the baseline year 2018.

Table 23: Recommended LED retrofits, savings potential, and simple payback period for Bush Bus.

Building	Lighting Fixture	Number of Units/ Hours of Operation	Proposed LED retrofit	Annual Money Savings ($/year) [43]	Simple Payback (months) [43]
1	18W CFL	93 Units/ 8 hours	12 W	185.71	21
	60W Incandescent	15 Units/ 8 hours	6 W LED	191.05	2.4
2	18W CFL	10 Units/ 24 hours	12 W LED	59.91	7
3	18W CFL	2 Units/ 24 hours	12 W LED	11.98	7
4	150W Metal Halide Lamp	4 Units/ 24 hours	80 W LED	256.30	2.5
5	13W CFL	2 Units/ 24 hours	9 W LED	8.81	7.3
6	13W CFL	1 Units/ 24 hours	9 W LED	4.09	7.3
	13W CFL	1 Units/ 11 hours	9 W LED	1.87	16
8	150W Metal Halide Lamp	13 Units/ 24 hours	80 W LED	832.97	2.5
	150W Metal Halide Lamp	13 Units/ 5.9 hours	80 W LED	204.78	10.3
9	175 W Metal Halide Lamp	31 Units/ 24 hours	85 W LED	2500.16	2
	175W Metal Halide Lamp	23 Units/ 12 hours	85 W LED	927.49	4
	13W CFL	1 Units/ 24 hours	9 W LED	4.09	7.3
	13W CFL	1 Unit/ 5.9 hours	9 W LED	1.00	30
	26W CFL	4 Units/ 24 hours	17 W LED	17.78	14.8
14	60W Incandescent	13 Units/ 24 hours	6 W LED	496.75	0.8
	32W T8 Fluorescent	18 Units/ Hours N/A	17 W LED	N/A	N/A

Case Study 3 Application: Old Court Metro Maintenance

There was a lighting study completed at Old Court in 2011, which assessed a total of 362 lighting fixtures. The results of this study were to retrofit some ballasts with energy efficient versions and not change any CFL or LED lighting in the facility. Thus, Old Court Facility still has a significant inventory of CFL lighting as well as some high-power incandescent bulbs that have not been upgraded to LEDs. The remaining lights have been noted in table 24 below with their potential savings and payback period based on the typical cost of 0.086 $/kWh for the Old Court Facility in 2018.

Table 24: Recommended LED retrofits, savings potential, and simple payback period for Old Court.

Building	Current Light	Number of Units and Hours of operation	Proposed LED retrofit	Annual Money savings ($/year) [43]	Simple Payback (months) [43]
Old Court Maintenance Building	26W CFL	4 Units / 8 hrs.	17 W LED	12.58	21.0
	26W CFL	22 Units / 24 hrs.	17 W LED	207.64	7.0
	100W Incandescent	24 Units / 24 hrs.	15 W LED	1779.67	0.9

Case Study 4 Application: Riverside MARC Maintenance

There is no record of lighting studies being completed at the Riverside Facility. Based on the questionnaires and inventory provided by facility managers, the Riverside Facility has almost all LEDs except for 2 fluorescent fixtures. The savings for replacing these have been given below in table 25. The savings and simple payback are based on the typical cost of 0.075 $/kWh found on EnergyCAP for baseline year 2018.

Table 25: Recommended LED retrofits, savings potential, and simple payback period for Riverside.

Building	Current Light	Number of Units and Hours of operation	Proposed LED retrofit	Annual Money savings ($/year) [43]	Simple Payback (months) [43]
Riverside Building 7	43W Fluorescent	2 Units / 8 hrs.	20 W LED	12.62	15.2

4.1.7 Air Curtains for Overhead Garage Doors

Large overhead garage doors are used in the maintenance facilities in order to bring in the metro, light rail, and MARC train cars as well as buses that require maintenance. By opening the garage doors, outside air is allowed to freely flow into the indoor environment and the indoor conditioned air is allowed to flow to the outdoor environment, also known as infiltration and exfiltration. By allowing infiltration and exfiltration there is a significant decrease in the indoor air quality, thermal comfort, and energy efficiency [44]. To reduce the amount of infiltration and exfiltration, when overhead garage doors are open, vertical air curtains should be considered for installation. Air curtains work by jetting air downwards which creates an air boundary that separates the two environments and prevents heat and mass transfer between the two while still allowing people or objects to move between them [44].

There are conventional air curtain systems that could be considered [45]. An air curtain uses a fan to force a curtain of air in a downward direction. The forced air creates an invisible barrier that helps to control temperatures by preventing hot or cold air from entering a doorway or building at an opening. Air curtains are also used to keep contaminants such as insects, dust, pollen, and other debris from entering interior space. Air curtains provide an ideal alternative to traditional doors (Fig. 29). In a study looking at the effect of air curtains in cold climates, it was found that for buildings that have multiple dock size doors and a typical 3-10 W/m^2 HVAC system, these curtains can lead to a 10-20% reduction in energy consumption when operating [46]. In most cases the payback period is less than 2 years [47].

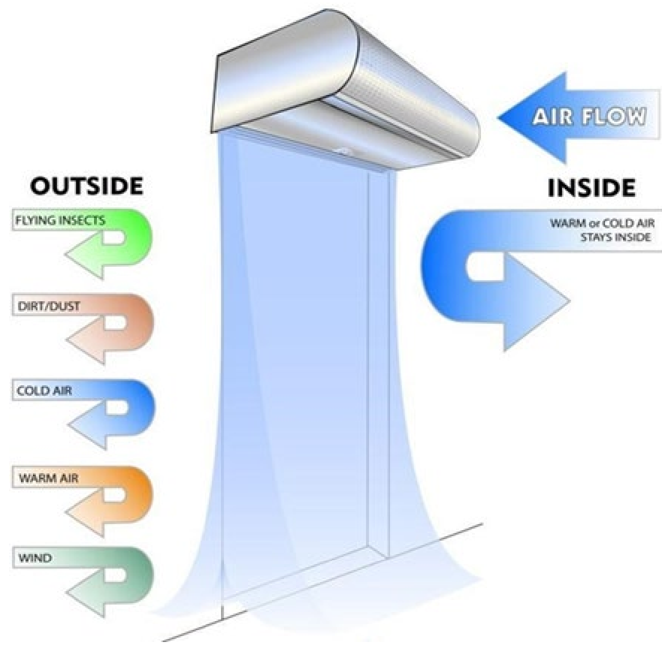


Figure 12: Air Curtain System [48]

Case Study 1 Application: North Avenue Light Rail Maintenance

The North Avenue Light Rail Maintenance Facility has 10 total overhead garage doors that are used to bring rail cars in and out of the maintenance facility. As shown in figure 13 below, there are five overhead garage doors on the front of the facility as well as five additional on the back of the facility as exits. These openings currently don't have any air curtains installed and could benefit from installation.

Figure 13: North Avenue overhead garage doors on the front of the facility.

Case Study 2 Application: Bush Bus Maintenance

In the Bush Bus facility, building 1 is solely used for administration so there are no overhead garage doors installed in the building. The remaining buildings at the facility have overhead garage doors, which can be partially seen in figure 14 below. A complete list of the buildings and the number of garage doors they have are listed below in table 26. These openings are the potential place of application for air curtain systems where energy savings could be obtained since there are no air curtains installed in the facility at all.

Table 26: Number of overhead garage doors by building at Bush facility.

Building	Number of Overhead Garage Doors
2	4
3	1
4	1
5	3
6	2
7	1
8	1
9	8
10	6
11	4
13	26
14	6

Figure 14: Building Numbering of the Bush Bus Maintenance Facility

Case Study 3 Application: Old Court Metro Maintenance

The Old Court Facility has a total of 5 overhead garage doors that are used for maintenance in the facility, shown in figure 15. There are no exit doors on the opposite side of the Old Court Facility and there are currently no air curtains installed in any of the 5 potential locations.

Figure 15: Overhead garage doors present at Old Court Facility

Case Study 4 Application: Riverside MARC Maintenance

Building 7 at the Riverside MARC Facility is strictly used for administrative purposes, which is the expected reason there are no garage doors in the exterior of the facility. Building 2 has 5 garage doors on the front with matching garage doors on the backside of the building, shown in figure 16. Buildings 3 and 4 each feature 3 garage doors spread along the exterior of the building. None of the garage door locations have air curtains installed in order to conserve energy.

Figure 16: Overhead garage doors at the Riverside MARC Facility

Table 27: Number of overhead garage doors by building at Riverside facility.

Building	Number of Overhead Garage Doors
2	10
3	3
4	3

4.2 EEM Compiled Results Summary

Table 28: Comprehensive EEMs recommended for the MTA facilities audited.

	Recommended Energy Efficiency Measures						
Building	BAS	PPL	ERV	Building Envelope	Solar Skylights	Lighting upgrades	Air Curtains
North Ave	✓	✓	✓	✓	✓	✓	✓
Bush Bus 1-11	✓	✓	✓	✓	✓	✓	✓
Bush Bus 13	X	✓	X	X	✓	✓	✓
Bush Bus 14	X	X	X	X	X	X	✓
Old Court Metro	✓	✓	✓	✓	X	✓	✓
Riverside MARC	✓	✓	✓	✓	✓	✓	✓

Legend: Recommended = ✓ Not Recommended = X

Chapter 5: Energy Modeling of Case Study 1: North Avenue

5.1 Energy Modeling Software Selection

Trace3D Plus offers a high level of customization, which suits the many different types of systems and zones found in the maintenance facility [49]. 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 [50], 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, in the summer months, there was a slight overestimation of energy use, and in the winter months, an underestimation, as shown below in Figure 17.

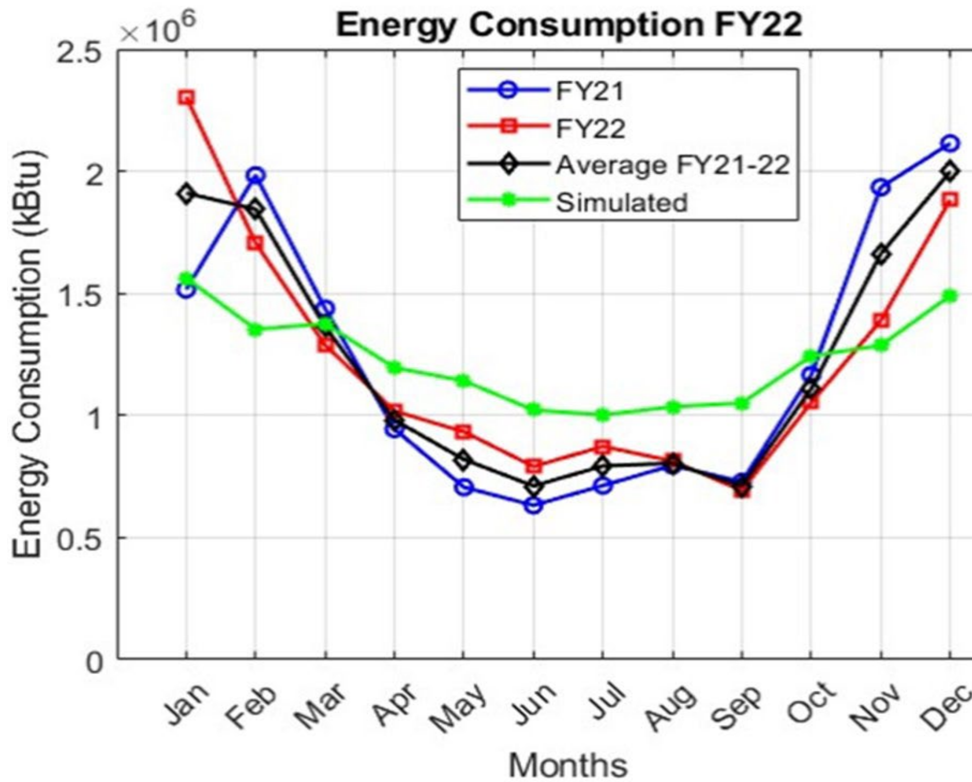


Figure 17: Simulated maintenance facility energy consumption compared to FY2021 and 2022.

Figure 17 shows the ability of the model to predict the baseline of the facility. It is important that an energy model emulates the facility's performance so that this baseline model 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, [51] 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 [52]. The maintenance facility energy model fell within these tolerance limits, hence validating the approach and the model's accuracy in replicating building energy performance. We thus concluded that 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.

5.2 Development of the Energy Model

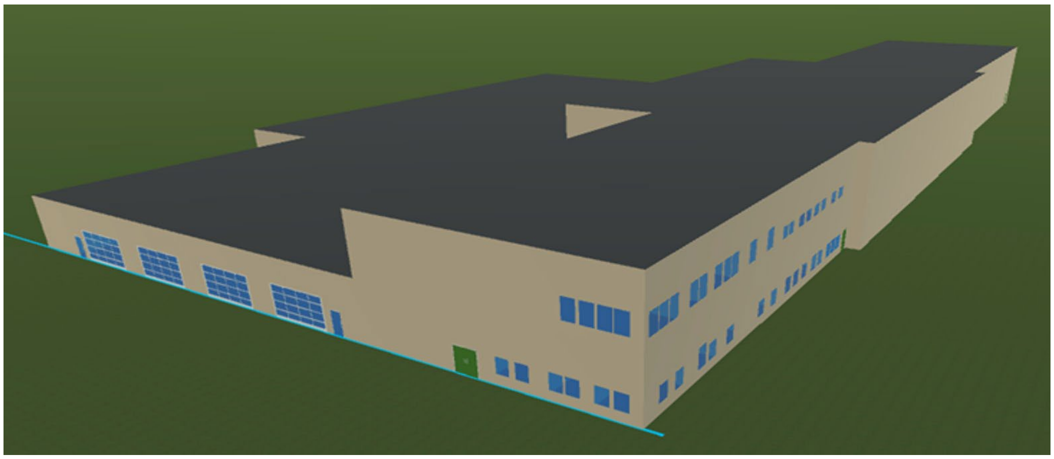


Figure 18: 3D model of the maintenance facility developed with Trace3D

The Trace3D Plus software allows users to customize libraries according to the nature of the building. This begins with constructing 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 baseline values [53]. Next, the building layout is built into the model, creating a full 3D model of the building with rooms. To create HVAC zones, rooms can be grouped together and later assigned to specific HVAC equipment. 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 was entered into the model, it was 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 takes the building's local weather data into account to simulate outdoor temperatures and the necessary heating and cooling requirements over the course of a year. The flowchart, shown in figure 19, depicts the process by which a working energy model is developed.

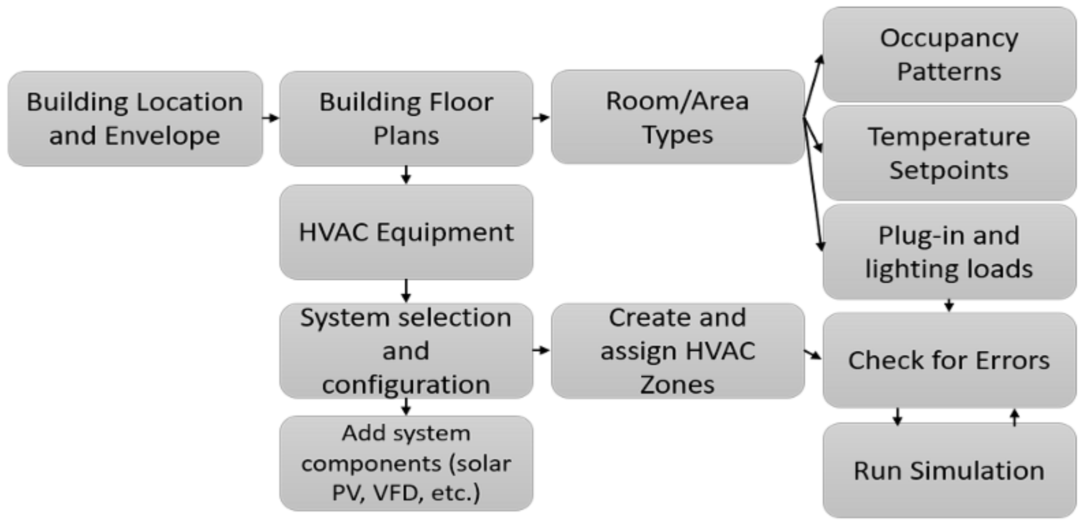


Figure 19: Flow chart of the Trace3D energy model development

Figure 20: First floor plan of maintenance facility in Trace3D

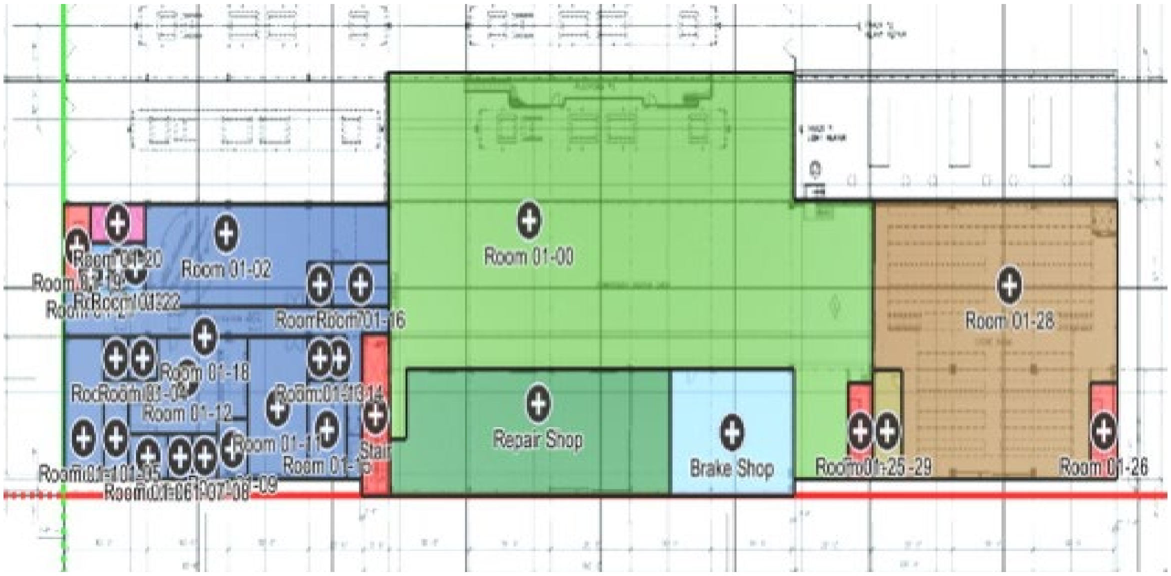


Figure 21: First floor plan of maintenance facility in Trace3D

5.3 Proposed Energy Conservation Measures

With the facility's energy performance being subpar, a wide range of energy efficiency improvements were identified to ameliorate the performance and adhere to the state’s goals of energy efficiency [7]. A study by [54] evaluated the effect of single-system retrofits vs 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.

5.3.1 LED Lighting Upgrades

A combination of 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 29 shows the lighting inventory of the maintenance facility.

Table 29: Lighting Inventory for the North Avenue maintenance facility.

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

A study by [55] 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 [56].

5.3.2 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 [57]. The maintenance facility faces a similar plight, with oversized equipment driving up energy consumption and costs. Table 30 shows the existing HVAC equipment in the facility and the amount by which it is oversized.

Table 30: Existing Equipment size and amount oversized by in the North Avenue facility.

Equipment	Capacity (MBH)	Oversizing (MBH)
Unit Heater - 1	17.1	11.2
Unit Heater - 2	30.6	10.2
Unit Heater - 3	17.1	1.5
Unit Heater - 4	30.6	10.2
Unit Heater - 5	20.4	10.2
Unit Heater - 6	102.0	7.8
Unit Heater - 7	34.2	8.0
Heat Pump - 1	21.8	15.4
Heat Pump - 2	21.8	15.4
Heat Pump - 3	39.0	28.1
Heat Pump - 4	14.5	13.8
Heat Pump - 5	11.5	5.5
RTU - 1	197.7	138.6
RTU - 2	244.7	115.6
Heating Ventilator - 1	160.0	0.0
Heating Ventilator - 2	160.0	0.0
Heating Ventilator - 3	160.0	0.0
Heating Ventilator - 4	160.0	1.6
Heating Ventilator - 5	121.6	0.0
Heating Ventilator - 6	95.0	46.0
Heating Ventilator - 7	160.0	129.6

As evident from Table 30, 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 CO_2 emitted annually ($51/metric ton) [58], 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 [59]. To ensure further the optimal operation of the systems, we modeled the installation of variable frequency drives on all motors above 5HP, which was found to be economically feasible and have lower payback periods [60]. 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, subsequently allow for facility managers and building owners to promote more efficient and cleaner operations [61].

5.3.3 Solar PV Installation

The maintenance facility has an available roof area of 60,750 ft^2 (~5,644 m^2) upon which rooftop solar PV could be installed to replace the facility's grid energy consumption with the energy generated from the solar PV. 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 [62] highlighted some of the important tradeoffs between costs and benefits while 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 subsequent increase in the number of photovoltaic arrays required to achieve this; it was found that to provide the last 3% coverage, 20% more panels are 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 [62].

5.3.4 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 year-round, regardless of the ambient temperature or occupancy levels. A study by [63] 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 31. The occupied temperature setpoint was maintained at 75°F, and the unoccupied temperature setpoint was 85°F and 65°F 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 31: Temperature setpoints in the North Avenue 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)

5.3.5 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-factor measures how well a window insulates, while the SHGC measures how much of the sun's heat comes through the window. A study by [64] 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 a SHGC lower than 0.4 [29]. The maintenance facility has single-pane windows original to the building, way past its useful life. For the reasons above, it was desired 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.

5.4 Energy Modeling Results

The purpose of the energy model is to determine the potential financial savings that could be generated by implementing the recommended EEMs to 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 with explanations and justification for the simulated values.

5.4.1 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 29, many inefficient lighting fixtures currently illuminate the facility, contributing to high energy consumption. Switching the lighting from the current types was completed using modeled presets that consider the heat transferred to surrounding air, efficiency, and other factors. The user defines inputs included are the lighting densities, wattages, and use basis of the area type and schedules. The resulting energy savings was a decrease of 54 MWh/year of electricity and an increase of 514 therms/year of natural gas.

The reason behind the rise in therms and decrease in electricity values is that LEDs operate at least 75% more efficiently than the currently installed bulbs [65]. However, they release less heat during operation, which means the natural gas must provide more heating in the building during the winter months to supplement the lower heat gain from lighting.

5.4.2 Decarbonization Savings: Re-sizing HVAC, VFDs, and Electrification

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. The model allows users to simulate changes in the energy sources of HVAC systems from electric, gas, and steam to electricity. 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 47,714 therms/year of natural gas could be achieved.

The natural gas usage at the facility was eliminated when the HVAC systems were all 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.

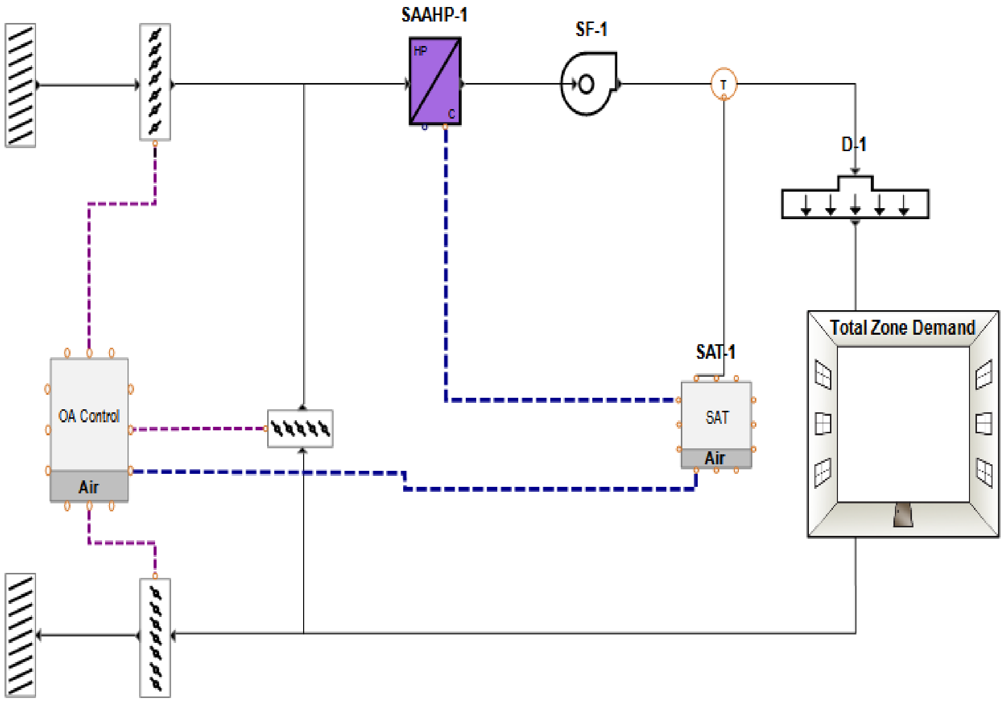


Figure 22: Example HVAC system with configurable components.

5.4.3 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 given orientation shown below in figure 22, as well as the user specified values, it is shown that 50 total arrays were needed. The simulated solar array decreased 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 further the savings potential of the facility by allowing for energy supplementation during fluctuations, such as peak demand [66].

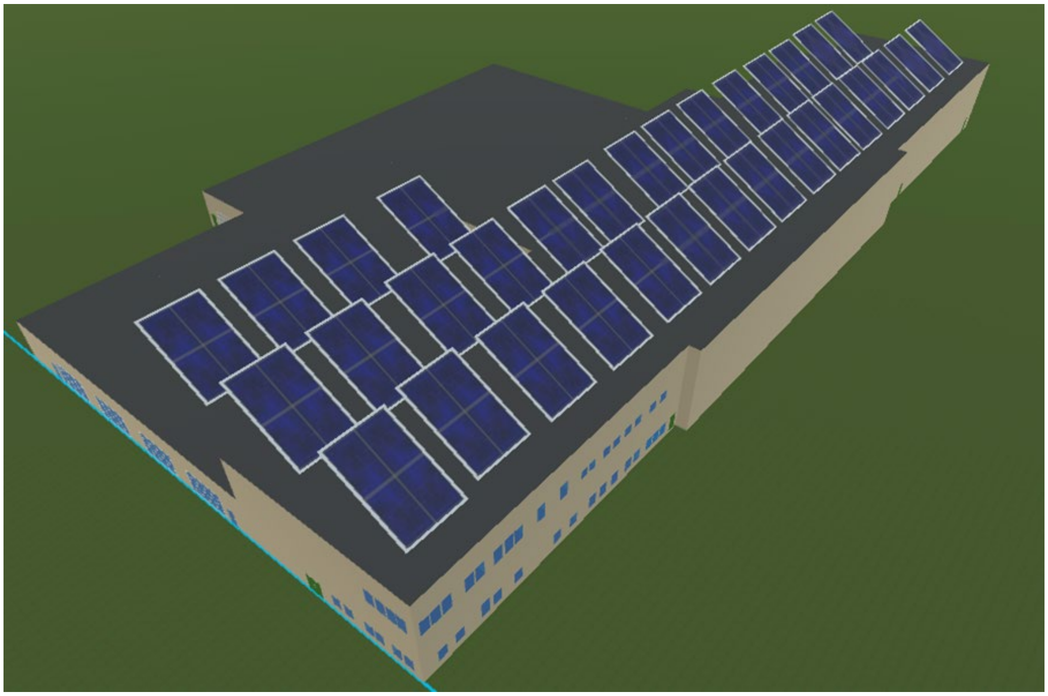


Figure 23: Model view of implemented Solar PV in Trace3D

5.4.4 Temperature Setbacks

Temperature setbacks at the maintenance facility were utilized for the office area since they operate 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 year-round for the offices. While that temperature is maintained when the offices are occupied, the drift point in the winter is set to 65°F and 85°F 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 to 5 PM Monday to Friday work schedule. In the new schedule generated for the office area, the winter months have a hold temperature of 75°F when occupied and drift to 65°F when unoccupied. Similarly, for the summer, the temperature when occupied is 75°F, and unoccupied drift is 85°F. 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 occupied temperature set points, the schedule accounts for this by starting the temperature change an hour before occupants enter the building (8 AM) and changing 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 [67].

5.4.5 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 ≤ 0.40 and U-factor ≤ 0.25 [68]. 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 3 therms/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 [69].

Table 32: Energy savings from different EEMs for the North Avenue facility.

#	EEMS	Energy consumption		Projected energy savings		Projected energy savings percentage	
		E (MWh/yr.)	NG (therms/yr.)	E (MWh/yr.)	NG (therms/yr.)	E (%)	NG (%)
1	LED Lighting Upgrade	2,873	48,227	54	-513	1.9	-1
2	Solar PV	1,948	47,714	980	0	33	0
3	Equipment Sizing and electrification	2,866	0	62	47,714	2.1	100
4	Window Upgrades	2,927	47,717	0.5	-3	0	0
5	Temperature Setbacks	2,922	47,713	6	0	1	0
Combined EEM's		1,902	0	1,086	47,714	37	100

Table 33: Utility cost savings from different EEMs for the North Avenue facility.

#	EEMS	Energy consumption		Utility cost savings		
		E (MWh/yr.)	NG (therms/yr.)	E ($/yr.)	NG ($/yr.)	Total ($/yr.)
1	LED Lighting Upgrade	2,873	48,227	$5,940	-$462	$5,478
2	Solar PV	1,948	47,714	$107,800	$0	$107,800
3	Equipment Sizing and electrification	2,866	0	$6,820	$42,943	$49,763
4	Window Upgrades	2,927	47,717	$55	-$3	$52
5	Temperature Setbacks	2,922	47,713	$660	$0	$660
Combined EEM's		1,902	0	$119,460	$42,943	$162,403

Table 32 and 33 highlight 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/therm, 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 [70].

Table 34 shows the reduction in GHG emissions that can be achieved by the EEM implementations. Using the coefficients of CO_2 equivalents from the EPA Power Profiler [71], the quantity of GHG emissions quantified in metric tons of CO_2 from electricity was calculated. The CO_2 equivalents for natural gas were obtained from the EPA's Emission Factors Hub [72].

Table 34: GHG reduction from EEMs in metric tons of CO_2 for North Avenue facility.

#	EEMS	Projected Energy Savings		Annual GHG Reduction - 2022		
		E (MWh/yr.)	NG (therms/yr.)	E (Mton/yr.)	NG (Mton/yr.)	Total (Mton/yr.)
1	LED Lighting Upgrade	54	-513	16	-3	14
2	Solar PV	980	0	299	0	299
3	Equipment Sizing and electrification	62	47,714	19	253	272
4	Window Upgrades	0.5	-3	0	0	0
5	Temperature Setbacks	6	0	2	0	2
Combined EEM's		106	47,714	32	253	286

Chapter 6: Summary and Proposed Future Work

6.1 Conclusions

This thesis covered the auditing process of MTA maintenance facilities across the Metro, MARC, Light Rail, and Bus subdivisions, providing a case study for each. In searching for how to conduct these audits a lack of literature covering the auditing process for maintenance facilities was found. This meant research for the auditing process for other building types had to be combined to create an initial auditing plan. Using the initial plan was useful but required additional adaptation to the specific building type. This included the type of ECMs that were recommended to be most beneficial towards the goal of lowering energy consumption and CO_2 production. As energy audits were conducted for the different types of public transportation within MTA, such as MARC, Metro, light rail, and bus, some of the ECMs became a common recommendation for most of the facilities. The analysis for the energy and cost savings of each of the ECMs was shown based on case studies and calculations. Then, a reason for why the ECM was applicable to each of the case studies was given, as there are numerous reasons that an ECM should or should not be applied to the maintenance buildings. While most of the ECMs were not applicable to all buildings, they were applicable to a majority and could produce significant energy and cost savings. To further provide justification for the potential energy savings based on ECMs, Case Study 1 was modeled with LED Upgrades, equipment sizing and decarbonization, Solar PV installation, temperature setbacks, and window replacements. The base model successfully followed the year 2022's energy consumption allowing for us to implement the ECMs and determine the GHG reduction, energy, and cost savings accurately. In doing so we found that by combining all the forementioned ECMs there would be a reduction of 286 MTons CO_2 a year, 4% of electricity use, 100% of natural gas use, and 54,603 $/year for the entire North Avenue MTA facility. The most influential ECM used was the equipment sizing and electrification, which fully eliminated natural gas use and reduced electricity use 62 MWh/year. As recommendations were made and then modeled successfully, it is perceived that these energy audits were successful in reducing the GHG emissions, energy use, and provide cost savings if they were to be implemented. As there is significant experience from the different suborganizations, represented by the different case studies, this can also act as a guide for future energy audits of maintenance facilities by matching it to the most similar case study.

6.1 Future Work

The State of Maryland conducts additional energy audit projects on their preferred facilities as determined by energy intensity use and CO2 emissions, among other factors. The said energy audits facilitate continued research into different ECMs based on case studies and emerging technologies to achieve the state's emission reduction goals. With the existing goal set forth by Governor Wes Moore to reduce all state-owned facility emissions by 20% by 2031 compared to base year 2018, there remains a significant amount of state departments that need to have energy analysis and audits completed. The in-person audit for MTA was completed in person by a contracting company and had the results provided to S2TS. The reason for this was due to security measures put in place by MTA that restricted access of on-site personnel. We believe in this instance it worked well, however, moving forward it would streamline the process and effectiveness of the audit if a representative of S2TS could be present as well. This would give the in-person auditing team knowledge of all the necessary information the needs to be collected on the site visit.

Additionally, the S2TS representative could interview essential personnel that have familiarity with the current building operation.

If this thesis is to be viewed as a potential guide for energy auditing of maintenance facilities, it would be beneficial to include all the buildings audited in the MTA. Each of the audits conducted for MTA were maintenance facilities that features different unique aspects such as the plug loads, use patterns, and building envelope. By adding these additional facilities to the energy auditing guide, it would allow for there to be more options as people try to determine which case study to use as a reference. Additionally, having these additional case studies present could also allow for audits with a mixture of case studies to reference the multiple versions and combine cases, similar to how the S2TS team initially built the process for maintenance buildings. However, this would streamline the process for future uses because it would be combining different maintenance facility audits rather than audits from multiple different building types. Another tool that could help streamline the energy audit process is the Rapid Energy Auditor (REA). REA is software being developed in the S2TS Lab that can perform a quick screening of facilities to bring specifically high energy savings potential aspects of the building to focus before a detailed walk-through occurs.

Finally, future work should include the modeling of additional similar facilities within other states or even internationally. Similar to the reason for adding more case studies, adding additional modeling can allow for a more comprehensive database to pull information from. Having such information and working models can further justify that the ECMs recommended are applicable to all the different types of maintenance facilities. The modeling of these different facilities could provide further insight into whether the ECMs can be as effective or should not be applied to a certain situation since it does not allow for an effective payback or energy savings.

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