## ABSTRACT

| | |
|---|---|
| Title of Document: | ENERGY AUDIT AND MODELING OF TWO MULTI-PURPOSE BUILDINGS ON THE COLLEGE PARK CAMPUS OF THE UNIVERSITY OF MARYLAND. |
| | Devashis Man Shrestha, Master of Science, 2020 |
| Directed By | Professor, Michael Ohadi, Mechanical Engineering |

Gossett Football House and Biology-Psychology Building are two high-energy consuming, multi-purpose buildings in the University of Maryland, College Park, Campus. This thesis details the energy analysis and energy model development for these buildings to identify energy savings opportunities. The research was conducted in three phases per building: (I)- A comprehensive summary of relevant building information collected from the energy audit walkthroughs and study of building records, followed by building utility analysis and benchmarking. (II)- Energy model development to simulate building energy consumption which was calibrated according to ASHRAE-14 guidelines. (III)- Analysis and simulation of savings from energy conservation measures to increase energy efficiency and reduce carbon footprint of the respective buildings. Combined savings of 3,876 MMBtu, 787,290-gal water and $100,800 per annum along with 515 MT $CO_{2eq}$ emission reductions per annum was projected for the two buildings. These savings directly contribute to the campus sustainability goals and increase energy efficiency of the campus buildings.

ENERGY AUDIT AND MODELING OF TWO MULTI-PURPOSE BUILDINGS ON THE COLLEGE PARK CAMPUS OF THE UNIVERSITY OF MARYLAND.

by

Devashis Man Shrestha

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science
2020

Advisory Committee:
Professor Michael Ohadi, Chair
Professor Yunho Hwang
Professor Bao Yang

# Dedication

I would like to dedicate this Thesis to my Parents and in memory of my late grandmother, whose support has helped me set and accomplish my goals.

# Acknowledgements

I would like to thank my advisor, Dr. Michael Ohadi, for his guidance and for providing me with the opportunity to complete this project. I would like to acknowledge Dr. Farah Singer for her consistent support and assistance in completion of this project. I would also like to thank Facility Performance Group Assistant Director, Mr. Donald L. Hill and Facilities Management staff, Mr. Joe Davis, Mr. Frank Davis, Mr. Alvin Davis for their generous help and support. I would like to thank office mate, Mr. Fabio Battaglia and Mr. Mark Stewart from UMD Sustainability Office for their valuable help, support, and insight.

# Table of Contents

# List of Figures

# List of Tables

# List of Abbreviations

ACH: Air Changes per Hour

AHU: Air Handling Unit

ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers

BAS: Building Automation System

BDL: Building Description Language

BLC: Building Loss Coefficient

CAPEX: Capital Expense

CEEE: Centre for Environmental Energy Engineering

CFM: Cubic Feet per Minute

CHP: Combined Heat and Power

COP: Coefficient of Performance

DD: Degree Day

DOE: Department of Energy

DX: Direct Expansion

ECM: Energy Conservation Measure

EES: Engineering Equation Solver

EIA: Energy Information Administration

EPA: Environment Protection Agency

ERU: Energy Recovery Unit

EUI: Energy Use Intensity

FM: Facilities Manager

HVAC: Heating Ventilation and Air Conditioning

LED: Light Emitting Diode

LEED: Leadership in Energy and Environmental Design

LPD: Light Power Density

NMBE: Normalized Mean Bias Error

NREL: National Renewable Energy Laboratory

PAU: Perimeter Air Unit

PV: Photovoltaic

RH: Relative Humidity

RTU: Rooftop Unit

SCUB: Satellite Central Utilities Building

VAV: Variable Air Volume

VFD: Variable Frequency Drive

# Chapter 1: Introduction

## 1.1 Project Background and Goal

The University of Maryland (UMD) has pledged to the "White House initiative American Campuses Act on Climate 2009". It is one of the 318 signatories that has pledged to accelerate transition to low Carbon Energy. By the year 2020, UMD aims to reduce its consumption by 20%, and 50 % by 2050. UMD also plans to become carbon Neutral by 2050.

To pursue this goal, the UMD has been working with team of Students led by Prof. Michael Ohadi and Dr. Farah Singer from Smart and Small Thermal Systems (S2TS) Laboratory, Energy and Engineering Division at Facilities Management, and UMD Sustainability office. The parties involved have been working together for the past 5 years to pursue the goals of the Climate Action Plan. This thesis project is a continuation towards achieving Climate Action Plan goals.

Two top strategies and priorities in achieving these goals were "conducting existing building retrofit and making research-related resources that relate to energy efficiency and economic and environmental sustainability available to the campus." The student-led research team has been working on ASHRAE Levels 1, 2 and 3 Energy audit and modeling techniques as an effective way of identifying and accessing potential retrofit feasibility, as well as making promising research-related resources available to the campus.

According to the Energy Information Administration (EIA) 2017 data, the total global primary Energy consumption was 582 Quadrillion BTUs, and it is projected to grow by 56% from 2010 to 2040 (US Energy Information Administration, 2019). Buildings energy efficiency has come to the forefront of political debates due to the high energy costs and climate change concerns (Kneifel, 2010).

Buildings account for 40% of primary energy consumption (U.S. DOE, 2020). Building Energy efficiency has come to the forefront of political debates due to high energy costs and climate change concerns (Kneifel, 2010). For this reason, many energy use and carbon footprint reduction initiatives and policies has surfaced over last few decades such as Better Building Challenge ( U.S. Department of Energy Better Buildings, 2019), Energy Star Program (Energy Star, 2019), Leadership in Energy and Environmental Design Program (LEED), tax incentive and rebate program (U.S. Department of Energy, 1995) and Energy Modelling Development program (U.S. Department of Energy, n.d.). There are also several different guidelines set by ASHRAE specific to various types of buildings that helps in making the building more energy efficient. There is huge potential for Energy savings from buildings which can help in controlling the Energy consumption graph.

My thesis follows the work of the student led research team which has accomplished modelling and analysis of twenty buildings on UMD campus. The project follows the work of CEEE graduates, J.M. Levy (J. M. Levy, 2014), S. Bangerth (Bangerth and Ohadi, 2017), D. Savage (Savage, 2017) and J. Kelly (Kelly, 2019) along with other fellow colleagues in the student – research team. Their efforts identified combined energy saving of 129,760 MMBTU and $3,100,614 per year for 20 UMD buildings and 35 data centers.

Following the successful completion of these highly technical and challenging projects, the Bio-Psychology building and Gossett Football House were identified by the Facilities Management (FM) as the Energy extensive buildings that need to be audited next.

## 1.2 Energy Modelling Overview

Over the past 50 years, several building energy programs have been developed and are in use today. A core tool in analyzing the energy consumption of a building is a whole-building Energy simulation software. It can provide user with energy use and demand data if given a complete set of building characteristics (Crawley et al., 2008). One of the more prevalent use of energy modelling comes during the building design. Energy consumption and loads can be modelled during the design phase to simulate and optimize energy consumption. The US Green Building Council's Leadership in Energy and Environmental Design (LEED) rating system requires Energy modelling to access the energy use of building and to quantify and validate the savings associated with the proposed design. When used properly, the simulation software can help save optimize the building energy consumption and allow a design team to prioritize of several cost-saving strategies during the design phase. This can also be used in studies aimed at reducing energy consumption in an existing building and in Energy audits to determine cost-effective strategies to lower building's energy consumption and carbon footprint.

The simulation software used in this thesis was eQUEST-3.65, by DOE. A brief overview about the software is discussed next.

### 1.2.1 Energy Modelling with eQUEST:

The eQUEST (Quick Energy Simulation Tool) simulation environment is underpinned by DOE-2.2 engine (Maile et al., 2007). eQUEST is supported as a part of the Energy Design Resources program which is funded by California utility customers and administered by Pacific Gas and Electric Company, San Diego Gas Electric, and Southern California Edison, under the auspices of the California Public Utilities Commission (DOE2, n.d.). DOE-2's source code originates back to 1960's. Steady development continued under Lawrence Berkeley National Laboratory until its last official release in 1994. DOE-2.2 remains one of the most used thermal simulation engines due to its ease of use, fast simulation time and the vast library of knowledge and expertise accumulated from its long-standing presence in the market (Crawley et al., 2008).

Figure 1 describes the general flow of data in energy models. Building geometry, weather data, HVAC system data, internal loads, operating schedules, and simulation specific parameters are input in the simulation engine which then simulates the energy consumption in the building.

DOE-2 engine simulates the thermal behavior of spaces without data feed-back. As illustrated in Figure 2, user inputs are combined with materials and construction library into Building Description Language (BDL) input processor which transforms the inputs into an appropriate data format what is used by the four sub-programs (Maile et al., 2007). eQUEST has its own library of weather files and can also accommodate custom files in bin format. User input data specifying building geometries need to be simplified from real geometries, for which eQUEST houses its own geometry tool.

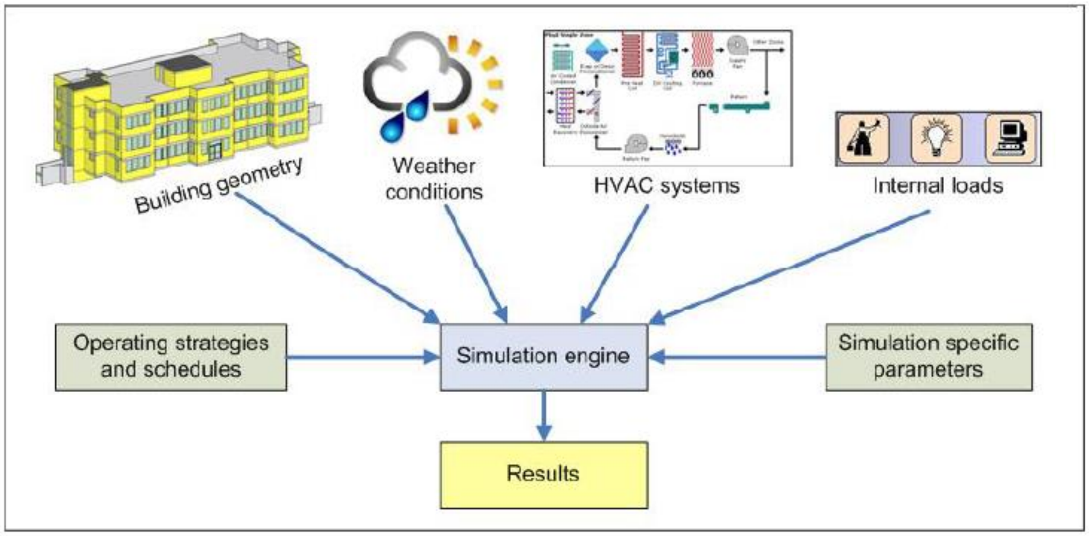



**Figure 1 General data flow of building energy simulation software (Maile et al., 2007)**

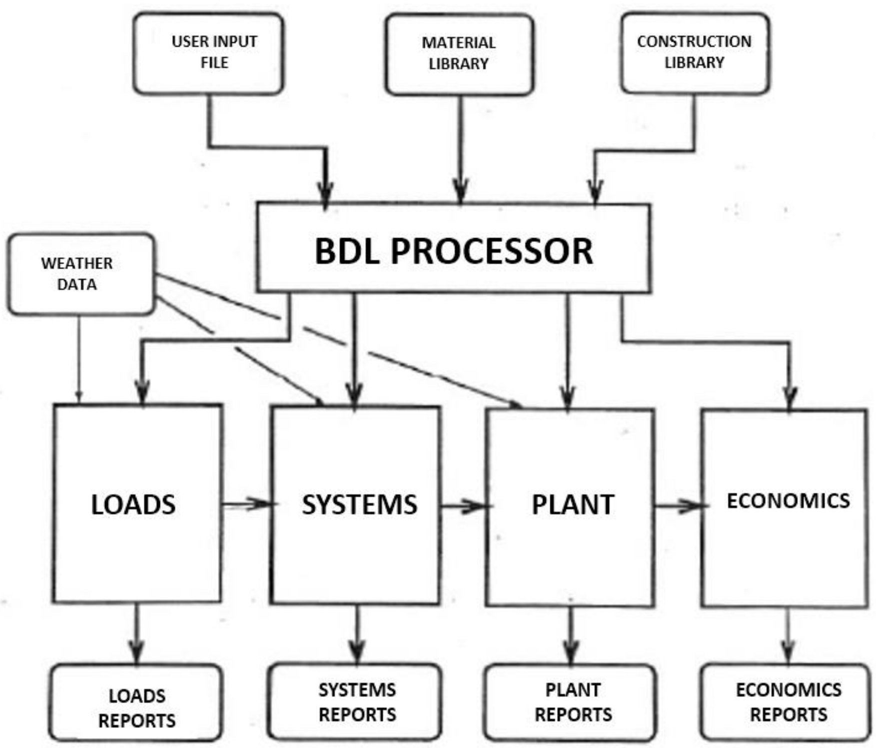



**Figure 2: Data flow of DOE-2 thermal simulation engine (Maile et al., 2007)**

The four subprograms: Loads, Systems, Plant and Economics are executed sequentially. The Loads program uses BDL descriptions and weather data to calculate heat loss and gains. Assumed heating and cooling loads of related systems at fixed space temperature govern these calculations. The Systems subprogram uses calculated gains and loss to determine additional heating and cooling needs for each space according to the set point temperature.

The Plant subprogram then calculates energy requirement of HVAC system to meet those calculated loads found in the Systems sub-program. Lastly, Economics subprogram calculates cost based on the energy requirement and utility cost structure (Maile et al., 2007). However, the Economics sub program was not used in this thesis as an in depth, transparent economic analysis in excel was preferred. Around 23 different types of air-side systems that can be designed from eQuest (James J. Hirsch and Associates et al., 2006).

DOE-2 has several limitations which are explicitly stated on the user manual. DOE-2 assumes well-mixed space temperatures and is therefore not useful for simulating spaces containing hot-spots such as those in data centers. Lack of data feedback can cause thermal comfort simulation to be inaccurate. Some other notable HVAC omissions in eQUEST include solar thermal, desiccant wheel, radiant cooling or heating and the ability to directly model steam loops (James J. Hirsch and Associates, 2010).

# Chapter 2: Literature Review

## 2.1 Energy Saving and Sustainability on US Academic Campuses:

As the crisis of climate change has been exacerbating by the day, the importance of sustainability has never been more critical. An increasing focus on Energy Efficiency and Sustainability has been growing globally and has now caught some major headlines. Much has been done to improve the state of environment by practicing Sustainability measures and energy efficiency practices. State and local governments are investing more resources to actively monitor, analyze and reduce municipal energy consumption. States like California and Washington, as well as cities such as Philadelphia, New York City, Chicago, and Washington DC have enacted energy benchmarking laws that require building owners to report their annual energy consumption (Coven, 2017). A University, with its large area, population and complexity can be regarded as a small city. Many sustainability measures can be practiced intensively in a University campus. The University of Maryland (UMD) became a charter signatory of the American College and University Presidents' Climate Commitment (now called the Carbon Commitment) in 2007 and finished its first Climate Action Plan (CAP) in 2009. UMD has pledged to the Climate Action Plan 2009 which makes it committed to reduce its energy consumption by 20% by 2020 and 50% by 2050 (UMD RIGHT NOW, 2014). There is also a lofty goal of 60% Carbon reduction from 2005 levels by 2025, and to become Carbon Neutral by the year 2050.

Since first signing in 2007, UMD has put forth a Strategic Plan in 2008, a Climate Action Plan 2009, a Facilities Master Plan in 2011, a Sustainable Water Use and Watershed Report in 2014, and several other guiding documents of its actions towards achieving sustainability. UMD's 2017/18 Progress Report states, among other things, that "UMD has achieved a 49 % reduction in greenhouse gas emissions compared to 2005" (Sustainable UMD, n.d.).

The University has expanded and restructured its internal energy management program by creating Department of Energy and Engineering within the facilities management and purchased 146,559 MWh of renewable Energy according to 2017/18 progress report. A 1.9 megawatts of photovoltaic (PV) power station (approximately 7,000 solar panels) was installed on three parking garages in 2017 along with 200 kilowatts of PV at Institute for Bioscience and Biotechnology Research (IBBR), combined with the existing 631-kilowatt system at the Severn building; in total the campus has approximately 2.7 megawatts of PV power so far (Sustainable UMD, n.d.). Facilities Management has collaborated with CITY@UMD, a university-sponsored group that investigates how University of Maryland infrastructures affect sustainability, to create Campus Dashboard (Feingold, 2016). The Dashboard allows personnel with UMD ID to log in and access sustainability impact of each building.

The Office of Sustainability at UMD has also been actively involved in achieving the Climate Action Plan goals by educating the campus community about sustainability, measuring and reporting on campus sustainability efforts and also creating a Sustainability Studies Minor among its other contributions (Sustainable UMD, n.d.)

The goal of sustainability can be met with economic resistance as building retrofits and renewable energy projects are capital intensive. However, Energy Conservation measures (ECM), such as those presented in thesis, can offer low-cost or no-cost ways to reduce energy consumption, greenhouse gases and utility bills; these ECMs are therefore a foundational component to any campus sustainability effort (Alshuwaikhat and Abubakar, 2008).

## 2.2 Laboratory Strategies

Research labs face a unique and significant challenge when developing sustainability plans and energy management strategies. They typically consume 5 to 10 times more energy per square foot than an average commercial building (Labs21, 2010). It can account for 40 % to 70 % of given campus's energy consumption (Savage, 2017). The efforts to reduce energy consumption in labs often conflict with various standards and guidelines to ensure safe air quality, relatively high lighting densities and operation of energy intensive equipment in presence of hazardous material.

Labs cover 35 % of the total area of the Bio-Psychology building. The labs are usually diverse, and their demands are unique, compared to other parts of the building. Energy star benchmark portfolio, which has a glossary of data of standard benchmark EUI (Energy Use Intensity) for various building types, does not have a benchmark set for labs due to their unique nature.

The Lawrence Berkley National Laboratory (LBNL), funded by the U.S. Department of Energy (DOE) and Environmental Protection Agency (EPA), is a leader in energy efficient design and operation of buildings in numerous sectors. Their Laboratories for the 21st Century (Labs21, 2010) program provide facility designers, engineers, owners, and facility managers with tools, resources, and innovative solutions for designing, constructing, and maintaining sustainable laboratory facilities (Labs21, 2010). Their program aims to exceed many of the minimum requirements for energy-efficient building design given by ASHRAE Std. 90.1: *Energy Standards for Buildings.* Table 1 lists labs21 tools and their purpose that was very helpful throughout the course of this project (Labs21, 2010).

**Table 1: Labs21 tools and their purpose (Labs21, 2010)**

| Tool | Purpose |
|---|---|
| *Design process tools:* | |
| Labs21 Process Manual | Guidance for sustainable design process. |
| Design Intent Tool | Documentation of design intent – objectives, strategies, metrics. |
| Environmental Performance Criteria | Point-based rating system for sustainability, based on LEED™. |
| *Core information resources:* | |
| Design Guide | Reference manual on energy efficiency features in laboratories. |
| Best Practice Guides | Information on design, construction and operation of specific technologies and strategies. |
| Case Studies | Whole building case studies of high-performance laboratories. |
| Energy Benchmarking | Energy use data for laboratory systems and buildings. |
| *Overview resources:* | |
| Intro to Low-Energy Design | Overview of key strategies for high performance labs. |
| Labs21 Video | Examples of high performance labs. |

Labs21 has a large and diverse data base of labs which can be used to benchmark the EUI for labs to be audited. It consists of documented Case Studies conducted between 1999 and 2010 to gain insight about common practices in designing and retrofitting laboratories for sustainability (Labs21, 2010). A total of 13 case studies were reviewed for dominant technology used in them.

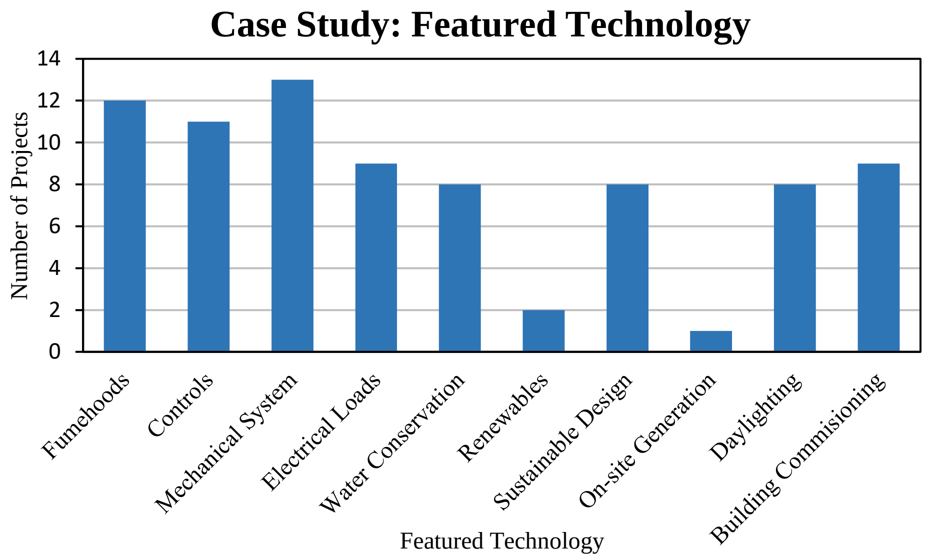



**Figure 3: Frequency of technologies used in the reviewed cases**

Figure 3 lists the frequency of technologies used in the reviewed cases. We can notice that almost all the labs from these case studies use fume hood, control technology and mechanical systems. These are very energy intensive technologies and thus render labs high-energy consuming facilities. Details from these case studies will be referenced throughout this report. If half of all the labs in USA were to reduce their energy consumption by 30 %, it would equal to energy consumed by 840,000 households (Labs21, 2010). The effect would be equal to environmental effect of removing 1.3 Million fossil fuel powered cars or preventing 56 million trees from being cut.

The latest effort by the DOE to encourage sustainability in laboratory buildings is the Smart Labs Accelerator program as set forth by The Better Buildings Initiative in 2016. Partners of the Smart Labs Accelerator program agree to establish energy efficiency targets, develop, and share their plans with the DOE, as well as collaborate and share with other partners in their efforts in achieving the energy efficiency targets.

## 2.3 Vivarium Strategies

A Vivarium houses animal for purposes of experimentation. Large number of the labs in the Bio-psychology building consist of vivarium sections. The temperature of the vivarium depends upon the temperature of habitat of the animals. Usually, the vivarium needs to be maintained at constant temperatures; thus, making them energy extensive. They require constant ventilation and certain amount of particle concentration. One of the pollutants that arise from vivarium is $NH_3$ (Ammonia). The odor threshold of ammonia is 2 ppm and irritation threshold are from 30 to 60 ppm.

Vivarium standards are specified by Accreditation of Lab Animal Care International (AAALAC). Previously AAALAC specified air exchange rate to be 10 to 15 ACH, which has been now be reduced according to the lab conditions (Oca et al., 2016). The most effective way to conserve energy in vivarium is to use a variable Air Ventilation system and schedule the air change rate to the latest standards. For very demanding species, their cages can be insulated to simulate temperatures of their habitat in an energy efficient manner (Oca et al., 2016).

# Chapter 3: Building Description

## 3.1 Gossett Football House

### 3.1.1 Building Overview

The Gossett Football House (building no. 379) is an athletic complex constructed in the year 1992 and renovated in 2002. The building has a total gross area of 63,914 $ft^2$. The building is ideally located at the South-Eastern side of the Capital One Football Stadium and is mainly used as a training facility, by the UMD Football team and the Lacrosse team. The building houses state of the art gym, a medical therapy room, a hydro-therapy room, training room, locker rooms, and several classrooms, offices, and study areas. Along with all these, The Gossett Football House also houses the dining area for the athletes along with an auditorium and several conference and meeting rooms. Figure 4 presents the location of Gossett FH.


**Figure 4: Location of Gossett FH**

### 3.1.2 Construction and Architecture

The Gossett Football House is a single storied building with a semi-basement. The semi-basement is space with two sections, the first of which is above grade, and the second of which is below grade. The back entrance of the building leads to the Capital One field, which is also used for training. Some of the architecture drawings were available from the archives during the course of the audit. All the data presented in this section was collected via the archive drawings, and interviews with the Facility personnel responsible of the building. The building envelope consists of a Common Masonry Brick with face-brick cavity wall and Batt insulation (3.5 inch) as described in Figure 5. The calculated R value of this envelop was 16.01 $ft^2 \cdot °F \cdot hr/Btu$ (ColoradoENERGY.org, 2019).

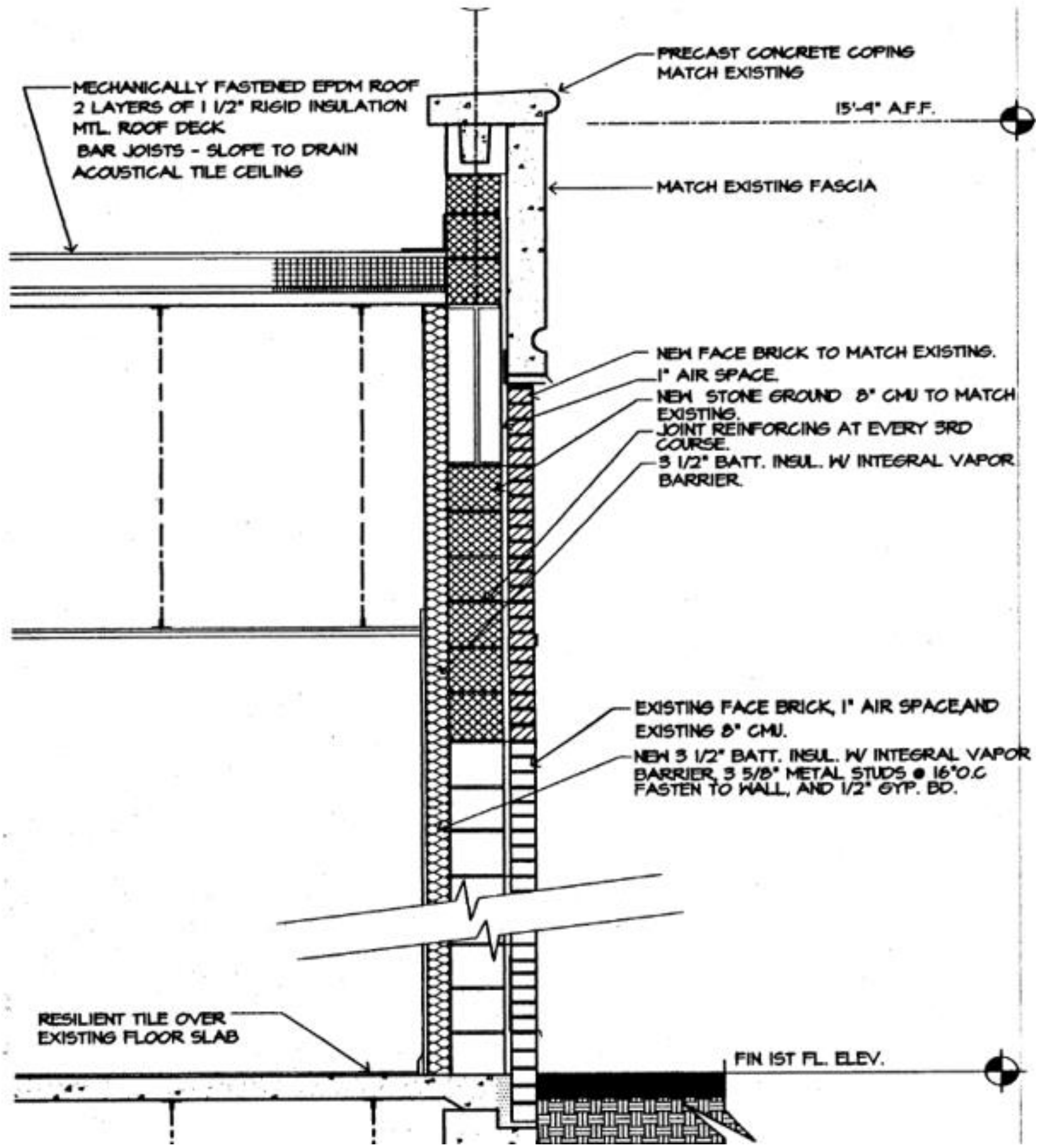



**Figure 5: General above grade Wall section of Gossett FH extracted from Civil Drawing**

### 3.1.3 Space Distribution

The Gossett Building is a multi-purpose athletic facility which caters the Maryland Football team and Lacrosse team. It also consists of an office space, study areas, dining hall and an auditorium in addition to the athletic training spaces. The following pie chart in Figure 6 describes the space distribution of the building. Majority of the building area consists of locker room. The spacious locker area features a double locker and footlocker for every player. The layout of the bottom floor (floor 0) allows easy access to the many amenities the building has to offer. The locker rooms, which house a sauna and shower facilities, are less than 100 feet away from the top-floor (floor 1) conference areas. The building consists of a state-of-the-art strength and conditioning gym with 12 tons of workout machinery spread across 7000 $ft^2$ on the bottom floor (floor 0). It also consists of a medical and hydro-therapy space to constantly cater the athletes' needs.

On the top floor (floor 1), building consists of classrooms and the auditorium which are also sources of high energy consumption. The Gossett building also houses office for coaches and staff, along with study spaces and conference/meeting rooms on floor 1. It also consists of dining space and a kitchen area which were the most energy consuming section of the building.

The building also had its own laundry room located on floor 0 which was a huge source of energy consumption as it housed an electric water heater (60 kW), 2 washer units (4.4 kW each) and 4 gas dryer units (48 kW each).

The building operates throughout the year with an influx in the fall season. The building operates from early morning (around 5 AM) to late at night (12 AM) to accommodate flexible hours of the athletes and the cleaning staff. Table 2 and Figure 6 presents the details of space distribution. Figure 7 presents the hydro-therapy room, and Figure 8 presents the medical/therapy space and the auditorium.

**Table 2: Space distribution of Gossett Football House**

| **Space Use** | **Area [ft$^2$]** | **Percentage [%]** |
|---|---|---|
| Office / Conference | 8,400 | 14 |
| Dining Hall and kitchen | 5,868 | 10 |
| Lobby/ Lounge | 4,361 | 7 |
| Auditorium | 3,620 | 6 |
| Locker room | 20,553 | 34 |
| Medical/Physiotherapy room | 2,575 | 4 |
| Corridor/Mech. room | 2,290 | 4 |
| Gym | 6,928 | 11 |
| Classroom | 5,728 | 9 |
| Laundry room | 444 | 1 |
| Total | 60,767 | 100 |

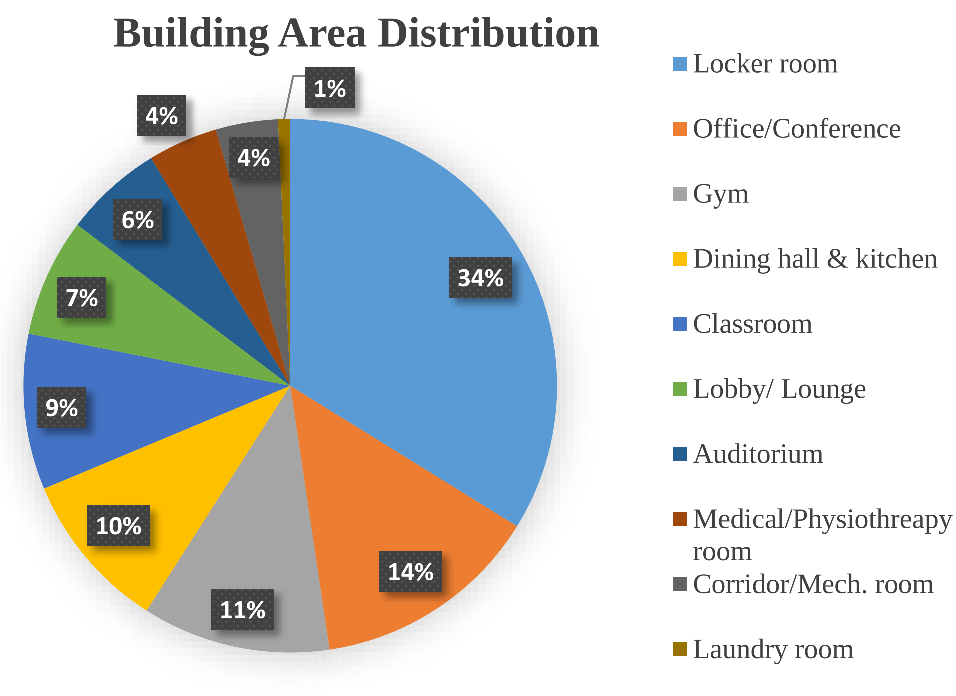



**Figure 6: Building area distribution in Gossett Football House**

**Figure 7: Hydro-therapy room in Gossett FH**


**Figure 8: Medical/therapy room and Auditorium in Gossett FH**

### 3.1.4 HVAC System

The Gossett building uses steam and electricity from the Combined Heat and Power Plant (CHP) of UMD to cater its energy needs. The building has its own in-house air cooled-liquid chiller system to supply chilled water for cooling. The HVAC system consisted of two 3 Air Handling Units (AHUs) and 6 Rooftop Units (RTUs). The largest AHU system, Air Handling Units-Air Conditioning-2 (AHU AC-2), was responsible for supplying conditioned air to the half basement (Floor 0). Air Handling Unit-Heating Ventilation 1 (AHU-HV1) was responsible of supplying hot air to the hydro room. Air Handling Unit- Air Conditioning-1 (AHU AC-1) and other RTU units were responsible for conditioning the ground floor. All AHU and RTU units were located at the roof of the building. There were no Energy recovery Units (ERUs). In addition to the RTUs and AHUs, the building also consisted of two additional make up air units. There were VAV (Variable Air Volume) boxes in almost every zone which reheats air from the main AHU system. There were also baseboard units in office spaces for additional heat during winter. A summary of the building HVAC systems is given in Table 3.

**Table 3: Summary of HVAC systems in Gossett FH**

| Units | Capacity (CFM) | Type | Coils | Air intake |
|---|---|---|---|---|
| AHU AC-1 | NA | Single zone Reheat | Steam, Chilled Water (CW) | Fixed Return Air (RA) |
| AHU AC-2 | NA | Single zone Reheat | Steam, CW | 100% OA (Outside Air) |
| AHU-HV1 | NA | Single zone Reheat | HW | 100% OA |
| RTU-1 | 10,000 | Const. volume, packaged unit | Steam, Direct expansion (DX) coils | Fixed RA |
| RTU-2 | 1,400 | Const. volume, packaged unit | Steam ,DX | Fixed RA |
| RTU-3 | 8,000 | VAV, packaged unit | Steam ,DX | Fixed RA |
| RTU-4 | 8,000 | Const. volume, packaged unit | Steam , DX | Fixed RA |
| RTU-5 | 10,000 | VAV, packaged unit | Steam ,DX | Fixed RA |
| RTU-6 | 2,600 | VAV, packaged unit | Steam , DX | Fixed RA |

AHU AC 2**:**

AHU-AC 2 was a single zone reheat system. The system is a typical Air Handling Unit consisting of consisted of steam coils and chilled water coils for conditioning the air. The steam was supplied from the CHP whereas the chilled water was supplied from the chiller unit in the building. AHU AC-2 did not consist of an economizer as the athletic building guidelines allows only 100 % fresh air to be circulated to locker rooms and training rooms.

The AHU and RTU units were old, but well maintained. The AHU system consisted of a damper unit followed by a filter section which led to steam heating coil and chilled water-cooling coils. The supply fan was of draw-through type. The system also consisted of five reheat units which were equipped with hot water coil to provide additional heating to maintain the supply temperature. Data regarding AHU size (in CFM) could not be found, so for the purpose of modelling, the AHU system was auto sized by using eQUEST at a safety factor of 1.15.

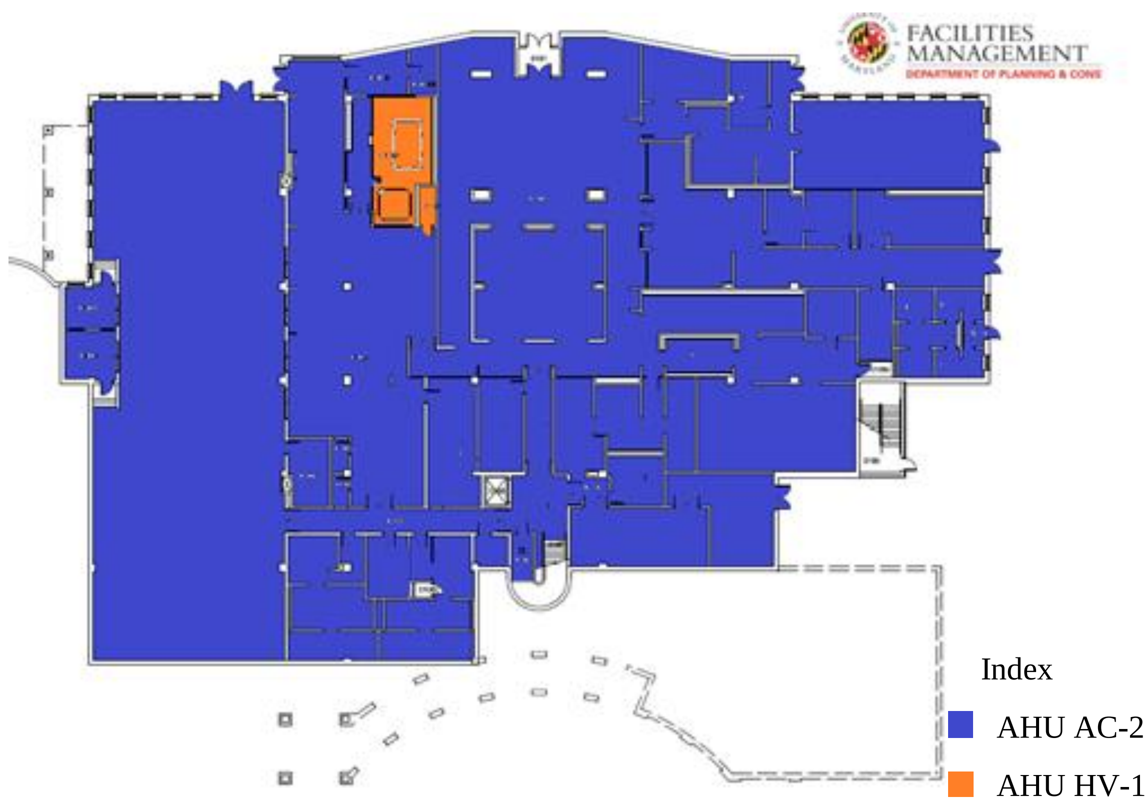



**Figure 9: HVAC Zoning in Floor 0 (Semi-basement) of Gossett FH from FM records.**

The AHU HV-1 was the smallest AHU unit consisting of only a heating coil and a reheat coil. It conditions only the hydro-therapy room. Figure 9 presents the areas served by AHU AC 2 and AHU HV 1 extracted from FM records. Figure 10 presents display of AHU AC 2 in MS 1800 system.

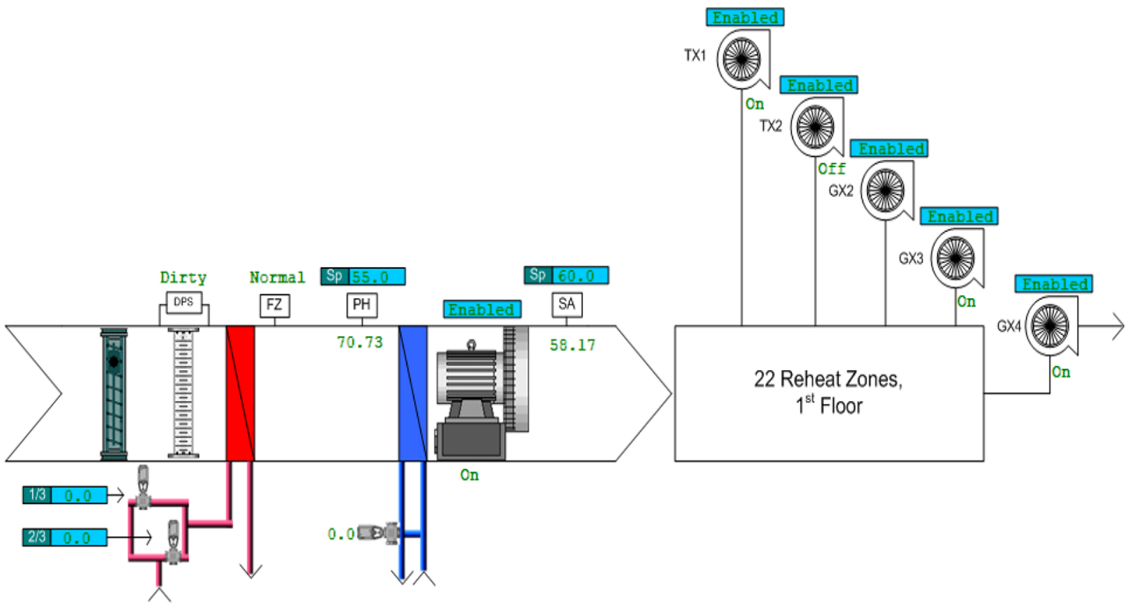



**Figure 10: Graphical representation of AHU AC 2 as shown in MS 1800 BAS**

AHU AC-1:

AHU AC-1 was responsible for circulating conditioned air in the zone consisting of mostly offices and classrooms. This system was a single zone reheat AHU system conditioned by steam heating coil and chilled water- cooling coil. It also consisted of reheat system supplied with hot water coils and an economizer that utilized the return air to provide free cooling whenever suitable.

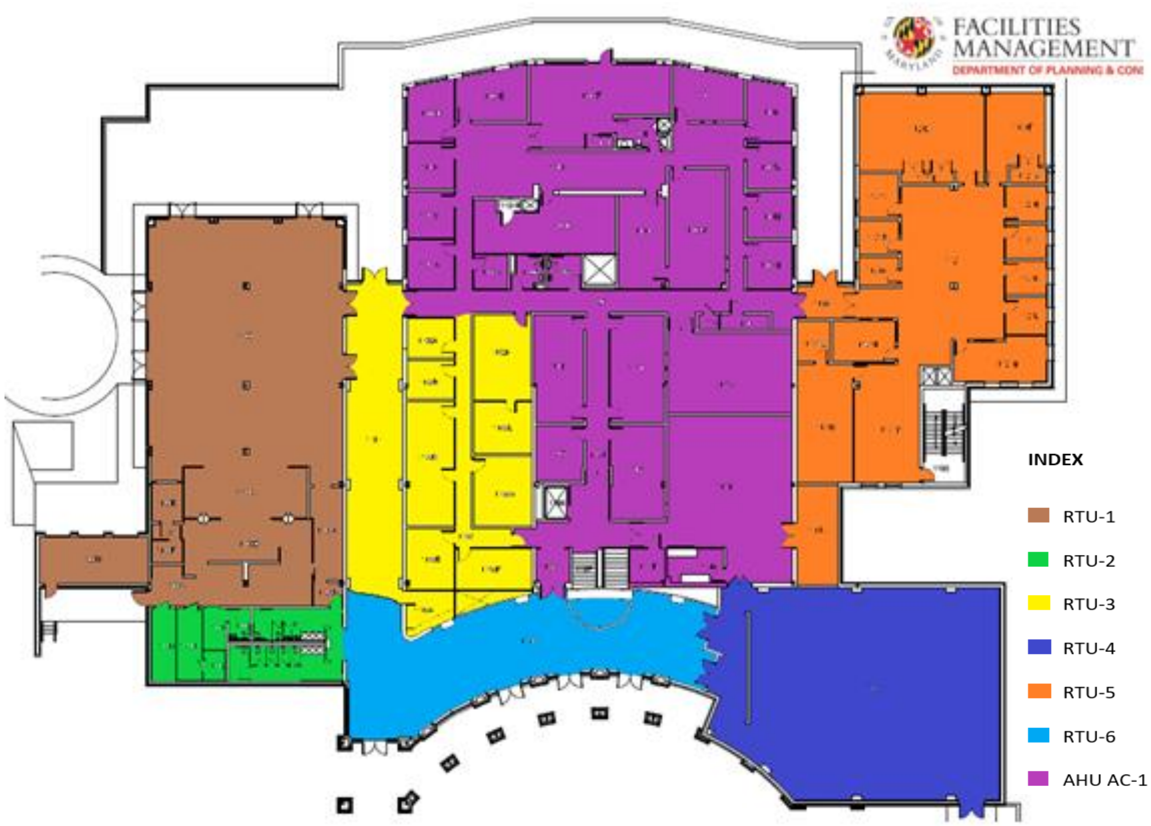



**Figure 11: HVAC zoning in floor 1 of Gossett Football House extracted from FM records.**

Figure 11 shows the various zones assigned to the respective AHU and RTU systems in Floor-1. This data was collected from interviews with the facility management staff and the archives data. The zone supplied by AHU 1 consists of an additional baseboard heating, and all zones had a terminal VAV system to supply additional heating. RTU 1 and 2 were dedicated to serve the dining hall, kitchen and the restroom whereas rest of the RTU and AHU in floor 1 served office areas, study spaces and classrooms. RTU 4 was solely responsible to supply conditioned air to the auditorium.

RTU System:

The Gossett building consisted of 6 RTU units assigned to various zones as described in Figure 11. The RTU units vary in size and capacity as shown in Table 3.

The RTUs utilize DX coils for cooling. For heating, they consist of a retrofitted hot water coil. The building has its own hot water loop. The fans of the RTUs were of draw through type. RTU-1 and RTU-5 are the largest units of 10,000 cfm capacity. RTU 1, 2 and 4 are of constant volume type, whereas RTU 3, 5 and 6 are of variable volume type. The Packaged Roof Top Units also consists of an economizer and have fixed return air systems. Figure 12 presents display of RTU 2 in MS 1800 BAS system.

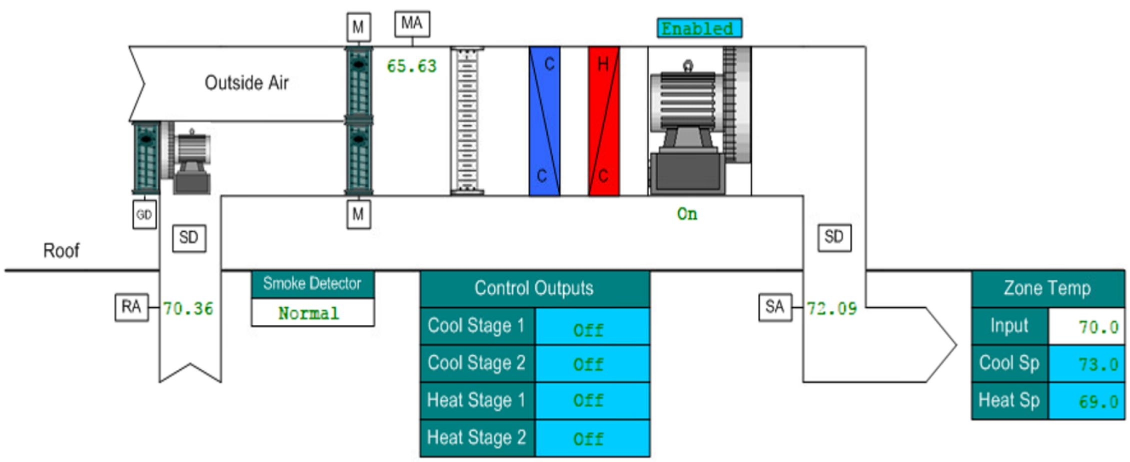



**Figure 12: Graphical representation of RTU 2 as shown in MS 1800 BAS**

### 3.1.5 Building Automation System (BAS) system

The BAS system used in Gossett building was MS 1800. All the AHUs and RTUs were controlled via this system. MS 1800 was very primitive compared to other BAS systems. The system had limited graphics and could display limited information; it was also notorious of being very slow and could not be accessed with ease.

## 3.2 Biology - Psychology Building

### 3.2.1 Building Overview

The Biology-Psychology (Bio-psy) building, Bldg. 144 at University of Maryland is an academic and research facility housing various labs, vivarium, classrooms, conference rooms and offices. Constructed in 1971, the building is precisely divided into Biology wing and Psychology wing. Biology Wing is filled with highly functional biology research labs and vivarium housing small mammals. The psychology mostly consists of classrooms, clinics, labs and office spaces. The building is located north of Hornbake plaza. Figure 13 presents the location of Bio-Psychology Building.

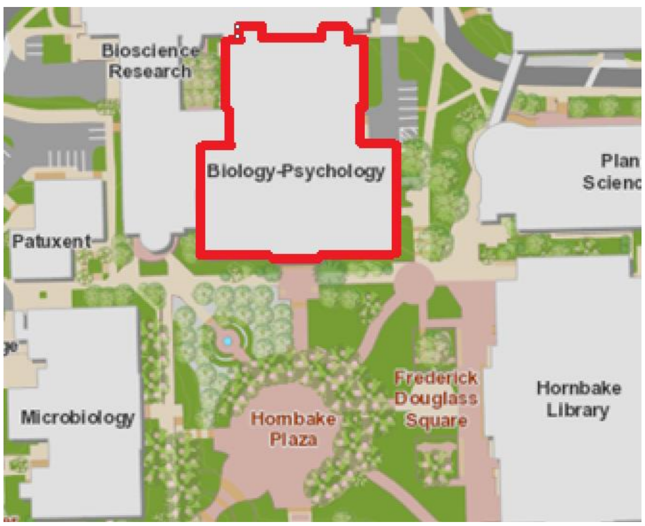



**Figure 13: Location of Bio-Psychology building**

The last major renovation was conducted in 2011 and minor renovations have been ongoing since then. At the time of the audit, there was roof maintenance work going on in the building, from April of 2019 to October 2019. During the 2011 renovations, Glycol Energy Recovery Units (ERU) were installed and Dual duct ventilation in the first floor, Psychology wing, was changed to single duct with VAV reheat terminal. The building is fully owned by the University of Maryland and is dedicated to serve the Biology and Psychology departments.

### 3.2.2 Building Construction and Architecture

The Bio-psychology building is attached to the adjacent Bio-Science building, but the utilities systems are separate. The total gross area of the building is 242,067 $ft^2$. It consists of a basement, a sub-basement, 4 floors above grade and a penthouse (roof).

From the archive records, it was found that building envelope consists of reinforced concrete, slag block, brick, and masonry insulation. The floors are made up of concrete, Vinyl Asbestos Tile (VAT), Quarry Tile (QT) and Vinyl Tile (VT). A generalized R value of the building envelop was calculated based to be 5.12 $ft^2$·°F·hr/Btu (Perlite Institute, 2013). Figure 14 presents the composition of above grade walls used in majority of the building envelope. The ceiling height varies from 8 to 9.5 feet and distance between floors is 13.5 ft.

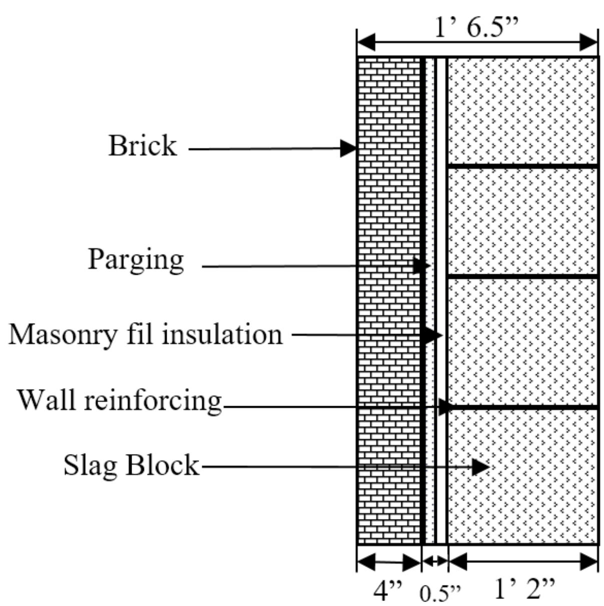



**Figure 14: General section of above grade wall in Bio-psychology Building**

### 3.2.3 Space Distribution

The building is a mixed-use space and is divided into a Biology and a Psychology wing. The biology wing is mostly divided into labs, clinical labs, vivarium, classrooms, and offices whereas the psychology wing mostly houses classrooms and offices. Table 4 and Figure 15 gives the details of the space distribution. The information was collected from the data provided by the Facilities Management.

**Table 4: Space distribution in Bio-psychology building**

| Space Specs. | Area covered [$ft^2$] | Percentage [%] |
|---|---|---|
| Research Lab/Vivarium | 79,965 | 37 |
| Clinic | 2,964 | 1 |
| Mechanical/Electric room | 26,363 | 12 |
| Office | 32,747 | 15 |
| Classroom | 8,638 | 4 |
| Restroom | 2,767 | 1 |
| Corridor, Elevator, Stair | 43,879 | 20 |
| Other (vestibule, storage space) | 17,063 | 8 |
| Total | 214,387 | 100 |

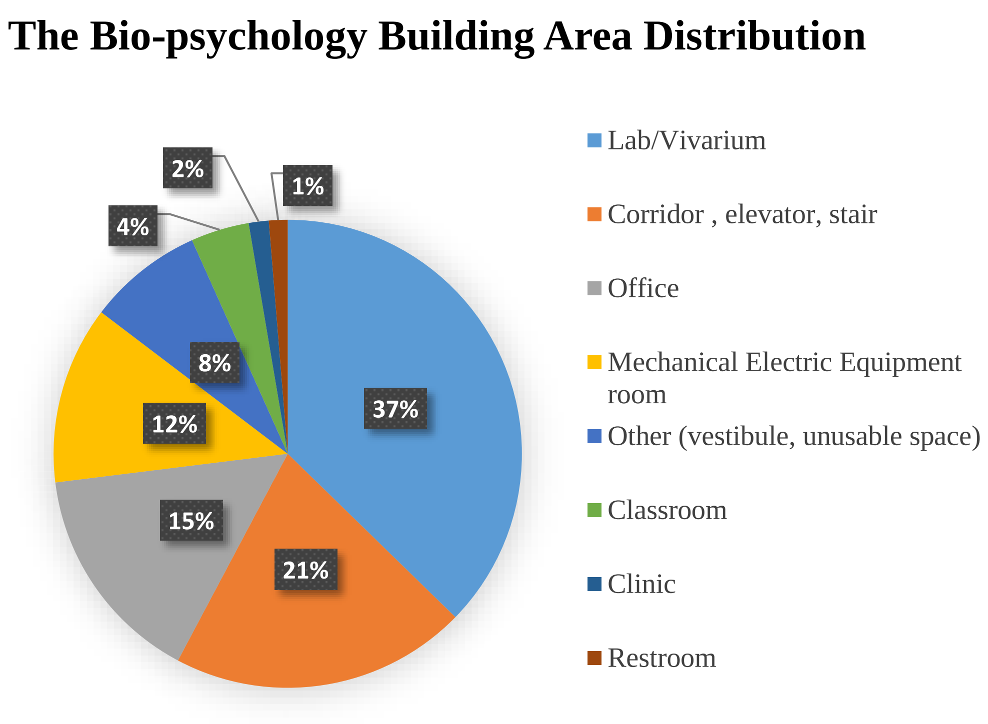



**Figure 15: Bio-psychology building area distribution**

### 3.2.4 HVAC System

The building uses steam and electricity from the Combined Heat and Power Plant (CHP) at UMD. In addition to steam and electricity, the building uses chilled water supplied from one of the five Satellite Central Utilities Buildings (SCUB).

The Biology wing needs to be continuously ventilated as most of it consists of labs and vivarium. Except for the sub-basement and penthouse, all the enclosures of the building were well ventilated. The sub-basement and penthouse both housed mechanical rooms which consisted of the AHU system. A network of ducts, supplied by the AHU, supplies each floor. The AHU uses steam and chilled water to condition the air. The ventilation system mostly consists of conventional dual duct system to ventilate majority of its zones. The building has 9 AHU units of which 8 are active. Along with 8 active AHU systems, there are also some Perimeter Air Units (PAUs) and Fan Coil Units (FCUs) with terminal reheat assigned to some zones. PAUs were present to boost heat transfer near windows. The details of the various AHU systems in the building are listed in Table 5.

**Table 5: Summary of HVAC system in Bio-psychology building**

| AHUs | CFM | Type | Coils | Air Intake | Location |
|---|---|---|---|---|---|
| AHU1 | Not in use | - | - | - | Sub-Basement |
| AHU6 | 81,000 | Dual Duct, Variable Air Volume (VAV) reheat | Hot water (HW), Chilled water (CW) | Fixed RA | Penthouse |
| AHU7 | 81,000 | Dual Duct, VAV reheat | HW, CW | Fixed RA | Penthouse |
| AHU8 | 31,000 | Single-zone terminal reheat | HW-preheat, HW, CW | 100%OA | Penthouse |
| AHU9 | 17,000 | Single-zone terminal reheat | HW-Preheat, HW, CW | 100%OA | Penthouse |
| AHU 10 | 100,000 | Dual Duct; VAV | Preheat (Glycol), HW, CW | 100% OA | Penthouse |
| AHU 11 | 100,000 | Dual Duct; VAV | Preheat (Glycol), HW, CW | 100%OA | Penthouse |
| AHU 12 | 2,000 | Single zone terminal Reheat | HW, CW | 100%OA | Floor 2 |
| AHU 13 | 3,000 | Single-zone term reheat | HW, CW, humidifier | Economizer | Sub-Basement |

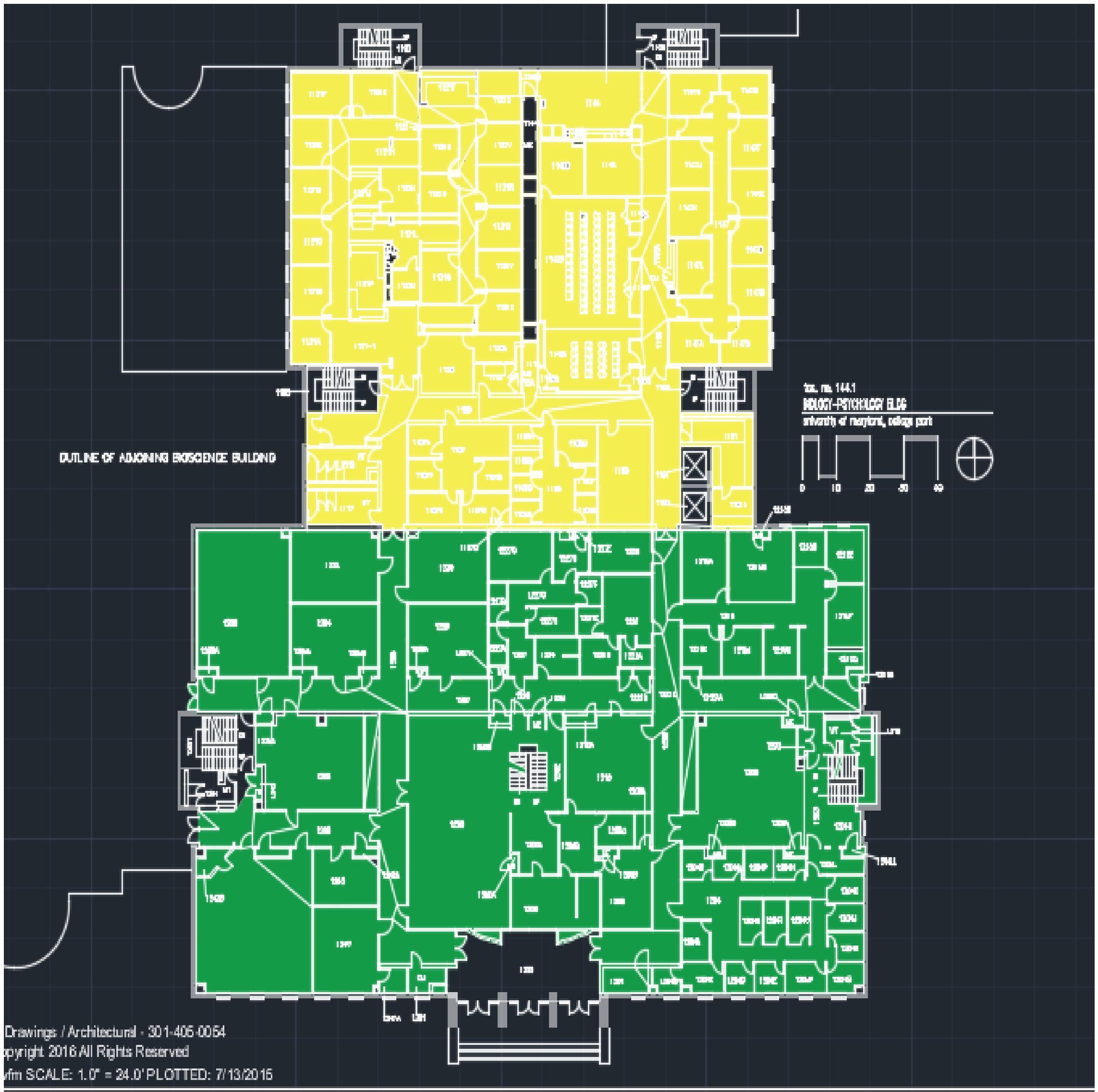
AHU 10 and 11 are the largest AHU systems, followed by 6 and 7. AHU-12 only serves the fish lab located in floor 2 and is the smallest system in the building. All the AHU systems except AHU-13, 6 and 7 use 100% Outside Air. The information about the AHU system were collected from interviews with the FM, and thorough investigation of the Mechanical Plan of the building. All systems could be viewed in real time by BAS network, which was used for monitoring and troubleshooting HVAC systems. Figures 16 to 20 presents the zones served by the respective AHU units. The entire thermal zoning of the eQUEST model was designed based on these zones.

Index: Floor Basement

AHU-6 and AHU-7 Fan coil Units AHU-8 AHU-13

AHU-10 and AHU-11

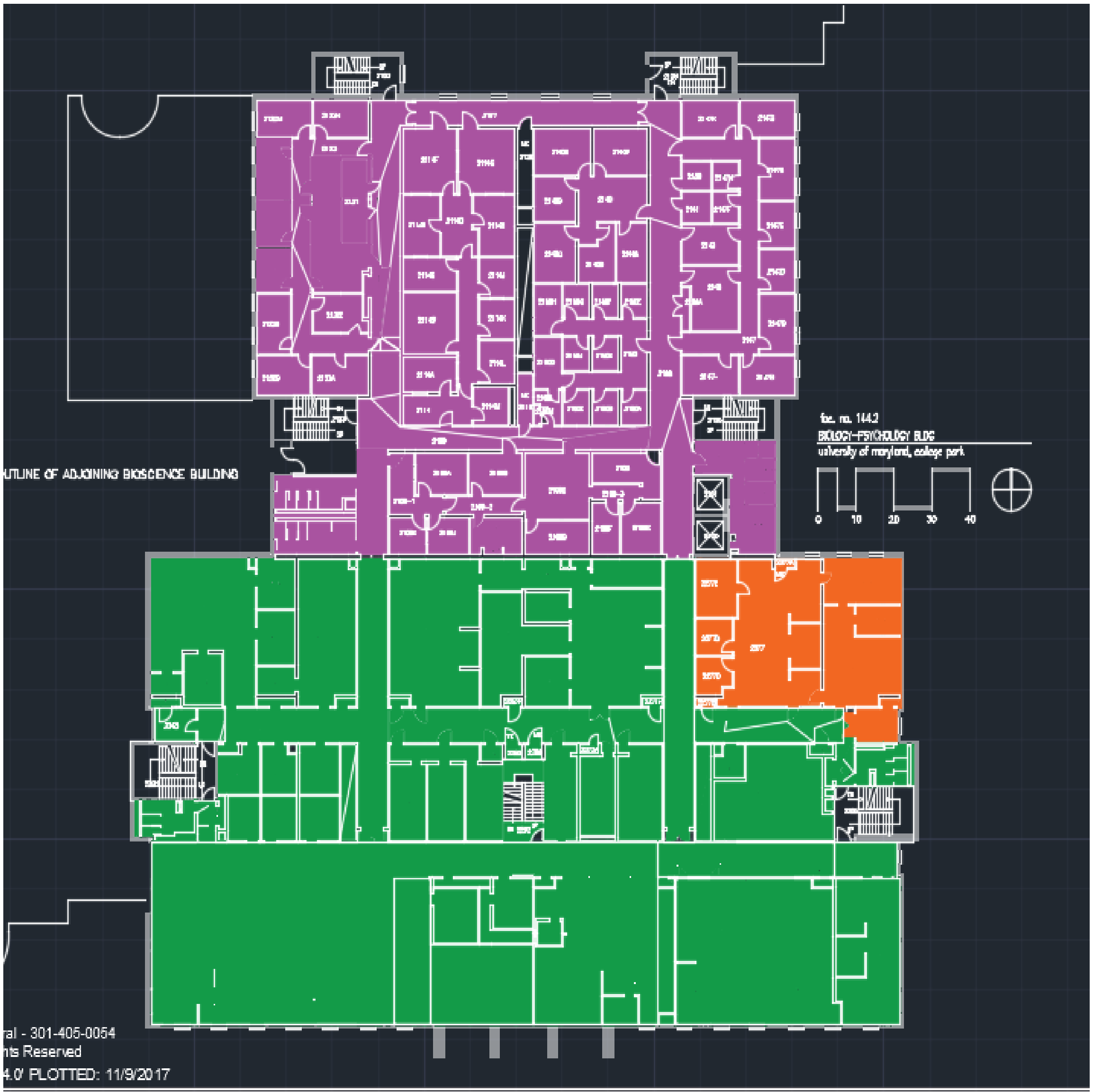
**Figure 16: Thermal zoning in Floor G (Basement) of Bio-psychology building**




Index: Floor 1

AHU- 6 and AHU- 7 AHU- 10 and AHU- 11

**Figure 17: Thermal Zoning in Floor 1 of Biopsychology building**




Index: Floor 2

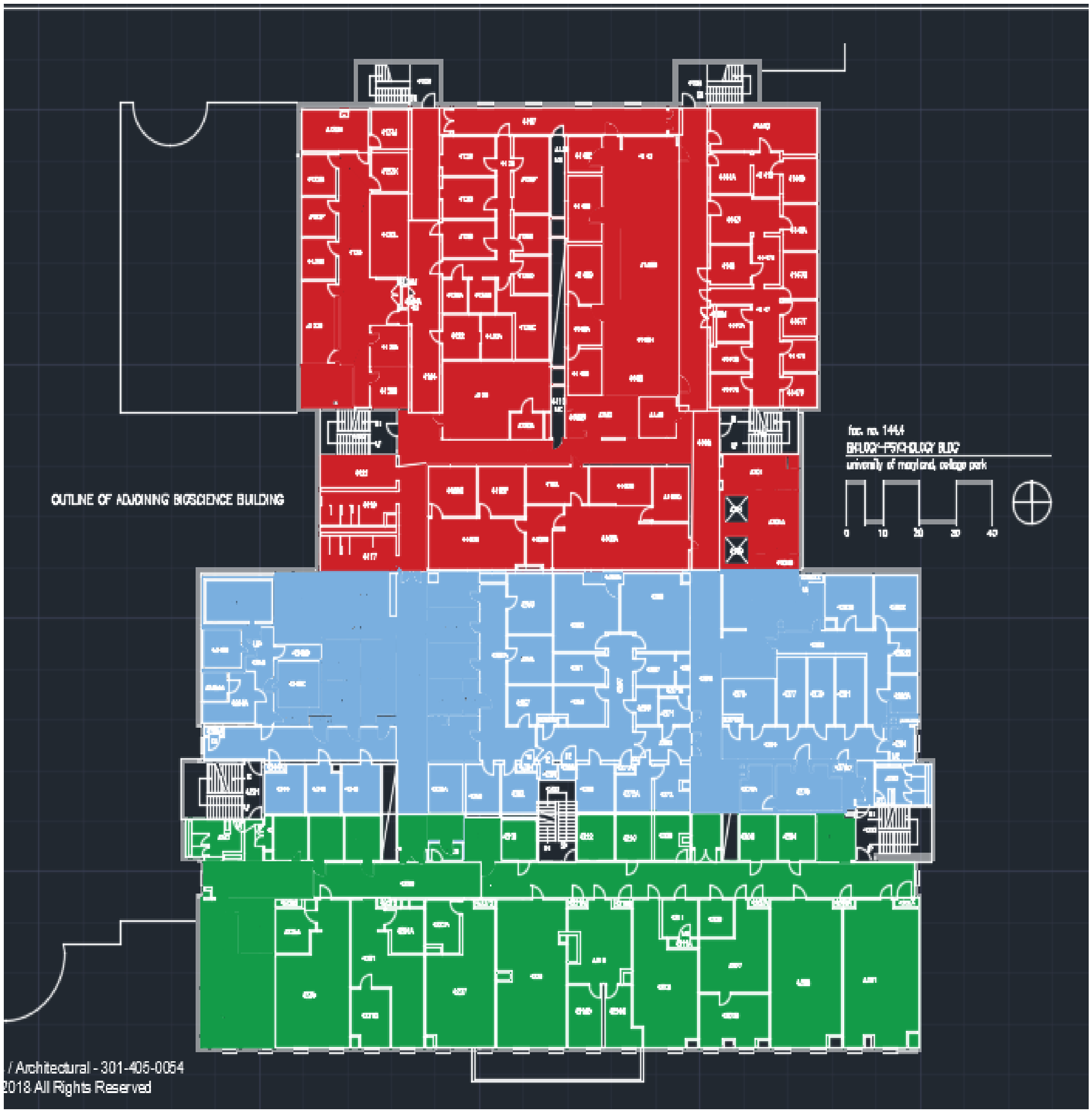
AHU- 6 and AHU- 7 | AHU- 12 | AHU- 10 and AHU- 11

**Figure 18: Thermal Zoning in Floor 2 of Bio-psy Bldg.**


Index: Floor 3

AHU- 6 and AHU- 7 AHU- 10 and AHU-11

**Figure 19: Thermal Zoning in Floor 3 of Biopsychology bldg**




Index: Floor 4

AHU- 8 AHU- 9 AHU- 10 and AHU- 11

**Figure 20: Thermal Zoning in Floor 4 of Biopsychology building**

**Glycol Energy Recovery Unit System (ERU):**

The Glycol Energy Recovery System (ERU) reuses the heat from the exhaust vents. Most of the labs house fume hoods that exhaust the air directly out of the lab environment and maintains a negative pressure in the lab. Figure 21 presents the graphical representation of the ERU system as shown in the Niagara BAS. There were four ERU units utilizing the exhaust air from AHUs 10 and 11. The energy recovered by the glycol system was utilized in AHU 10 and 11 for preconditioning the air as represented in Figure 22.

The ERU glycol system was enabled when outside temperature was below 40 $^{o}$ F for heating energy recovery, or above 80$^{o}$ F for cooling energy recovery.

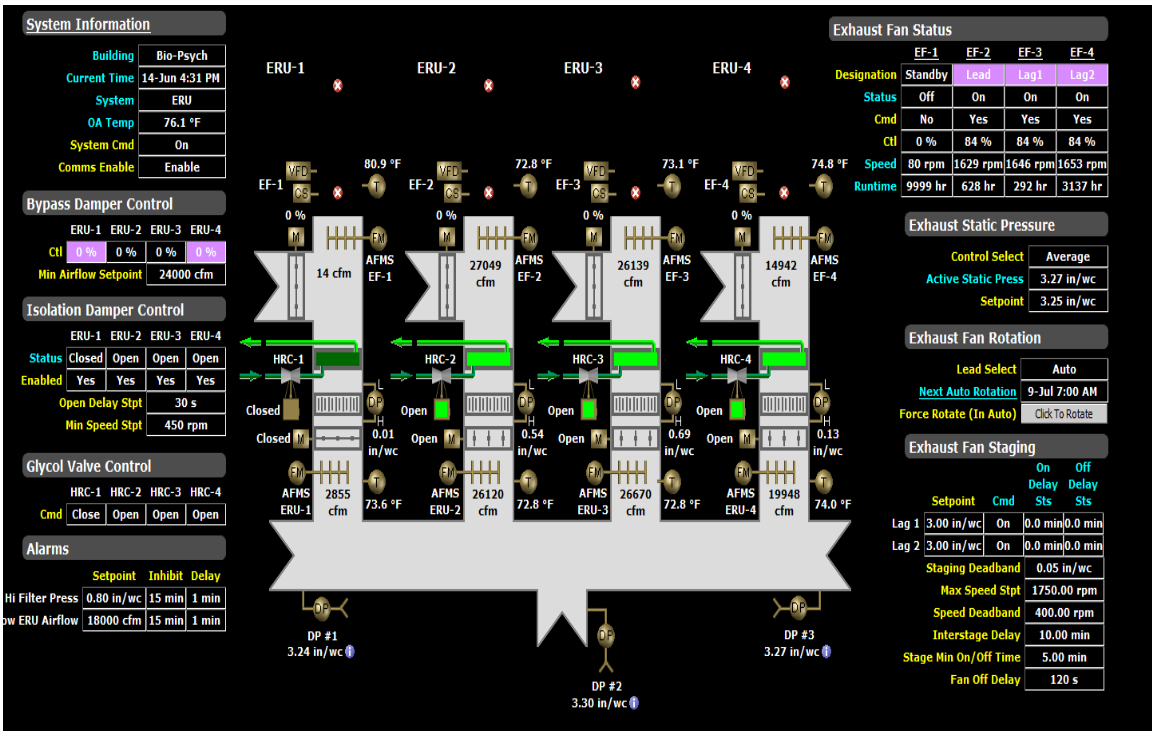



**Figure 21: Graphical representation of Energy Recovery Unit in Bio-psychology Building as shown in Niagara BAS**

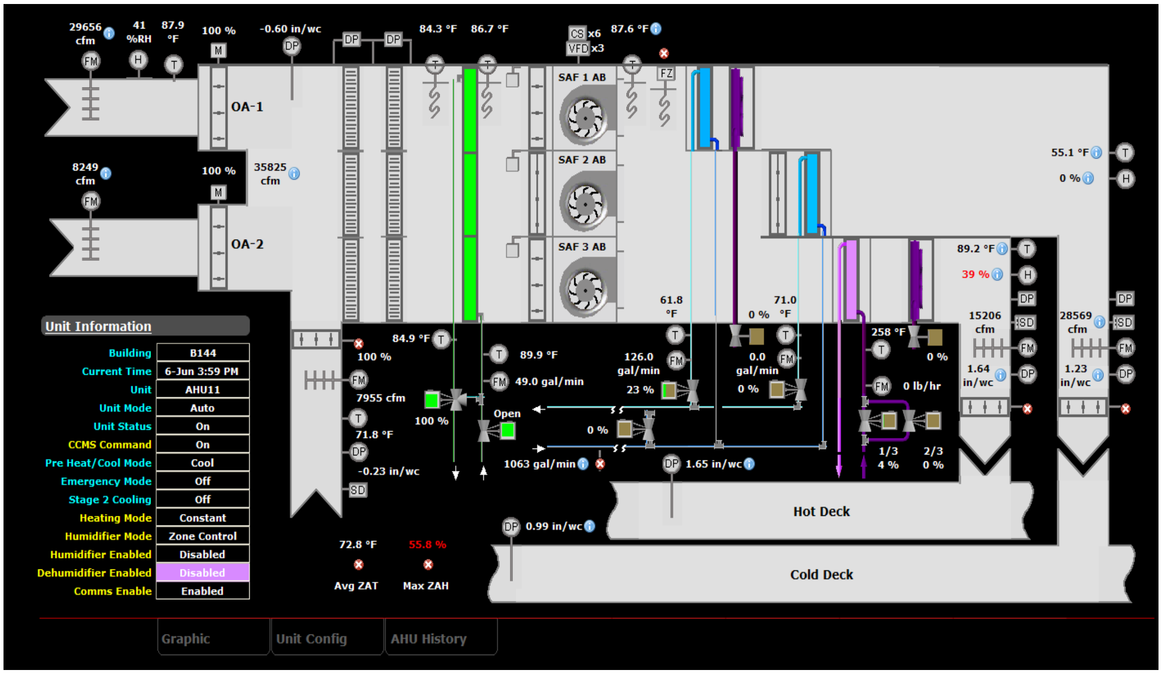



**Figure 22: Graphical representation of AHU 11 Dual Duct System with Glycol pre-conditioning (green) as shown in Niagara BAS**

### 3.2.5 Building Automation System (BAS)

The Building Automation System used in Bio-psychology building was "Talon Tridium Niagara" BAS. The Talon Tridium Niagara system was accessible through a Java Web Client. A read-only access was available for the analysis. From this access, live monitoring of equipment operation, thermal conditions in building spaces, as well as alarm statuses was possible. The system helped in better understanding the HVAC system in the building, and in troubleshoot any possible problems. Figure 23 presents the display of home page of Niagara BAS system.

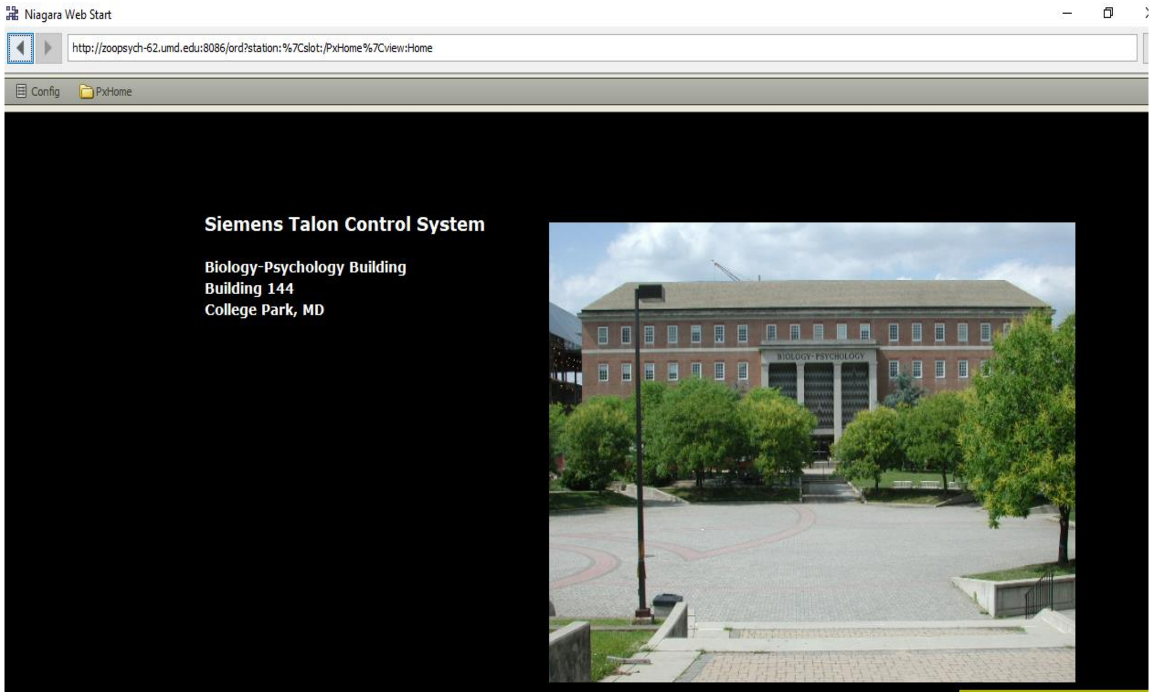



**Figure 23: Display of home page of Niagara BAS**

# Chapter 4: Energy Audit and Modelling Methodology

The energy audit and modelling process consists of three phases: (1) Building comprehension, (2) Energy Model Development, and (3) Energy Conservation Measures (ECM) modelling and analysis. A schematic diagram of the workflow algorithm is presented in Figure 24. The algorithm was adapted from Levy (J. M. Levy, 2014).

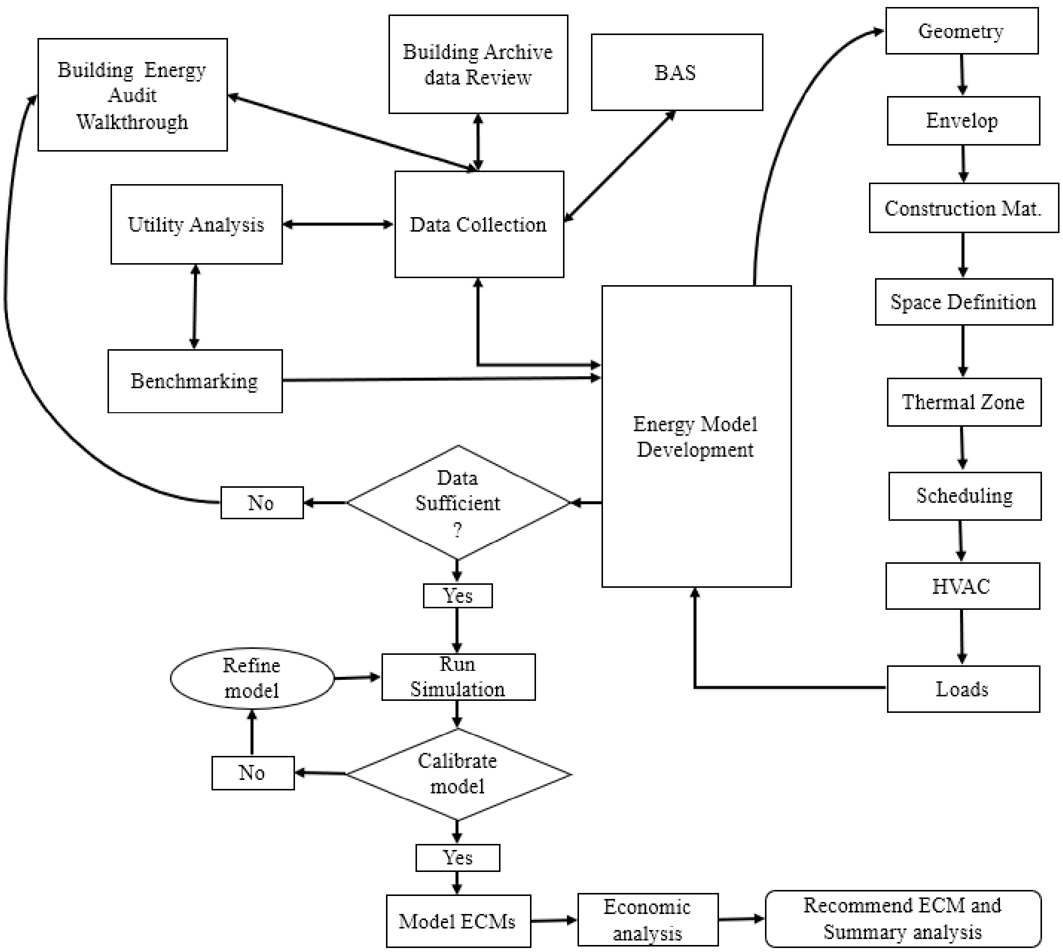



**Figure 24: Flow chart of Energy Audit process**

## 4.1 Building Comprehension

Building comprehension was the first phase of the Energy Audit process. Required data of the building was collected from various sources in this phase. The first step of data collection was via initial energy audit walkthrough, followed with study of archive records, plans, utility consumption analysis and analysis of Building Automation System.

The Energy Audit walkthroughs were organized accompanied by the building Facilities staff which helped in identifying common problems just by observing the state of the building systems. Walkthroughs were conducted for both Gossett and Bio-psychology buildings. During the walkthroughs, a good relation was established with the facilities staff which helped us in gathering further data about the working of the building.

Archival review was done by collecting the mechanical, architectural, electrical, plumbing, lighting, and renovations drawings. The data was provided by the Facilities Management. Due to the number of renovations and age of the buildings, some of the data could not be acquired. Archival review helped in understanding the various mechanical and electrical systems in the building.

The building utility consumption data provided by the FM was used to analyze the building's energy consumption. The building utility data was then compared with the national average benchmark to recognize the status of energy consumption of the building.

The Building Automation System was also very essential in analyzing the details of the mechanical system of the building. The Gossett ran on MS 1800 whereas Bio-psychology ran on Talon Tridium Niagara BAS. The Talon Tridium Niagara system was accessible through a Java Web Client. Compared to Niagara BAS, MS 1800 BAS system has limited graphics and details. A read-only access was available to us, for all the BAS systems. From this access, live monitoring of equipment operation, thermal conditions in building spaces, alarm status as well as scheduling history was also made possible. The

Niagara system had more details compared to the MS 1800 with better graphics and user-friendly access. These details helped us understand the building system in detail and collect data to simulate the building working in Energy Modelling software.

## 4.2 Energy Modelling

The steps of building comprehension were repeated until all the data required for the model was obtained. Usually, energy modelling and data collection was a to-and-fro process in which data was also collected during the modelling phase if required. Both, Bio-psychology and Gossett buildings, were modelled in eQUEST after careful analysis of their systems.

eQUEST is a freeware utilizing DOE 2.2 simulation environment developed and provided by the Department of Energy and the Lawrence Berkley National Laboratory (Maile et al., 2007).The software was qualified for commercial building tax deductions and had widely been used in comprehensive building energy analysis for over 20 years. The software has a user friendly “Wizard Edit Mode” and “Detailed Data Edit” of which latter is used for a detailed modelling.

The Wizard Edit Mode was used to first set up the model and then details were added via Detailed Data Edit mode. One very important issue to keep in mind is that one cannot go back to Wizard Edit mode after Detailed Edit mode or else all changes in “Detailed edit” mode will be lost.

eQUEST has its own building geometry platform, unlike many other modelling software, which makes it easier to operate. The primary use of the geometry tool was to construct the building envelope. For this, firstly, an AutoCAD model of the building footprint was created. The AutoCAD file was then imported to the eQUEST geometry platform. Using the tools in geometry platform, various zones and envelope were created. eQUEST automatically extrudes the 2-D footprint along with specified zones and shells into a 3-D model. Other floors can be similarly modelled by importing the respective footprint and be stacked on top of the other.

After the Building footprint and envelope, the boundary conditions, fenestration, and construction materials, as well as simplified space type definitions like thermal zones, schedules, plant loops, and basic HVAC definitions were designed using "Design Development Wizard", it was refined using "Detailed Design Mode."

The simulated results were then exported to Microsoft Excel for further computational analysis. After the model was created, it was refined until calibrated to simulate the current utility consumption of the building. The model was calibrated according to ASHRAE 14 guidelines, which is further mentioned in chapter 6 of this thesis. Figure 25 represents the Geometry tool in eQUEST and Figure 26 shows the "Detailed Design" mode in eQUEST.

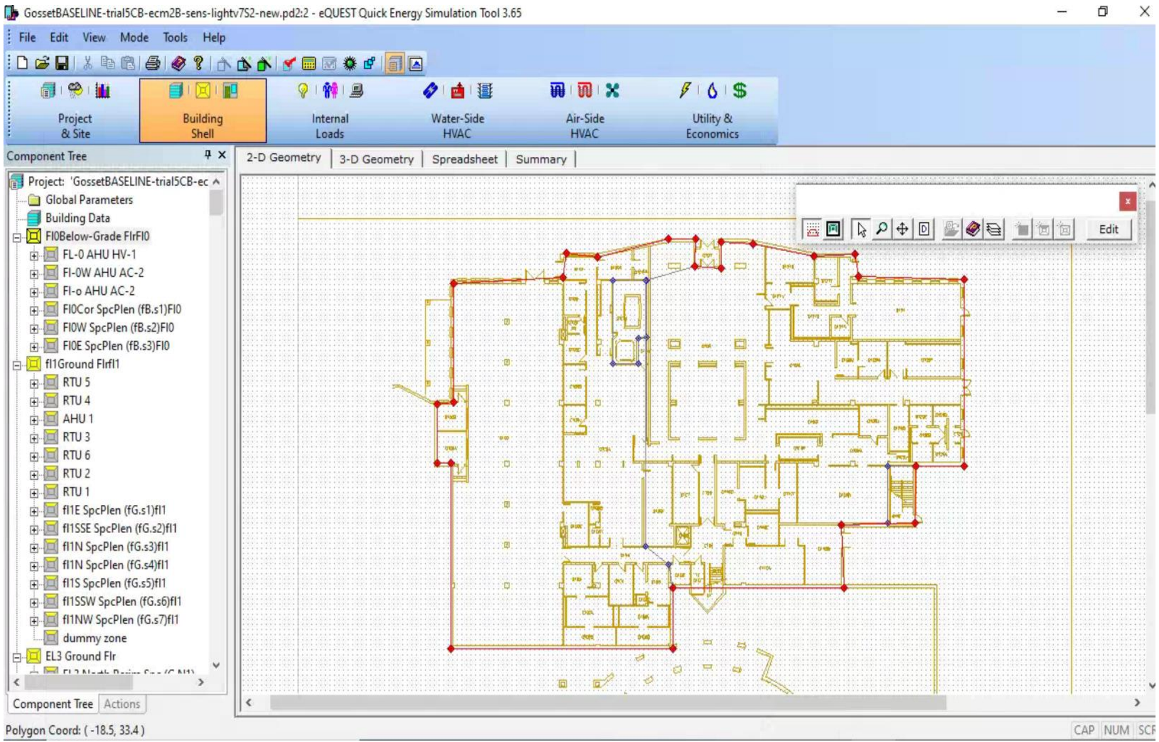



**Figure 25: Example display of eQUEST Geometry tool**

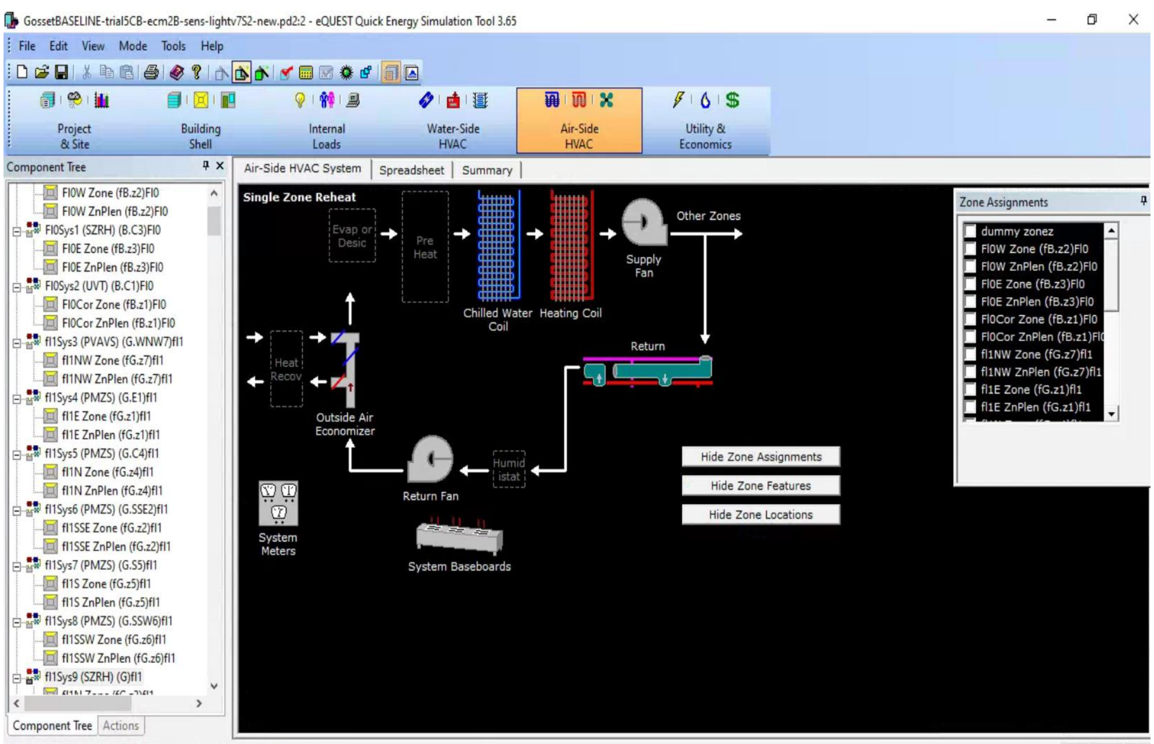



**Figure 26: Example display of eQUEST Detail Design mode**

## 4.3 Energy Conservation Measure Analysis

After calibrating the model, it was used to test Energy Conservation Measures (ECMs) by introducing them in the model and observing the simulated results. The ECMs usually sought after were low-cost/no-cost ECMs with low capital investment and short pay-back period. Some of the ECMs could be analyzing the HVAC schedule to obtain the most optimal schedule of operation, replacing old components with new, and more efficient versions. A variety of software and tools were used to perform energy saving calculations in addition to eQUEST such as, online VFD tools, Excel and EES.

The possibility of implementing these ECMs were discussed with the FM, which could be the future scope of this project.

# Chapter 5: Utility Analysis

This was the most important phase to understand the current energy consumption status of the building. Utility consumption data of both the buildings were collected from the FM records which helped in understanding the consumption pattern of the building. The building's consumption data was then compared with the benchmark data to identify the status of the building and research for further improvements. This chapter presents the detailed analysis of utility data in Gossett Football House and Bio-psychology building along with the national average benchmarks used.

## 5.1 Gossett Football House

The Gossett Football House consumes steam and electricity provided by the Combined Heating and Power (CHP) plant. The building consumes an average of 2,241,600 kWh of electricity and 6,573,870 lb of steam per annum (Average from 2011 to 2018) which amounts to an average of 14,156 MMBtu per year

The data for space cooling could be deduced from the electricity data as the facility has its own in-house electric chiller. Steam was supplied at saturated conditions under a pressure of 115 psi before being reduced to medium and low-pressure steam. The Figure 27 details the average annual consumption from year 2011 to 2018 for Electricity and from year 2010 to 2018 for steam consumption. Steam and electricity make up 47% and 53 % of total energy consumption per annum respectively as presented in Figure 28. Steam consumption peaks at winter months and electricity consumption peaks in summer months.

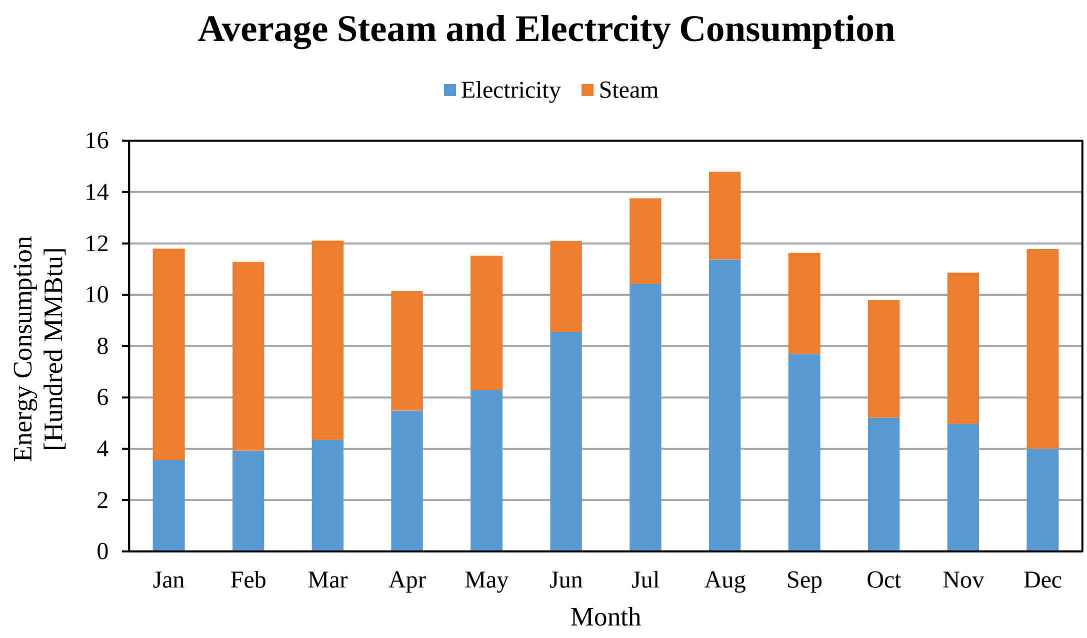



**Figure 27: Average monthly electricity consumption of Gossett Building**

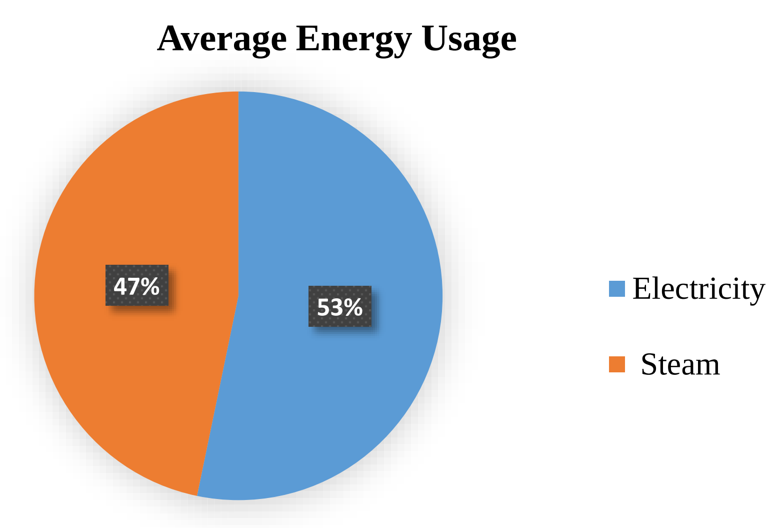



**Figure 28: Average energy usage, Gossett Building**

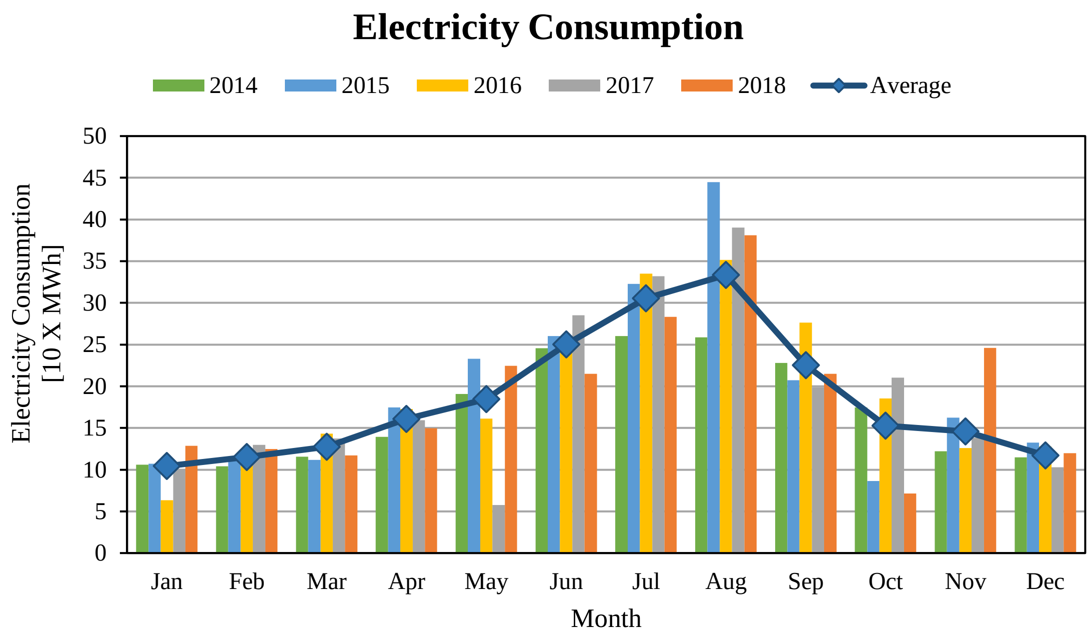



**Figure 29: Electricity consumption over the years in Gossett FH**

Figure 29 presents the detail of electricity usage in years 2014, 2015, 2016, 2017, 2018 and the average from the year 2011 to 2018. Since the electricity also accounts for cooling energy, the consumption is high in summer months and low in winter months. It can be observed that there were high fluctuations in various years, especially 2017. Some of the peaks could be explained by over-use of the facility resources or higher number of cooling degree days for the particular year. The inconsistency in some years could be explained by varying occupancy in the building. On average, the consumption peaks in summer months as the cooling is provided by electricity through the in-house chiller and RTUs.

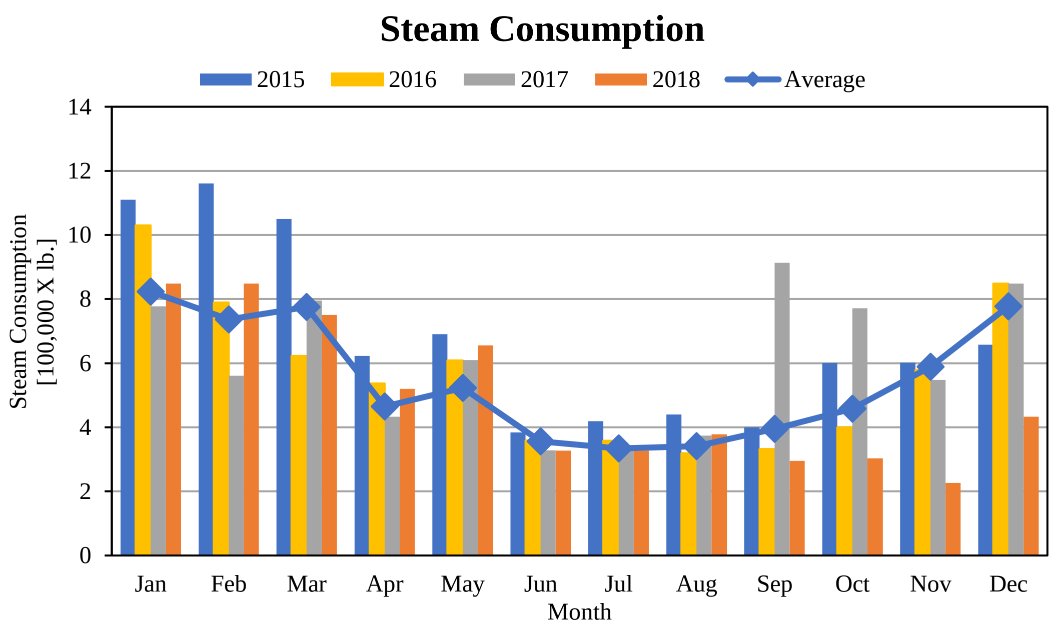



**Figure 30: Steam consumption over the years in Gossett FH**

Figure 30 presents the detailed monthly steam consumption in pounds of steam. On average, the consumption is high in winter months and low during summer months. The annual steam data for year 2017 showed an unusual peak in the month of September. Upon investigating, it was concluded that the reason behind it could have been leakage in the steam coil in one of the AHU systems. The state of the mechanical rooms at the beginning of audit was very poor. The insulation of most of the steam valves and condenser tanks had fallen off and were in dire need for replacement which might have been the reason for inconsistency in the data. During the time of the audit, many valves, pipes, and condenser tanks were reinsulated. The building occupancy is low during winter break and summer break which might explain comparatively low energy consumption during December.

The occupancy in the building could also be a reason for the yearly fluctuation, followed by poor state of the equipment, and respective heating and cooling degree days.

Additionally, during the time of audit, the steam meter was damaged which could have explained some faulty readings or loss in some of the readings.

On average, the steam consumption was highest in the winter months and lowest during summer months of June and July. Except for 2017, all other data followed this trend.

Figure 31 shows that in the big picture, the anomaly in 2017 did cause an increase of about 2% compared to the consumption in 2016 but was not extremely odd. The total energy consumption has risen significantly from 2011 (at least 15%) which might be due to the degradation of the HVAC performance due to time and due to varying number of hot/cold degree days.

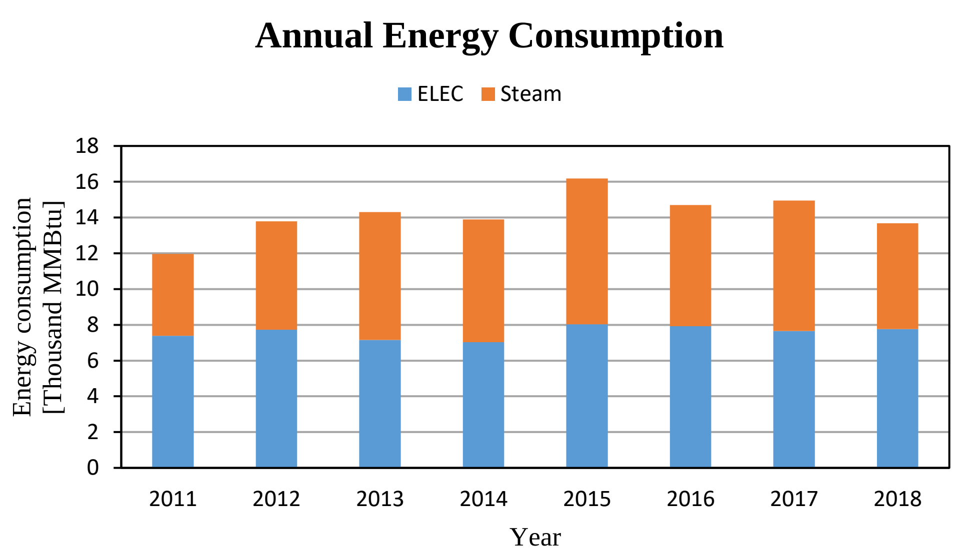



**Figure 31: Annual energy consumption in Gossett Building**

### 5.1.1 Cost and Consumption

Throughout the University, buildings were almost never billed directly, since energy commodities are received from a variety of sources. Utility rates provided by the

Facilities Management was used to perform a brief economic analysis. Figure 32 represents the average relative contributions of utilities to the total energy consumption and utility bill. Steam is used 46% and is responsible for 36% of the total utility cost whereas electricity is used 54% and is responsible for 64% of the cost. The average utility cost for Gossett building from the utility data was $369,442 per annum. Table 6 presents the utility rates made available by the FM and the conversion factors.

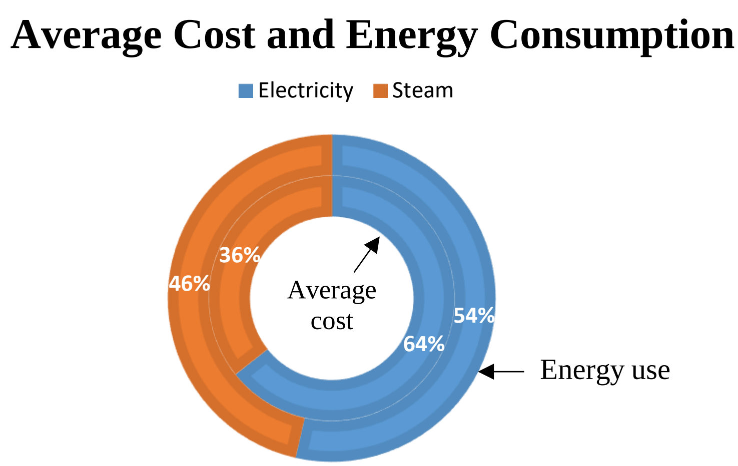



**Figure 32: Average Cost (Inner circle) and Energy use (Outer circle) of Gossett FH**

**Table 6: Utility rates and conversion factors**

| Utility | Unit | Cost per unit [$] | Conversion factor to kBtu |
|---|---|---|---|
| Electricity | kWh | 0.10 | 3.41 |
| Steam | lb. | 0.02 | 1.00 |
| Chilled Water | Ton-Hr | 0.18 | 12.00 |

### 5.1.2 Benchmark Comparison

The standard metric used to compare buildings' energy consumption is Energy Use Intensity (EUI), calculated by dividing the building's energy consumption by Gross Foot

Area, and has the unit of [kBtu/ft$^2$/yr.]. Table 7 represents the average EUI per annum of Gossett Building calculated from utility data of years 2011 to 2018.

**Table 7: EUI calculated from average utility data of Gossett FH**

| Utility | Average EUI [kBtu/ft$^2$/yr.] |
|---|---|
| Electricity | 119 |
| Steam | 105 |
| Total | 224 |

After collecting the data for Gossett, the next step was to establish an appropriate benchmark value. The building is a multi- functional facility housing athletic facility, class rooms, offices and even an auditorium, thus various spaces having their own benchmark standards. Keeping all these in mind, the ENERGY STAR Portfolio Manager was used to set a benchmark value. Respective Site EUIs were gathered for various spaces using the ENERGY STAR portfolio manager data (Energy Star Portfolio, 2018). Energy Star portfolio consists of both Source EUI and Site EUI, but in this case, only site EUI is used as the utility data available is of onsite type (i.e. Does not considers energy consumed at source).

Table 8 presents the space distribution and the respective weighted EUI. According to the high standards of Energy Star, the site benchmark should be 82 kBtu/ft$^2$/yr. The actual EUI of the building, calculated from average of utility data was 224 kBtu/ ft$^2$/yr., which was 173 % greater than the benchmark value, thus concluding that the building has a high potential to improve its energy efficiency and is in dire need of it. Figure 33 shows the energy consumption of various spaces in the building estimated according to the benchmark EUI.

**Table 8: EUI benchmarking results for Gossett FH**

| Space | Area [$ft^2$] | Percentage covered [%] | Source EUI [$kBtu/ft^2/yr.$] | Site EUI [$kBtu/ft^2/yr.$] | Weighted EUI [$kBtu/ft^2/yr.$] |
|---|---|---|---|---|---|
| Office/Conference | 8,400 | 14 | 116 | 53 | 7 |
| Dining hall and kitchen | 5,868 | 10 | 574 | 325 | 31 |
| Lobby/ Lounge | 4,361 | 7 | 110 | 56 | 4 |
| Auditorium | 3,620 | 6 | 112 | 56 | 3 |
| Locker room | 20,553 | 34 | 112 | 51 | 17 |
| Medical/Therapy room | 2,575 | 4 | 138 | 62 | 3 |
| Corridor/Mech. room | 2,290 | 4 | 89 | 40 | 2 |
| Gym | 6,928 | 11 | 112 | 51 | 6 |
| Classroom | 5,728 | 9 | 181 | 84 | 8 |
| Laundry room | 444 | 1 | 97 | 48 | 1 |
| Total | 60,764 | 100 | | | 82 |

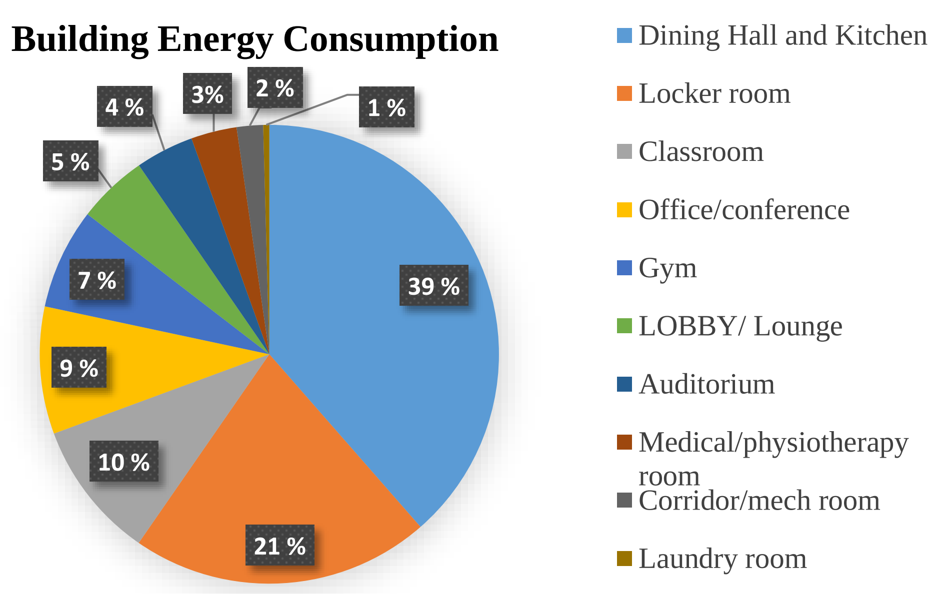



**Figure 33: Building energy consumption distribution in Gossett FH**

## 5.2 Biology - Psychology Building

The building consumes steam, electricity and chilled water provided by the Combined Heat and Power Plant. Like Gossett FH, steam was supplied at saturated conditions under a pressure of 115 psi before being reduced to medium and low-pressure steam. Steam was used to heat water for domestic and heating end uses, as well as consumed in the building's autoclaves to sterilize laboratory equipment. The data of steam and chilled water consumption for the years 2011, 2014, 2015, 2016 and 2017 was provided by the Facilities Management (FM). The electricity consumption data was available only for the years 2011, 2009 and 2008.

Chilled water was supplied from Satellite Central Utilities Building-4 (SCUB-4) units via steam powered chillers. Based on the utility data provided, the average annual energy consumption was 67,206 MMBtu. The units of cost used in the economic analysis were the same as in Table 6.

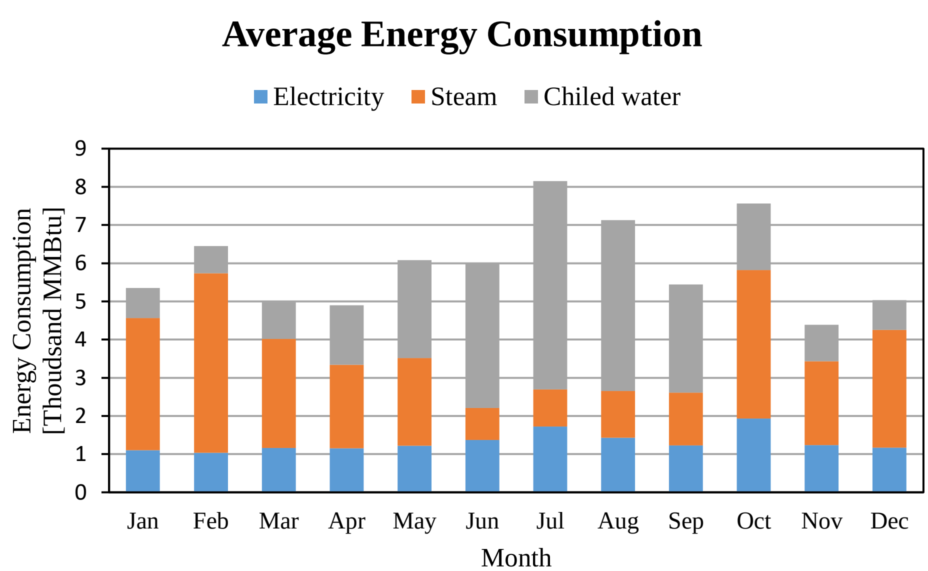



**Figure 34: Average monthly energy consumption of Bio-psychology Building**

Figure 34 presents the average monthly energy consumption averaged throughout years 2008, 2009, 2011, 2014, 2015, 2016 and 2017. It was observed that building consumes high amounts of steam consumption was high in winter months and chilled water consumption was high in summer months. On an average, the building consumes 4,618,096 kWh of electricity, 29,101,335 lb of steam and 2,218,632 Ton-Hr of chilled water per annum.

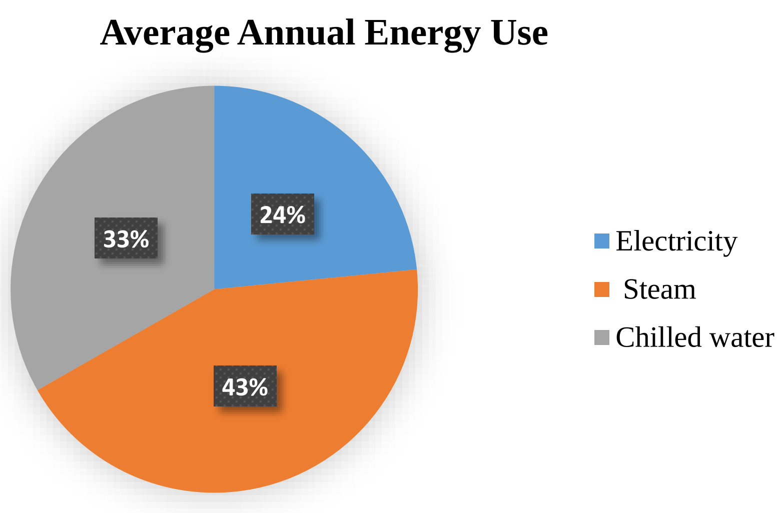



**Figure 35: Average energy use per year in Bio-psychology Building**

Figure 35 presents average energy consumed per annum in Bio-Psychology Building. Steam was the most consumed utility, followed by chilled water and electricity.

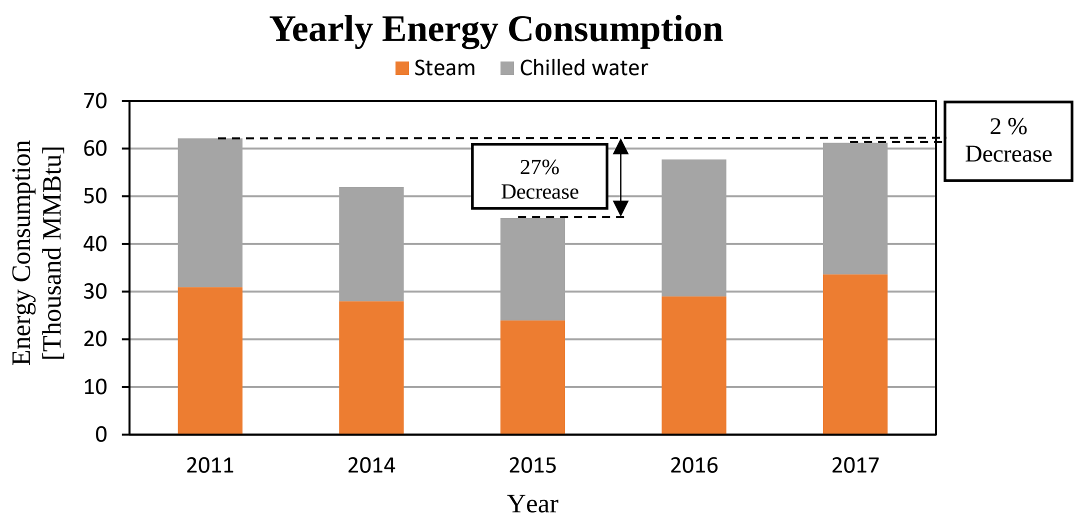



**Figure 36: Energy consumed per year in Bio-psychology Building**

Figure 36 presents steam and chilled water consumption in years 2011, 2014, 2015 and 2017. Electricity data past 2011 was not made available by the FM, thus analysis of only steam and chilled water consumption was possible for the years. It was identified that, there was 2% reduction in terms of steam and chilled water consumption in 2017 compared to 2011. Reduction was highest in 2015 at 27 %. The main reason for reduction being the major renovations in 2011. However, the energy use had since increased after 2015 and was the highest in 2017. The fluctuation was thought to be due to varying degree days, aging of the system and several different reasons discussed further in this chapter.

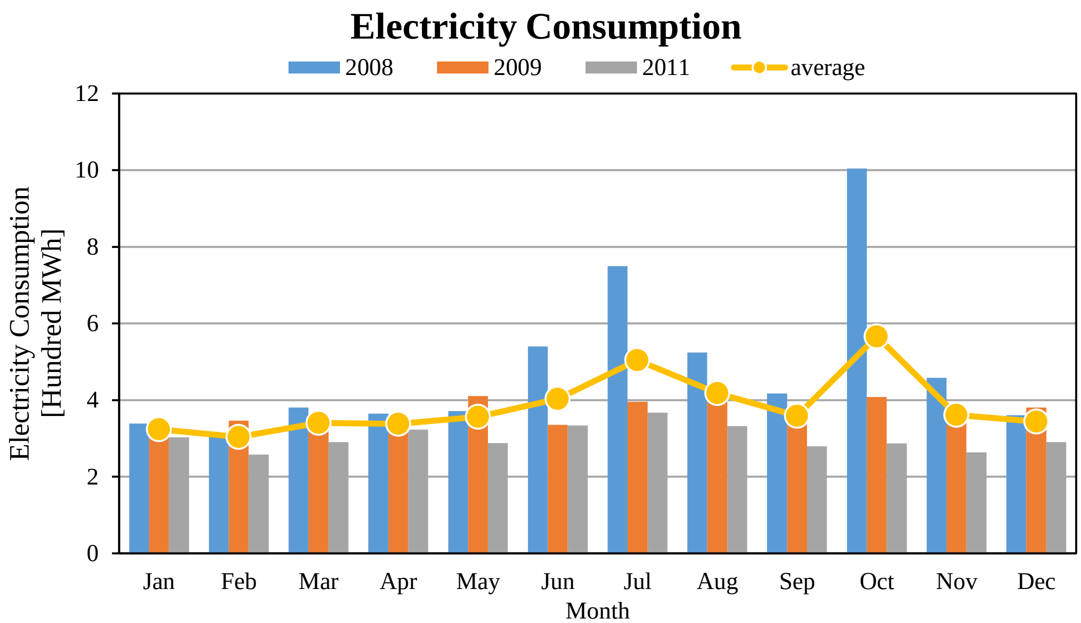



**Figure 37: Monthly electricity consumption for various years in Bio-psychology Building**

The average monthly electricity consumption is presented in Figure 37. The pattern seems to follow a trend line that is without very high variation throughout the year with some peaks in July and October. The unusual spike in October of 2008 might have been due to an overload on the equipment in lab or faulty metering according to description of the facility staff.

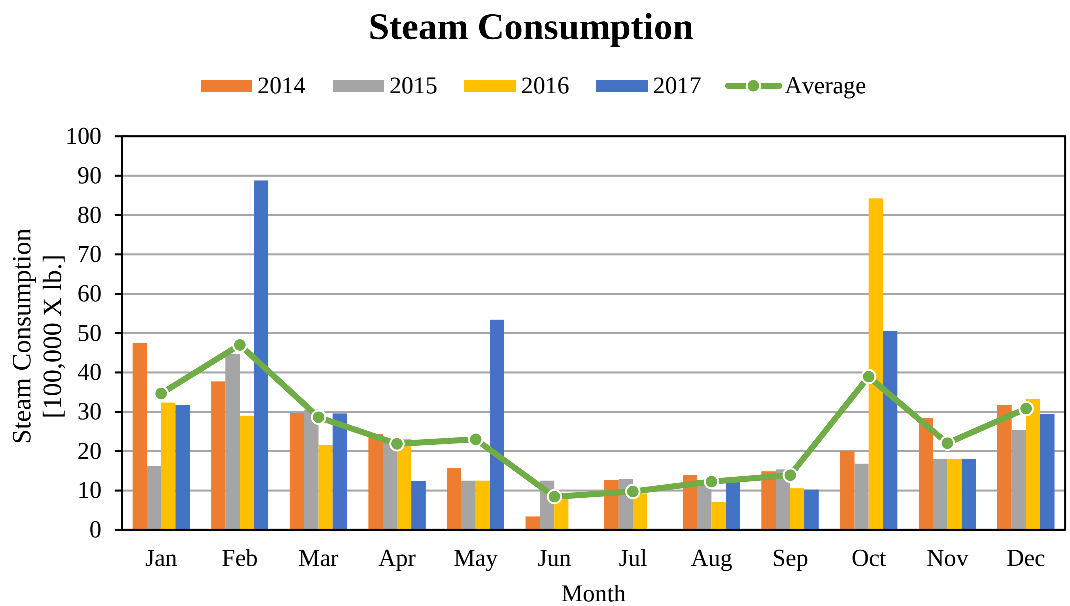



**Figure 38: Monthly steam consumption data for various years**

Figure 38 presents steam consumption data. The steam consumption data was very inconsistent, especially for the year 2017. On average, the consumption was high in winter months and low in summer months.

When spoken to the Facility in charge, it was explained that there might have been lapses in the measurements due to issues in the steam-meter or leakage in the system during some years. The fluctuation might also have been due to the fluctuating use of laboratories and the building occupancy. The building occupancy was low in January and December due to winter break and in June, July, and August due to summer break which has been reflected with the steam consumption pattern.

The building uses a dual duct system which was very energy intensive and demands high energy for adjusting the indoor set point temperature which may explain high consumption in October. Thus, an average of all the data was considered, so that a trend line could be considered to design the energy model.

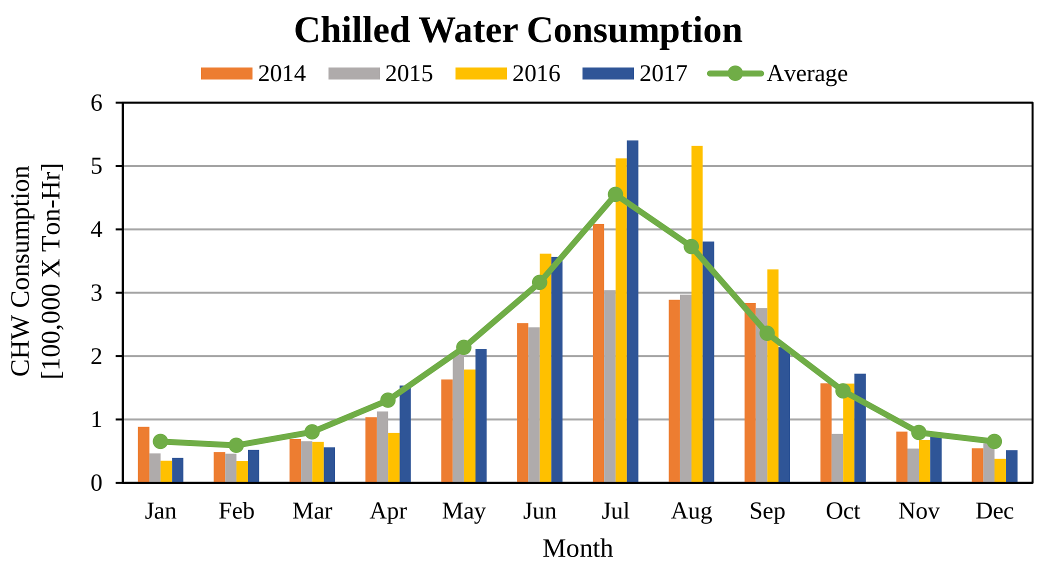



**Figure 39: Monthly chilled water consumption for various years in Bio-psychology Building**

Figure 39 presents the chilled water consumption data. The chilled water was used to provide cooling energy to the building. It was observed that there was high consumption in summer and low consumption in winter months, which was an expected result. The same pattern was seen throughout the years.

### 5.2.1 Cost and Energy Consumption

Like the Gossett FH, the Bio-psychology building was not billed directly, since energy commodities were received from a variety of sources. Utility rates provided by the Facilities Management, described in Table 6, was used to perform an economic analysis. The average Energy bill estimated to be $ 1,464,940 with annual energy consumption of 67,206 MMBtu. Figure 40 presents the average relative contributions of utilities to the total energy consumption and utility bill. Steam accounts for 43% and is responsible for 41% of the total utility cost, while electricity accounts for 24% and is responsible for 32% of the cost, and chilled water makes up 33% of utility and 27% of the total cost.

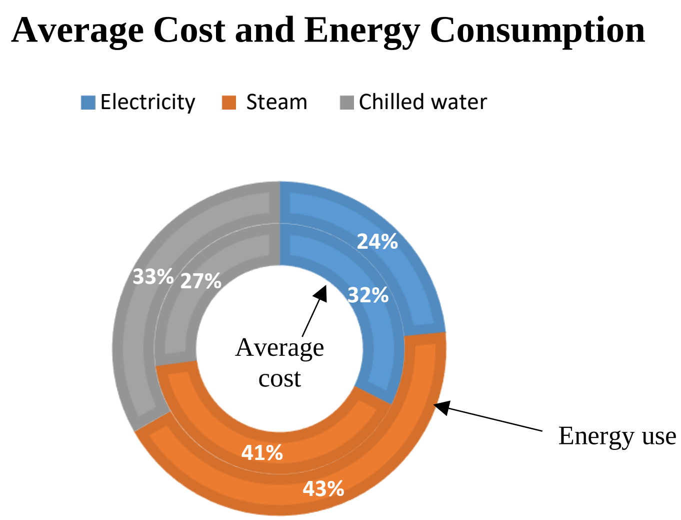



**Figure 40: Utility Cost and energy use of Bio-psychology Building**

### 5.2.2 Benchmark Comparison

Bio-psychology building is a mixed building consisting of research labs, animal vivarium, classrooms, and offices. The building has a psychology wing and a biology wing, of which the latter houses research labs and vivarium. The energy consumed by the various components of the building was benchmarked using the guidelines from Energy Star; however, these guidelines were not enough for the labs. An online tool from Labs21 was used to estimate the standard benchmark for the biology labs (Labs21, 2010). The online tool estimated the benchmark EUI by accessing its vast database of diverse labs. The climate zone, building properties, building system, fumehood operation and lab type had to be defined to operate the tool.

After defining the labs as Biology lab and vivarium, and defining all other specifications, Labs21 tool would estimate the median EUI based on its database. The lab area was defined as 100 % of the building in Labs21, and the estimated EUI was later weighted with respect to lab area of Bio-psychology building.

The median site EUI was selected from the data of the buildings containing Biology labs and vivarium, and matching the specifications of Bio-psychology building from Labs21. The EUI of various spaces of the building, according to Energy Star portfolio (Energy Star Portfolio, 2018) and Lab21 (Labs21, 2010), are listed are in Table 9.

**Table 9: EUI benchmarking results of Bio-psychology Building**

| Space | Percentage covered [%] | Source EUI [kBtu/ft$^2$/yr.] | Site EUI [kBtu/ft$^2$/yr.] | Weighted EUI [kBtu/ft$^2$/yr.] |
|---|---|---|---|---|
| Research lab (clinic, animal quarter) | 39 | 755 | 481 | 187 |
| Office Space | 15 | 116 | 53 | 8 |
| University (Classrooms, learning space) | 26 | 130 | 84 | 22 |
| Corridor and Stairs | 20 | 130 | 84 | 17 |
| Total | 100 | | | 234 |

For this study, site EUI was considered, since only the end-use data was required. Considering the percentages of various spaces, the total benchmark EUI was calculated to be 234 kBtu/ft$^2$/yr. The calculated EUI from the average of utility data available was 294 kBtu/ft$^2$/yr., which was 25 % more than the national average benchmark. Thus, there was a lot of room for improvement in terms of energy efficiency. Energy consumption of various spaces in the building estimated from the benchmark are described in the Figure

41. Most of the energy is consumed by research labs followed by classrooms, study space, mechanical/electrical rooms, corridors, and office space. Table 10 presents the EUI calculated from the utility data of Bio-psychology building.

**Table 10: EUI calculated from average of utility data of Bio-psychology Building**

| Utility | Average EUI [kBtu/ft$^2$/yr.] |
|---|---|
| Electricity | 65 |
| Steam | 120 |
| Chilled Water | 109 |
| Total | 294 |

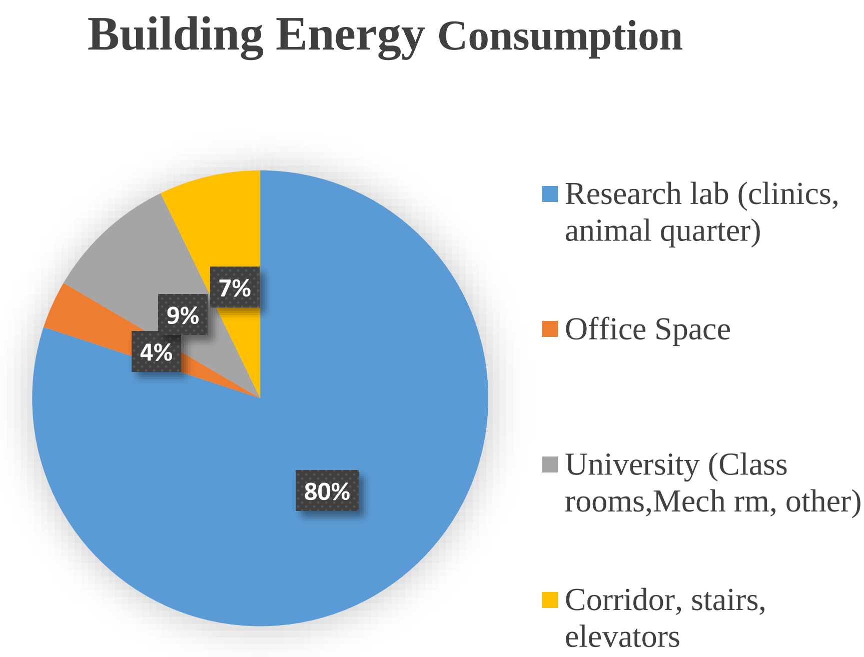



**Figure 41: Building energy consumption distribution in Bio-psychology building**

## 5.3 Comparative Prism Analysis

Inverse modeling methods can be a valuable tool in evaluating and improving building energy efficiency (Moncef, 2011). It can be used to identify periods with abnormally high-energy consumption and help in verification and estimation of expected savings from a set of ECMs. A Prism analysis was performed to better understand base heating/cooling loads of the two buildings.

A Prism analysis of both the buildings was performed with monthly energy consumption as dependent variable and monthly degree days as the independent variable. A correlation between degree days and energy consumption could be better understood through this. In this analysis, the energy consumption of a billing period could be estimated using the Equation 1 (Moncef, 2011). From this correlation, we can observe the high energy consumption in the buildings due to degree days. The degree days used in this analysis was extracted from an online tool, “www.degreedays.net” (Bizee Degree Days, 2020). The degree days was acquired for the location of College Park Airport, for the year 2019/2020, with base temperature of 60$^{o}$F; “www.degreedays.net” consists of wide archive of historical degree days and uses integration method to generate its data. (Bizee Degree Days, 2020)

$$E_{H/C} = 24 * (BLC/\eta_{H/C}) * DD_{H/C}\left(T_{b,H/C}\right) + E_{base,H/C}$$ **Equation (1)**

Where,

H/C is “heating” or “cooling”

$E_{H/c}$ = Energy consumption

BLC= Building Loss Coefficient

$\eta_{H/C}$ = Average seasonal energy efficeincy

$DD_{H/C}\left(T_{b,H/C}\right)$ = Heating or cooling degree days as a function of balance temp.

$E_{base,H/C}$ = Baseload for building energy use

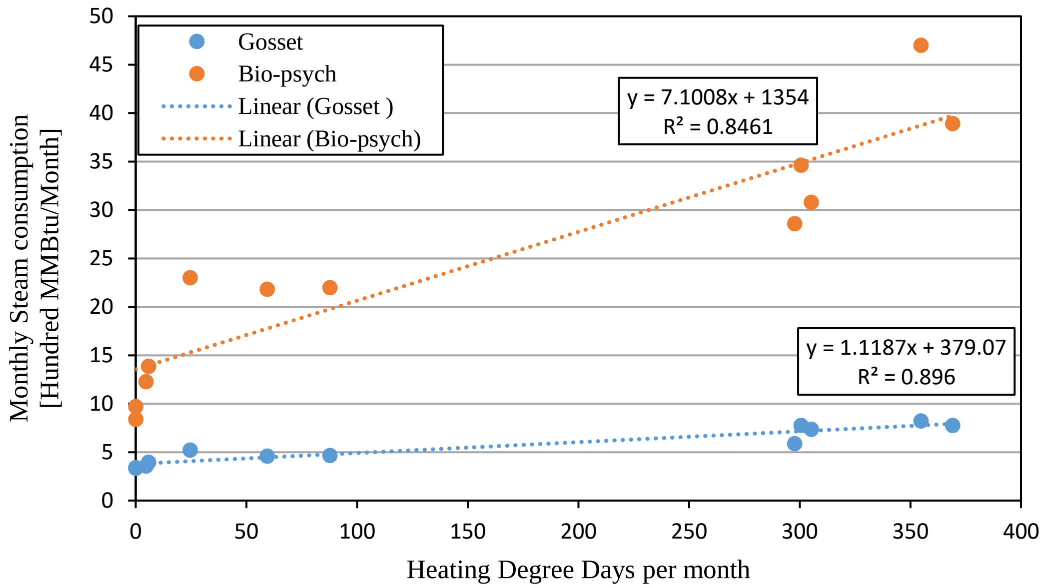



**Figure 42: Correlation between monthly steam consumption and heating degree days per month for both the buildings**

Figure 42 presents the correlation between monthly steam consumption and heating degree days per month for both buildings. Figure 43 presents the correlation between the monthly chilled water consumption and the cooling degree days per month, for Bio-psychology with base temperature of 65°F. The cooling load data of Gossett was mixed with other electrical loads, thus as not available for a similar analysis.

The values in Table 11 are obtained from the regression analysis. The Y-intercept is the baseload (Heating or Cooling) for building energy use. The slope is 24*BLC/$\eta_{H/C}$. The heating base consumption of Bio-psychology is 3.6 times that of Gossett which illustrates Bio-psychology's high base heating energy consumption. These numbers can be used to estimate energy savings from ECMs that reduce building's base heating or cooling energy consumption.

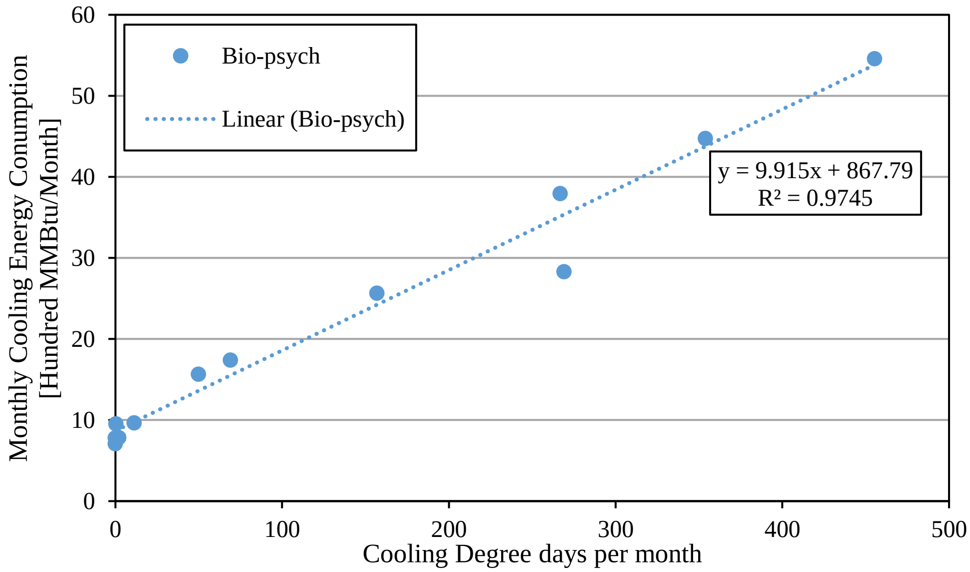



**Figure 43: Correlation between monthly CHW consumption and cooling degree days per month for Bio-psychology Bldg.**

**Table 11: Result from analysis of two buildings**

| | **Gossett FH** | **Bio-psy Bldg.** |
|---|---|---|
| $\frac{24*BLC}{\eta_H}$ **[MMBtu/ºF-days]** | 1 | 7 |
| $E_{base_H}$ **[MMBtu/Month]** | 379 | 1,354 |
| $\frac{24*BLC}{\eta_C}$ **[MMBtu/ºF-days]** | NA | 10 |
| $E_{base_C}$ **[MMBtu/Month]** | NA | 868 |

# Chapter 6: Energy Models

## 6.1 Gossett Football House

### 6.1.1 Energy Model Overview

eQUEST was used in the modelling of the Gossett Football House. The physical structure was designed using the eQUEST geometry tool. The footprint diagram made available by the Facilities Management was used to design the structure. All dimensions were rounded off to the nearest foot. Only internal walls separating the thermal zones as determined by examining the Mechanical Drawings and AHU/RTU assignment area documentation were drawn into this model. Internal doors and aesthetic architectural features such as towers were also neglected. The goal was to simulate the thermal and energy load of the building.

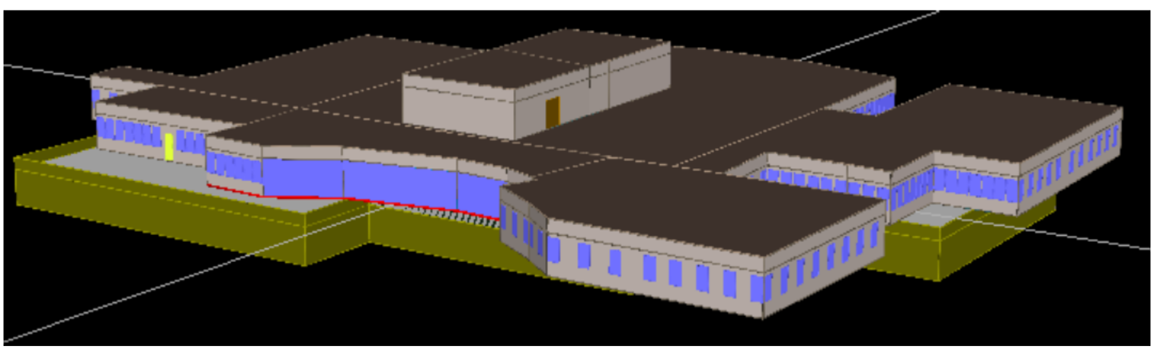


**Figure 44: 3-D Model of Gossett Football House in eQUEST**

The Gossett Building is a low-rise building consisting of a half basement and a ground floor. The 3-D model of the building as designed in eQUEST is presented in Figure 44. Firstly, the half basement was designed as completely below grade space and later adjusted into a half below grade structure. The ground floor was then designed above it and carefully adjusted to match the half basement appropriately. The roof consists of a space housing the two AHUs and mechanical systems. The fenestration details were first designed in Detail Wizard mode and then rearranged in Detail Design Mode. A window to wall approach was used to design windows, a standard simplification method whereby the total area of windows is divided by total exterior surface of exterior walls per floor to reduce simulation time.

The model has a total of 11 thermal zones assigned to respective RTU/AHU Systems. The HVAC units were then designed for each zone. Each zone was provided with respective terminal VAV specification, exhaust system and thermostat. The Make-up Air Unit was also established by creating a dummy zone. The HVAC systems are modelled based their specifications described in section 3.1.3 and 3.1.4.

Loops for Hot water, chilled water and domestic hot water supply were also defined which linked up directly with the HVAC System. Thirteen different types of spaces were specified by which includes: exercise center (gym), medical and clinical care, locker and dressing room, laundry, office, lobby, dining area, kitchen and dining hall, auditorium, classroom/lecture room, conference room, corridor, mechanical room. Load consumption for various spaces were specified according to the data from walkthrough and archive records. Specific load, occupancy and HVAC schedule were specified for all designed components.

Energy density of each space was identified by walkthroughs and analyzing equipment and schedule. Spaces such as kitchen had a very high energy density, of almost 65 Watt/ft$^2$ due to very high energy intensive equipment for cooking, followed by the hydrotherapy room (36.5 Watt/ft$^2$).

Details about various definitions were collected thorough investigation of building records, walkthroughs, and interviews with the experienced Facilities Management. The weather file used was the local TMY (Typical Meteorological Year) hourly weather file for Washington DC. Though enough data was collected to build the model, some architectural documentation were missing which would have provided more concrete justification for some of the assumptions.

### 6.1.2 Model Results

After developing a model, it was very important to verify it by calibrating the model, to validate results from it. The model was calibrated to closely match actual building data according to ASHRAE guidelines. ASHRARE guidelines suggests that a Normalized Mean Bias Error (NMBE) of $\pm 5\%$ is acceptable (Bandera and Ruiz, 2017) to consider a simulated model as calibrated. Equation 2 presents the formula used to calculate NMBE.

$$\mathrm{NMBE} = 1/\overline{\mathrm{m}} * \Sigma_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{m_i} - \mathrm{s_i})/(\mathrm{n} - \mathrm{p}) * 100(\%)$$ **Equation (2)**

Where;

$\overline{\mathrm{m}}$ = Mean measured utility value

$\mathrm{m_i}$ = Measured Utility value

$\mathrm{s_i}$ = Simulated value

n = Number of measurements

p (No. of adjustable model parameters)=0 (Bandera and Ruiz, 2017)

The average monthly utility consumption was compared to eQUEST model results using Microsoft Excel. Figure 45 presents the simulated electricity consumption compared to the average measured utility data (2010 to 2018). Slight adjustments to the electric equipment scheduling were made to mimic the energy consumption data. The model's annual electricity consumption results deviate 1.64 % from the actual average electricity data. The NMBE (Normalized Mean Bias Error) was -1.64%. The utility data is very inconsistent throughout the years and was very challenging to mimic. However, the pattern of data consumption has been captured. The electricity data here, represents space cooling as well since the building houses its own chiller and the same is designed for the eQUEST model.

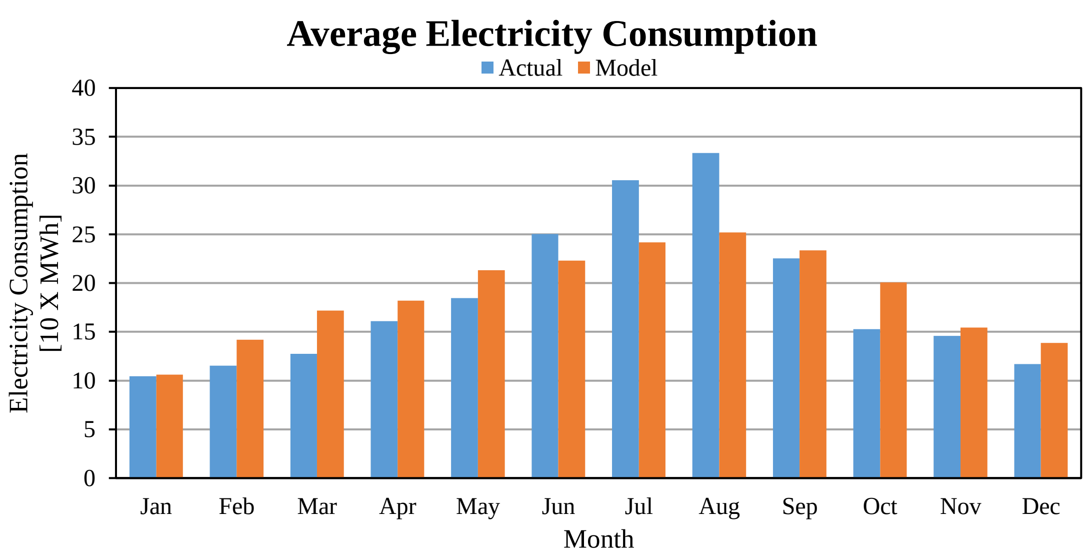



**Figure 45: Comparison of simulated electricity consumption and actual average electricity consumption of Gosset FH**

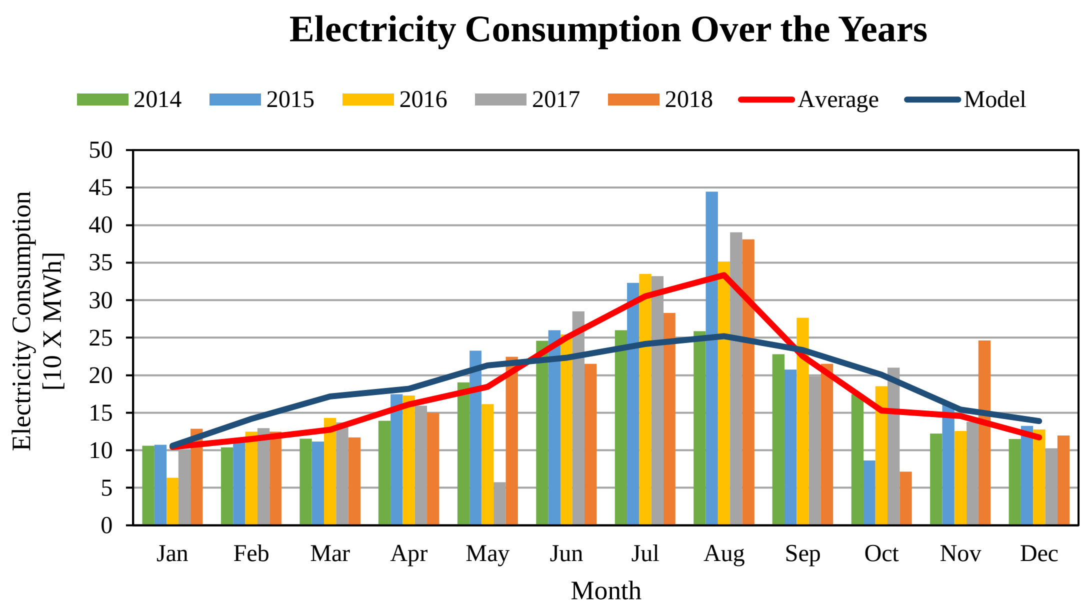



**Figure 46: Simulated electricity consumption data and actual yearly electricity consumption data varied throughout years in Gossett FH**

Figure 46 presents average utility data throughout different years compared with the model simulated result.

The eQUEST model simulation is unable to directly model steam loop and district chilled water loop. An on-site boiler and hot water distribution system were used to approximate the consumption of district steam.

In the simulation, a boiler consumes natural gas to create hot water that was used throughout the building's heating coils with a default heat input ratio of 1.25. Therefore, the simulation gas consumption was adjusted by this factor to simulate the total amount of steam consumed.

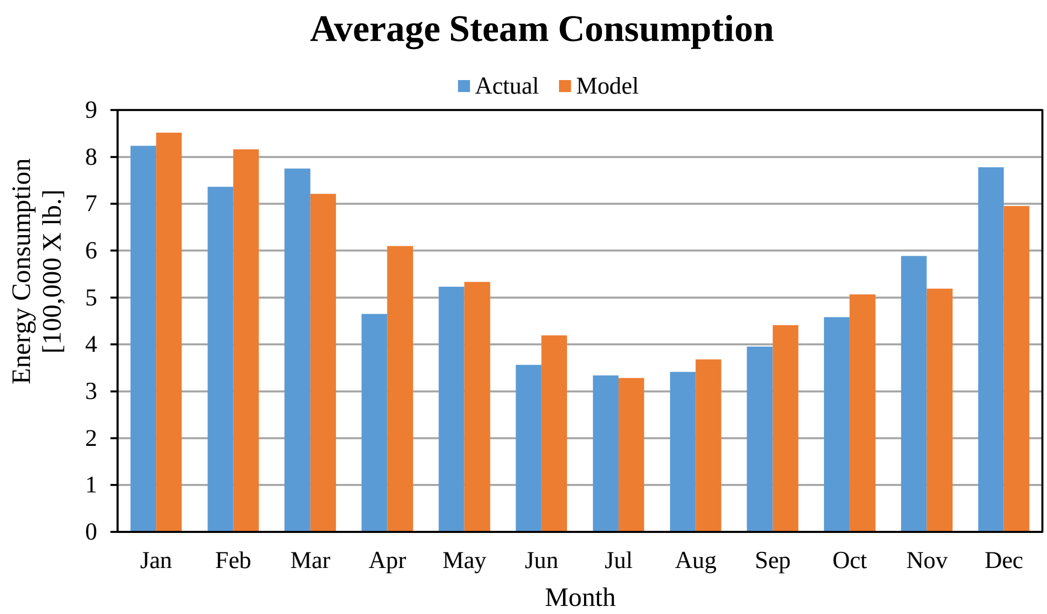



**Figure 47: Comparison of simulated steam consumption and actual average steam consumption of Gossett FH**

Figure 47 compares average annual steam consumption with simulated result for steam consumption after the raw data from simulation had been processed by the methods described above. The pattern of simulated data matches with the average annual steam data with a deviation of 3.58 %. The NMBE was -3.58%, thus calibrated. The utility data has been fluctuating throughout years in response to varying factors discussed previously in utility analysis section. The data of 2014 was the closest to the simulated result, only varying by 1.57%. Also, the steam pipe insulation was not properly maintained which might explain the inconsistency of utility steam data throughout the years. Figure 48 compares the model simulated result with utility data over the years.

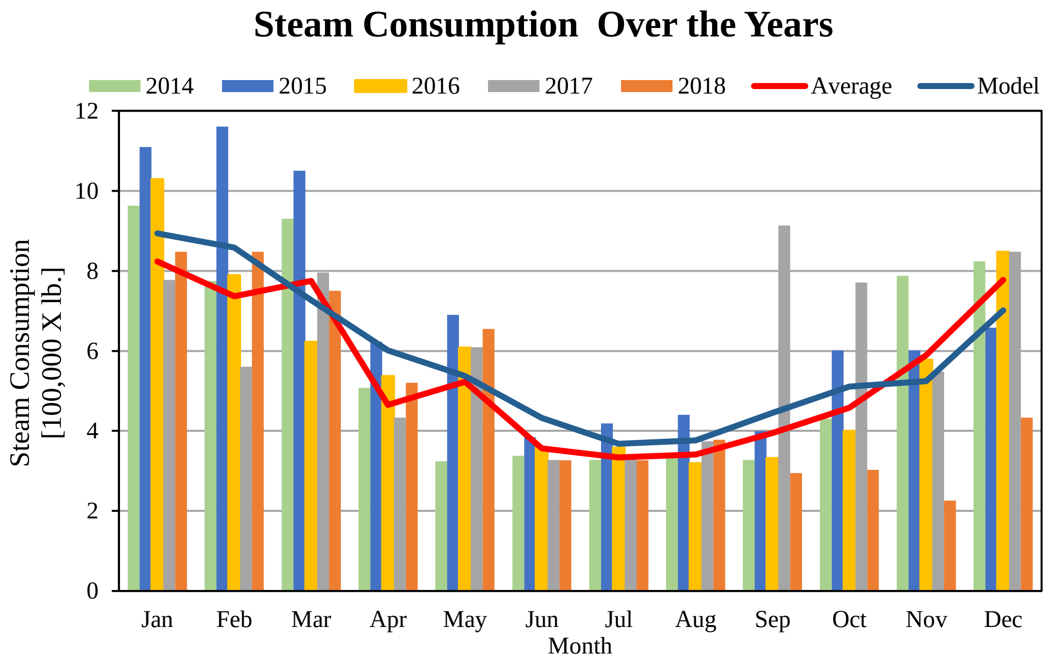



**Figure 48: Comparison of annual steam consumption throughout the years and simulated steam consumption of Gossett FH**

Figure 49 presents a display of the hot water loop which was set up in eQUEST to simulate steam consumption.

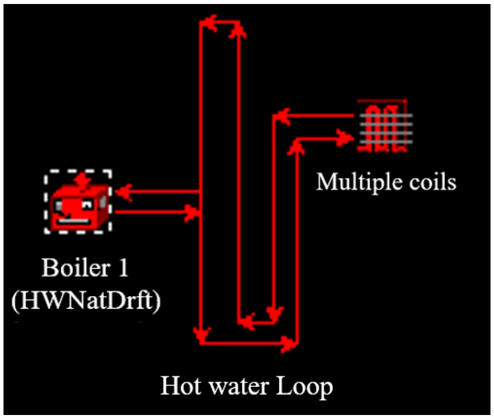



**Figure 49: Display of hot water loop defined in eQUEST**

### 6.1.3 Sensitivity Analysis

A sensitivity analysis was conducted to figure out what parameters were responsible for changes in the energy consumption. The effects of various factors to the model could be comprehended from it and can further pave a path to research on effective Energy Conservation Methods. Five parameters were considered for the examination based on their significance in affecting building energy consumption and energy simulation results. Table 12 presents parameters with their original values as Baseline (BL), respective Upper Limit (UL) and Lower Limit (LL) along with their effects on energy consumption.

Figure 50 presents sensitivity analysis due to changes in certain parameters. The baseline (BL) is represented by the 0% deviation line. Numerous sources were consulted in determining an appropriate upper limit (UL) and lower limit (LL) for parameter values; however, due to the lack of architectural drawings, age of the building and the numerous renovations therein, typically a wider-than-normal range was considered.

**Table 12: Gossett FH sensitivity analysis parameters and results**

| Parameters | Unit | BL | UL | LL | Energy Use Deviation | | |
|---|---|---|---|---|---|---|---|
| | | | | | BL [%] | UL [%] | LL [%] |
| Chiller efficiency | Electric Input Ratio (EIR) | 0.3 | 0.2 | 0.5 | 0.0 | -1.1 | 2.7 |
| Roof additional insulation | $ft^2 \cdot °F \cdot hr/Btu$ | 25.0 | 40.0 | 10.0 | 0.0 | 0.0 | 0.2 |
| Zone thermostat set point (Heating months) | °F | 73.0 | 75.0 | 63.0 | 0.0 | 0.4 | -3.5 |
| Zone thermostat set point (cooling months) | °F | 75.0 | 75.0 | 62.0 | 0.0 | 0.0 | 0.5 |
| AHU fan Motor efficiency (supply and Exhaust fan) | Ratio | 0.5 | 0.7 | 0.4 | 0.0 | -1.6 | 2.0 |

It was observed that thermostat set point can have a large impact on saving energy, almost 3.5% of energy can be saved by setting the heating month temperature to the lowest point. Decrease in motor efficiency of the AHU fan can increase the energy usage by 2 % and low chiller efficiency can be responsible for 2.7 % increase in energy consumption. Additional roof insulation, when increased to upper limit did not have much impact on energy consumption, but when decreased to lower limit, increased the energy consumption by 0.2 %.

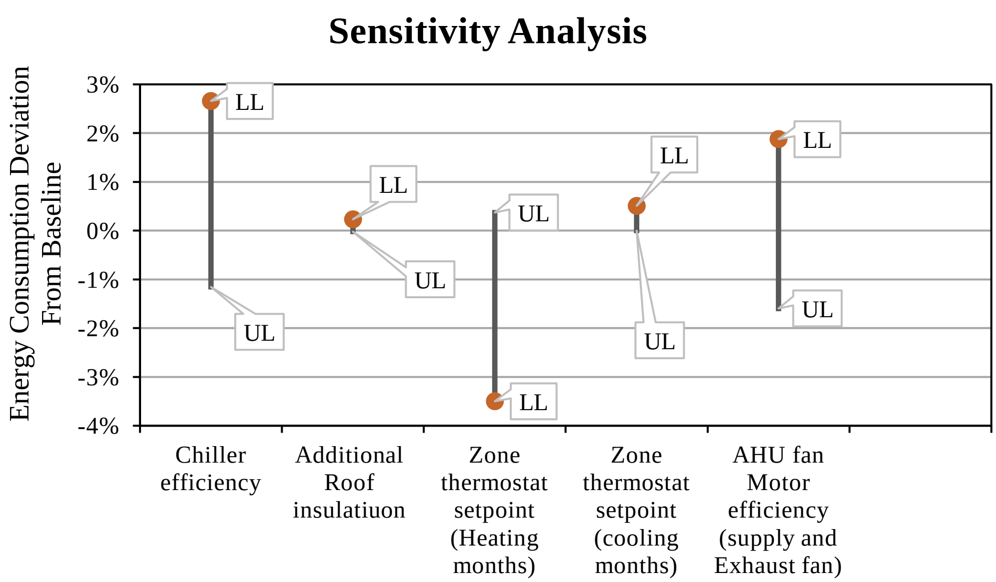



**Figure 50: Gossett FH sensitivity analysis result**

Figures 51 and 52 represents correlation between energy usage per year and set point temperature according to eQUEST simulations of the building. The study about correlation between set point temperature and energy consumption was helpful in quantifying the amount of energy savings that could be obtained by setting an appropriate set point temperature. There was significant reduction in energy when temperature was lowered in heating months and increased in cooling months. But, the temperature set point should comply with thermal comfort. ASHRAE Standard-55 suggests an average indoor temperature to be between 67°F to 82°F.

Gossett FH had set point temperature of 73°F for heating months and 75°F for cooling months when the building was occupied. During the period of unoccupancy, temperature would be set to 55°F in heating months and 80°F in cooling months in order to conserve energy. Thus, the temperature set point in Gossett FH was deemed appropriate regarding the comfort level of occupants and energy consumption.

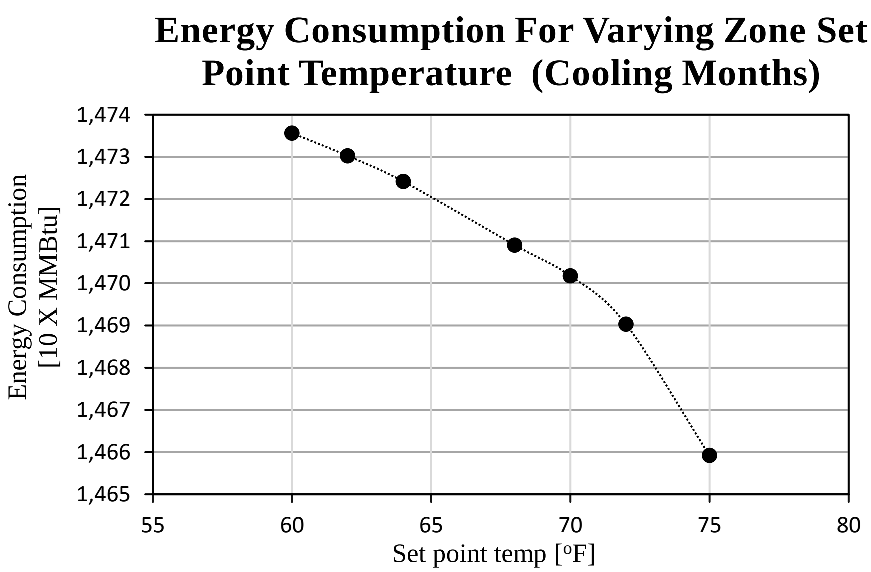



**Figure 51: Energy usage versus set point temperature (Cooling Months) in Gossett FH**

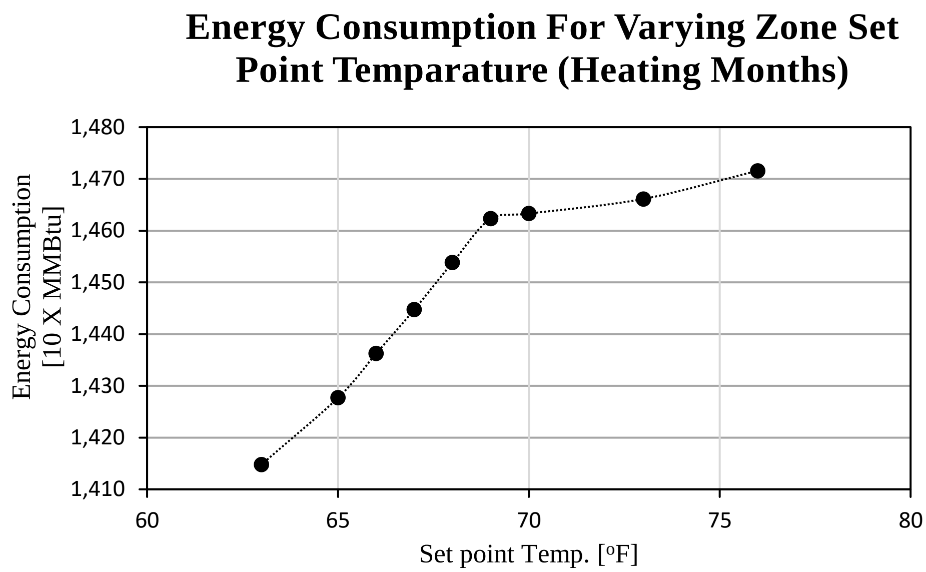



**Figure 52: Energy usage versus set point temperature (Heating Months) in Gossett FH**

### 6.1.4 Energy Conservation Measures

Various energy-related issues of the building were discovered through steps of building comprehension and respective ECMs to solve them were researched and simulated in detail. The focus was mainly on low cost/no cost ECMs with low capital investment and short payback period, making them more prone to be implemented by the FM. Various ECMs for Gossett FH are described as follows.

#### *6.1.4.1 ECM #1 - Night-time Scheduling of HVAC System*

It was discovered that AHU systems 1, 2, HV 1 and RTU 6 ran throughout the clock, 24*7. They did not have a night time shut down schedule. After careful observation and discussion with the FM about the practicality of implementing a night time shut down, a new non-aggressive shut down schedule was proposed. The proposal was to set a night time shut down from 1 AM to 4AM in order to comply with the busy occupancy period of the building. The new schedule was modelled in the eQUEST model which simulated the energy savings from this ECM. The summary of savings is presented in Table 13. Figure 53 presents the current schedule of AHU AC-2 which describes that the AHU system is always on.

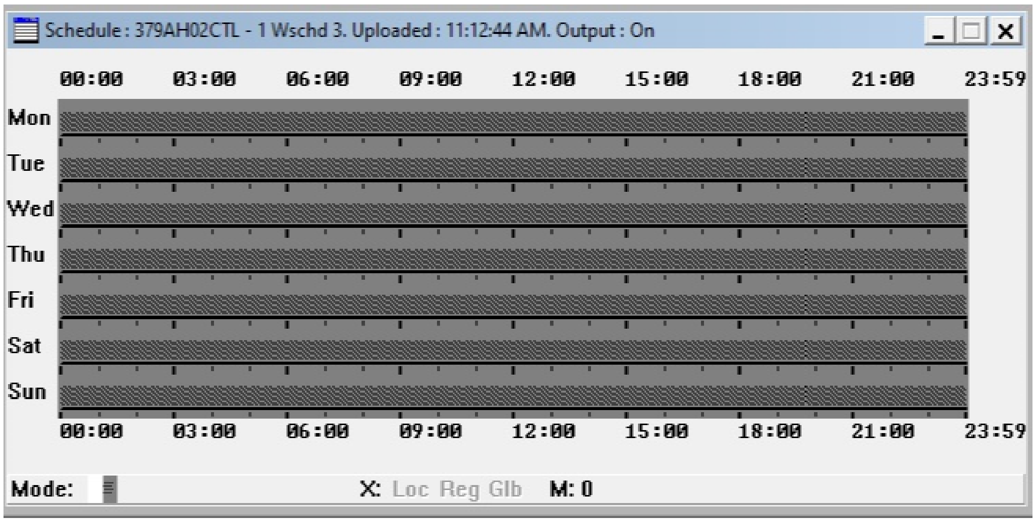



**Figure 53: Representation of AHU AC- 2 schedule from MS 1800 BAS in Gossett FH**

**Table 13: ECM #1 Savings for Gossett FH**

| Savings per annum | | | | | Simple Payback [yr.] |
|---|---|---|---|---|---|
| Electricity [kWh] | Steam [lb.] | Cost [$] | Total Energy [MMBtu] | Energy Reduction [%] | |
| 47,000 | 247,500 | $10,688 | 407.8 | 2.8 % | Immediate |

It was observed that a total saving of $10,688 could be achieved by implementing the night-time schedule. There was no capital investment required to implement this ECM. The total energy reduction after the implementation of this ECM was 2.8 %. Table 14 compares the model as designed and model with implementation of ECM 1. The total utility bill was projected to be reduced by 2.7 %.

**Table 14: Comparison of saving from ECM #1 in Gossett FH**

| | Model (as designed) | Model ECM 1 | Percentage saved |
|---|---|---|---|
| TOT. utility Cost/year | $ 394,206 | $ 383,518 | 2.7% |

*6.1.4.2 ECM #2 - VFD Installation on RTU 1, 2 and 4*

Variable-frequency drives (VFDs) are electronic devices used to control electrical-motor speed and torque by varying motor input frequency and voltage. These help to optimize the performance and life of the motor. They also help in precise control of temperature, lower energy consumption and lower fan noise. The VAV system would help to reduce duct static pressure to reduce air flow when occupancy is low.

Although installing a VFD has many benefits, there are potential problems that could arise. Reflected voltage waves, increased change in voltage per unit change in time (dV/dt), increased peak voltage in the motor windings and unwanted harmonics on the AC input line can all occur if a VFD is incompatible. However, to minimize the risk of problems due to a VFD installation, one should always check with the motor manufacturer first to see if the motor is compatible with a VFD (Miller et al., 2012). It can be seen from Equation 3 that the power consumption of a fan is a function of the cube of the rotor speed (Hepperle, 2018) (Miller et al., 2012).

$\text{Power Coefficeint} = P/(\rho * N^3 * d^5)$________________________________**Equation (3)**

Where,

P=Power

$\rho$= Density of air

N= Revolutions per second

d= Diameter

Hence, for the same fluid and the same size rotor, if the rotor speed is halved, the power consumption decreases by a factor of 8 (Miller et al., 2012). Thus, retrofitting supply fans with VFDs has the potential to achieve significant energy savings, as the speed of the fan motor can be modulated appropriately in relation to the ambient temperature and requirements, leading to energy savings. An online tool from vfds.org (vfds.org, n.d.) was used to calculate energy savings from retrofitting the RTU- 1, 2 and 4 with VFD.

The specifications of supply fan motors were collected from archive data and calculations were projected using the online tool for possible energy savings. The online tool required details about motor, its usage, and cost along with electricity cost. The exact energy saving is not possible to be calculated, due to many things going on when the variable frequency drive application is working, load change, material characteristics, efficiency, mechanical coupling, (vfds.org, n.d.). Thus, the tool could analyse only the general savings that could be achieved for optimal conditions.

The capital cost of VFD was estimated by reference of various vendor websites. The drives used in this analysis were sold by Grainger (Grainger USA, n.d.) which were compatible with the current RTU supply fan specification.

An electrician and an instrumentation technologist would be required to install the VFD, filters, thermo-couples, transmitters, Mod Bus cards, analog input cards, and junction boxes (Miller et al., 2012). A welder is required to install the pipe stands to support the transmitters and to install miscellaneous supports required for the cable tray and junction boxes (Miller et al., 2012). Technical support to install the VFD and to integrate the VFD with the control system could come from an internal or external employee, and is assumed to charge $100/h (Miller et al., 2012).

The cost labor cost and installation cost were not definite, so an assumption was made based on all the available information. Table 15 displays the total capital expense (CAPEX) required according to the assumptions. An additional 5% of the total cost was added as Operation and Maintenance cost (OM). Table 16 presents the savings calculated from the online tool, “www.VFD.org” (vfds.org, n.d.).

An estimated savings of 217,290 kWh per annum and $21,729 per annum could be achieved. The average simple payback period was calculated to be 0.7 years.

**Table 15: Total CAPEX of ECM #2 in Gossett FH**

| Motor | Model no. | Units | Item Cost | Installation Cost est. | OM cost est. | Total CAPEX est. |
|---|---|---|---|---|---|---|
| RTU 1 fan | HMX01134NAP6 | 1 | $2,347 | $3,000 | $267 | $5,614 |
| RTU 2 fan | ATV340U07N4E | 1 | $1,300 | $3,000 | $204 | $4,286 |
| RTU 4 fan | HMX01134NAP6 | 1 | $2,347 | $3,000 | $267 | $5,614 |
| Total | - | - | - | - | - | $15,514 |

**Table 16: Savings from ECM #2 in Gossett FH**

| Motor VFD | Electricity Savings [kWh] | Cost Savings [$] | Simple payback [yr.] |
|---|---|---|---|
| RTU 1 VFD | 77,980 | $ 7,798 | 0.7 |
| RTU 2 VFD | 61,340 | $ 6,134 | 0.6 |
| RTU 4 VFD | 77,970 | $ 7,797 | 0.7 |
| Total | 217,290 | $ 21,729 | - |

*6.1.4.3 ECM #3 - Closing Steam Loop to Prevent Condensate Loss*

It was noticed that Gossett Building was wasting its condensate steam. The steam was primarily used for heating purpose, mainly to heat the air through the AHU system. After passing through the steam coils, the steam condensate was collected in a condenser tank (approx. 330 lit.) which was then drained to sewer. This was deemed as an unsustainable practice as condensate could be reused in several ways or could be transported back to the CHP. With that in mind, a study was conducted to measure the amount of condensate lost per day and explore possible solutions. The solution proposed to this problem was to pump the water back to the CHP boiler feed water tank, thus reutilizing the waste water and closing the steam loop.

An economic analysis of implementing the project to pump waste condensate back to the CHP boiler feed water tank as an ECM was then performed. Figure 54 presents the steam condensate which is being wasted.

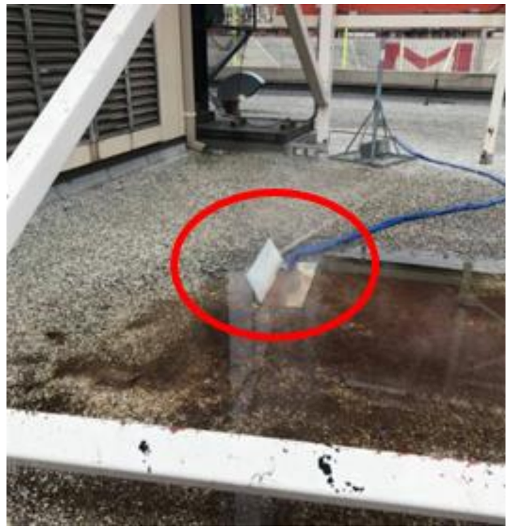


**Figure 54: Steam condensate being wasted in Gossett FH**

An average of 2,157 gal of condensate water was wasted every day. It was discovered that the CHP plant purchased make-up water from the State which was used in production of steam. The idea of this ECM was to reutilize the waste water to minimize the purchase of water. The current cost of waste water and purchased amounts to 2 Cents per gallon (Washington Suburban Sanitary Commission, 2019), as presented in Table 17. Table 18 presents the total loss in terms of cost due to this issue. If the condensate can be utilized, $15,824 could be saved per annum.

**Table 17: Water rates (Washington Suburban Sanitary Commission, 2019)**

| Unit | Water rate | Wastewater rate | Combined |
|---|---|---|---|
| Cost/Gal | $ 0.0076 | $ 0.0125 | $ 0.0202 |

**Table 18: Total cost loss due to wasted condensate**

| Wasted condensate | Wastewater cost | | Water purchase cost | | Total cost loss |
|---|---|---|---|---|---|
| gal/day | cost/day | Cost/annum | cost/day | Cost/annum | Cost/Annum |
| 2,157 | $27 | $ 9,841 | $16 | $5,983 | $ 15,824 |

**Pumping water back to the CHP plant.**

An economic analysis was done with the available data , resources and assumptions to determine cost of transporting the condensate back to the CHP plant and close the open loop. The calculation details for this ECM is described in detail in the Appendix-A section. According to the calculations and assumptions, the cost of implementing this ECM amounts to $78,737, as presented in Table 19.

**Table 19: Total potential cost of ECM #3 for Gossett FH**

| | Price per unit | Qty. | Total |
|---|---|---|---|
| AMT pump | $1,253 | 1 | $ 1,253 |
| Pipeline [per feet] | $7 | 4920 ft. | $ 33,584 |
| Labor Cost est. [per hour] | $100 | 240 hr. | $ 24,000 |
| Storage Tank [120 gal] | $1,000 | 1 | $ 1,000 |
| Valve/Bends/Joints | - | - | $ 18,900 |
| Total Capital Cost | - | - | $ 78,737 |

For cost analysis, an appropriate pump, "AMT 287 series pump" (Appendix A), whose pump curve satisfied the required value was selected. The labor cost assumed in this case was based on general plumbing cost (Homeadvisor, 2020) and may be subject to change. The cost of pipes was estimated from online market sources (AFsupply, n.d.). The Operation and Maintenance cost of 5% of the total cost was further added when calculating the payback period. According to these estimates, payback period would be 5.8 years. An additional increase in water price (US DOE-Office of Energy Efficiency and Renewable Energy, 2017) was also included in this analysis.

The payback period of this ECM may seem very high with huge capital investment, but savings would be fruitful on the long run. A resource like water is a valuable commodity that will get more expensive in the future. The average annual price escalation rate for water, based on reported rates from 2008 through 2016 (US DOE-Office of Energy Efficiency and Renewable Energy, 2017) was 4.1% and wastewater is 3.3%.

Figure 55 displays that due to increasing trajectory of water cost, the cost of surplus from the project kept on increasing linearly. The blue line indicates the cost to be paid back and the orange line presents the cumulative surplus from the project. As the project starts saving money, the payback can be achieved in 5.8 years.

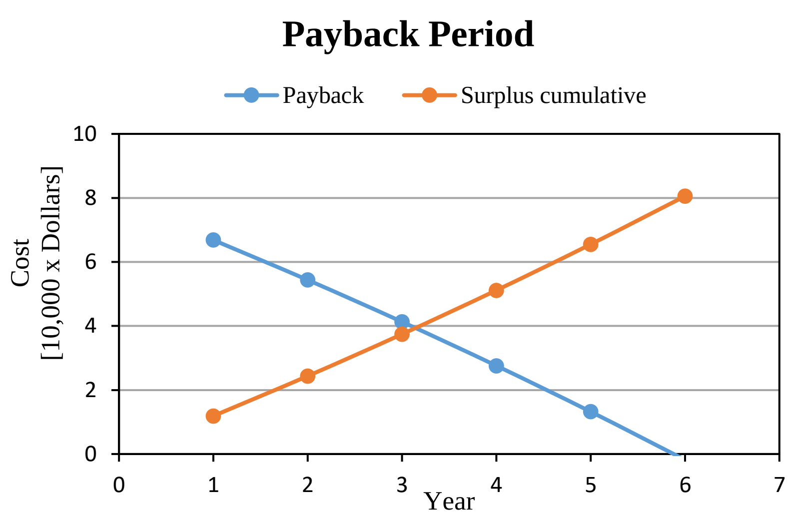



**Figure 55: Payback period of ECM #3 in Gossett FH**

Calculations and assumptions for ECM 3 is summarized in the Appendix-A.

### *6.1.4.4 ECM #4 - Insulaion of Condenser Tank.*

The condenser tank in the mechanical room located at the roof was found to be uninsulated at the time of Energy Audit, thus the proposed solution being re-insulation of the tank. During the start of the audit (December 2019), insulation of the steam pipes, valves and condenser tanks were in very poor condition. The whole system was reinsulated during the timespan of then Energy Audit project. A technical and economic analysis was done to identify heat loss due to lack of insulation on the condenser tank.

An analysis of only the steam condenser tank was possible as all other systems were re-insulated during the time of study. Since this ECM was already implemented on other exposed pipeline by the FM, it would be interesting to see the new utility consumption data. Figure 56 presents the worn out insulation in the mechanical room during the span of audit. Figure 57 represents thermographic image and normal image of the uninsulated condenser tank.

**Figure 56: Image of Worn out insulation in Mechanical room of Gossett FH**

**Figure 57: Thermographic image of condenser tank (LHS) and normal image of condenser tank (RHS) in Mechanical room of Gossett FH**

From the calculations summarized in the appendix-B, it was found that heat loss from the condensate tank due to convection and radiation was 900 J/s and 483 J/s respectively. This amounts to 46,122 lb/annum steam loss and loss of $1,083 per annum. Table 20 gives the summary of cost and energy saved from this ECM.

**Table 20: Cost saved from ECM 4, Gossett FH**

| Annual Heat loss [kBtu/yr.] | Cost loss per year [$] | Solution | Energy reduction [%] | Energy saved [kBtu/yr.] | Cost saved per year [$] | Simple payback [yr.] |
|---|---|---|---|---|---|---|
| 46,122 | $1,083 | Insulation | 87 % | 40,130 | $943 | 0.1 |

For the re-insulation of the tank, a one inch thick ceramic jacket glass fiber insulation was considered, which is a common yet effective insulation. Simple market search allowed its price to be known which was $ 24/m$^2$ and R value was 5 Ft$^{2}\cdot{}^{o}$F·hr /Btu

(Unitherm, n.d.). The insulation would save 87 % of the wasted energy and save $943 per annum. The estimated payback period was less than six months. Calculation details of ECM 4 are in Appendix-B.

*6.1.4.5 ECM #5 – LED Lighting Retrofit*

From the analysis of lighting plan of the floor 0 (the halfbasement) it was noticed that all the lights in floor 0 of the building was T-8 fluorescent light bulbs. This was an opportunity to reduce the Light Power Density (LPD) by retrofitting LED lamps.

LEDs have an efficiency of 18 % whereas traditional fluorescent lamps only has an efficiency of 11%. With current advancement in LED bulb technology, retrofitting has been direct, easier, and cheaper.

This ECM is an analysis of energy and cost saved by retrofitting all the light bulbs in the semi basement by LED bulbs. This simple analysis was done using a formulated excel spreadsheet.

Firstly, the lighting plan was inspected for the number of T-8 bulbs (32 Watts), total lumens and light power Density (LPD) for each room/space. LPD was then compared with ASHRAE standard (ASHRAE standard 90.1, 2010) for respective room area which was observed to be greater than required standard for some areas. Then, T-8 bulbs were assumed to be replaced by LED bulbs (14 Watts) without compromising the original lumens provided by T-8 bulbs. The result of the analysis concluded savings of $ 3,607 per annum. Since quantity of lumens was not compromised, there was need for extra LED bulbs and fixtures (PLT, n.d.) to be installed which would add on the installation and new wiring cost. Average LPD according to ASHRAE standard was 0.85 Watt/ft$^2$. The average LPD was reduced by 35 % after implementation of this ECM.

Table 21 represents LPD of various spaces before and after LED retrofit. Table 22 consists of details about energy savings after installation of LED lighting system and Table 23 presents economic analysis of this ECM with the simple payback period of 3.6 years. Cost of LED bulb is based on the price of 14 Watt "Lunera LED T-8 bulbs" (Energy Avenue, n.d.). The cost of labor is not included as it was not made specific by the Facilities Management.

**Table 21: LPD of various spaces in Gossett FH**

| Space | LPD before ECM #5 [Watt/ft$^2$] | ASHRAE LPD Std. [Watt/ft$^2$] | LPD after ECM #5 [Watt/ft$^2$] |
|---|---|---|---|
| Corridor/hallway | 0.49 | 0.66 | 0.32 |
| Gym | 0.78 | 0.72 | 0.51 |
| Medical room | 1.15 | 1.28 | 0.76 |
| Locker room | 0.75 | 0.75 | 0.50 |
| Coach locker | 0.40 | 0.75 | 0.26 |
| Laundry room | 0.74 | 0.70 | 0.49 |
| Mech. room | 0.72 | 0.95 | 0.48 |
| Equipment room | 0.65 | 0.95 | 0.43 |

**Table 22: Energy savings after installation of LED lighting system in Gossett FH**

| | |
|---|---|
| Electricity Savings per year | 34,786 kWh |
| Cost savings per year | $ 3,607 |
| Total Average LPD Before ECM #5 | 0.71Watt/ft$^2$ |
| Total Average LPD After ECM #5 | 0.46 Watt/ft$^2$ |

**Table 23: Cost analysis of ECM #5 in Gossett FH**

| | |
|---|---|
| Cost of 1 LED | $ 8 |
| Tot. LED Units | 1,028 |
| Total LED Cost | $ 8,728 |
| Fixture Cost | $ 4,456 |
| Tot. Cost | $ 13,185 |
| Simple Payback | 3.6 yr. |

### 6.1.5 Summary of ECMs

After the implementation of all the ECMs, savings of 13.4 % and 4.4 % was observed in electricity and steam consumption respectively. According to the simulations and calculations, a 14.3 % of the utility cost and 9.2 % of the total energy consumption could be saved along with 787,290 Gal. of water. The total energy saved was projected to be 1,308 MMBtu per annum. The payback period for each ECM was different. ECM 1 cosisted of the shortest payback period and ECM 3 included the longest.

Table 24 presents the summary of all the ECMs analyzed. The Energy Reductions percentage column presents the amount of energy reduced with respect to building energy consumption.

**Table 24: Summary of ECMs in Gossett FH**

| Savings (Annual) | | | | | | | Payback [yr.] |
|---|---|---|---|---|---|---|---|
| ECM | Electricity [ kWh] | Steam [lb.] | Water [Gal] | Tot. Energy savings [MMBtu] | Cost Saving [$] | Energy Reduction [%] | |
| ECM #1: Night-time scheduling | 47,000 | 247,500 | N/A | 407.9 | $10,687 | 2.9 | Immediate |
| ECM #2: VFD installation | 217,290 | N/A | N/A | 741.4 | $21,729 | 5.2 | 0.7 |
| ECM #3: Steam condensate return loop | N/A | N/A | 787,290 | N/A | $15,824 | N/A | 5.8 |
| ECM #4: Insulation of condensate tank | | 40,130 | | 40.1 | $942 | 0.3 | 0.1 |
| ECM #5: LED light retrofit | 34,786 | N/A | N/A | 118.7 | $3,607 | 0.8 | 3.6 |
| Total | 299,067 | 287,361 | 787,290 | 1,308.0 | $52,791 | 9.2 | N/A |

## 6.2 Biology-Psychology Building

### 6.2.1 Energy Model Overview

eQUEST was used in the modelling of the Biopsychology building. The physical structure was designed using the eQUEST geometry tool. The footprint diagram made available by the Facilities Management was used to design the structure. All dimensions were rounded off to the nearest foot. Only internal walls separating the thermal zones, as determined by examining the Mechanical Drawings and AHU/RTU assignment area documentation, were drawn into this model. Internal doors and aesthetic architectural features such as towers were also neglected. The goal was to simulate the thermal and energy load of the building.

The Biopsychology building consists of a basement, a sub basement, 4 floors above grade and a penthouse. Each floor was carefully constructed by the help of the building footprint which was imported to eQUEST from Autocad. Figure 58 presents the 3D view of Bio-Psychology building in eQUEST.

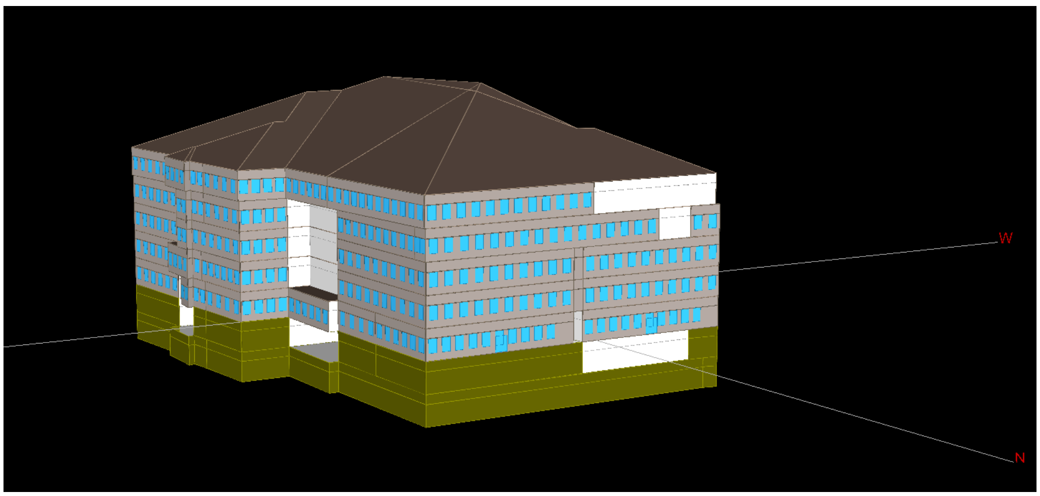



**Figure 58: 3-D Model of Bio-psychology building in eQUEST**

The 3-D model in eQUEST could only display the conditioned zones. The model was divided into a total of 15 zones, which is described above in the section 3.2.4. Each zone was assigned to a specific HVAC system which was precisely modelled with all its features.

AHUs 10 and 11 were designed as a common unit since they are both identical units serving the same area area as described in section 3.2.4. Similarly AHUs 6 and 7 were also designed as the same unit. The PAU (Perimeter Air Unit) heating terminal was designed as baseboard heaters operating on hot water loop. AHU units 10, 11, 6 and 7 were conventional Dual Duct units, which was also one of the reasons for high energy consumption in the building.

Eight space types were divided to specify lighting, plug loads, occupancy, and their associated schedules: office (executive/private), mechanical/electrical room, corridor, conference room, research labs, classroom/lecture hall, clinic, restroom and others (includes undefined space). Vivarium were included under research labs, but the air change rate was carefully specified for them in the detailed design mode. The most common source of energy consumption in labs were fume hoods and freezer units. Laboratories typically consume 5 to 10 times more energy per square foot than office buildings of similar size (Labs21, 2010). All other miscelanious data, load data, occupancy data, and lighting data were collected from the Facilities management, walkthroughs, archive drawings, and BAS system. Some were also assumed according to ASHRAE standards for labs and educational spaces (ANSI/ASHRAE Standard 62.1, 2013). The simulation was then performed for the local weather data for the year 2020 in eQUEST.

### 6.2.2 Model Results

After creating a rudimentary model from the collected data, it was caliberated to match the utility data. Many simulations were performed to spot errors and adjustments were made to correct them. After many trials, the model was caliberated to best match the utility data. During the process of refining the model, data was rechecked and additional walkthroughs were organized to verify them. The simulated result was analyzed and compared to the utility data by using excel.

The simulated annual electricity consumption deviates 4.19 % from the utility data. The NMBE was -4.20. ASHRAE guidelines suggests that an NMBE of $\pm 5\%$ is acceptable

(Bandera and Ruiz, 2017) to consider a model as calibrated. The average electricity data was the average from 2008, 2009 and 2011. By replicating the building schedule and load, the trend had been captured. There was an irregular spike in electric consumption for month of october of 2008 which when consulted with the Facilities management, they advised it might have been because of high number of expriments or overuse of resources or due to faulty equipment at that time. Figure 59 displays comparison between simulated electricity consumption and actual electricity consumption.

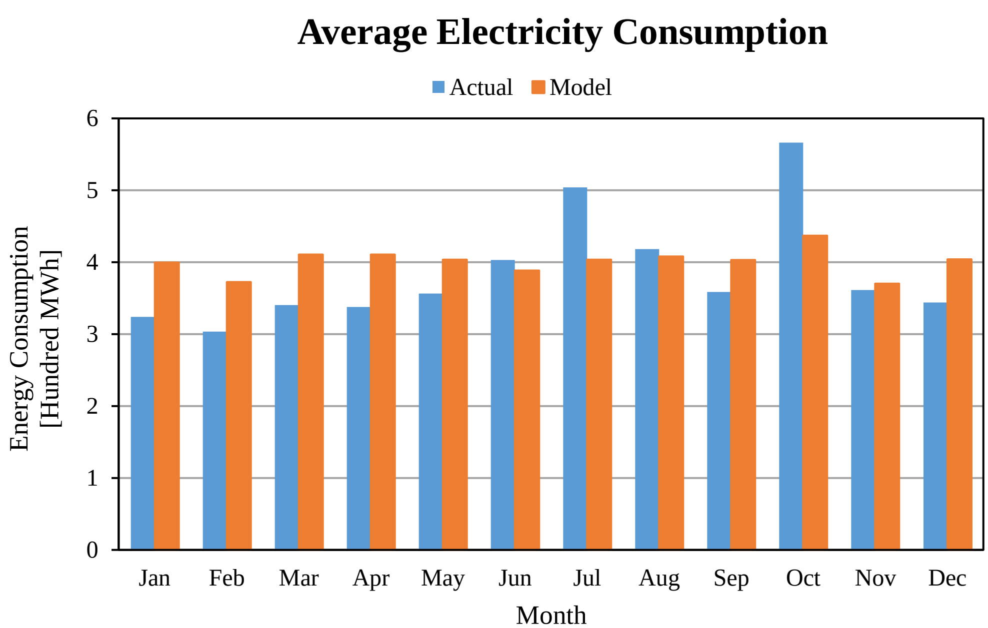



**Figure 59: Comparison of Model Simulated Electricity consumption and Actual average electricity consumption in Bio-psy bldg.**

The eQUEST model simulation was unable to directly model steam loop and district chilled water loop. An on-site boiler and hot water distribution system were used to approximate the consumption of district steam, and an on-site electric chiller system was used to approximate the consumption of district chilled water.

In the simulation, a boiler consumes natural gas to produce hot water that is used throughout the building's heating coils with a default heat input ratio of 1.25. It was therefore assumed that the simulation gas consumption to be adjusted by this factor to simulate the total amount of steam consumed.

Figure 60 compares the simulated steam data with the actual average utility steam data (2011, 2014, 2015 and 2016). The simulated steam data deviates from utility data by 2.64 %. The NMBE was -2.65%, thus calibrated.

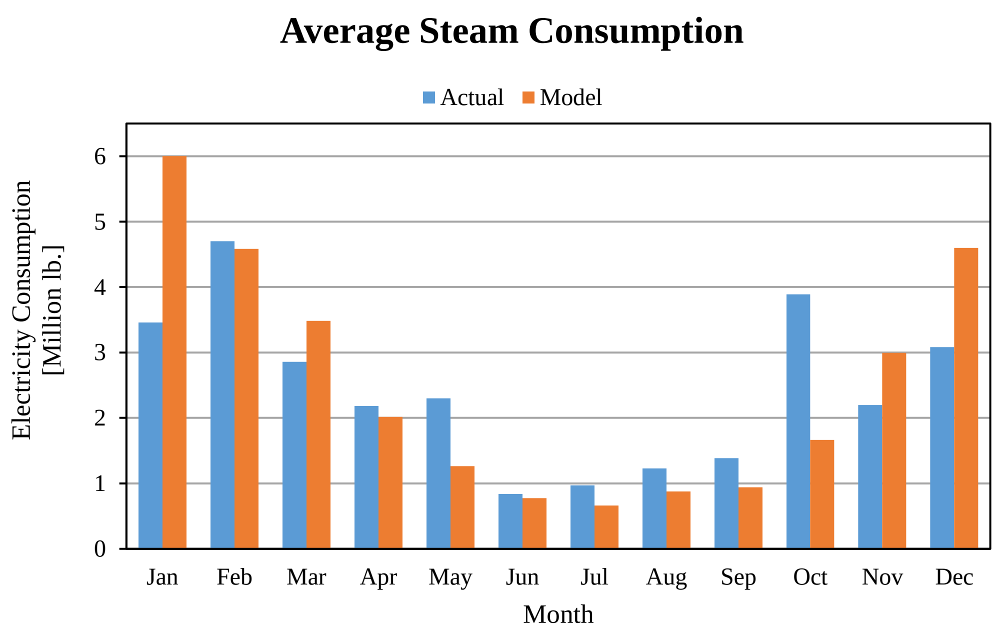



**Figure 60: Comparison of simulated steam consumption and actual average steam consumption in Bio-psychology Bldg.**

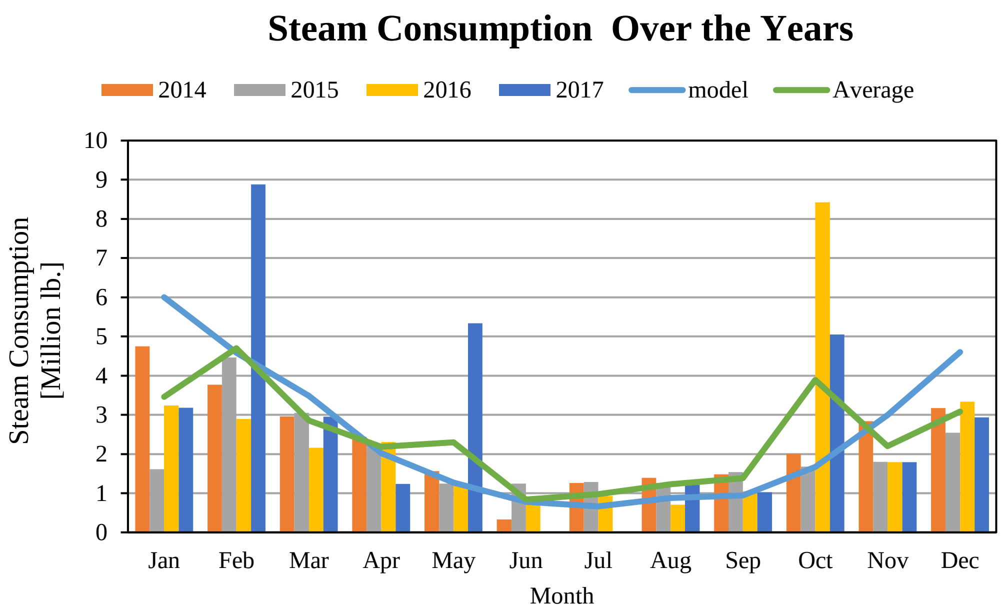



**Figure 61: Comparison of yearly steam consumption data varied over the years and simulated steam consumption data of Bio-psychology Building**

Figure 61 displays how the utility data had changed throughout the years, making modelling quite tricky. The change was very random which when consulted with the Facilities management, they advised it might have been because of faulty steam meter at that time or due to some leakage problems.

Raw simulation data for CHW needed to be processed in a similar manner to steam. The simulation provided the electrical load in kWh from a simulated chiller. The default Electric input ratio (0.192) was then used as a conversion factor to calculate the appropriate total simulation cooling load in Ton-Hr.

Figure 62 displays comparison between simulated chilled water and the average utility chilled water data (averaged over 2011, 2014, 2015,2016 and 2017). The total deviation of simulated data from the utility data was 3.65 %. The NMBE was -3.65 %.

Figure 63 shows variation of chilled water consumption from 2014 to 2017. The variation in consumption may be due to the varying degree days as mentioned in Chapter 5.

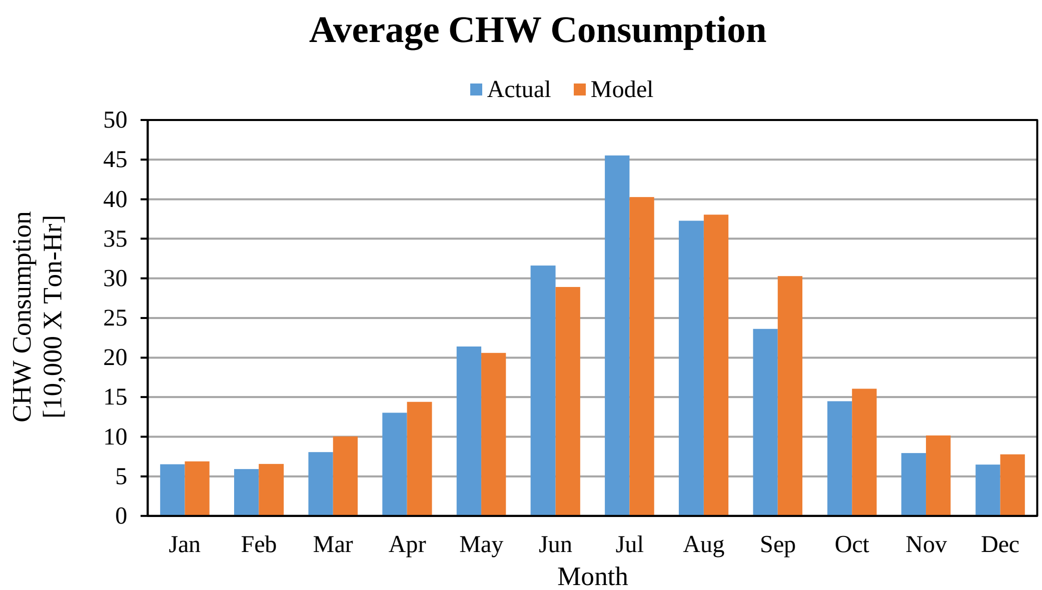



**Figure 62: Comparison of simulated CHW consumption and Actual average CHW consumption in Bio-psy building**

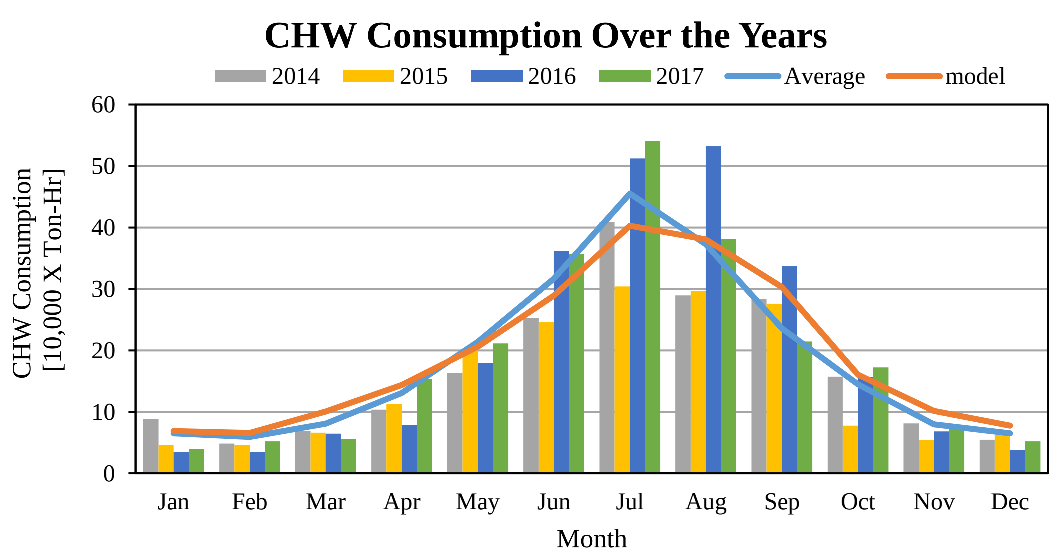



**Figure 63: Comparison of CHW consumption over the years and simulated data, Bio-psy Building.**

### 6.2.3 Sensitivity Anaysis

The parameters selected for sensitivity analysis of the model were Zone setpoint,Sensible effectiveness of the glycol ERU system, AHUs 9 and 10 Motor efficiency and Air Change Rate (ACH) in vivarium. Results for various parameters are presented in Table 25 and Figure 64.

**Table 25: Bio-psy building sensitivity analysis parameters and results**

| Parameters | Unit | Baseline (BL) | Upper Limit (UL) | Lower Limit (LL) | Energy Use Deviation | | |
|---|---|---|---|---|---|---|---|
| | | | | | BL [%] | UL [%] | LL [%] |
| Air change rate | ACH | 10.0 | 15.0 | 5.0 | 0.0 | 5.0 | -4.2 |
| Sensible effectiveness ERU | ratio | 0.6 | +50% | -50% | 0.0 | -0.1 | 0.2 |
| Thermostat setpoint | °F | 73.0 | 76.0 | 70.0 | 0.0 | 0.2 | -0.3 |
| AHU Motor efficeincy | ratio | 0.6 | 0.8 | 0.5 | 0.0 | -0.3 | 1.4 |

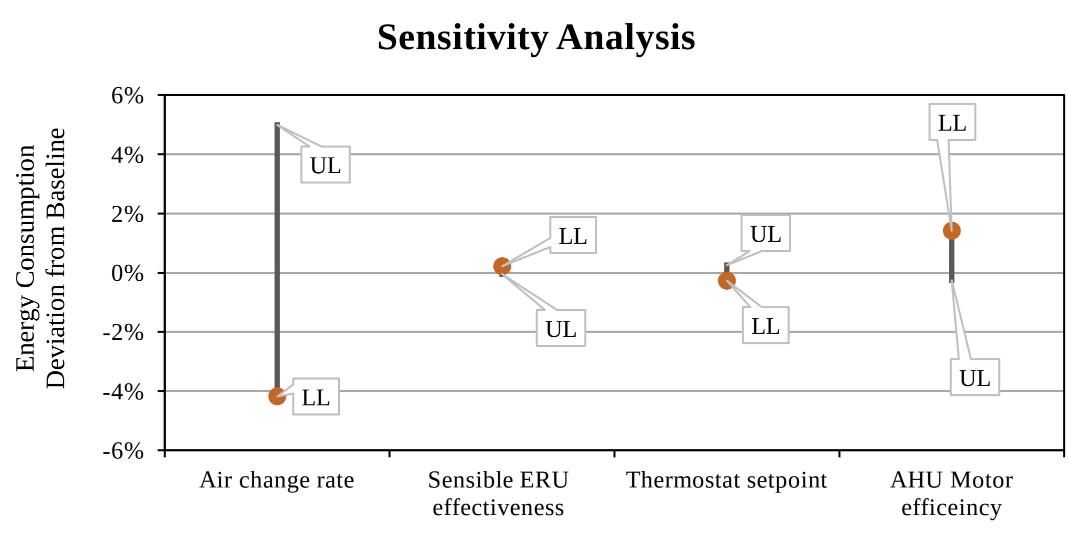



**Figure 64: Bio-psy Building sensitivity analysis results**

It was observed that Air change rate has the highest effect on energy consumed by the model. Energy consumption decreased by 4.2% when considering an air change rate of

5 and increased by 5 % when ACH was changed to 15. Sensitive effectiveness of ERU had little effect on the model when its efficeincy was lowered to the lower limit. AHU motor efficiency had the second most impact after air change rate. Thermostat set point was lowered to only 70 $^{o}$ F because the biology wing had to be maintained at 70$^{o}$ F at all times. The restriction was due to labs and animal quarter requirements. A best practice environment can be created by using these results and implementing possible changes such as not overheating the environment and preventive maintainance of AHU motor units to maintain the efficiency.

### 6.2.4 Energy Conservation Measures (ECMs)

#### *6.2.4.1 ECM #1-Night-time Scheduling of HVAC System*

It was discovered that all the AHU units except AHU 13 were scheduled to run for 24 hours. This was an opportunity to save energy by scheduling the AHU systems. AHU 13 was scheduled to run from 6 AM to midnight. The schedule of AHUs serving the biology wing could not be altered as they were serving labs and vivarium which required a continuous supply.

AHUs serving the psychology wing, which consisted of mostly classrooms and offices, could be scheduled. A night time shut-down from midnight to 6 AM, by turning off AHUs 6, 7 and 8, was tested for simulation. The timing for shut-down was chosen based on the discussions with the FM. Table 26 presents the savings from the simulated result. The payback period of this ECM was immediate. A total of 540 MMBtu was projected to be saved from this ECM which would reduce total energy consumption by 0.8 %.

**Table 26: Simulated savings from ECM #1 in Bio-psy bldg.**

| Annual Savings | | | | | | Simple Payback [yr.] |
|---|---|---|---|---|---|---|
| Electricity [ kWh] | Steam [lb.] | Chilled Water [Ton-Hr] | Cost [$] | Total Energy [MMBtu] | Energy Reduction [%] | |
| 18,400 | 438,550 | 3,253 | $13,705 | 540 | 0.8 % | Immediate |

### *6.2.4.2 ECM #2-Air-side Economizer Installation in AHUs 6 and 7:*

Economizers can be used to achieve free cooling and save energy consumption of the building. According to the mechanical drawings and BAS data, only AHUs-6, 7 and 13 utilize return air. The other AHU systems uses 100 % fresh air. Among those AHUs only AHU 13 comprised of an air side economizer system. The goal of this analysis was to analyze the costs and benefits of installing economizers in AHUs 6 and 7. Figure 65 presents the National Renewable Energy Laboratory (NREL) data for dry bulb temperature and relative humidity averaged for a year. The data consists of hourly data averaged from years 1976 to 1999. From this data, we could conclude that the region surrounding University of Maryland was hot and humid throughout the summer, with the highest recorded RH of 100% in some months. Winter months were cold and less humid.

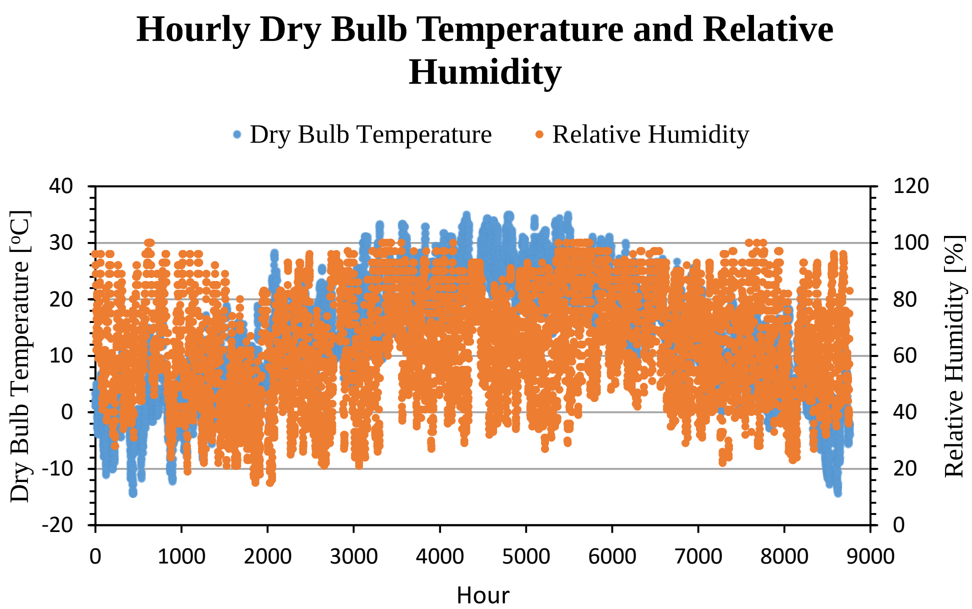



**Figure 65: Relative humidity and temperature averaged throughout the years (NREL, n.d.)**

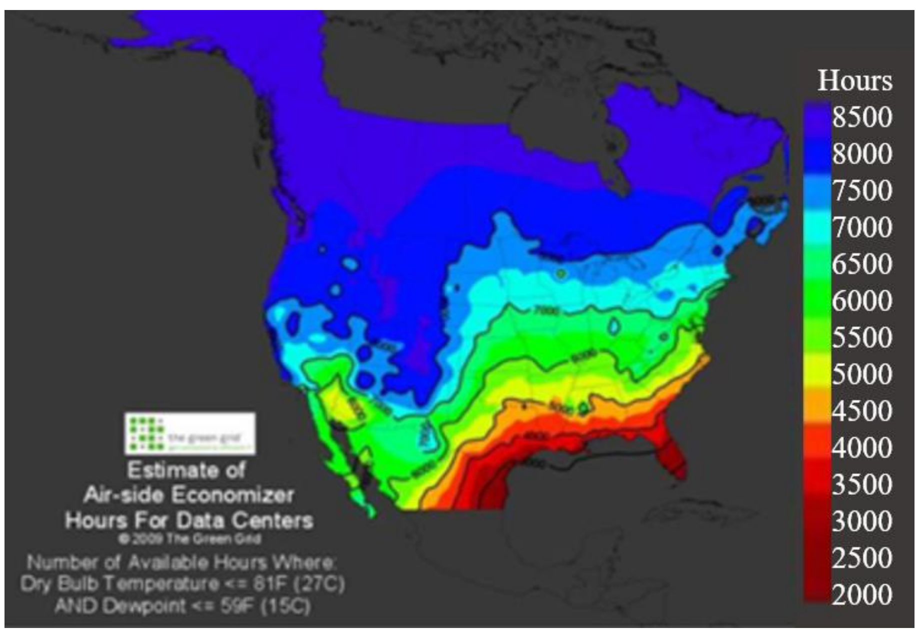



**Figure 66: Ideal hours of free cooling (Energy Star, 2009)**

Figure 66 presents ideal hours per year to use an air side economizer. The state of Maryland has around 6600 hours for ideal free-cooling conditions (Energy Star,2009), thus validating the proposal of installing an economizer system.

The best type of economizer sensor that could be used in this case, keeping in mind the cost and ease of use, was fixed or differential dry bulb temperature sensors. Enthalpy sensors should be avoided as it has a lot of complications in practical applications which is not worth the investment (Taylor and Cheng, 2010). A temperature control Economizer was designed for AHUs 6 and 7 and tested in eQUEST.

**Cost of using economizers:**

The cost of installing an economizer in an existing AHU could not be known directly. Economizers uses a combination of sensors, dampers, actuators, and logic units. Sensors detect outside air or both outside and return air and operates the dampers so that optimum free cooling can be achieved.

Various vendors were consulted to estimate the cost, but the exact cost could not be confirmed without a vigorous inspection of the system. Thus, a generalized cost estimation was done. Considering, 100 Refrigeration Ton (RT) system of RTU would cost USD 4000, our estimated 81000 CFM system (202.5 RT as per relation of 400 cfm per 1 RT) would cost USD 8000 (Prism Engineering Canada, 2019), with additional estimated installation cost of USD 2000, adding to a USD 10,000 per AHU. The total Capital Expense (CAPEX) for installing economizer in AHUs 6 and 7 would be around USD 20,000. An annual Operation and Maintenance cost which was 5% of the total investment was also considered in the economic analysis. Table 27 summarizes the cost and energy savings along with payback period after installing an air side Economizer system.

**Table 27: Simulated Savings from ECM #2 in Bio-psy Bldg.**

| Annual Savings | | | | | CAPEX [$] | Simple Payback [yr.] |
|---|---|---|---|---|---|---|
| Electricity [ kWh] | Steam [lb.] | Chilled Water [Ton-Hr] | Cost [$] | Energy Saved [MMBtu] | | |
| (-2,400) | (-615,980) | 193,843 | $20,086 | 1,702 | $20,000 | 1.0 |

The simulation was done in eQUEST by defining an economizer system with a fixed dry bulb temperature sensor. Since the air side economizer was used for free cooling, the system needed to use more steam to maintain the set point temperature, explaining the negative sign in Table 27. It was noticed that even with excess use of steam, net energy savings was positive. Total cost savings amounts to $20,086 with an estimated payback period of around one year. A total energy savings of 1,702 MMBtu was projected which amounts to energy reduction of 2.5 %.

### *6.2.4.3 ECM #3 - VFD Installation in AHU 12*

As discussed earlier in Chapter 6, Variable Frequency Drive is an important tool which can be used to save energy. According to the walkthroughs and data collected, AHU 12 was not equipped with a VFD drive. The AHU system ran on a constant volume system. Also, AHUs 8 and 9 consisted of an optional VFD system which had been bypassed at the time of inspection. Figure 67 presents BAS view of AHU 12.

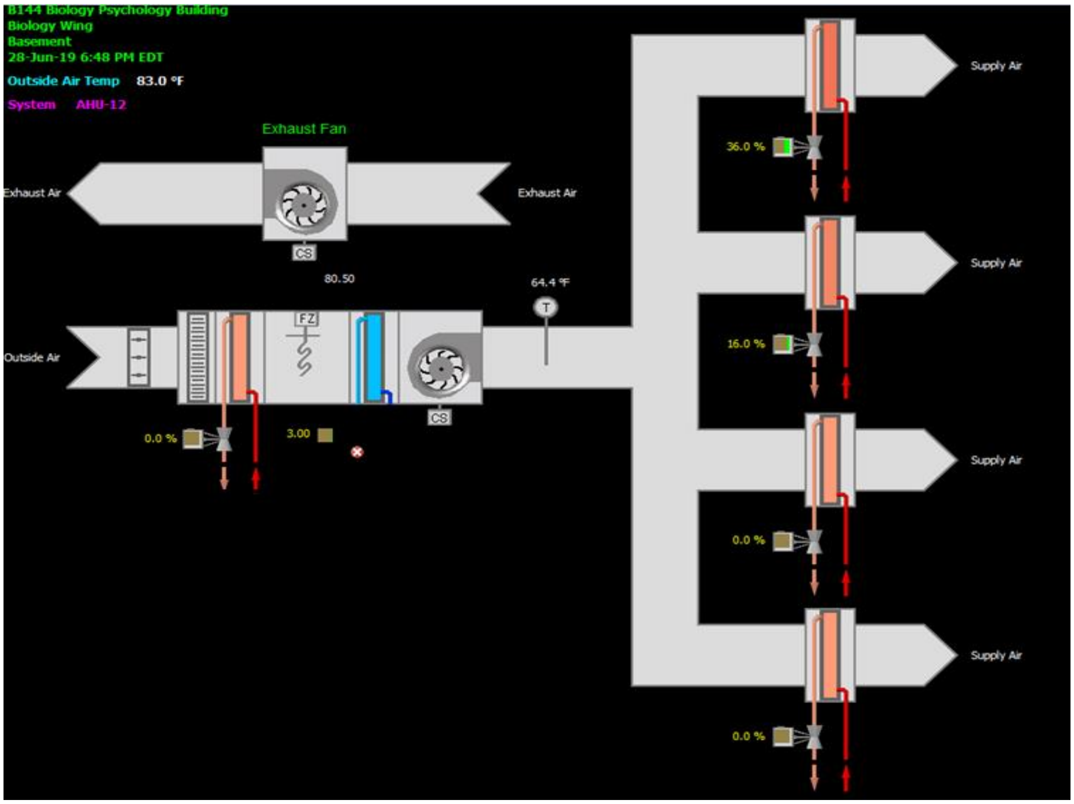



**Figure 67: Graphical representation of AHU 12 in Niagara BAS in Bio-psy bldg.**

For analysis of this ECM, AHU -12 with a VFD system was simulated in an online VFD tool (vfds.org, n.d.). The aim was to observe how much saving could be done if AHU-12 incorporated a VFD system.

AHU-12 uses a 5 HP, 60 Hz 3-phase motor. It supplies the Fish lab and surrounding office areas. The capital cost of VFD was estimated by reference of various vendor websites (Grainger USA, n.d.). The cost of installation was subject to change according to FM policy. An additional Operation and Maintenance (OM) cost was added which was 5% of the total cost. Table 28 presents the detail about capital investment and operation and maintenance cost required. Table 29 presents details of energy savings of 39,810 kWh and cost savings of $3,981 per annum along with the payback period of 1 year.

**Table 28: Cost details of ECM #3 in Bio-psy Bldg.**

| VFD Model | Item Cost | Installation cost est. | OM cost est. | Total Cost |
|---|---|---|---|---|
| FujiElectric-FRN0020C2S-2U | $860 | $3,000 | $193 | $4,053 |

**Table 29: Total savings from ECM #3 in Bio-psy Bldg.**

| | Electricity Savings [ kWh] | Cost saving [$] | Payback [yr.] |
|---|---|---|---|
| AHU 12 | 39,810 | $3,981 | 1.0 |

### *6.2.4.4 ECM #4 - LED Lighting Retrofit*

An analysis of energy conserved by LED retrofitting was done by analyzing spaces that used conventional lighting. List of rooms and spaces with traditional fluorescent lamps were extracted by the help of FM. The list consisted of a collection of restrooms, research labs, Staff office, equipment rooms, and storage room and corridor space. This simple analysis was done using a formulated excel spreadsheet.

Firstly, the sample was inspected for the number of T-8 bulbs (32 Watts), total lumens and Light Power Density (LPD) for each space. LPD was then compared to ASHRAE standard (ASHRAE standard 90.1, 2010) for respective room area, which was observed to be greater than required standard. The solution to this was to upgrade fluorescent bulbs with LED lamps in order to reduce the LPD.

For this analysis, T-8 bulbs were assumed to be replaced by LED bulbs (14 Watts) without compromising the original lumens provided by T-8 bulbs. The result of the analysis concluded savings of $6,295 per annum. Since quantity of lumens was not compromised, there was need for some extra LED bulbs and fixtures (PLT, n.d.) to be installed which would add on the installation and new wiring cost. Average LPD according to ASHRAE standard for the spaces inspected was 1.04 Watt/ft$^2$. Table 30 presents LPD of various inspected spaces, along with ASHRAE standards and LPD after LED light retrofit.

**Table 30: LPD of variuos space in Bio-psy Bldg.**

| Area | LPD before ECM #4 [Watt/ft$^2$] | ASHRAE LPD [Watt/ft$^2$] | LPD after ECM#4 [Watt/ft$^2$] |
|---|---|---|---|
| Lab | 4.10 | 1.81 | 2.72 |
| Restroom | 1.24 | 0.98 | 0.81 |
| Staff office | 1.80 | 1.11 | 1.19 |
| ME Equipment | 0.40 | 0.95 | 0.26 |
| Storage | 0.62 | 0.95 | 0.41 |
| Corridor | 3.78 | 0.66 | 2.50 |

Table 31 shows the savings in energy, cost and the reduced average LPD. The average LPD was calculated to be reduced by 35 % after implementation of this ECM.

**Table 31: Energy Savings from ECM #4 in Bio-psy Bldg.**

| | |
|---|---|
| Electricity savings per year | 60,702 kWh |
| Cost Savings per year | $ 6,295 |
| Average LPD before ECM #4 | 1.45 Watt/ft$^2$ |
| Average LPD after ECM #4 | 0.93 Watt/ft$^2$ |

Table 32 presents the capital cost required and simple payback period of 1.8 years. Cost of LED bulb is based on the price of 14 Watt “Lunera” LED T-8 bulbs (Energy Avenue, n.d.). The cost of labor was not included as it was not specific according to discussions with Facilities Management.

**Table 32: Cost analysis of ECM #4 in Bio-psy bldg.**

| | |
|---|---|
| Cost of 1 LED | $ 8 |
| Tot no. LED | 897 |
| Total LED cost | $ 7615 |
| Fixtures cost | $ 3,960 |
| Total cost | $ 11,576 |
| Simple pay back | 1.8 yr. |

### 6.2.5 ECM Summary

The energy model, using comprehensive simulation engines has the capability of capturing the effect on building energy consumption caused by multiple energy conservation measures that may not be independent.

In this case, the aggregate effect on predicted energy savings by modeling ECM #1 and ECM #2 simultaneously was not equal to the sum of the savings when each ECM is modeled separately. The “Combined model” predicts the energy savings resulting from implementation of ECM #1 and ECM #2 together. The total energy reduction after implementing the ECMs was projected to be 3.8 % which amounts to savings of $48,012 per annum. The total energy saved was projected to be 2,568 MMBtu per annum. ECM #1 had the shortest payback period whereas ECM #4 had the longest.

A Summary of the recommended ECMs and respective savings along with their payback period are presented in Table 33.

**Table 33: Bio-psy Bldg. ECM summary**

| Savings (Annual) | | | | | | | Payback [yr.] |
|---|---|---|---|---|---|---|---|
| ECM | Elec. [kWh] | Steam [lb.] | Chilled Water [Ton-Hr] | Tot. Energy Savings [MMBtu] | Cost Saving [$] | Energy reduction [%] | |
| ECM #1 Night-time scheduling | 18,400 | 438,550 | 3,253 | 540.4 | $13,705 | 0.8 | Immediate |
| ECM#2 Economizer retrofit AHU 6,7 | (-2400) | (-615,980) | 193,843 | 1,701.9 | $20,086 | 2.5 | 1.0 |
| Combined model | 15,900 | (-153,480) | 193,696 | 2,225.1 | $37,736 | 3.3 | 1.0 |
| ECM#3 VFD AHU-12 | 39,810 | N/A | N/A | 135.8 | $3,981 | 0.2 | 1.0 |
| ECM#4 LED light retrofit | 60,701 | N/A | N/A | 207.1 | $6,295 | 0.3 | 1.8 |
| Total | 116,412 | (-153,480) | 193,696 | 2,568.0 | $48,012 | 3.8 | NA |

## Chapter 7: Carbon Consumption

The CHP plant produces 245,000 MW-hours electricity and 900 million pounds of steam per year according to the FM records and documents. The plant generally emits 126,000 Metric Ton (MT) $CO_{2eq}$ per annum according to discussions with the UMD Sustainability office (UMD Office of Sustainability, n.d.). From this data, $CO_{2eq}$ emission per kWh was calculated to be 1.02 lb per kWh.

The total steam produced by plant per annum was 900 million pounds, thus, 0.28 lb $CO_{2eq}$ was emitted for every pound of steam. The chilled water was produced by SCUB-4 units using steam chillers. According to CHP plant data sheet, two steam chillers produce 3,800 Ton-Hr of cooling using 39,750 lb of steam. With this relation, it was concluded that 10.46 lb of steam was used to produce 1 Ton-Hr of cooling. From the relation between steam and the emitted $CO_{2eq}$, the $CO_{2eq}$ emission due production of one Ton-Hr of chilled water could be calculated (Ton-Hr *0.28*10.46).

After deducing $CO_{2eq}$ emission per unit of the utility, $CO_{2eq}$ emission reduction due to the recommended ECMs could be calculated. A combined reduction of 515 MT $CO_{2eq}$ emission was projected for both the buildings after the implementation of recommended ECMs. Thus, the reduction of carbon footprint of the building could be quantified. Table 34 presents $CO_{2eq}$ emission reduction in Bio-psychology building and Gossett Football House along with the combined total reduction due to implementation of the recommended ECMs.

**Table 34: Bio-psy Bldg. and Gossett FH $CO_{2\ eq}$ emission reduction**

| **Bio-Psychology Bldg.** | |
|---|---|
| ECM | $CO_{2eq}$ emission reduction [MT] |
| ECM#1 | 76 |
| ECM#2 | 196 |
| combined | 270 |
| ECM#3 | 20 |
| ECM#4 | 31 |
| Total | 322 |
| **Gossett FH** | |
| ECM | $CO_{2eq}$ emission reduction [MT] |
| ECM#1 | 59 |
| ECM#2 | 112 |
| ECM#4 | 5 |
| ECM#5 | 18 |
| Total | 193 |
| Combined Total | 515 |

# Chapter 8: Conclusions and Future Work

The Biology-Psychology and Gossett Football House were successfully audited, utility consumption benchmarks were established by comparing with the national average and energy consumption was successfully simulated in eQUEST. After calibrating the model, various ECMs were identified and simulated to improve the energy efficiency of the buildings.

When implemented, the ECMs were projected to reduce total Energy consumption by around 4 % and 9 % in Biopsychology and Gossett buildings, respectively. In addition to energy, water savings of 787,290 Gal, and 515 MT of $CO_{2eq}$ emission reduction per annum could also be achieved. The combined cost savings per year at current Energy costs were estimated to be $100,800.

Both buildings were completely different, serving different purposes. The Bio-psychology housed labs, vivarium, and classrooms whereas the Gossett FH was a mixed athletic facility housing gym, locker room, classrooms, offices, auditorium, and a dining hall. Both buildings consumed high amounts of energy to meet their demands due to their specification. Research labs and vivarium in Bio-psychology had very high energy demands. Similarly, the dining hall, auditorium and therapy rooms in Gossett FH used most of its energy.

One of the ECMs common to both buildings was night-time schedule of the HVAC system. Most of the facility HVAC system was running for 24 hours irrespective of occupancy schedule. ECM 1 for both buildings was recommended to solve this issue. In ECM 1, the occupancy period of the building was thoroughly analyzed and studied to identify periods of unoccupancy and practicality of shutting down certain HVAC units for the respective period. The proposed HVAC schedule resulted in significant savings of 407 MMBtu/yr. in Gossett FH and 540MMBtu/yr. in Bio-psychology building, which accounted for 3 % and 1 % of the total energy consumption per annum in Gossett FH and Bio-psychology respectively. The total cost savings was $13,705/yr. for Bio-psychology and $10,688/yr. for Gossett FH.

Another surprising discovery was the poor condition of the insulation in the mechanical room of Gossett FH. Most of the insulation was wearing off and the condenser tank was fully uncovered. The re-insulation was done by the Facilities Management during the span of the project, which was one of our suggested ECMs. The re-insulation covered most of the exposed area. A study was done on the heat loss due to the uninsulated condenser tank which was also re-insulated by the end of the project. This resulted in energy savings of 40MMBtu per annum, which accounted for energy reduction of 0.3 % and cost savings of $943 per annum. The Gossett FH was also wasting a large amount of water in the form of steam condensate which was deemed as an unsustainable practice. An estimated 787,290 gal of water was wasted per annum. ECM #3 in Gossett FH was proposed to solve this issue by recirculating the water to CHP plant, which resulted in savings of $15,800 per annum and a payback period of 5.8 years. This was the most expensive ECM but was necessary to make the building sustainable and save an important commodity.

Bio-psychology building was comparatively an older building and was equipped with low energy efficient HVAC technology, like the dual-duct system. The building follows some restrictions, such as no temperature setback was allowed in research labs, and specific air change rate had to be maintained, which made recommending some of the ECMs challenging. The building did not have an economizer system. An economizer could be installed only in AHU systems 6 and 7 as the other systems used 100 % outside air. A simulation of installing a fully functional air-side temperature control Economizer on AHUs 6 and 7 was done, projecting savings of 1700 MMBtu per year. An energy reduction of 2.5% was achieved from this, and thus recommended as ECM #3 for Bio-psychology. The total cost saving was projected to be $20,086 per annum. When this ECM was simulated together with ECM 1 for Bio-psychology, the total cost savings amounted to $ 37,736 per annum with energy saving of 2,225 MMBtu per annum, which was responsible for 3.3 % of total energy reduction. The building also had fume hoods in research labs which had been practicing a "Shut the stash" campaign (Savage, 2017), making them more energy efficient.

Some of HVAC systems in both the buildings were constant volume systems. A study of installing Variable Frequency Drive in AHU motors was done which was one of the high energy saving ECMs. Savings of 740 MMBtu/yr. in Gossett FH and 135 MMBtu/yr. in Bio-psychology building, which accounted for energy reduction of 5.2 % and 0.2 % in Gossett FH and Bio-psychology respectively, were projected along with combined cost saving of $ 25,710 per annum. The VAV system would help to reduce duct static pressure to reduce air flow when occupancy is low.

Since the buildings were quite old, they had traditional fluorescent lighting and many spaces lacked lighting sensors. A case study of retrofitting LED lamps in various spaces was done and recommended as a simple yet effective ECM. This contributed to savings of 34,786 kWh/yr. in Gossett FH and 60,701 kWh/yr. in Bio-psychology, accounting for 1 % and 0.3 % energy reduction in Gossett FH and Bio-Psychology respectively. The combined cost savings for both buildings due to this ECM was estimated to be $9,900 per annum.

Therefore, by implementation of these low cost/no cost ECMs, the energy efficiency of the buildings could be increased with low investment cost, making them more sustainable and aid in the pursuit of climate action goals.

## Challenges Faced and Future Work

A challenge faced during the span of this project was that on-demand access to view the building automation system and the buildings' mechanical rooms housing AHU's, pumps, sensors etc. was not made available. A more open student access to these resources, given a certain level of confidence in the student conducting a similar project, could enhance future projects' completion time and may lead to additional insights for energy conservation measures. Buildings' BAS systems should be upgraded as the modern BAS systems are more robust and would bolster the energy audit process.

For future work, the suggested ECMs should be implemented in the buildings, which would be useful in further developing the model and validating the projections. Energy Audit is a continuous process, and the buildings should be audited regularly to understand the state of building's performance and increase its energy efficiency.

Another important take-away message from this thesis is that the ECMs and energy audit method suggested here could be applied to other campus buildings with similar profiles, helping them achieve sustainability goals. The developed energy models can be used in future to test more ECM technologies.

# Appendix-A

**Calculation and Assumption for Gossett Football House ECM#3**

Following are the assuptions and conditions for this calculation which are sourced from facilities management:

i) Consider pressure in the storage tank at CHP and condenser tank is at atmospheric pressure. It was known from FM that elevation of feed water tank at CHP is at ground level (Z2=0).

ii) The distance between Gossett teamhose and CHP is 1500m.

iii) Elevation of condensate tank in Gossett (Z1) is 4.5 m.

iv) Diameter of pipe is 3 inches and pipe used is cast iron pipe.

v) Pipe diameter is the same, thus, by theory of conservation of mass; $V_1 = V_2$

A pump system was proposed on calculations based on the steady state incompressible energy equation utilizing Darcy-Weisbach friction losses as well as minor losses (LMNO Engineering Research and Software Ltd., n.d.). The system was designed to achieve a flow rate of at least 2 lit/sec (31.7 gpm). While designing, it was oversized to reach flow rate of 5 lit/sec.

Symbols used:

A = Pipe cross-sectional area, [$m^2$]

D = Pipe diameter, [m]

e= Pipe surface roughness, [m]

f = Moody friction factor, unit-less

g = 9.8 [$m \cdot s^{-2}$]

$h_f$ = Major (friction) losses, [m]

$h_m$ = Minor losses, [m]

$H_p$ = Pump head (Total Dynamic Head), [m]

$K_m$ = Sum of minor loss coefficients, unit-less

$P_1$ = Upstream pressure, [$N \cdot m^{-2}$]

$P_2$ = Downstream pressure, [$N \cdot m^{-2}$]

Re = Reynolds number, unit-less.

Q = Flow rate in pipe, [$m^3 \cdot s^{-1}$]

S = Weight density, [$kg \cdot m^{-3}$]

V = Velocity in pipe [$m \cdot s^{-1}$]

$V_1$ = Upstream velocity, [$m \cdot s^{-1}$]

$V_2$ = Downstream velocity, [$m \cdot s^{-1}$]

$Z_1$ = Upstream elevation, [m]

$Z_2$ = Downstream elevation, [m]

$v$ = Kinematic viscosity, [$m^2 \cdot s^{-1}$]

L= Length of pipe, [m]

**Equations used:**

Steady State Equation (Cengel and Cimbala, 2008):

$$H_p + Z_1 - Z_2 + \frac{P_1 - P_2}{S} + \frac{V_1^2 - V_2^2}{2 * g} = h_f + h_m$$

Where;

$$h_m = K_m * \frac{V^2}{2g} \text{ ; } Re = \frac{VD}{\upsilon} \text{ ; } A = \frac{\pi}{4} * D^2$$

Darcy − Weisbach equation:

$$h_f = f * \frac{L}{D} * \frac{V^2}{2g}$$

If laminar: (Re< 4000), $f = \frac{64}{Re}$

If turbulent: ($4000 \leq Re \leq 10^8$) Then,

Colebrook Equation:

$$1/\sqrt{f} = -2 * \log(\frac{\frac{e}{D}}{3.7} + \frac{2.51}{Re*\sqrt{f}})$$

Known values:

$A = 0.004536 m^2$

D = 0.076 m

e = 0.00008 m

$g = 9.8\ m \cdot s^{-2}$

$Q = 0.005\ m^3 \cdot s^{-1}$

$S = 1000\ kg \cdot m^{-3}$

$Z_1 = 4.5$ m

$Z_2 = 0$ m

$v = 0.553*10^{-6}\ m^2 \cdot s^{-1}$

$P_1 = 101.5 * 10^3\ N \cdot m^{-2}$

$P_2 = 101.5 * 10^3\ N \cdot m^{-2}$

L=1500 m

Value of $K_m$ value is as follows (LMNO Engineering Research and Software Ltd., n.d.):

| Material | $K_m$ |
|---|---|
| Globe valve | 10.0 |
| Pipe round entrance | 0.2 |
| Elbow fitting every 4m | 97.5 |
| Pipe exit | 1.0 |
| Total | 108.7 |

For the value of $K_m$, a globe valve was assumed along with elbow fitting every 4m distance.

**Results:**

Renolds number, Re= 151,475

f (Moody friction factor) = 0.0216

$H_p$ (Pump head)= 28.61 m

$h_f$ (Major friction loss) = 26.42 m

After calculation of the head pump, an appropriate pump was selected for the required pump head of 28.61 m (93.86 ft.) and flow rate of 5 lit/sec (79.25 gpm). Figure 68 represents the pump curve of the pump used which is “AMT 287 series 7.5HP” (AMT Pump, n.d.)

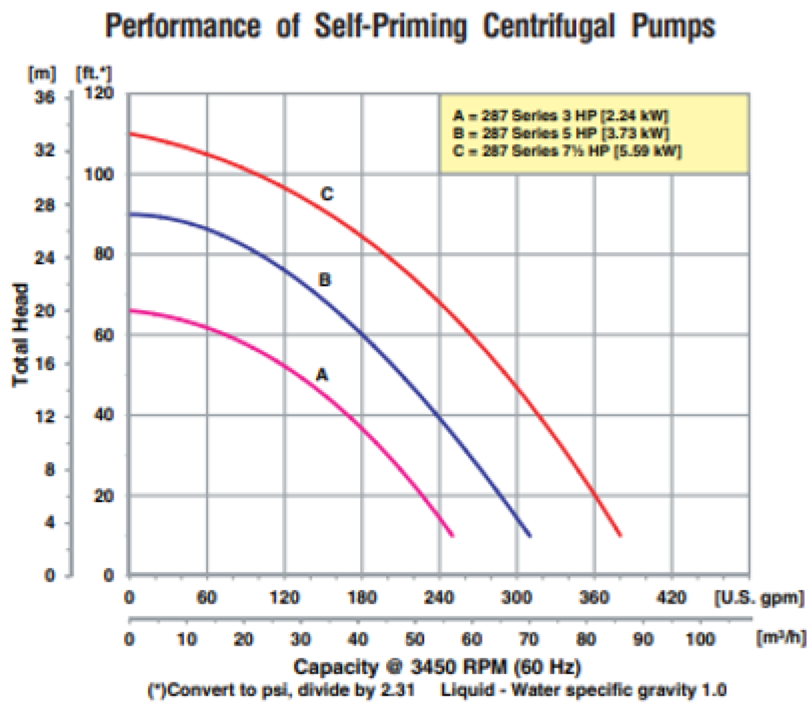



**Figure 68: Display of recommended Pump curve; choice of pump is option C, AMT 287 series 7.5 HP**

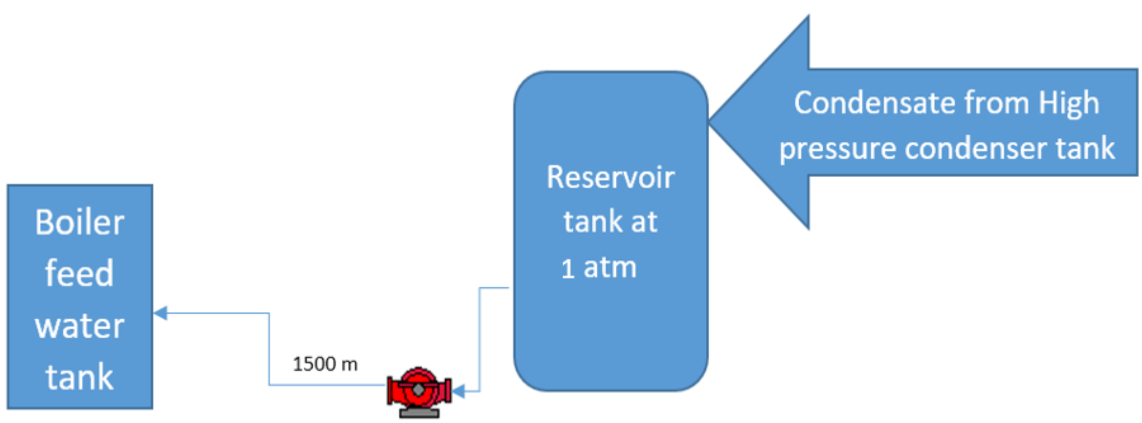



**Figure 69: Flow Diagram for ECM 3, Gossett FH**

The Figure 69 represents a flow diagram for this proposl. The condensate from high pressure condensate tank was being dumped at atmospheric pressure at an average flow rate of 0.09 lit/sec. The proposal was to utilize the waste condensate and pump it back to

CHP plant system. First, the waste condensate was to be collected at a reservoir tank of 1000 litre capacity at atmospheric pressure, which could be placed on the roof. Then, the designed pump and pipeline system could pump the condensate from the reservoir tank to the make up feedwater tank in CHP. Since the exit flow rate from the reservoir tank is greater than fill up rate, the process of pumpting can be activated once the water level in reservoir reaches maximum capacity.

# Appendix-B

**Calculation for Gossett ECM#4:**

**Calculation Details of Heat loss Through Uninsulated Tank:**

The condenser tank is considered to be a cylinder for the purpose of the calculation with diameter (D) of 0.61 m and 1.115 m and surface area 4.91 $m^2$.The surface temperature of tank ($T_s$ ) was 66.6$^0$C and quiescent temperature ($T_\infty$) is considered as 25$^o$C

**Symbols used:**

| Symbol | Definition |
|---|---|
| $T_\infty$ | Quiescent temp, [K] |
| $T_S$ | Surface temp [K] |
| D | Diameter of tank, [m] |
| L | Length of tank, [m] |
| A | Area of tank, [$m^2$] |
| $T_f$ | Film temp, [K] |
| $h_{conv}$ | Convective Heat transfer coefficient, [$Watt \cdot m^{-2} \cdot K^{-1}$] |
| k | Thermal conductivity of air, [$Watt \cdot m^{-1} \cdot K^{-1}$] |
| ε | Emissivity (Steel) |
| υ | Kinematic viscosity, [$m^2 \cdot s^{-1}$] |
| β | Thermal expansion coefficient, [$K^{-1}$] |
| α | Thermal diffusivity, [$m^2 \cdot s^{-1}$] |
| Nu | Nusselt number |
| Ra | Raleigh number |

| | |
|---|---|
| Pr | Prandtl number |
| g | Acceleration due to gravity, [$m \cdot s^{-2}$] |
| σ | Stephan Boltzmann constant (5.67E-08 $Watt \cdot m^{-2} \cdot K^{-4}$) |
| dt | ($T_\infty$-$T_S$) |

**Total Heat Transfer is:**

$Q_{total}$=$Q_{convection}$+ $Q_{Radiation}$

$Q_{convection}$=$h_{Conv.}$ * A* dt

$$Q_{Radiation} = \varepsilon * \sigma * (T_s^4 - T_\infty^4)$$

$$h_{conv} = \frac{Nu * k}{D}$$

Nusselt number correction for horizontal cylinder (Bergman and Incropera, 2006)

$$Nu = \left( 0.60 + \frac{0.387 * Ra^{\frac{1}{6}}}{\left(1 + \left(\frac{0.559}{Pr}\right)^{\frac{9}{16}}\right)^{\frac{8}{27}}} \right)^2$$

Where Raleigh number is as follows.

$$Ra = g * \beta * (T_s - T_\infty) * \frac{D^3}{\alpha * \upsilon}$$

Properties of air at Film temperature, 1 atm. Pressure is as follows.

$$T_f = \frac{T_s + T_\infty}{2} = 90^0 C$$

$$\upsilon = 2.201 * 10^{-5} m^2 \cdot s^{-1}$$

$$Pr = 0.7132$$

$k = 0.0302$ Watt·$m^{-1}$·$K^{-1}$

$\alpha = 3.086 * 10^{-5}\ m^2 \cdot s^{-1}$

$\beta = \frac{1}{T_f} = 0.021819769\ K^{-1}$

**From the equations and relations, the results of calculations are presented below.**

Nu= 89.62

Ra= $4.41098 * 10^8$

$Q_{Radiation} = 483.55$ J·$S^{-1}$

$h_{conv} = 4.39$ Watt·$m^{-2}$·$K^{-1}$

$Q_{convection} = 900.33$ J·$S^{-1}$

**Thus, Total heat loss (Q) = 1383.89 Watt·$m^{-1}$**

## References

AFsupply. n.d. *AF Supply.* Accessed April 20, 2020. https://www.afsupply.com/no-hub-cast-iron-pipe-3-x-10.html?gclid=CjwKCAjwguzzBRBiEiwAgU0FT3rPYx1JS_sS4k1MMsieqVCt3qrsGd-9Z4Oqjy2J0XfhP5pKuROE4hoCLncQAvD_BwE.

Alshuwaikhat, Habib M., and Ismaila Abubakr. 2008. "An integrated approach to achieving campus sustainability: assment of the current campus environmental management practices." *Journal of Cleaner Production 16, 1777-1785.* (Science Direct).

AMT Pump. n.d. *3˝ Self-Priming pump, technical specifications.* Accessed April 20, 2020. https://amtpumps.com/site/wp-content/uploads/2017/01/SPE-15-16.pdf.

ANSI/ASHRAE Standard 62.1. 2013. "Ventilation for Acceptable Indoor Air Quality."

ASHRAE standard 90.1. 2010. "ASHRAE standard 90.1-2010." 83-84.

Bandera, Fernández Carlos, and Germán Ramos Ruiz. 2017. "Validation of Calibrated Energy Models." *Energies 2017, 10(10), 1587.*

Bangerth, Stefan, and Michael M. Ohadi. 2017. "Energy Analysis of LEED Silver Certified Dining Hall on an Academic Campus - A Revisit Three Years After its Initial Certification." *ASHRAE Transactions* 123 (1): 129-139.

Bergman, T. L., and Frank P. Incropera. 2006. *Fundamentals of Heat and Mass Transfer.*

Bizee Degree Days. 2020. *Degree Days Calculated Accurately for Locations Worldwide.* April 20. https://www.degreedays.net/.

Cengel, Yunus A., and John M. Cimbala. 2008. *Fluid Mechanics, Fundamentals and Application.* McGrawHill Education.

ColoradoENERGY.org. 2019. "R-Value Table." *http://www.coloradoenergy.org/.* Accessed April 30, 2020. http://www.coloradoenergy.org/procorner/stuff/r-values.htm.

Coven, J. F. 2017. *Why Benchmarking is Required.* Accessed April 15, 2020. http://www.seattle.gov/environment/climate-change/buildings-and-energy/energy-benchmarking/why-benchmarking-is-required.

Crawley, Drury B., Jon W. Hand, Michael Kummert, and Brent T. Griffith. 2008. "Contrasting the capabilities of building energy performance simulation programs." *Building and Environment* (Elsevier) 43 (4): 661-673.

DOE2. n.d. *www.doe2.com.* Accessed April 30, 2020. http://www.doe2.com/equest/.

Energy Avenue. n.d. *energyavenue.com.* Accessed April 30, 2020. https://www.energyavenue.com/Lunera/HN-T8-D-48-14W-850-G1?keyword=&gclid=Cj0KCQjwtLT1BRD9ARIsAMH3BtXVXUm2PwmjtgZkqarn8IDvbJARXypeqkEXdfgZXSe2taEShsva16MaAlRfEALw_wcB.

Energy Star. 2019. "About ENERGY STAR for Commercial Buildings-2019." https://www.energystar.gov/sites/default/files/asset/document/2020_About_BUILDINGS_032520_508%20v4.pdf.

—. 2009. "Energy Efficient Products, Air-Side Economizer." *www.energystar.gov.* Accessed May 8, 2020.

https://www.energystar.gov/products/low_carbon_it_campaign/12_ways_save_energy_data_center/air_side_economizer.

Energy Star Portfolio. 2018. *U.S Energy Use Intensity by property type.* Energy Star. Accessed April 30, 2020. https://portfoliomanager.energystar.gov/pdf/reference/US%20National%20Median%20Table.pdf.

Feingold, Lindsey. 2016. "UMD Dashboard application enables access to campus utility usage." *www.dbknews.com.* May 3. Accessed April 30, 2020. http://www.dbknews.com/2016/05/03/umd-dashboard-sustainability-facilities-management/.

Grainger, USA . n.d. *www.grainger.com.* https://www.grainger.com/category/motors/speed-controls-encoders-and-soft-starts/motor-speed-controls/variable-frequency-drives.

Hepperle, Martin. 2018. *Aerodynamic Characteristics of Propellers.* November 9. Accessed April 30, 2020. https://www.mh-aerotools.de/airfoils/propuls3.htm.

Homeadvisor. 2020. *homeadcisor.com.* April 15. https://www.homeadvisor.com/cost/plumbing/.

J. M. Levy. 2014. *"Simulation and Analysis of Energy Consumption for an Energy-Intensive Academic Research Building,".* Masters' Thesis, Department of Mechanical Engineering, Masters Thesis, Univeristy of Maryland, College Park.

James J. Hirsch and Associates, Lawrence Berkeley National Laboratory. 2006. "Building Energy Use and Cost Analysis Program Volume 3: Topics." Accessed April 30, 2020. http://doe2.com/download/doe-22/DOE22Vol3-Topics.pdf.

James J. Hirsch and Associates. 2010. "eQuest Introductory Tutorial, version 3.64." Accessed April 30, 2020. http://doe2.com/download/equest/eQ-v3-64_Introductory-Tutorial.pdf.

Kelly, Jason. 2019. *Simulation and Analysis of Energy Consumption for Two Complex and Energy Intensive Buildings on UMD Campus.* Masters Thesis, Department of Mechanical Engineering, University of Maryland, College Park, College Park: University of Maryland.

Kneifel, Joshua. 2010. "Life-cycle carbon and cost analysis of energy efficiency measures in new commercial buildings." *ElsevierEnergy and Buildings Volume 42, Issue 3* 333-340.

Labs21. 2010. "Labs21 2010 Annual Conference." Accessed April 30, 2020. https://www.i2sl.org/labs21/conference/conference2010.html.

LMNO Engineering, Research, and Software, Ltd. n.d. *Pipe Flow calculator.* Accessed April 30, 2020. https://www.lmnoeng.com/DarcyWeisbach.php.

Maile, Tobias, Martin Fischer, and Vladimir Bazjanac. 2007. *Building Energy Performance Simulation Tools - a Life-Cycle and Interoperable.* Sanford University, Facil. Eng. (CIFE) Working Pap.. 107.

Maryland Today. 2019. "Maryland Today." *https://today.umd.edu/articles.* https://today.umd.edu/articles/university-halves-carbon-emissions-ahead-schedule-5a997df7-b736-4d72-b938-3fa5ff8e94c2?utm_source=MD%20Today&utm_campaign=1d8bbf73dd-EMAIL_CAMPAIGN_2019_12_06_07_46&utm_medium=email&utm_term=0_a897daf4c7-1d8bbf73dd-48020627.

Miller, Patrick, Babatunde Olateju, and Amit Kumar. 2012. "A techno-economic analysis of cost savings for retrofitting industrial aerial coolers with variable frequency drives." *Energy Conversion and Management, Elsevier* 54 (1): Pages 81-89.

Moncef, K. (2011). 2011. *Energy Audit of Building Systems an Engineering Approach (2nd ed.).* Boca Raton, FL: CRC press.

NREL . n.d. "tmy3 weather data for Baltimore-Washington Int'l Airport."

Oca, Nicole A. Monts de, David W Brammer, Mitzi Laughlin, and John Jenkins. 2016. *Energy Efficiency of a Large Vivarium: A University of Houston Research Study.* Aircuity White Paper Series. https://flowtechinc.com/aircuity-white-paper-energy-efficiency-large-animal-vivarium/.

Office of Sustainability and the Center for Integrative Environmental Research. 2009. *"University of Maryland Climate Action Plan," College Park, 2009.* Univesity of Maryland.

Perlite Institute. 2013. "Perlite loosefull Masonry insulation." *www.perlite.org.* https://www.perlite.org/wp-content/uploads/2018/03/perlite-loosefill-insulation.pdf, .

PLT. n.d. *1000LEDbulbs.com.* Accessed April 30, 2020. https://www.1000bulbs.com/product/192382/PLT-20026.html?cc=400&gclid=Cj0KCQjwtLT1BRD9ARIsAMH3BtUzruoKDcKNkXN_hvr46iAUHN__enwdswAsyNum09avpfzGAORGzM8aAmmcEALw_wcB.

Prism Engineering Canada. 2019. *Economizers for Packaged Air Conditioning Units.* https://www.prismengineering.com/resources/technologies/economizers.

Savage, Dana M. 2017. *SIMULATION AND ANALYSIS OF ENERGY CONSUMPTION FOR TWO COMPLEX AND ENERGY-INTENSIVE BUILDINGS ON UMD CAMPUS.* Masters Thesis, College Park: University Of Maryland.

Sustainability Office, UMD. n.d. "Dashboard, UMD Energy." *UMD Energy Dashboard.* https://sustainability.umd.edu/campus/energy.

Sustainable UMD. n.d. "Education and Research." *www.sustainability.umd.edu.* Accessed April 30, 2020. https://sustainability.umd.edu/education-research/student-projects.

—. n.d. "Power." *www.sustainability.umd.edu.* Accessed April 30, 2020. https://sustainability.umd.edu/progress/climate-action-plan/power.

—. n.d. "Progress Report." *www.sustainability.umd.edu.* Accessed April 30, 2020. https://sustainability.umd.edu/progress/progress-report.

Taylor, Steven T, and C. Hwakong Cheng. 2010. "Economizer High Control Limit and Why Enthalpy Economizers Don’t Work." *ASHRAE Journal* (ASHRAE) 52 (11). Accessed April 20, 2020. http://www.taylor-engineering.com/wp-content/uploads/2020/04/ASHRAE_Journal_-_Economizer_High_Limit_Devices_and_Why_Enthalpy_Economizers_Dont_Work.pdf.

The White House. 2015. "American Campuses Act on Climate." https://www.whitehouse.gov/the-press-office/2015/12/11/american-campuses-act-climate.

U.S. Department of Energy. n.d. *Building Energy Modelling.* Accessed April 20, 2020. https://www.energy.gov/eere/buildings/building-energy-modeling.

—. 1995. *Tax Credits, Rebates & Savings.* Accessed April 16, 2020. https://www.energy.gov/savings/dsire-page.

U.S. Department of Energy-Better Buildings. 2019. *"Working Toward a More Innovative,Affordable, and Energy Efficient Future.".* Progress report., Better Buildings, U.S. Department of Energy.

U.S. DOE. 2020. *US Energy InformationAdministration.* April 15. https://www.eia.gov/tools/faqs/faq.php?id=86&t=1.

UMD Office of Sustainability. n.d. *Sustainable UMD.* Accessed April 20, 2020. https://sustainability.umd.edu/.

UMD RIGHT NOW. 2014. "UMD Announces President's Energy Initiatives." *https://umdrightnow.umd.edu/.* April 22. Accessed April 30, 2020. https://umdrightnow.umd.edu/news/umd-announces-presidents-energy-initiatives.

Unitherm. n.d. *Ceramic Fiber Insulation Blanket.* Accessed April 20, 2020. https://www.homedepot.com/p/UniTherm-Ceramic-Fiber-Insulation-Blanket-R-Value-2-27-6-Density-2300-F-1-in-x-24-in-x-25-ft-CF6-1-24X25/309520232.

University of Maryland Climate Action plan Workgroup. 2009. *University of Maryland Climate Action Plan.*

US DOE-Office of Energy Efficiency and Renewable Energy. 2017. "Water and Wastewater Annual Price Escalation Rates for Selected Cities across the United States." Office of Energy Efficiency and Renewable Energy, US DOE. https://www.energy.gov/sites/prod/files/2017/10/f38/water_wastewater_escalation_rate_study.pdf.

US Energy Information Administration. 2019. *US Energy Information Administration.* https://www.eia.gov/consumption/residential/index.php.

vfds.org. n.d. *vfds.org.* http://www.vfds.org/vfd-savings-calculator.html#saving]-.

Washington Suburban Sanitary Commission. 2019. *www.wsscwater.com.* July. Accessed April 30, 2020. https://www.wsscwater.com/rates.