ABSTRACT

Title of Document:	SIMULATION AND ANALYSIS OF ENERGY CONSUMPTION FOR AN ENERGY-INTENSIVE ACADEMIC RESEARCH BUILDING
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The University of Maryland's Jeong H. Kim Engineering Building is a state-of-the-art academic research facility. This thesis describes an energy analysis and simulation study that serves to identify energy saving opportunities and optimum operation of the building to achieve its goals of high energy efficiency and substantial CO_2 emission reduction. A utility analysis, including a benchmarking study, was completed to gauge the performance of the facility and a detailed energy model was developed using EnergyPlus to mimic current operation. The baseline energy model was then used to simulate eight energy efficiency measures for a combined energy savings of 16,760 MMBtu, reducing annual energy use by 25.3%. The simple payback period for the proposed measures as a single project is estimated to be less than one year. Due to the high-tech and unique usage of the Kim Engineering Building, including cleanrooms and research labs, this thesis also contributes to the development of energy consumption benchmarking data available for such facilities.

SIMULATION AND ANALYSIS OF ENERGY CONSUMPTION FOR AN ENERGY-INTENSIVE ACADEMIC RESEARCH BUILDING

By

Jared Michael Levy

Thesis submitted to the Faculty of the Graduate School of the
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Professor Michael Ohadi, Chair
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Dedication

This work is dedicated to my incredible girlfriend, Regina, whose support and encouragement over the past six years has helped me to accomplish my goals. I would also like to dedicate this work to my parents for always pushing me academically and helping me to develop the personal drive to set those 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. Kyosung Choo for his consistent support and assistance and for being an outstanding office-mate. I also owe a debt of gratitude to Chauncey Jenkins in the Facilities Management Dept. at UMD for his unwavering aid and cooperation with my project. Finally, I would like to thank the UMD faculty and staff members that provided personal assistance with the project including Ms. Susan Corry of the UMD Facilities Management Dept., Bill Hohenshilt, Bill Grubb, Kevin Fahey, Don Hill, Jim O'Connor, John Fratangelo, Rob Williams, Dr. Amir Shooshtari, and Dr. Serguei Dessiatoun,.

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Nomenclature

ACR – Air Change Rate
AHU – Air Handling Unit
ASHRAE – American Society of Heating, Ref., and Air Conditioning Engineers
BMS – Building Management System
CAV – Constant Air Volume
CBECS – Commercial Building Energy Consumption Survey
CDD – Cooling Degree Day
CFM – Cubic Feet per Minute
CHW – Chilled Water
DDC – Direct Digital Controls
DHW – Domestic Hot Water
EEM – Energy Efficiency Measure
EF – Exhaust Fan
EIA – Energy Information Administration
EPA – Environmental Protection Agency
EUI – Energy Use Index
E+ – EnergyPlus
FCU – Fan Coil Unit
FM – Facilities Management
HDD – Heating Degree Day
HHW – Heating Hot Water
HVAC – Heating, Ventilation, and Air Conditioning
KBTU – One Thousand British Thermal Units
KEB – Kim Engineering Building
LEED –Leadership in Energy and Environmental Design
MAH – Makeup Air Handler
MBH – One Thousand British Thermal Units per Hour
MMBTU – One Million British Thermal Units
OA – Outside Air
PSI – Pounds per Square Inch
PSIG – Pounds per Square Inch (Gauge Pressure)
RAF – Return Air Fan
RAH – Recirculating Air Handler
SAF – Supply Air Fan
SAT – Supply Air Temperature
SCUB – Satellite Central Utilities Building
UMD – University of Maryland
VAV – Variable Air Volume
VCB – Variable Control Box
VFD – Variable Frequency Drive
VRF – Variable Refrigerant Flow

Chapter 1: Introduction

1.1 Project Background and Goals

1.1.1 Project Background

The Jeong H. Kim Engineering Building (KEB) is a 166,000-square foot state-of-the-art academic research building on the University of Maryland's (UMD) College Park campus. The facility was a significant addition to the A. James Clark School of Engineering and serves as a research and education center shared across departments to foster multidisciplinary work. The KEB houses a variety of laboratories and programs that address many opportunities and challenges that face society today, including product design and manufacturing, energy and the environment, transportation, healthcare, robotics, and telecommunications (A. James Clark School of Engineering).

The mechanical, electrical, and plumbing design for the KEB was completed as a joint venture between OKKS Studios, Inc. (Chevy Chase, MD) and SmithGroupJJR (Washington D.C.). The design was completed in three separate phases and lasted for approximately seven years. Clark Construction Group (Bethesda, MD) was the general contractor for the project, and construction was completed in 2007 (Clark Construction Group, 2007).

The KEB was designated by the University of Maryland Energy Sustainability Office and Facilities Management to become the lead project in a campus-wide initiative to reduce UMD's energy consumption and carbon footprint. UMD has major energy reduction goals that span energy conservation in existing buildings, carbon-neutral new construction, and a transition to renewable energy sources. UMD aims to reduce its electric consumption by 20% by the year 2020 (Sustainability at UMD, 2014). In conjunction with this energy analysis and reduction study, there is a professional retro-commissioning project ongoing simultaneously by MBP, a multi-discipline construction consulting firm based in Fairfax, VA.

1.1.2 Project Goals

The primary goal for this project was to produce an energy model of the Kim Engineering Building that accurately portrays facility energy consumption. Three deliverables for the project include a baseline energy model, an "as-designed" energy model, and a high-efficiency energy model. A well-developed and comprehensive energy model for the KEB can be used in energy projects to help decision makers determine impacts that alterations to the building will have on utility bills. A second aim of this thesis is to propose a series of low-investment energy efficiency measures (EEMs) that will save 20% of the KEB's annual utility consumption. Achieving this goal will result in two major consequences: reduced utility costs and a lowered energy use index (EUI), the most common building energy use parameter. Finally, the lessons learned from this project can be applied to other buildings on the University of Maryland campus.

1.2 Energy Modeling

1.2.1 Energy Modeling Overview

According to the 2013 U.S. Energy Information Administration (EIA), global energy use was 524 quadrillion Btus in 2010 and is predicted to grow by 56% from 2010 to 2040. The U.S. consumes the second largest amount of energy annually, behind only China, accounting for 19% of global energy consumption in 2010 (U.S. EIA, 2013). In the United States, the buildings sector is responsible for approximately 41% of primary energy consumption in 2010, 22% from residential buildings and 19% from commercial buildings (U.S. DOE, 2012). Building energy efficiency has come to the forefront of political debates due to high energy costs and climate change concerns (Kneifel, 2010). For these reasons, many energy use and carbon footprint reduction initiatives and policies have surfaced over the last few decades including the Better Buildings Challenge, Energy Star program, LEED program, tax incentive and rebate programs, and energy modeling software development programs.

Over the past 60 years, hundreds of building energy programs have been developed and are in use today. Whole-building energy simulation software is a core tool in the building energy field. It can provide a user with energy use and demand data if given a complete set of building characteristics (Crawley, 2008). Whole-building energy modeling (energy modeling in this thesis) can be used for a variety of purposes. One of the more prevalent uses of energy modeling occurs during building design. Energy consumption and loads can be modeled for various design options, providing insight to an engineer submitting design options in terms of energy cost to a building owner. The tool is often used in the conceptual design, schematic design, design development, and construction documents phases of a project. Furthermore, the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) Rating System requires energy modeling to assess the energy use of a building and to quantify the savings associated with the proposed design. If used properly, energy modeling can help optimize a building design and allow a design team to prioritize a set of energy saving strategies (Rosenbaum, 2003). In addition, energy modeling can be used in studies aimed at reducing energy in an existing building or in an energy audit to determine *cost-effective* strategies to lower the building's energy consumption and carbon footprint.

1.2.2 Energy Modeling Approach

The energy simulation software used in this project is EnergyPlus Version 8.0.0. EnergyPlus (E+) is an open-source program built from two existing programs: DOE-2 and BLAST. DOE-2 was sponsored by the U.S. Department of Energy (DOE), and its source code originates back to the 1960s. BLAST, sponsored by the Department of Defense (DOD), dates back to the early 1970s. The development of both of these programs was supported by the federal government for multiple decades. Both of these programs are composed of hundreds of subroutines that collectively simulate heat and mass energy flows throughout a building. Development of E+ began in 1996 and was a project meant to merge the best capabilities and features from both of its parent programs. Although E+ was based on DOE-2 and BLAST, its code was written from scratch in a joint effort from U.S. Army Construction Engineering Research Laboratories (CERL), University of Illinois, Lawrence Berkeley National Lab (LBNL), Oklahoma State University, and DOE (Crawley, 2001).

EnergyPlus was selected as the energy modeling tool for this project for a few reasons. The author of this thesis was more familiar with E+ than any other software at the start of the project, as he used it as the primary tool for a previous project and has attended numerous formal E+ training sessions. The consistent improvement and updates to the software make it an attractive program that can be used for years to come. Finally, a cost-free program is useful if the energy model needs to exchange possession within the University of Maryland in the future.

Figure 1 shows the program structure of E+ (University of Illinois, 2013). E+ was developed with the expectation that third-party user interfaces would be developed. In this way, third-party software can be used to create a text file that describes the building of interest, pass the file to E+ for the annual energy simulation, and view results in graphics or spreadsheets.

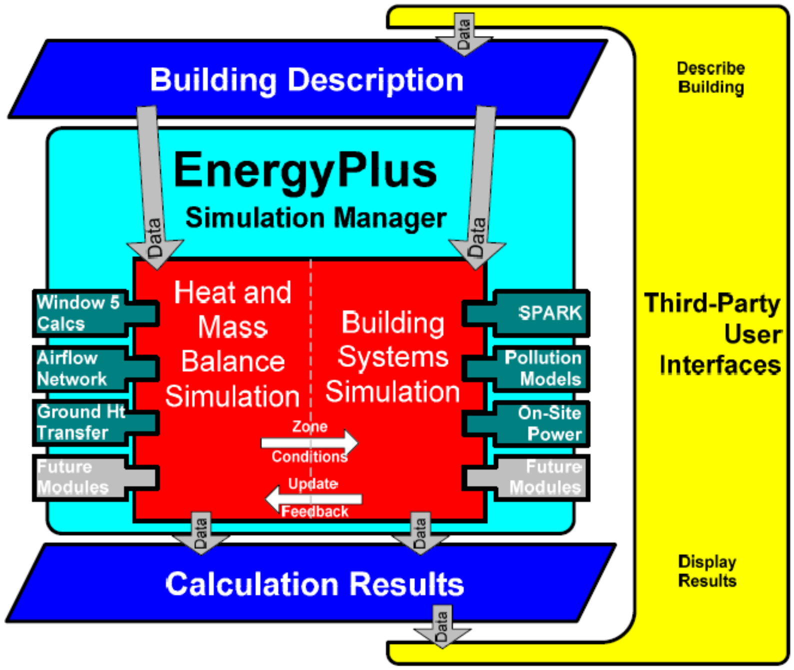


Figure 1: EnergyPlus program structure

Two open-source third-party software packages were utilized in this project for a more user-friendly interface. The first is Trimble SketchUp Make, an architectural tool that was used to define the location of all surfaces and nodes in three-dimensional space. The second is OpenStudio, a "cross-platform collection of software tools to support whole building energy modeling using EnergyPlus" (National Renewable Energy Laboratory). OpenStudio can be used to develop a complete energy model for simple buildings or can be used to lay the foundation of an energy model for complex projects. The OpenStudio software package contains a plug-in for SketchUp which allows both programs to be used simultaneously. Figure 2 shows a screenshot of a project using SketchUp and the OpenStudio plug-in (U.S. DOE, 2013).

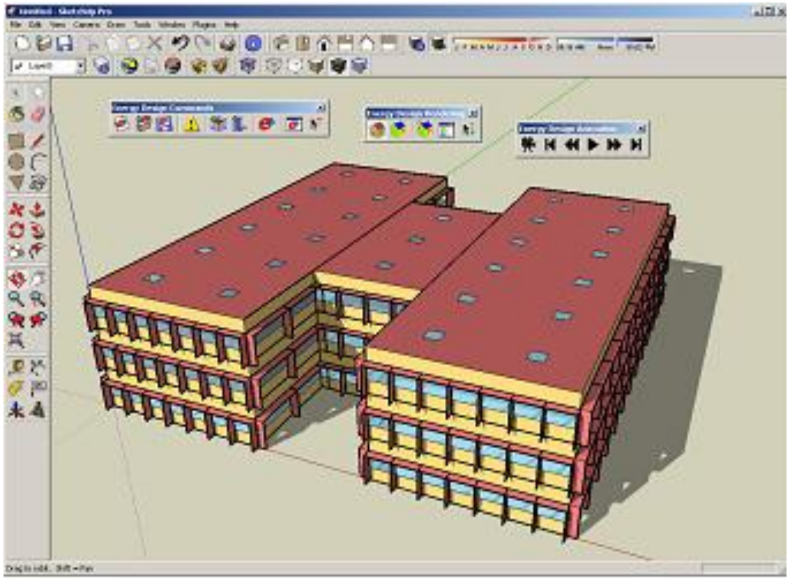


Figure 2: OpenStudio plug-in used with SketchUp

Chapter 2: Literature Review

2.1 Energy Savings on Academic Campuses

Sustainability on university and college campuses has become an increasingly popular topic of discussion and reform in recent years. There are many energy challenges, competitions, and initiatives to encourage the reduction of nonrenewable energy consumption on higher education campuses. The American College and University Presidents' Climate Commitment (ACUPCC) is "a high-visibility effort to address global climate disruption undertaken by a network of colleges and universities that have made institutional commitments to eliminate net greenhouse gas emissions from specified campus operations, and to promote the research and educational efforts of higher education to equip society to re-stabilize the earth's climate." There are currently 684 college and university presidents or chancellors that have signed the commitment, including the University of Maryland, College Park (ACUPCC, 2007). Campus Conservation Nationals (CCN) is an example of a competition created to encourage energy (electricity and water) savings in higher education facilities. In 2013, 1,400 buildings in 119 colleges and universities competed (Campus Conservation Nationals, 2014).

2.2 Cleanroom Energy Strategies

The KEB contains 10,000 square feet of cleanroom space. Due to the air quality and processes within cleanrooms, they are known to be extraordinarily energy-intensive.

These types of buildings typically have demands for high reliability and safety to protect the workforce and ensure high process performance. Once they are built and meet their requirements, little is done to look for efficiency measures since improving energy efficiency is a low priority. However, lowering energy demand and consumption in cleanrooms yields great economic returns due to their high EUIs and 24/7 operation (Tschudi, 2002).

The Energy Efficiency Design Applications team (A Team) at the Lawrence Berkeley National Laboratory (LBNL) is a leading research group in cleanroom energy efficiency. The group has conducted extensive benchmarking studies for cleanroom energy consumption and completed five successful industry cleanroom energy reduction projects. Energy reduction measures proposed in these case studies include but are not limited to the following list (LBNL Applications Team, 2002):

- Chiller plant efficiency upgrade and optimization
- Variable speed drives (VSDs) on fan and pumps motors
- Makeup air handler discharge air temperature reset
- High-efficiency boilers and boiler economizers
- Cleanroom declassification by recirculating airflow reduction
- High-efficiency motors and equipment

Simple payback periods for the five projects ranged from 7 months to 2.7 years (LBNL Applications Team, 2002).

A 2010 featured ASHRAE journal article called “Cleanroom Energy Efficiency” discusses several best-practice measures to lower cleanroom energy consumption. Cleanrooms are pressurized with respect to surrounding spaces, but the authors recommend using minimum acceptable room pressurization to reduce the static pressure requirements in the supply fans. Figure 3 shows LBNL cleanroom benchmarking data for space pressurization.

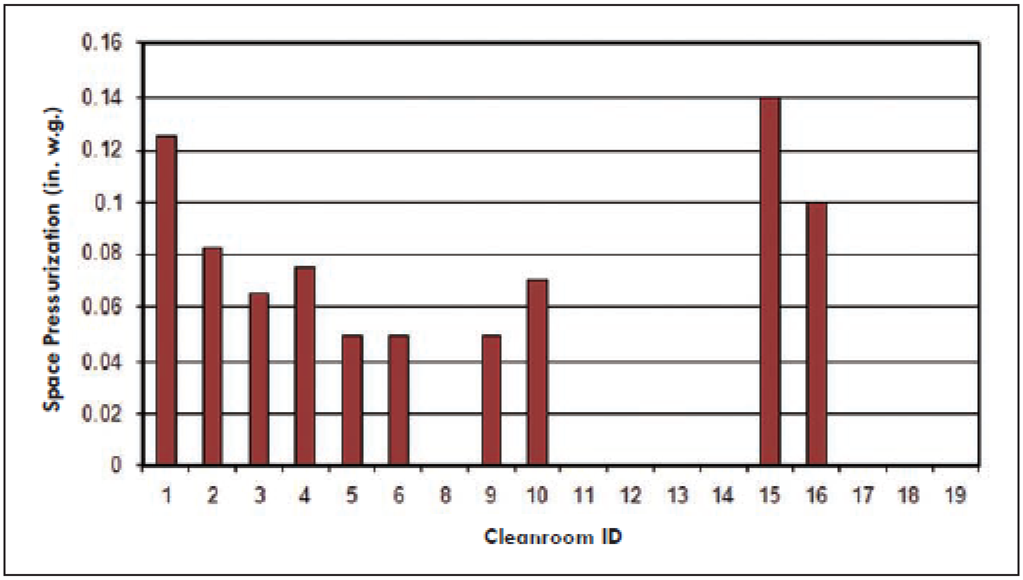


Figure 3: LBNL cleanroom benchmarking pressurization data

The ASHRAE article also notes that temperature and humidity are often kept within a tight band, which requires significant energy use. Cleanroom operators should question whether the facility requires such tight tolerances. Figure 4 and Figure 5 display measured and designed temperature and humidity values during the LBNL benchmarking study. In addition, the authors of the article recommend optimizing recirculated airflow to maintain air cleanliness requirements. Air change rates vary significantly among cleanrooms with the same classifications, and individual recirculation requirements are building-specific, depending on contamination rates, which are usually not understood in the design phase. Finally, the authors recommend installing high efficiency HVAC systems for cleanrooms (Matthew, 2010).

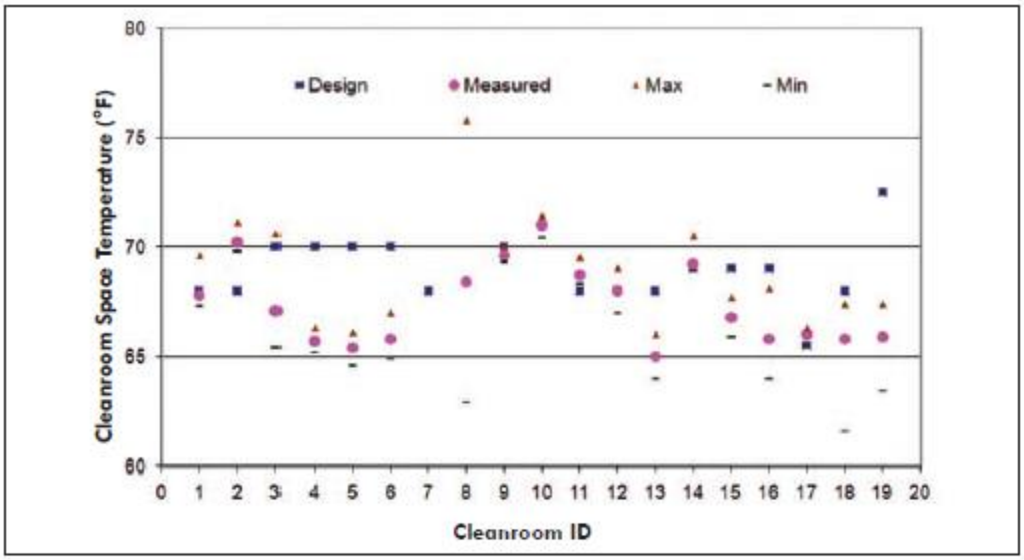


Figure 4: LBNL cleanroom benchmarking temperature data

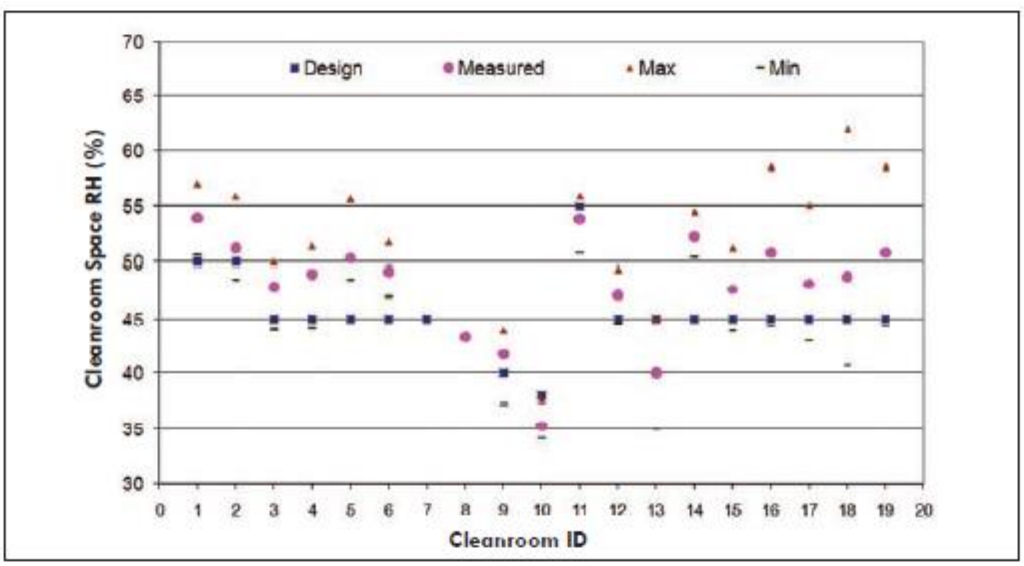


Figure 5: LBNL cleanroom benchmarking temperature data

In January 2011 Pacific Gas and Electric Company (PG&E) published a design guideline for high-performance cleanrooms. The document discussed principles, approaches to design, and benchmarking/case studies for various design topics including air change rates, demand-controlled filtration, dual-temperature chilled water loops, exhaust optimization, fan-filter units, low pressure-drop air systems, mini-environments, HVAC air systems, vacuum pump optimization, water-side free cooling, and deionized water generation and usage reduction (Pacific Gas and Electric Co., 2011).

In 2010, Kircher et al. at Cornell University completed a project in which they modeled the energy consumption in a university cleanroom along with four energy reduction measures using TRNSYS software. Three of the measures were proposed for 14.9% energy savings accounting for $164,000 per year. The three measures included exhaust air energy recovery (11.4%), improved lighting controls (0.3%), and demand-controlled filtration (4.4%). Solar preheating of desiccant dehumidifier regeneration air was also modeled but resulted in a long payback period. Figure 6 displays the energy savings summary from the Cornell cleanroom study (Kircher, 2010).

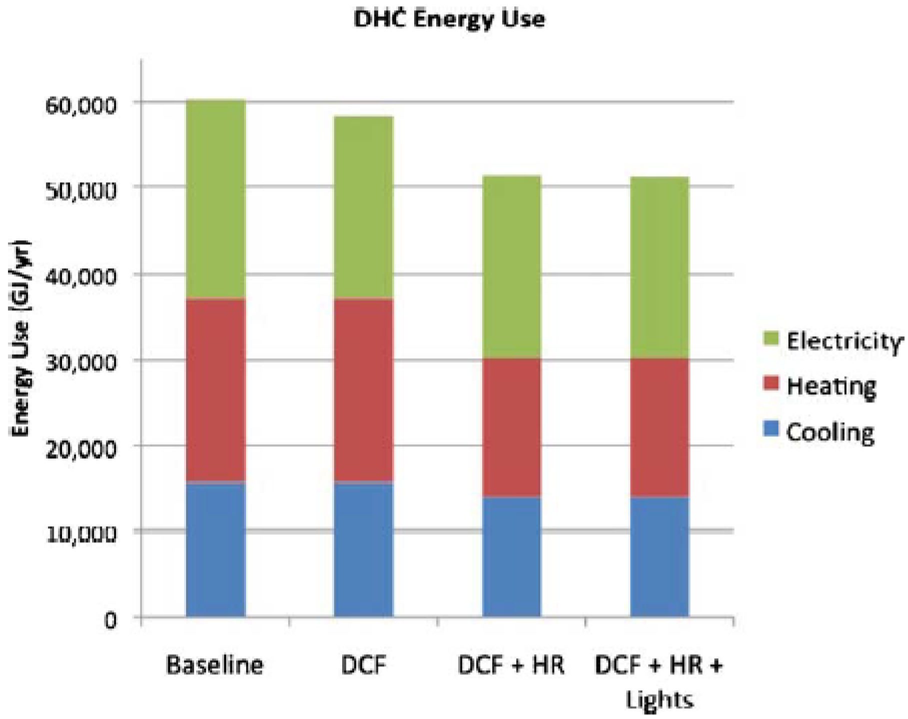


Figure 6: Cornell University cleanroom energy savings summary

Chapter 3: Facility Description

3.1 Facility Overview

The University of Maryland's Jeong H. Kim Engineering Building (Bldg. 225) was designed as a state-of-the-art research and education center. It houses laboratories for advanced study in many engineering disciplines ranging from microelectronics to intelligent transportation systems and contains the university's Nanocenter Fabrication Laboratory (FabLab). Construction was completed in 2007 (Clark Construction Group, 2007), and the building has a replacement value of $87,235,586 (UMD Facilities Management). It is a four-story facility with a gross floor area of approximately 166,000 ft^2 and a net assignable floor area (occupied area) of 95,700 ft^2.

The KEB provides classrooms and seminar rooms for academic classes and discussion, offices for faculty, staff, and graduate students, and laboratories for research. The building is also home to class 1,000 and class 100,000 cleanroom spaces for nanoscale and microscale lab work and fabrication.

The facility was designed and constructed in three phases. The initial phase, referred to as Phase I in this report, includes the main east and west sections of the building, the south wing of the first floor, and the south corridors on the second floor. The second phase, referred to as the Fischell Addition in this report, includes labs and offices in the south wing of the second floor. The final stage of the project, referred to as the Cleanrooms in this report, includes the cleanrooms and supporting spaces, all located in the south wing. A floor plan of the first level of KEB obtained from the UMD facilities management website is shown in Figure 7 (UMD Facilities Management).

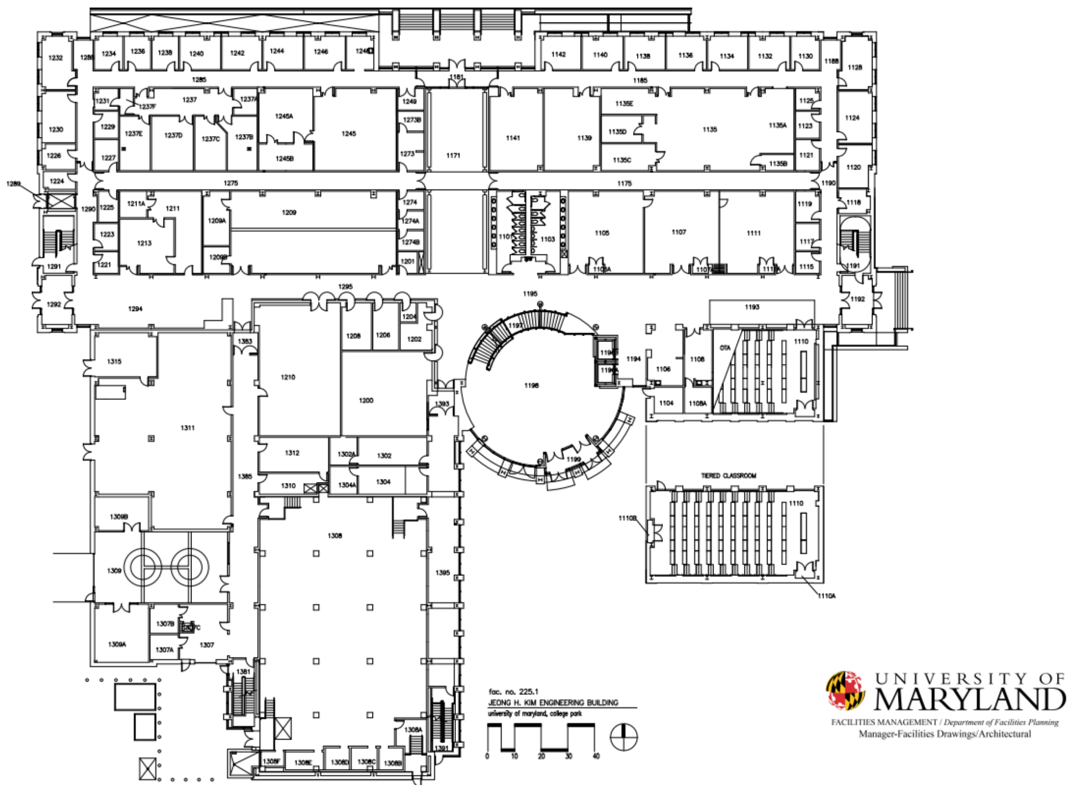


Figure 7: First level floor plan of KEB

The northern, exterior sections of all three floors are lined with faculty and graduate student offices. Labs are typically located in the interior of the floor plan with exceptions in the south wing. The cleanroom and its supporting spaces are located in the east side of the south wing. There is a significant number of public and common areas in the KEB including the atrium, hallways, lounges, and the "Engineering Hall of Fame."

The KEB doors are open from 6:30 am to 8:00 pm Sunday through Saturday. As an academic building, the facility is typically occupied during most hours of the night by faculty and students. Due to the irregular and unpredictable occupancy, the building was designed for constant operating conditions at all times.

3.1.1 Cleanrooms

A cleanroom is a highly controlled critical environment where the number of airborne particles or contaminants is kept to a preset maximum. Different cleanroom classes exist to dictate the air cleanliness inside the space. The KEB's cleanrooms follow the U.S. General Service Administration's standards (FS209E). The International Standards Organization (ISO) also developed its own cleanroom classification system, which is used more prevalently today. It is expected that the ISO Standard 14644-1will replace FS209E completely within a few years. A summary of the cleanroom standards is shown in Table 1 (Terra Universal Critical Environment Solutions, 1999). Although the standard systems are not identical, ISO standards can be approximated to coincide with those of the English standard system.

Table 1: Cleanroom particle concentration standards

Standards		Paricles / ft^3					
English Class	ISO Class	0.1 um	0.2 um	0.3 um	0.5 um	1.0 um	5.0 um
Class 1	ISO 3	28.3	6.7	2.9	1.0	NA	NA
Class 10	ISO 4	283	67	29	10	2.4	NA
Class 100	ISO 5	2,830	670	290	100	24	0.83
Class 1,000	ISO 6	28,300	6,700	2,900	1,000	240	8.3
Class 10,000	ISO 7	283,000	67,000	29,000	10,000	2,400	83
Class 100,000	ISO 8	NA	NA	290,000	100,000	24,000	830
Class 1,000,000	ISO 9	NA	NA	NA	NA	240,000	8,300

The KEB houses a 6,100 ft^2 class 1,000 cleanroom, a 170 ft^2 class 10,000 cleanroom, and a 4,030 ft^2 class 100,000 cleanroom. The HVAC system was designed to filter the air enough to maintain particle counts below the standards at all times. Specifics about the KEB's cleanrooms are discussed in the sections to follow.

3.2 Lighting and Architecture

Space lighting in the KEB is primarily composed of Philips U-Bent Rapid Start T8, 32W recessed fluorescent lamps. This is the same lamp that was installed during construction of the building. Upon inspection, it was determined that most offices contain lighting occupancy controls to save electricity when unoccupied. The three-story rotunda was designed to utilize daylighting controls to save electricity during the day. Maximum lighting densities for various space types in the KEB were calculated using original electrical design documents and are shown in Table 2.

Table 2: Lighting densities of various KEB space types

Space Type	Lighting Density (W/ft^2)
Grad/Fac Office	0.89
Rotunda	0.83
Corridor	1.00
Sub Fab	NA
Cleanroom	NA
Computer Lab	0.87
Gen Office	1.30
Lab	1.75
Elec/Telecom/Mech	0.80
Storage	0.70
Classroom/Conference	1.52
IT Room	0.92

Architectural design documents show varying construction types throughout the building. The KEB was originally designed as a learning tool for students and thus contains many different architectural aspects. For example, some windows are single pane and some are double pane. Moreover, there are different window glazings in different sections of the building. Although not all walls, ceilings, and roofs were constructed the same, they are summarized in Table 3 using the design documents.

Table 3: KEB construction types

Constructions		
Construction Name	Material	Thickness (in)
External Wall	Brick	3.625
	Air Space	1.875
	Rigid Insulation	1.500
	CMU (cont moisture barrier)	8.000
	Batt Insulation (~R5 / in)	2.000
	Gypsum Wall Board	0.500
Ceiling/Floor	Acoustic Ceiling Panels	0.750
	Steel Deck	1.000
	Concrete Slab	4.000
	Tile	0.125
Internal Wall	Gypsum Wall Board	0.500
	Sound Attenuation Blanket	2.000
	Gypsum Wall Board	0.500
Roof	Ballast	1.000
	Built-Up Roofing	NA
	Tapered Insulation	1.500
	Steel Deck	1.000

3.3 Heating, Ventilation, and Air Conditioning

3.3.1 Energy Sources

The KEB consumes energy from three utilities: electricity, steam, and chilled water. Electricity is widely used throughout the building for many purposes including lighting, motors (fans, pumps, and compressors), computers and IT equipment, laboratory equipment, and various other plug loads. Steam is received from the campus cogeneration plant and is used for steam heating coils, humidification clean steam generation, heating hot water heating, domestic hot water heating, and laboratory equipment cleaning. Steam leaves the plant and is supplied to the UMD campus at saturated conditions at a pressure of 115 psi before it is reduced to medium and low pressure steam (Edwards, 2012).

The KEB chilled water (CHW) system is a closed loop system that is cooled at a heat exchanger within the satellite central utilities building (SCUB) located across the street from the KEB. The SCUB houses water-cooled absorption chillers that utilize the campus steam system. The KEB CHW is cooled down to a design temperature of 42°F and is used solely for cooling coils within the facility.

3.3.2 HVAC Overview

The KEB generally uses variable air volume (VAV) and constant temperature HVAC systems. In VAV systems, the supply and return fan motors are controlled by variable frequency drives (VFD) to automatically adjust flow rates based on building load. The VAV systems use VAV terminal boxes (also referred to as Volume Control Boxes) towards the end of supply duct lines to individually control supply air flow rate and temperature for each thermal zone. Figure 8 shows a schematic of a VAV terminal box from the original design documents serving multiple office spaces.

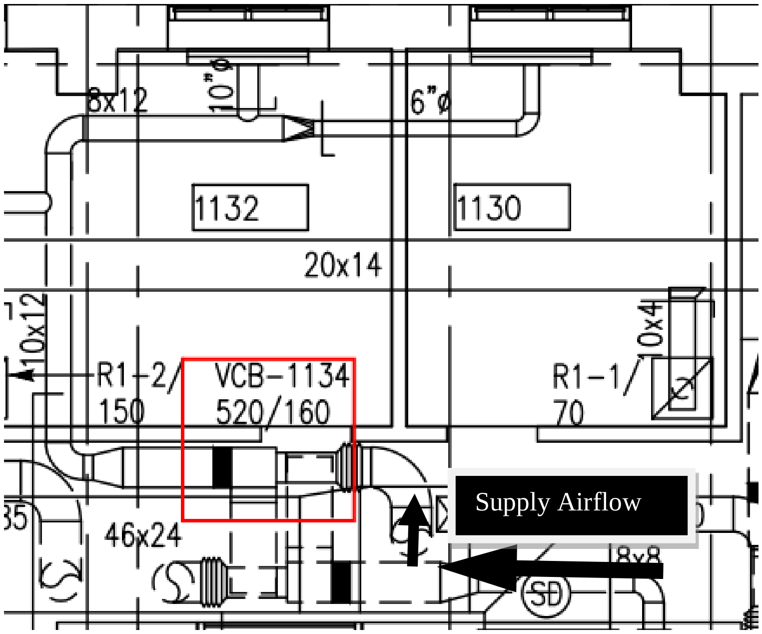


Figure 8: VAV terminal box (VCB) serving multiple offices

The VAV terminal boxes contain an air damper and actuator that controls the air supply and hot water reheat coils. Reheat at the zone-level is necessary due to the constant air handler unit (AHU) supply air temperature (SAT) of 55°F. A thermal zone may consist of multiple rooms with similar space loads and setpoints, but it is controlled by one thermostat. There are approximately 165 thermal zones in the KEB.

3.3.3 Phase I

Phase I represents the main east and west wings of the building, the first floor in the south wing, and the corridors on the second floor of the south wing. The east and west wings are primarily conditioned by four AHUs in the mechanical penthouse. Two of these units supply the east wing of the building via a common duct system and two supply the west wing of the building through a single supply duct. Each of these AHUs contains a heat recovery coil, steam preheat coil, steam humidifier, CHW cooling coil, two supply fans in parallel, one return fan, and three filters. Figure 9 displays a schematic of AHU-1 and AHU-2, which serve the west wing. AHU-3 and AHU-4 are almost identical and serve the east wing of the KEB. To utilize outdoor air conditions, an economizer mode is available in all four AHUs when the outside air (OA) enthalpy is lower than the mixed air enthalpy.

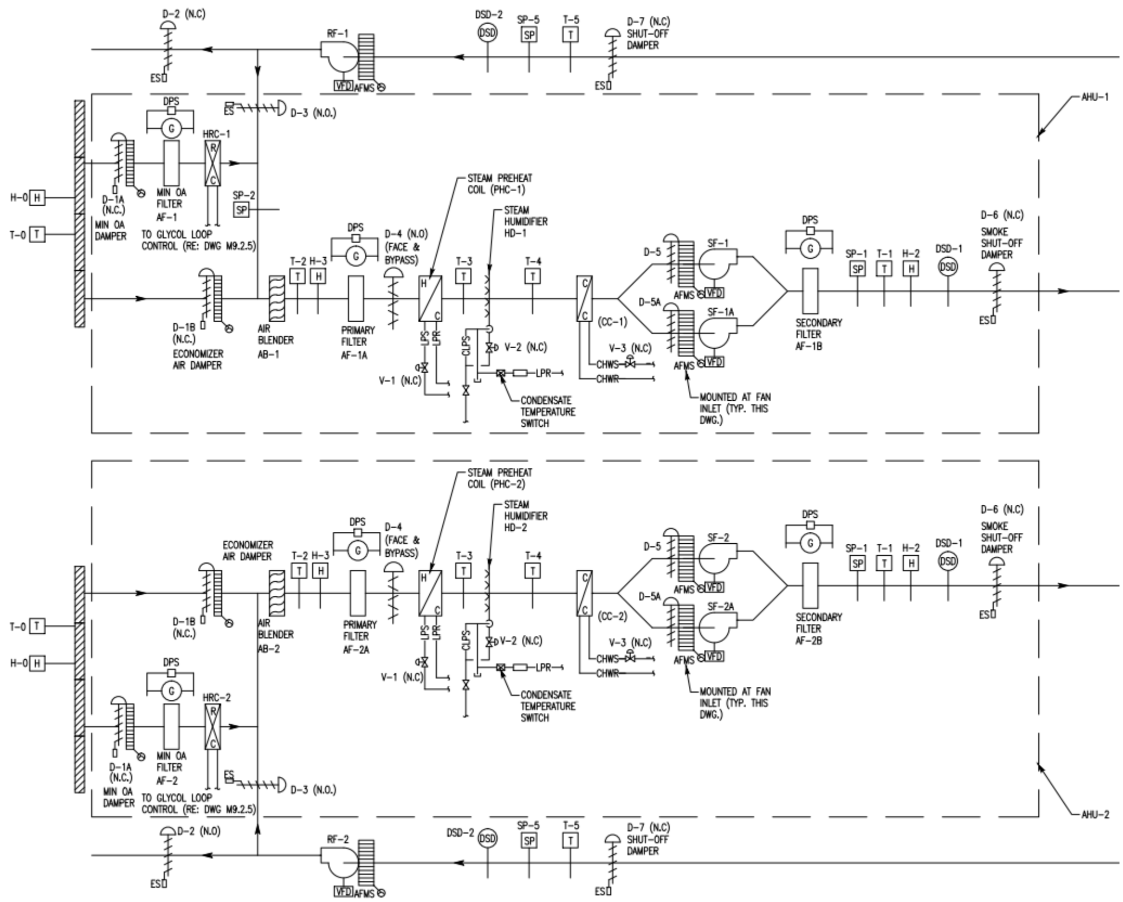


Figure 9: AHU-1 and AHU-2 controls schematic

The main mechanical room and aforementioned sections of the south wing are each served by one AHU (AHU-6 and AHU-5, respectively). The mechanical room is heated only and uses 100% outside air in the supply stream. AHU-5 is similar to AHUs 1-4, but has less capacity, only contains one supply fan, and has no heating coil. Both of these systems are located in the main mechanical room on the first floor.

Phase I also contains small unoccupied spaces that require cooling. They are conditioned by individual fan coil units (FCUs) and are not served by the AHUs. The FCUs contain a fan and CHW coil and typically only use recirculated air. KEB stairwells are heated but not cooled. Moreover, there are select spaces in the KEB that do not require heating or cooling, such as maintenance storage rooms.

3.3.4 Fischell Addition

The Fischell Addition is served by a single AHU located on the west side of the roof (AHU-7). It uses 100% outside air in its supply stream and contains a run-around heat recovery loop from the Fischell Addition lab exhaust air. AHU-7 houses a glycol heat recovery coil, steam heating coil, steam humidifier, cooling coil, supply fan, and two filters. This unit serves Fischell Addition offices and laboratories.

3.3.5 Cleanrooms

The KEB cleanrooms are served by a series of systems in the cleanroom mechanical penthouse, located directly above them. Due to the process requirements in these spaces, significant filtration and conditioning of makeup air and return air must occur before being sent into the cleanrooms. The year-round setpoint temperature and relative humidity in the cleanrooms are approximately 67°F and 45%, respectively. Although six of seven cleanroom AHUs were designed and installed with VFDs, they are set to operate at constant operating conditions below capacity at all times.

There are three dedicated makeup air handling units (MAHs) that serve the cleanrooms. MAH-1 and MAH-2 serve the class 1,000, 10,000, and 100,000 spaces. They filter, heat, cool, humidify, and dehumidify makeup air before mixing with return air from the cleanrooms. MAH-3 serves the "SubFab," a large room located beneath the cleanrooms that house supporting process equipment. There is no return air in the SubFab. Hence supply air is 100% outside air. There are also four recirculating air handling units (RAHs) that filter and cool a mixture of makeup air from the MAHs with return air from the cleanrooms before sending it back into the cleanrooms. The class 1,000 cleanroom is fed by RAH-1, RAH-2, and RAH-3. It is surrounded by a plenum where the supply air is sent. Fan-powered HEPA filter units located on the ceiling draw air into the cleanroom from the plenum. In the class 100,000 cleanroom, air is sent directly from RAH-4 into the spaces via ceiling filter units. Figure 10 shows a cross-sectional schematic of a typical cleanroom HVAC system's airflow (Schneider, 2001). Figure 11 shows a schematic of the seven AHUs that serve the KEB cleanrooms.

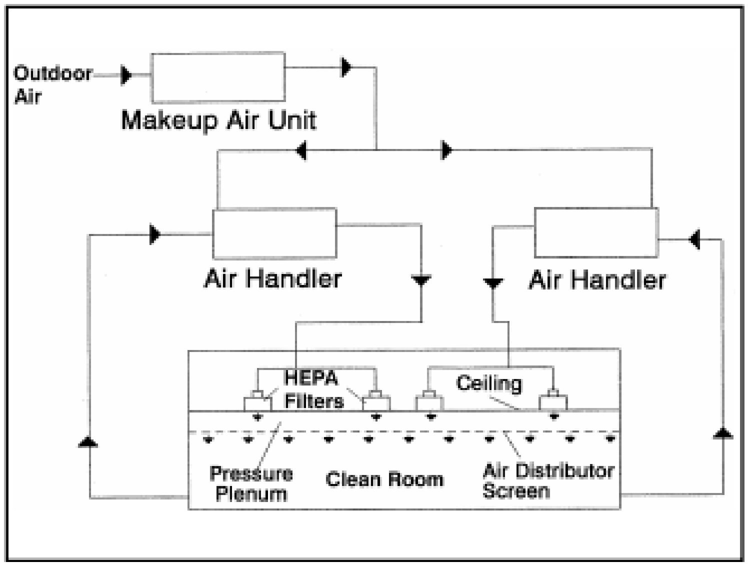


Figure 10: Typical cleanroom HVAC airflow diagram

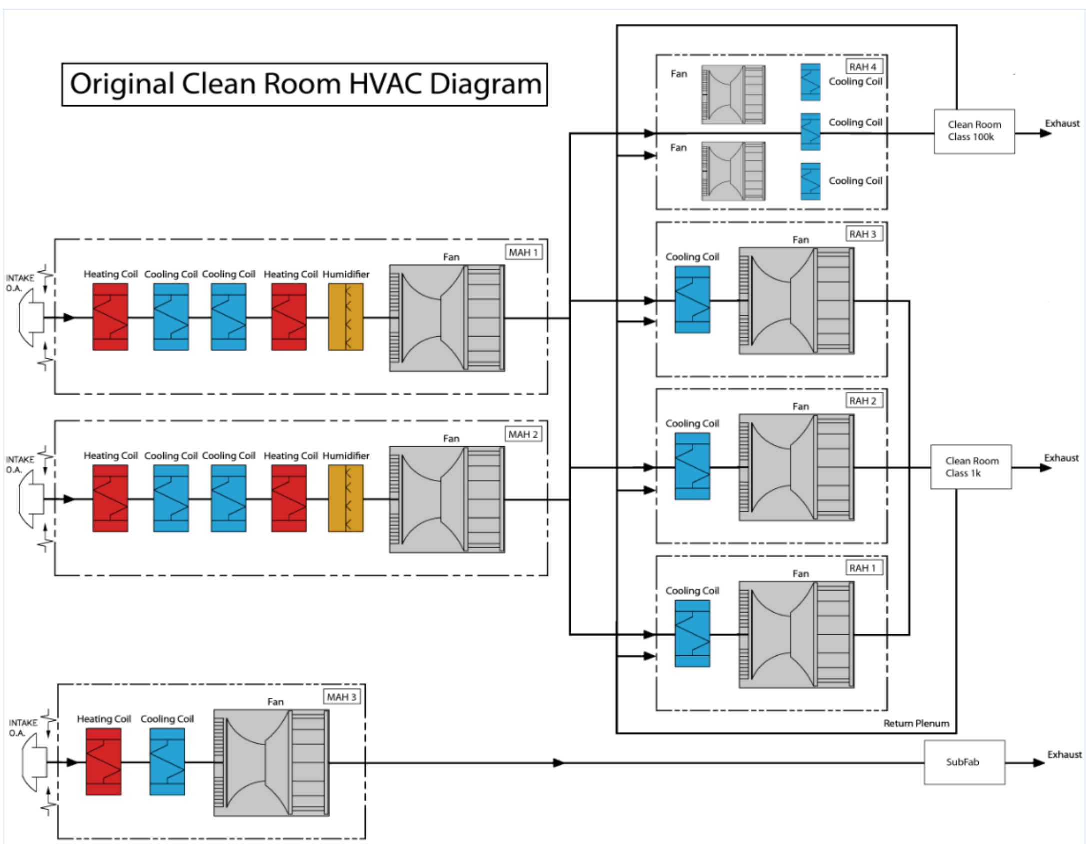


Figure 11: KEB cleanroom HVAC airflow diagram

3.3.6 HVAC Specification Summary

Altogether, there are 14 AHUs that serve the KEB in addition to many unitary systems that condition single rooms. Table 4 and Table 5 summarize the technical specifications for all central air systems in the KEB. It should be noted that these represent equipment capacities and *not* operating conditions.

Table 4: Specification summary for AHUs in Phase I and Fischell Addition

Phase I + Fischell Addition	AHU-1	AHU-2	AHU-3	AHU-4	AHU-5	AHU-6	AHU-7
Location	West Penthouse		East Penthouse		Main Mech Rm		West Roof
Service Area	West fl 1,2,3		East fl 1,2,3		South fl 1,2	Main Mech Rm	South fl 2
System Type	VAV with reheat					Const Volume	VAV with reheat
VFDs	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Heat Recovery Coil	Yes	Yes	Yes	Yes	No	No	Yes
Maximum CFM	34,700	34,700	34,200	34,200	11,200	3,000	15,000
Minimum Outside Air	14,700	14,700	18,200	18,200	2,240	3,000	15,000
Total Static Pressure (in wc)	8.0	8.0	8.0	8.0	5.8	2.0	7.3
Total Supply Fan HP	80	80	80	80	15	5	30
Return Fan HP	20	20	15	15	7.5	-	-
CHW Cooling Capacity (MBH)	2,025	2,025	2,350	2,350	450	-	1,395
Steam Heating Capacity (MBH)	465	465	900	900	-	178	970

Table 5: Specification summary for AHUs in Phase I and Fischell Addition

Clean Rooms	MAH-1	MAH-2	MAH-3	RAH-1	RAH-2	RAH-3	RAH-4
Location	CR Mech	CR Mech	Sub Fab	CR Mech	CR Mech	CR Mech	CR Mech
Service Area	CR Class 1k and 100k		Sub Fab	CR Class 1k			CR Class 100k
Fan Motor VFD	Yes	Yes	No	Yes	Yes	Yes	Yes
Heat Recovery Coil	No	No	No	No	No	No	No
Supply Air (CFM)	28,000	28,000	6,500	24,000	24,000	24,000	28,000
Total Static Pressure (in wc)	5.9	5.9	2.4	2	2	2	2.5
Fan BHP (HP)	44.8	44.8	5.1	12.5	12.5	12.5	8.3
CHW Cooling Capacity (MBH)	2,613	2,613	495	440	440	440	356
LT CHW Cooling Capacity (MBH)	396	396	-	-	-	-	-
Steam Heating Capacity (MBH)	1,834	1,834	-	-	-	-	-
Hot Water Heating Capacity (MBH)	695	695	550	-	-	-	-

Chapter 4: Methodology

An organized task flow is required for any energy analysis or energy audit project. Figure 12 displays an energy audit flow chart that represents the task flow for the KEB project. Energy model development and refining consume the largest portion of time. Although data collection is listed as one of the first tasks, it is a process that does not end until the project is complete.

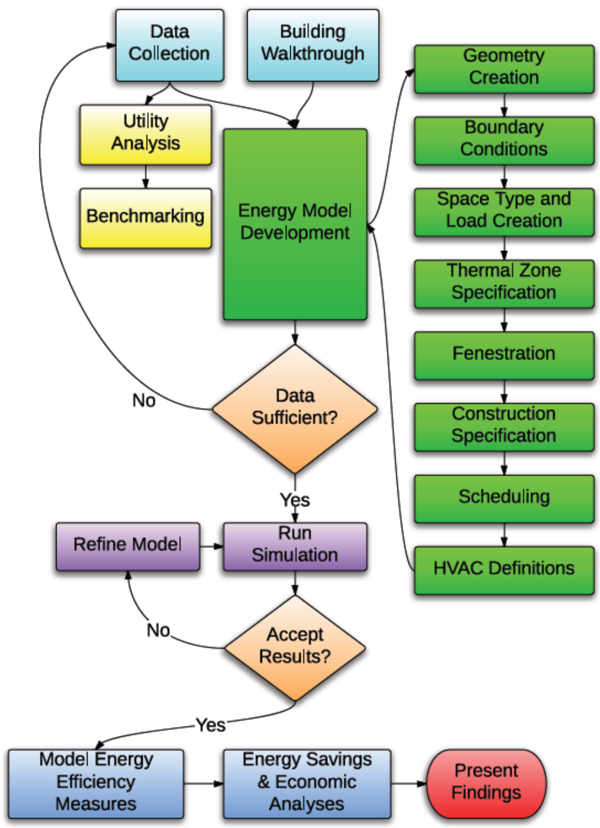


Figure 12: KEB energy analysis project flow chart

4.1 Building Walkthrough and Information Gathering

Perhaps the most important step in the project was the first one. A building walkthrough was conducted alongside the building operator, facilities management personnel, and building designers. The walkthrough provided a first-hand look at all building spaces and equipment that are not available to the public. Moreover, it aided in establishing a relationship with the individuals that would play an essential role in providing information needed to successfully complete the project.

Due to the complexity of the KEB's geometry and layout, space use, HVAC systems, and operation, large amounts of data and information were required to accurately model it. The building engineer provided hard copies of original architectural, mechanical, electrical, and plumbing (MEP) design documents for all sections of the building except cleanrooms. Facilities management provided a limited amount of architectural and MEP design documents in PDF format, which aided greatly in understanding floor plan dimensions. The UMD sustainability office contributed building meter data along with utility rates. In addition, view-only access to the building management systems (BMS) was granted about halfway through the project in order to gain a higher understanding of building operation and associated deficiencies. Many different people offered a variety of resources that together, allowed for nearly complete facility understanding.

4.2 Baseline Energy Model Development

Most of the beginning phases of energy model development were done using Trimble SketchUp and OpenStudio. The energy model was then passed to E+ for the higher-level tasks, with some overlap between these phases.

SketchUp and the OpenStudio plug-in were used in the initial phases of energy model development to create the KEB geometry. The complexity of the model's building geometry was adjusted numerous times to avoid extensive simulation run-time. Space types, thermal zones, and building stories were easily assigned using the OpenStudio plug-in. The OpenStudio user interface was then used to define space loads, schedules, constructions, thermostats, plant loops, and basic HVAC loops.

Extensive energy modeling in the E+ IDF editor and text mode was completed towards the later phases of the project. For example, the entire cleanroom HVAC system (including controls) was built from scratch in E+. The uniqueness of the system required lengthy development, and the resulting file was added to the master file in E+ text mode. Energy runtime language (ERL) and higher level control strategies, variable reporting, plant adjustment, heat recovery, and secondary HVAC systems were also implemented in the energy model in the E+ environment.

Data reduction and results viewing is a crucial part of any energy modeling project. Due to the volume of simulations run for this project, it was important to expedite the analysis of each simulation's results. All results were exported to and viewed in Microsoft Excel. To verify proper functioning of all controls networks and HVAC systems, many variables were reported in Excel on an hourly basis. This process was essential in verifying that the energy model properly mirrored KEB operation. For each simulation the *AllSummaryAndMonthly* summary report was outputted as an Excel file. It was then copied and pasted into a preformatted Excel workbook prepared to process the data into tables and charts that were easy to understand. This streamlined the results analysis process in order to focus more time on energy modeling activities.

4.3 Energy Efficiency Measures

The EEMs proposed for the KEB are split into two sections. The “As-designed” EEMs are aimed at bringing the operation of the facility back to design conditions. These measures were determined by studying the design documents along with the BMS sensor variables. The goal of the second set of EEMs is to further improve the energy performance of the KEB to a level at least 20% better than current performance. The second set of EEMs was chosen based on literature reviews for commercial buildings and cleanrooms and current KEB operation. Due to the high sensitivity of the cleanroom portion of the energy model, energy savings calculations for the two cleanroom EEMs were performed in Excel and verified using the energy model.

Chapter 5: Utility Analysis

5.1 Historical Energy Consumption

The first step in understanding effective ways to reduce a building's energy consumption is to complete a utility analysis to determine how it currently uses energy and to what extent. Historical energy consumption provides insight into each utility's monthly usage profiles, relative energy consumption, and associated costs. Utility bills from 2010 to 2012 were plotted for electricity, steam, and chilled water and are shown in Figure 13 through Figure 15.

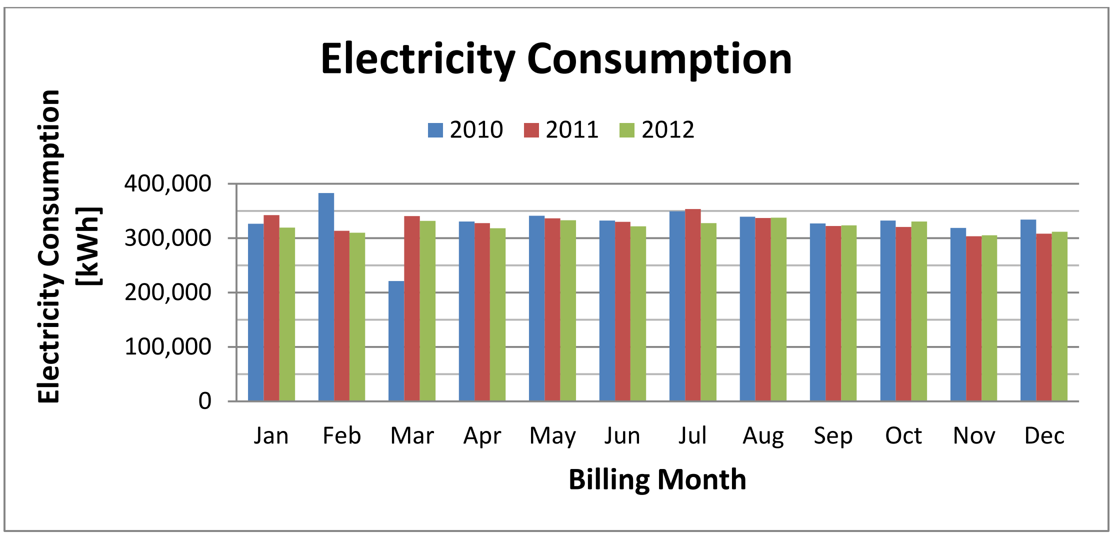


Figure 13: KEB electricity consumption from 2010-2012

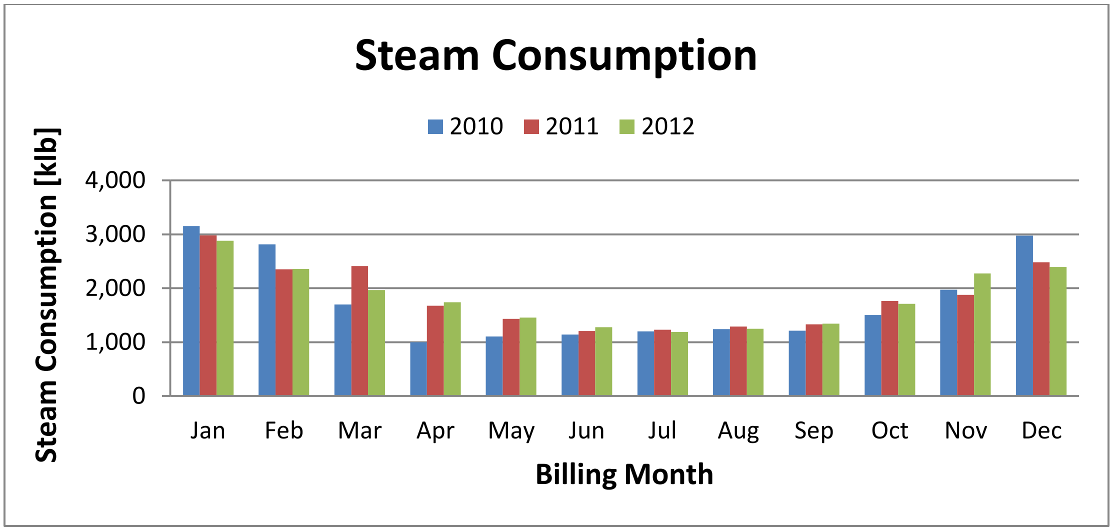


Figure 14: KEB steam consumption from 2010-2012

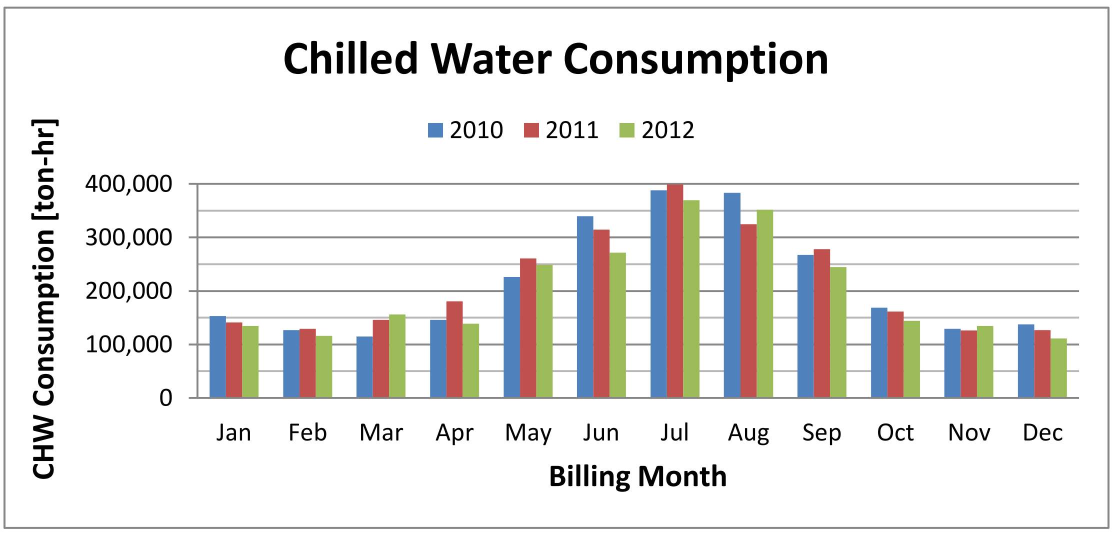


Figure 15: KEB chilled water energy consumption from 2010-2012

Electric consumption shows to be very consistent throughout the year, implying that it is not used heavily in heating or cooling the building. The electric consumption for each month hovers at about 325,000 kWh for all three years except for two months. Figure 14 shows that the steam consumption is much greater in the winter months, but there is still significant heat energy used during the summer months. This can be attributed to two major end uses. In the cleanrooms, dehumidification of makeup air in the MAHs will often cool the outside air lower than the setpoint temperature. The air must be heated by hot water coils after the dehumidification process. Very strict humidity levels in the cleanrooms will call for consecutive cooling and heating of air in the MAHs. Steam heating during the summer also occurs very often in the VAV terminal boxes throughout the building. Due to the year-round 55^{O}F SAT from the AHUs, reheat of the air must occur before it enters each zone to maintain zone setpoint temperatures. Significant steam use during the *cold* months will also include humidification and steam pre-heating in the AHUs and MAHs. Chilled water consumption shows a contrasting pattern in that more cooling energy is used in the summer months than the winter months, yet there is steady usage of CHW in the winter. The winter CHW cooling energy stems from conflicting control sequences in the AHUs and MAHs which will be described in detail in Chapter 6: Energy Model.

The variability in data for all three utilities between the three years is very low, and the average annual consumption is used to calculate the energy use index (EUI). The EUI represents the annual energy consumption normalized by building gross floor area and is the most commonly used parameter in comparing facility energy consumption. The energy consumption from each utility was converted to the same energy units (kBtu). Conversion from CHW ton-hrs to kBtu is accomplished using the simple relation between the two units (12 kBtu = 1 Ton-hr). To convert pounds of steam measured at the KEB steam meter into energy consumption, the enthalpy of saturated steam at 125 psig was used (Kowal, 2009). The EUI is shown in Table 6.

Table 6: Summary of KEB EUI calculation

Electric Consumption [kBtu]	13,359,210
Steam Consumption [kBtu]	25,836,264
Chilled Water Consumption [kBtu]	30,373,644
Building Floor Area [ft^2]	166,100
Building EUI [$kBtu/ft^2$-yr]	419

Since the KEB obtains most of its energy from the University of Maryland combined heat and power plant (CHP), direct utility rates were not available. Economic analyses in this report use auxiliary utility rates billed to internal KEB customers obtained from UMD's Sustainability Office. They are shown in Table 7.

Table 7: KEB auxiliary utility rates

Utility	Unit	Price per Unit
Electricity	kWh	$0.1127
Steam	lb	$0.0298
Chilled Water	Ton-hr	$0.1600

Figure 16 shows a breakdown of annual energy consumed and costs associated with each utility. The inner ring represents energy consumed and the outer ring represents utility costs. Although cooling accounts for the highest portion of energy use, it represents the smallest portion of utility cost. Electricity has the highest unit utility rate, followed by steam and CHW.

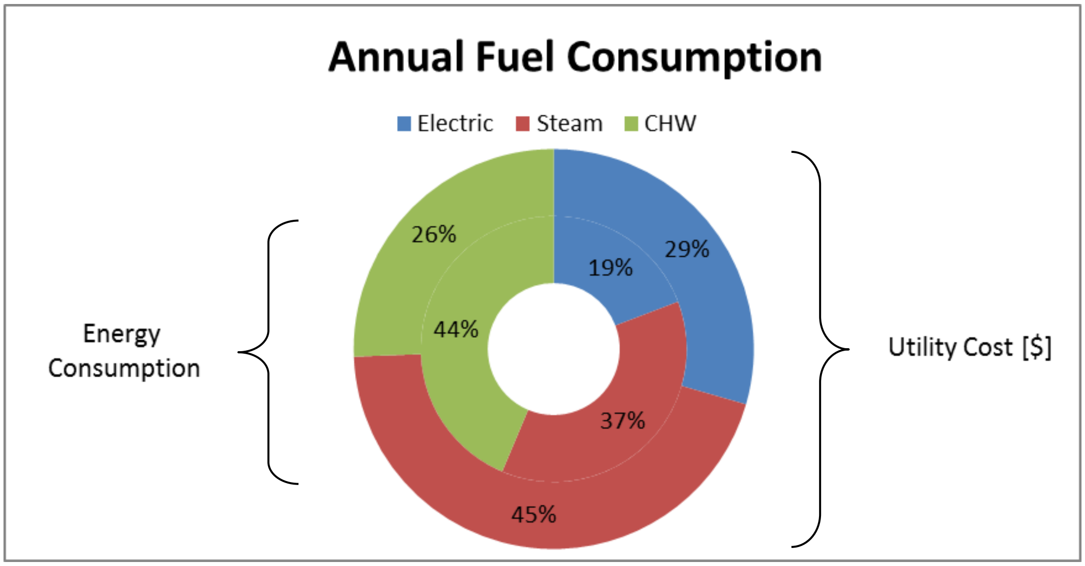


Figure 16: KEB energy consumption and costs associated with each utility

5.2 Benchmarking Study

Benchmarking is the process of developing a comparison between the energy performance of the facility being studied and other buildings with similar characteristics. A strong benchmarking study of any building using appropriate data is a fundamental component to any energy analysis project. It answers the two most basic questions of "How are we doing?" and "How do we know?" The most widely used commercial-scale benchmarking software is the Environmental Protection Agency's ENERGY STAR Portfolio Manager. Due to the unique building activity of the KEB, the Portfolio Manager could not be utilized to its full potential. Rather, data were taken directly from the Commercial Building Energy Consumption Survey (CBECS), the cornerstone of the Portfolio Manager software. CBECS is described in the excerpt from the Energy Information Agency:

> The Commercial Buildings Energy Consumption Survey (CBECS) is a

> national sample survey that collects information on the stock of U.S. commercial buildings, including their energy-related building characteristics and energy usage data (consumption and expenditures). Commercial buildings include all buildings in which at least half of the floor space is used for a purpose that is not residential, industrial, or agricultural. By this definition, CBECS includes building types that might not traditionally be considered commercial, such as schools, hospitals, correctional institutions, and buildings used for religious worship, in addition to traditional commercial buildings such as stores, restaurants, warehouses, and office buildings.

The most recent available CBECS data are from 2003 and include energy consumption information for 5,215 commercial buildings nationwide. The data were filtered three separate times to determine the EUIs of office buildings, laboratories, and public assembly spaces. These building activities most accurately constitute those within the KEB (excluding the cleanrooms). The data were filtered for geographic location, building floor area, year constructed, principle building activity, and capability for heating and cooling. EUI data further than two standard deviations from the mean were assumed to be outliers and deleted from the sample. Table 8 shows the results of the CBECS data reduction.

Table 8: CBECS filtered data benchmarking statistics

Statistic	Office	Public Assembly	Laboratory
Filtered Sample Size	28	62	14
Median EUI (kBtu/ft^2/yr)	98	88	336
Average EUI (kBtu/ft^2/yr)	110	106	334

Due to the small number of labs in the CBECS data, the Lawrence Berkeley National Laboratory's (LBNL) Labs21 (Labs for the 21st Century) benchmarking data were used, which provided an EUI of 357.5 kBtu/ft^2-yr after filtering the data. CBECS does not contain information for cleanroom energy consumption. In a cleanroom benchmarking study conducted by Paul Matthew at LBNL, energy consumption data from a California cleanroom study were scaled using degree days to estimate energy consumption in New York cleanroom. A similar strategy is used in this study to scale the California data using Maryland degree days. California heating degree days (HDD) and cooling degree days (CDD) used in the LBNL were 2,508 and 1,094, respectively (Matthew, 2008). TMY2 weather data for Baltimore were used to approximate the College Park, MD degree days, resulting in 5,027 HDD and 1,269 CDD. The calculation of cleanroom energy consumption is shown in Table 9. It is assumed that fan energy is not affected by outdoor conditions and humidity differences between locations are not accounted for.

Table 9: Interpolation of MD cleanroom energy consumption

Cleanroom Metrics	Cleanroom Class				
	1 and 10	100	1,000	10,000	100,000
Fan Intensity (kBtu/sf-yr)	2,839	2,208	945	314	157
CA Cooling Intensity (kBtu/sf-yr)	386	386	386	386	386
MD Cooling Intensity (kBtu/sf-yr)	447	447	447	447	447
CA Heating Intensity (kBtu/sf-yr)	634	634	634	634	634
MD Heating Intensity (kBtu/sf-yr)	1,271	1,271	1,271	1,271	1,271
MD Total Site Intensity (kBtu/sf-yr)	4,557	3,926	2,663	2,032	1,875

The expected EUI of MD cleanrooms, median EUIs of offices, public assembly spaces, and labs, and respective floor areas of each space type in the cleanroom can be used to determine the overall expected EUI of the KEB, which is 320 kBtu/ft^2-yr. The calculation is summarized in Table 10. The SubFab is included in the Laboratory floor area.

Table 10: Summary of KEB EUI calculation

Principle Building Activity	Square Footage	Percentage of KEB Area	Benchmarking EUI (kBtu/sf-yr)	Benchmarking Energy Consumption (kBtu)
Office	50,800	31%	97.7	4.96E+06
Laboratory	53,600	32%	357.5	1.92E+07
Public Assembly	51,200	31%	87.8	4.50E+06
Clean Room Class 1k	6,100	4%	2,663.0	1.62E+07
Clean Room Class 100k	4,400	3%	1,875.0	8.25E+06
Sum	166,100	100%		5.31E+07
			Overall EUI (kBtu/sf-yr)	**320**

It should be noted that although this value provides a baseline to compare the KEB's energy consumption, there is uncertainty associated with it. Based on the benchmarking analysis the KEB expected EUI is 23.6% lower than the current operational EUI.

Chapter 6: Energy Model

6.1 Baseline Energy Model

6.1.1 Energy Model Overview

The physical representation of the KEB was developed in Trimble SketchUp Make using architectural design documents as reference. Three floors were created, each with a unique floor plan to match those in the building. Window areas were individually calculated for each wall to accurately reflect solar radiation heating loads. The main mechanical penthouse was not included in the model due to very low heating and cooling energy consumption. Internal doors were not included in the model. A graphical representation of the energy model is shown in Figure 17.

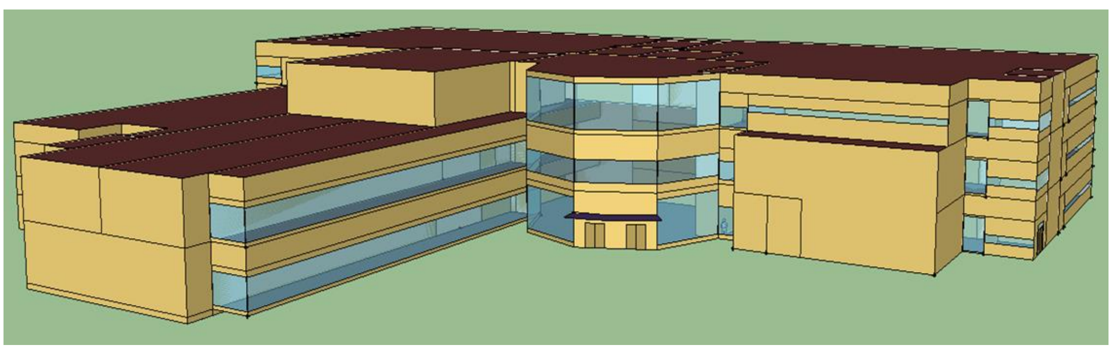


Figure 17: KEB energy model viewed in Trimble SketchUp Make

Due to the complex geometry of the building, slight simplifications were made to reduce simulation run time. To decrease the number of nodes and surfaces, a selection of adjacent spaces were combined if they were of the same space type. For example, three graduate offices on the north side of the building were combined into one larger office since they all have the same internal loads, day lighting characteristics, and similar temperature setpoints. In addition, the atrium was built using an octagonal shape to reduce the number of surfaces. Windows were combined to accurately represent window-to-wall ratios, as shown in Figure 17.

The KEB has approximately 165 thermal zones, each with its own VAV terminal box and thermostat for temperature control. The energy model was simplified to 51 thermal zones, each provided with unique VAV terminal units and thermostat settings. Lighting, plug loads, occupancy, and their associated schedules are defined using space types. These definitions were developed using information from the building walkthroughs, design documents, interviews, personal knowledge, and ASHRAE standards. Twenty-two space types were created and applied in the energy model. Construction was assigned at the building level and applied to the entire model. Figure 18 through Figure 21 display the energy model rendered by boundary condition, construction type, space type, and thermal zone, respectively.

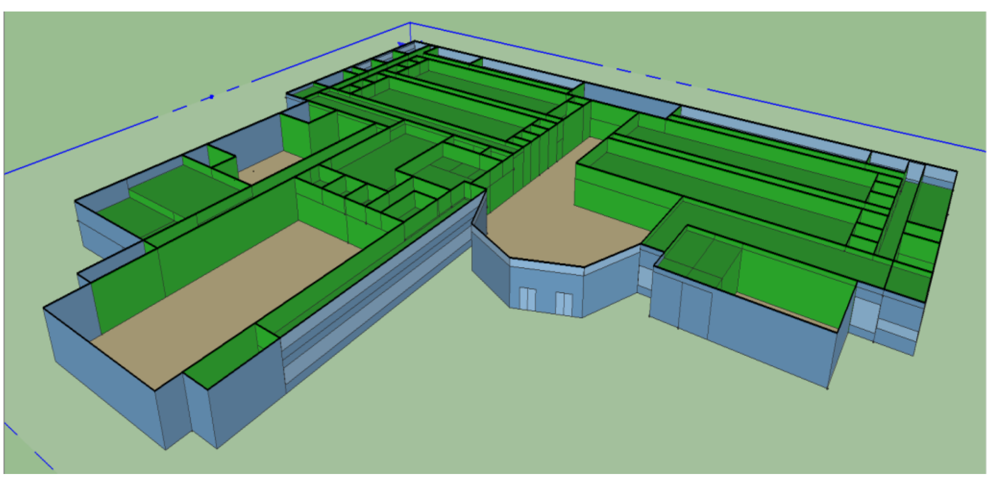


Figure 18: Energy model rendered by boundary condition

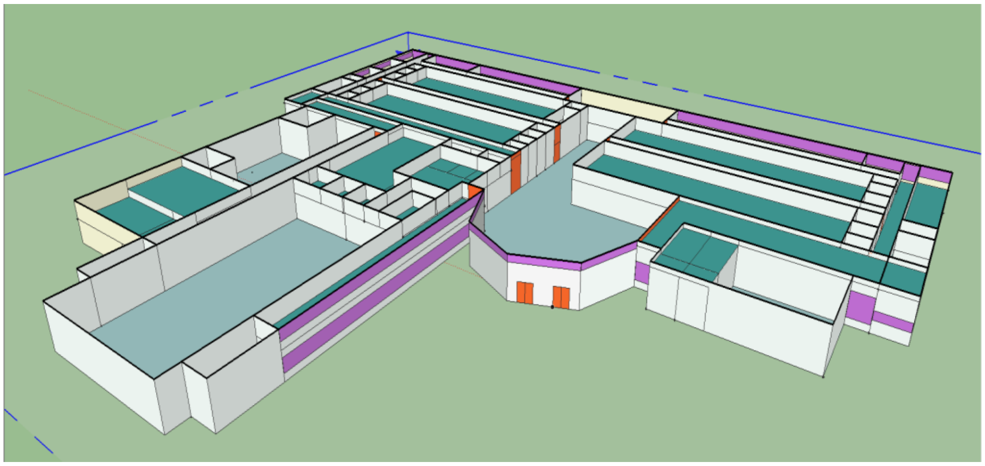


Figure 19: Energy model rendered by construction

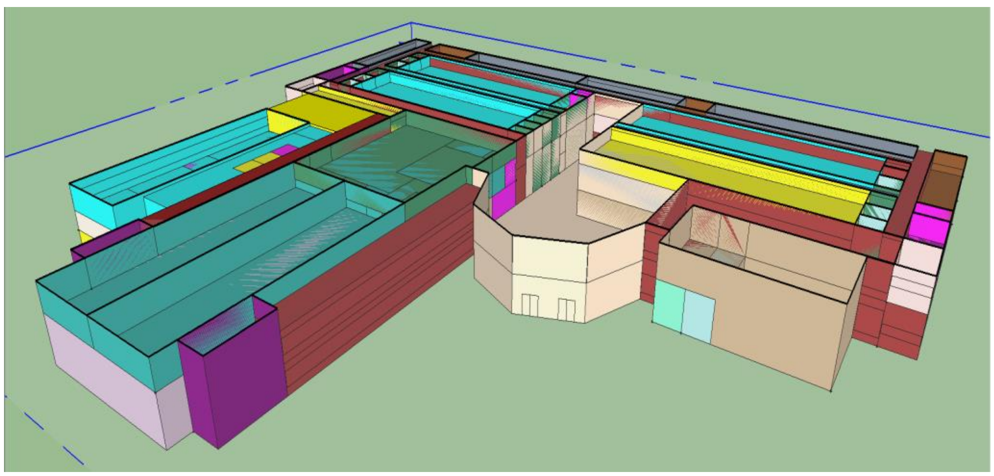


Figure 20: Energy model rendered by space type

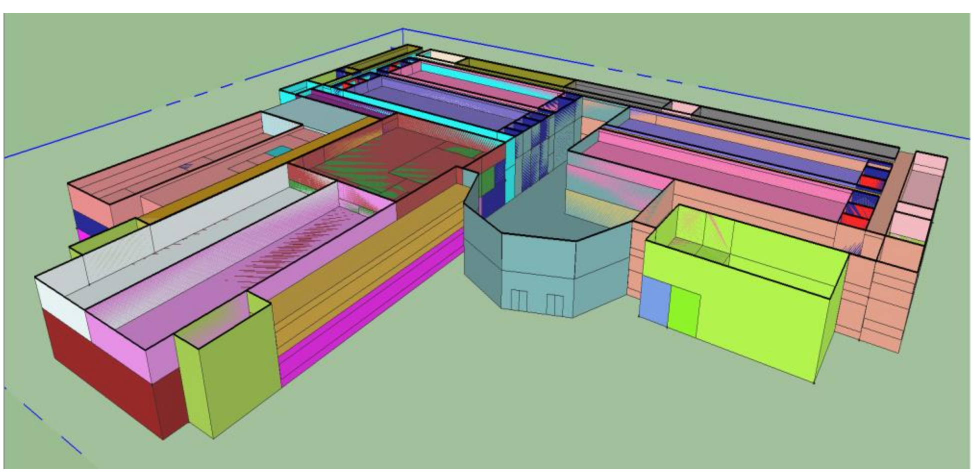


Figure 21: Energy model rendered by thermal zone

6.1.2 Energy Model Validation and Results

A crucial step in developing an energy model is calibrating the baseline model by validating it with real building consumption data. In the case of the KEB, there were only three meters set up at the beginning of the project to represent total building consumption, as discussed in the utility analysis section of the report. The monthly usage of all three utility types was compared to the monthly usage reported in the simulation results to ensure that the energy model was operating the same way that the KEB is currently operating. Figure 22 displays the comparison between utility data and baseline energy model monthly electricity consumption. The model shows a 1.2% annual deviation from the utility bills. Electric equipment space loads were the main inputs that were refined to reach this level of precision between model and reality.

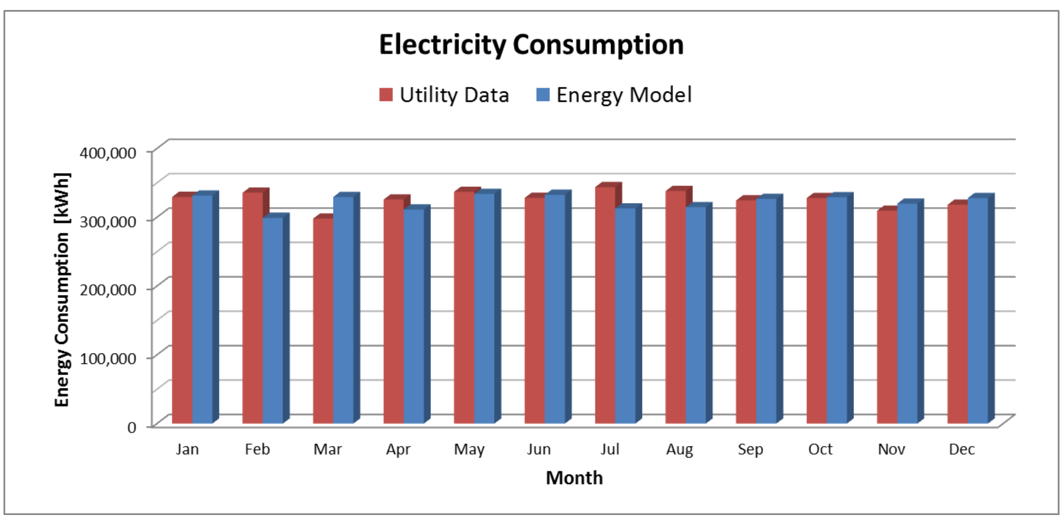


Figure 22: Electricity consumption - utility bills vs. energy model

The cleanroom contains two electric meters that were not running at the start of the project. Data from those meters were logged from December 3rd to January 7th and used to validate the energy model's cleanroom electricity consumption. The upper and lower data points in Figure 23 show the electric demand data from these two meters at 15 minute intervals. The nearly flat data imply constant operating conditions in the KEB cleanrooms. The middle data represent exactly one half of the cleanroom electric consumption in the energy model. Although it does not sit exactly between the metered data, there is less than 10% deviation.

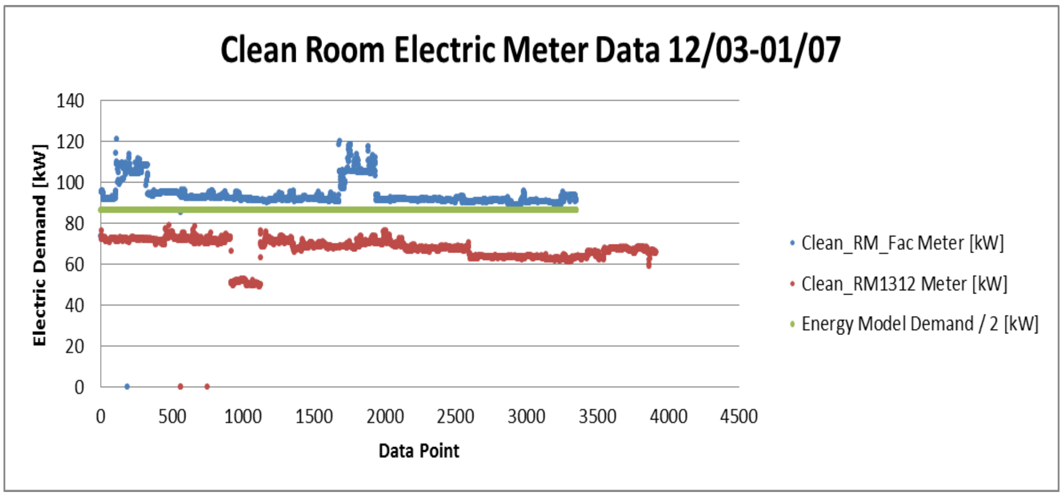


Figure 23: Energy model cleanroom electricity consumption validation

Figure 24 plots monthly utility and energy model steam consumption side by side. Considerable time was spent fine-tuning the energy model to closely match steam consumption with utility data. For example, node by node temperature comparisons were done using E+ variable reporting capabilities and real-time BMS sensor reporting. The large amount of time spent matching consumption between model and reality allowed for a greater understanding of the KEB's operational characteristics, especially its weaknesses. The annual energy model steam consumption deviates

4.3% from utility bills.

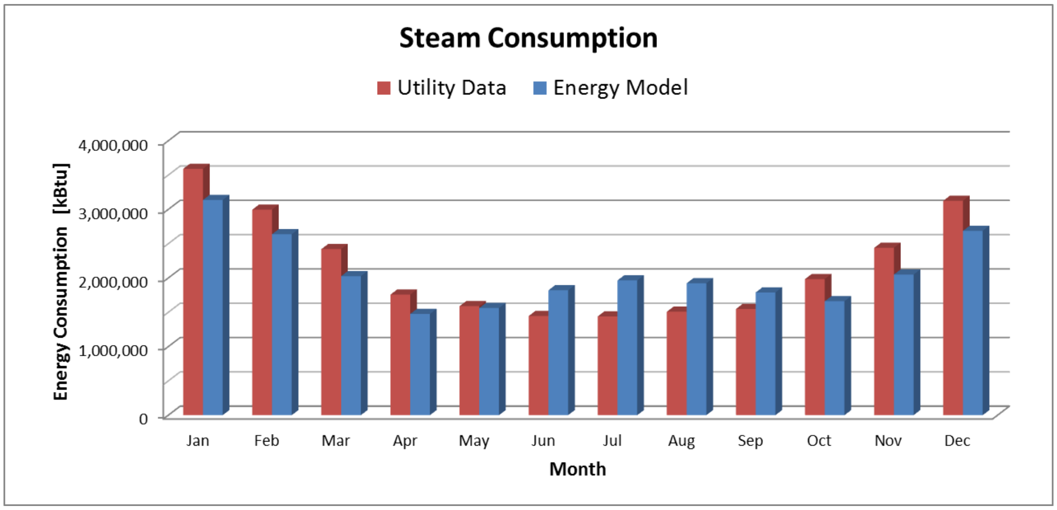


Figure 24: Steam consumption - utility bills vs. energy model

Similarly, the energy model CHW consumption profile did not resemble that of the utility bills until an in-depth study revealed some of the operational flaws of the KEB. For instance, there should be minimal cooling energy used in the winter months, but the utility bills don't reflect that. Once "as is" operation was successfully modeled, the annual deviation from utility bills was reduced to 8.3%. The CHW energy use from the energy model and utility bills are plotted side by side in Figure 25.

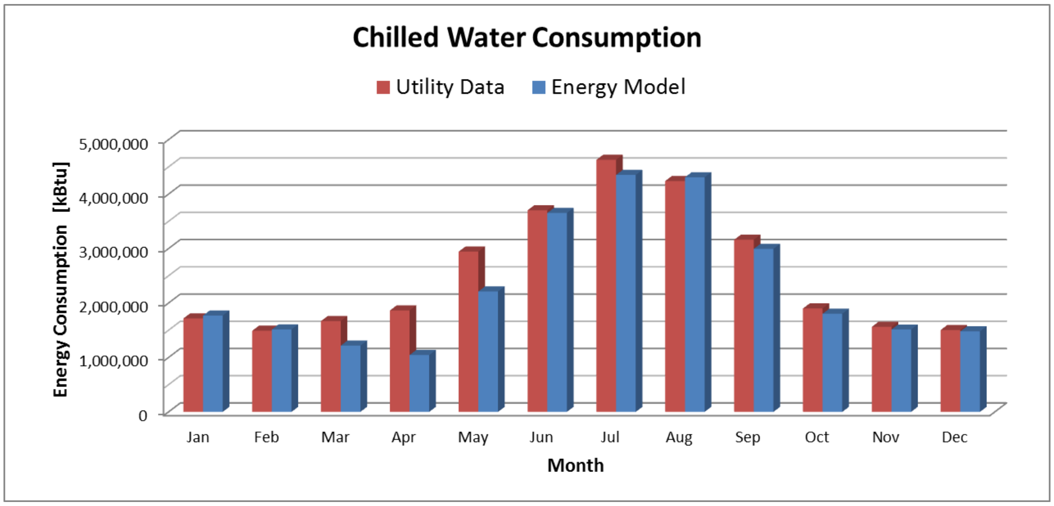


Figure 25: Chilled water energy consumption - utility bills vs. energy model

The annual baseline energy model energy usage for all three utilities results in a 5.4% deviation from the utility bills. Once the baseline energy model calibration was completed, annual consumption by end use reports were created to take a deeper look into the KEB's energy usage. Figure 26 provides an energy usage breakdown for all major building end uses. According to the results, heating and cooling account for nearly 78% of the KEB's energy consumption. According to the Buildings Energy Data Book from the DOE, a typical commercial building only uses 37% for heating and cooling (U.S. DOE, 2012). There are a few primary reasons why the KEB heating and cooling loads differ greatly from a typical office building:

1. The building is always in "occupied mode" and thus unconditioned makeup air is brought into the building and subsequently requires conditioning.

2. The building's zone setpoint temperature schedules don't utilize any setback at night or during the weekends.

3. The cleanroom setpoint temperature and humidity lie within a very narrow band. This often leads to intense dehumidification and reheating of makeup air.

4. AHU controls strategies have been altered from "as-designed" to produce inefficient operating conditions.

As a result of such high heating and cooling energy usage, the percent contributions of the remaining end uses are lower. In a typical office building, lighting accounts for 13.6% of annual energy use (U.S. DOE, 2012). Although the KEB's lighting energy is comparable to an office building, it only accounts for 3.7% due to the heating and cooling demands. Fans account for nearly 11% of the building's energy, interior equipment for almost 5%, and steam to steam humidification for 2.5%. Pump energy accounts for less than 1%. Figure 26 makes it clear that heating and cooling should be targeted when looking for energy savings opportunities in the KEB.

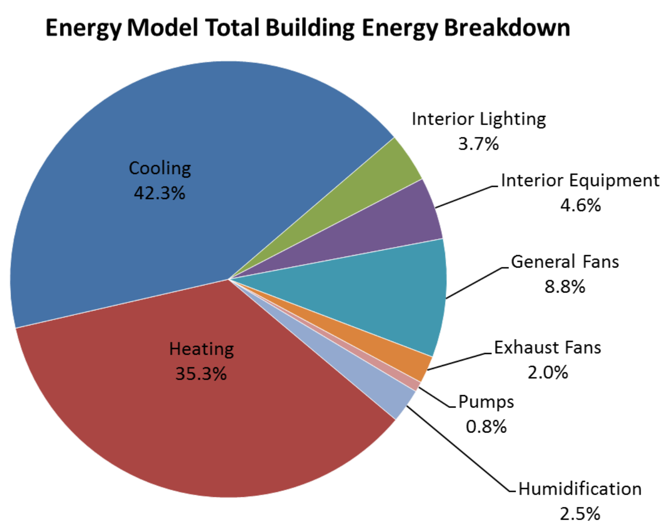


Figure 26: Annual KEB energy consumption by end use

Figure 27 and Figure 28 display a breakdown of heating energy and cooling energy, respectively. Under current KEB operation, nearly half of the heating energy occurs at the VAV box hot water reheat coils. Since the AHU supply air temperatures are 55°F, little heating is actually carried out by the AHU heating coils. The cleanrooms and SubFab contribute to 44% of annual heating energy. In contrast, the Phase I and Fischell Addition AHUs account for 47% of the KEB's cooling energy consumption. The cleanrooms and SubFab account for 52%, and only 1% comes from the FCUs.

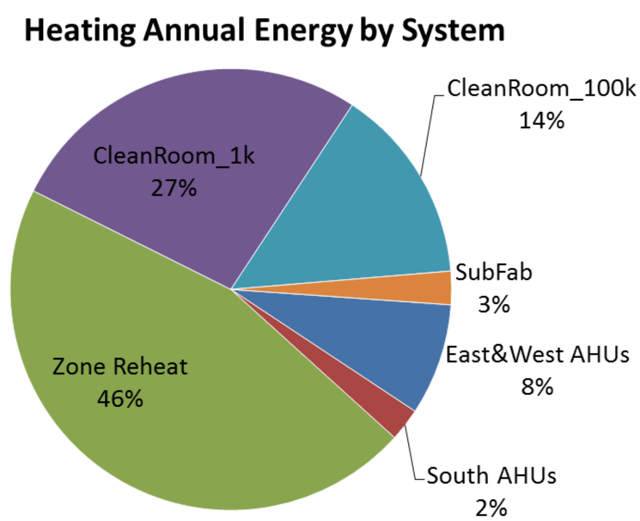


Figure 27: Annual KEB heating energy by system

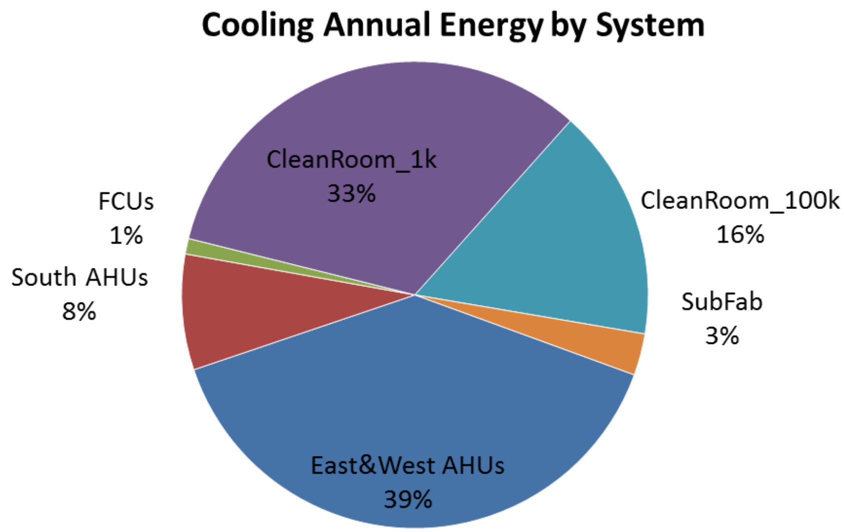


Figure 28: Annual KEB cooling energy by system

According to the energy model results, nearly all cleanroom energy consumption stems from HVAC demands, with the majority heating and cooling energy. Figure 29 shows a breakdown of the energy model's cleanroom energy consumption. Dehumidifcation energy is naturally included in the cooling category since the dehumidification coils also cool the supply air. Including cleanroom supporting spaces, such as the mechanical room and SubFab, the KEB's resulting cleanroom energy model EUI is 1,493 kBtu/ft2-yr.

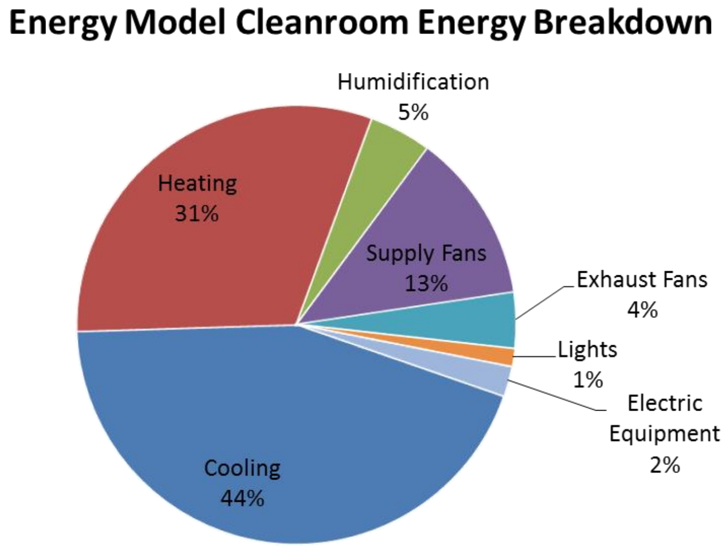


Figure 29: Annual cleanroom energy breakdown

6.1.3 Uncertainty Analysis

An uncertainty analysis was performed to determine the effect that certain energy model input variations have on the results. Eight parameters were chosen and reasonable high and low values were selected that could realistically capture the true KEB values with high confidence. These parameters are shown in Table 11. Each parameter variation was simulated individually, and the resulting building consumption deviations from the baseline model were plotted in Figure 30. It should be noted that the baseline values for heating and cooling in this sensitivity analysis were both 71°F, although the baseline energy model used different values. There is no high value because the heating setpoint must always be lower than the cooling setpoint in E+.

Table 11: High and low parameter values used in uncertainty analysis

Parameter	Unit	Baseline Value	Low Value	High Value
Wall Thermal Resistance	ft^2-hr-F/Btu	16.2	12.2	20.2
Roof Thermal Resistance	ft^2-hr-F/Btu	13.1	9.1	17.1
Infiltration	ft/min-area	0.0446	-30%	30%
Plug Loads	W/ft2	NA	-50%	50%
Occupancy Density	people/ft2	NA	-50%	100%
Building Setpoint Temperature	°F	71	+/- 3F	NA
Fan Efficiencies	Ratio	NA	-0.1	0.1
Weather File Location	NA	Baltimore	Dulles	Philadelphia

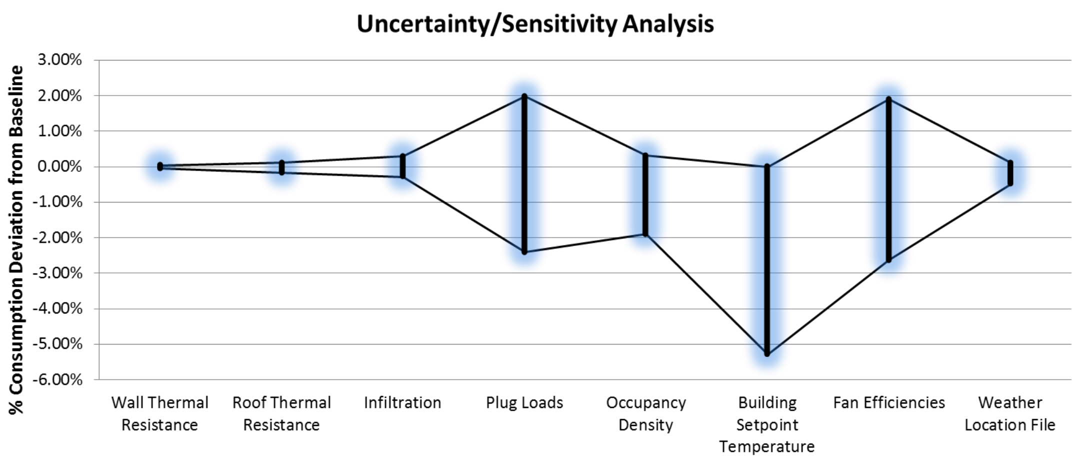


Figure 30: Energy model uncertainty results

E+ documentation recommends that at least four time steps per hour be used in energy simulations, which was the calculation frequency used for this project. Although smaller time steps can result in more accurate simulations, it also increases computational time. Figure 31 displays the effect that different step sizes have on annual energy consumption, using 15 minutes as the baseline value. Due to the number of simulations that were run in this experiment and the amount of time allotted for the project, it would have been unreasonable to use smaller time steps.

Interestingly, there is a positive correlation between the E+ solver step size and energy consumption.

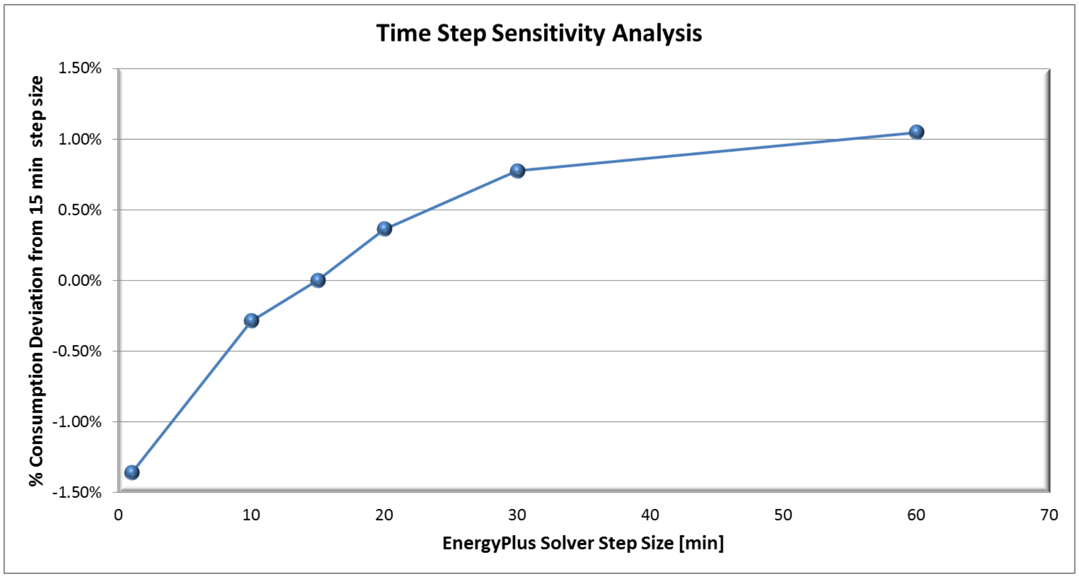


Figure 31: EnergyPlus time step sensitivity analysis

The building setpoint temperature uncertainty analysis was taken a step further to determine the relationship between building temperature and energy consumption. The heating and cooling setpoints were relaxed from 1-5°F from 71°F and the annual building energy consumption was simulated in E+. The results from this sensitivity analysis are shown in Figure 32. The relationship between temperature and energy use is linear with a 1.7% decrease in total building annual energy consumption with every degree that the temperature setpoints are relaxed. The setback in this study does not include cleanrooms or rooms served by FCUs.

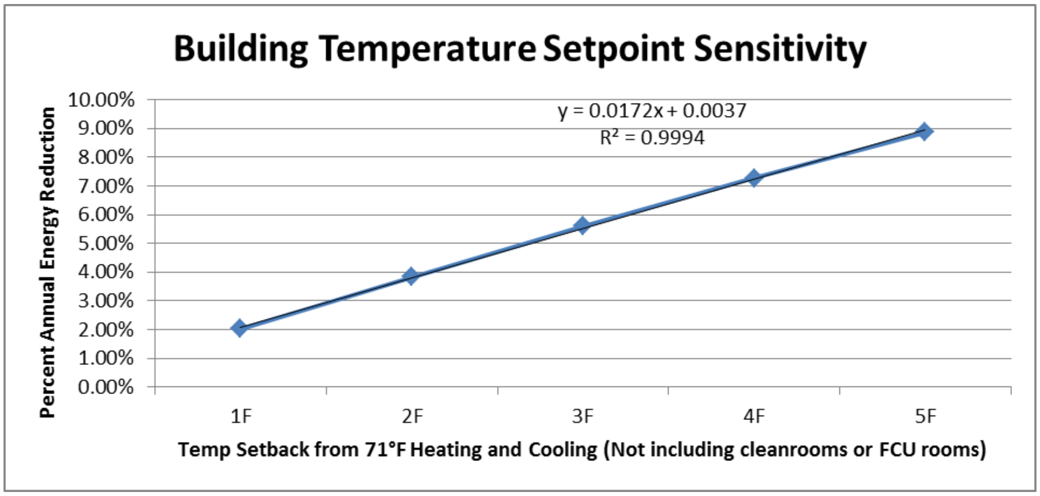


Figure 32: Building temperature vs. energy consumption sensitivity analysis

6.2 As-designed Energy Model

The baseline energy model represents the current operation of the KEB. The as-designed energy model represents how the KEB was designed to operate. This includes three EEMs, all of which correct AHU temperature control problems that were discovered when developing the baseline energy model.

6.2.1 EEM #1.1 – Cleanroom Freeze State Setpoint Temperatures

A freeze stat contains a sensor and actuator used in AHUs that provides freeze protection in water coils when the outside air temperature is cold. A photograph of a freeze state is shown in Figure 33. If any section of air flowing over the freeze stat falls below the setpoint (typically 38°F), then the mechanism will trip, usually shutting down the supply fan.

Figure 33: Picture of a generic freeze stat

The cleanroom air system uses two freeze stats, one in each MAH at the exit of the steam preheating coil. Their locations can be seen in Figure 34. Due to the large amount of makeup air in the cleanrooms, the operation of these freeze stats are crucial.

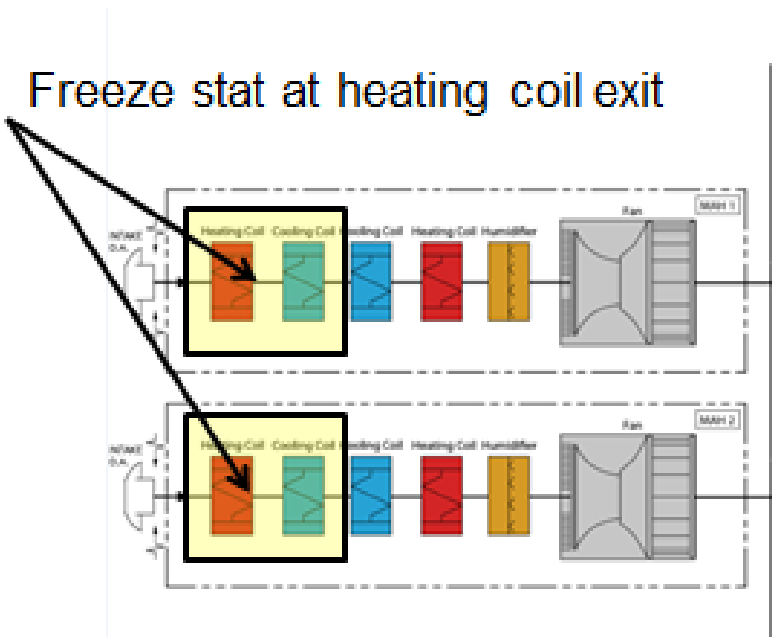


Figure 34: Location of freeze stats in the cleanroom MAHs

Upon analysis of the cleanroom MAHs in the BMS, it became apparent that the air exiting the steam preheating coil was often heated to roughly 80°F. Further research and discussion with the facility operators revealed that false tripping of the freeze stat has resulted in steam preheating coil temperature setpoints of 80°F when the outdoor temperature is less than 55°F. This was implemented to ensure that the systems would always stay online. However, this setpoint results in overheating the air, which requires subsequent cooling in the CHW coil that follows. To make up for exhaust air, about 18,300 CFM is consistently brought in via the MAHs. Fixing the cleanroom freeze stat issue and returning the temperature setpoint to 38°F at all times will result in 5,140 MMBtu of energy savings, or 7.8% reduction from the baseline model. Energy savings are summarized in Figure 35. Using the auxiliary utility rates, an estimated $99,000 can be saved with this EEM.

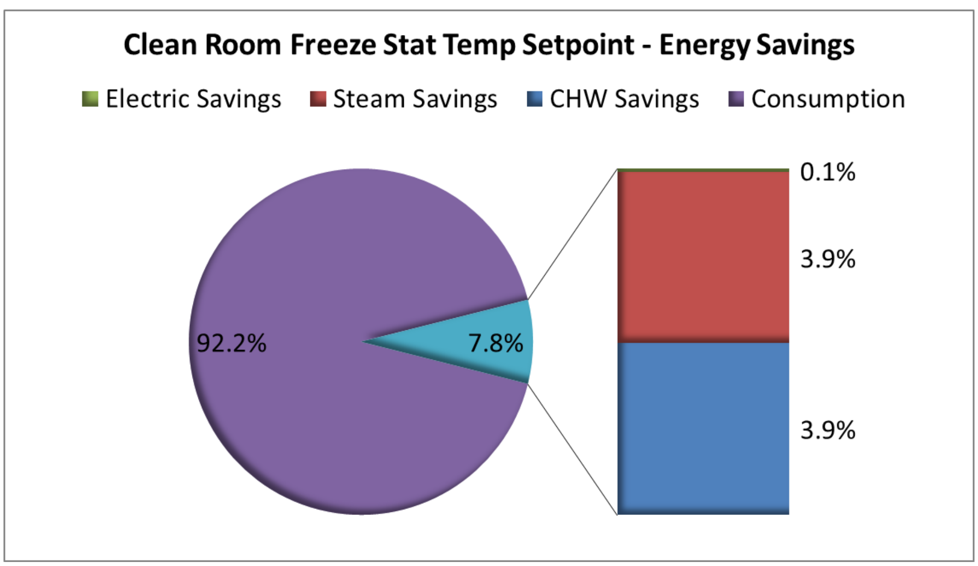


Figure 35: EEM #1.1 energy savings

6.2.2 EEM #1.2 – AHU 1-4 Freeze State Setpoint Temperatures

A similar issue exists with the freeze stats in the east and west AHUs. Data logging using the BMS showed that the setpoint temperature is raised when the outdoor air temperature is less that 40°F. Moreover, it is unclear what the setpoint was raised to because the capacity of the steam preheating coils did not allow the air to reach the setpoint. Figure 36 below shows a screen shot of AHU-4 in the BMS with the mixed air, heating coil outlet, and supply temperatures highlighted in yellow. Although the mixed air temperature should not cause the freeze stat to trip, it is heated to 77°F and subsequently cooled to about 52°F, wasting a significant amount of energy.

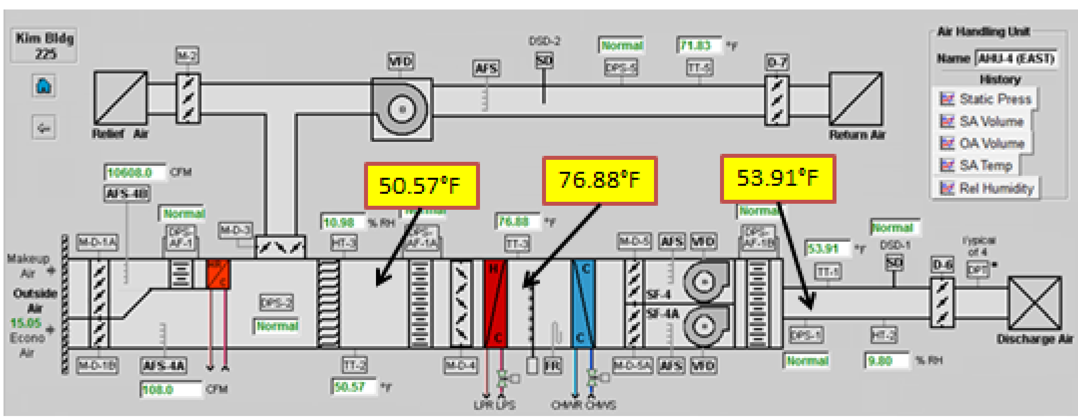


Figure 36: Snapshot of AHU-4 operation from BMS at 12:27 PM, Jan 28

Energy saved from setting the heating coil outlet temperature to 38°F at all times is shown in Figure 37. As in EEM #1.1, an equivalent amount of heating and cooling energy is saved. 3,700 MMBtu and $71,400 can be saved annually by implementing this EEM.

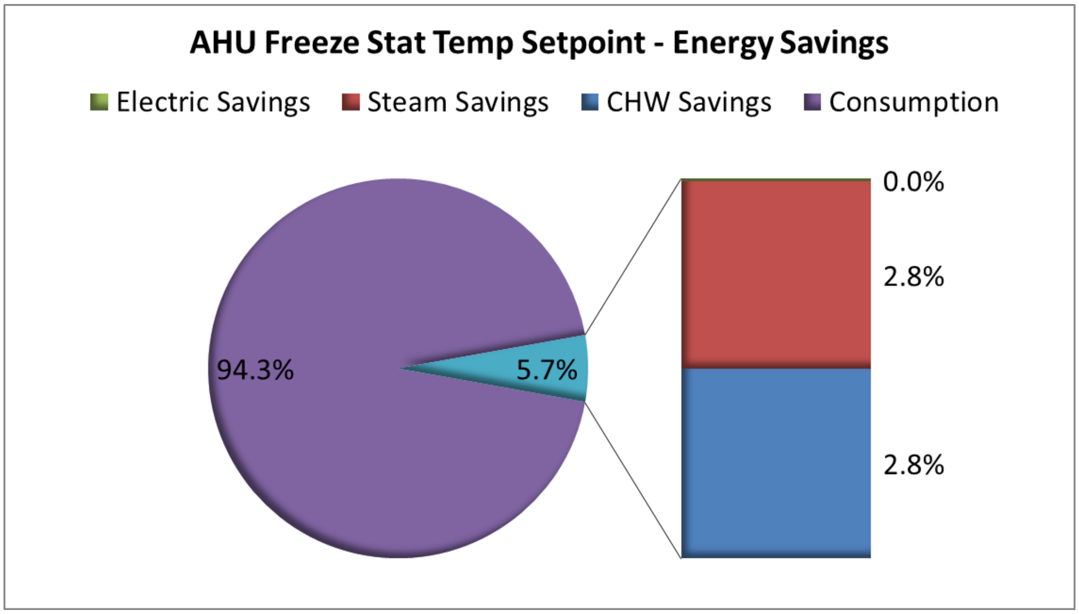


Figure 37: EEM #1.2 energy savings

6.2.3 EEM #1.3 – AHU Mixed Air Setpoint Temperatures

The BMS indicates that under current operation the mixed air nodes in all AHUs (except AHU-6) have a 60°F temperature setpoint. This results in year-round use of the cooling coils to bring the SAT to 55°F. The original design had the mixed air set to 2°F lower than the SAT such that the fan motor energy released into the air stream will make up the difference. By lowering the mixed air temperatures to 53°F, 912 MMBtus and 2% energy savings from the baseline can be realized.

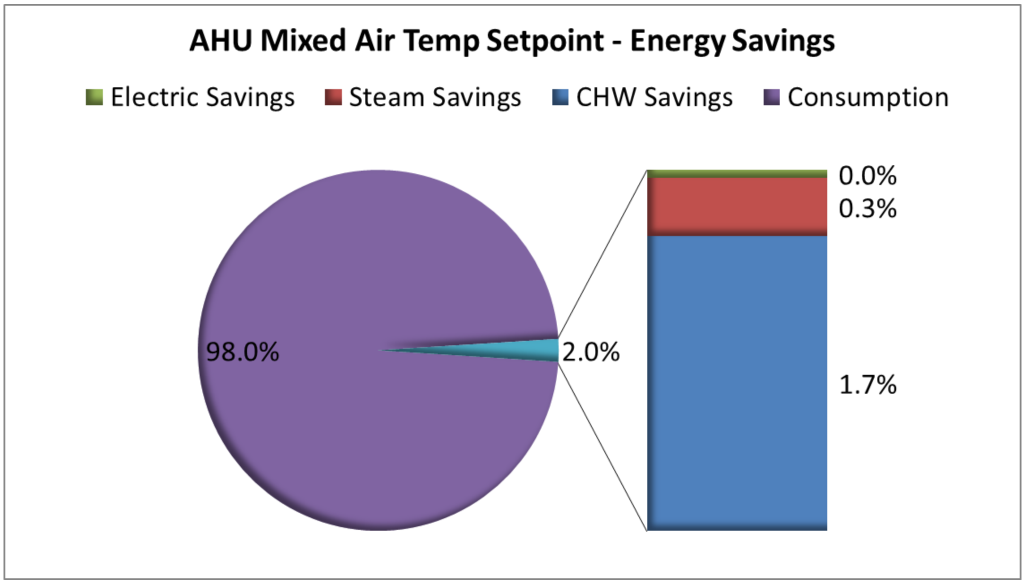


Figure 38: EEM #1.3 energy savings

6.2.4 As-Designed Energy Model Summary

One of the major benefits to energy modeling is the ability to simultaneously simulate the effect of multiple energy efficiency measures that may not be completely independent. For example, modeling EEM #1.2 and EEM #1.3 together will not produce the same energy savings as the sum of the savings when modeling them separately. The as-designed energy modeled represents the savings incurred from following through with all three EEMs discussed in this section. 16.1% of baseline energy consumption (10,570 MMBtu) and $196,100 can be saved.

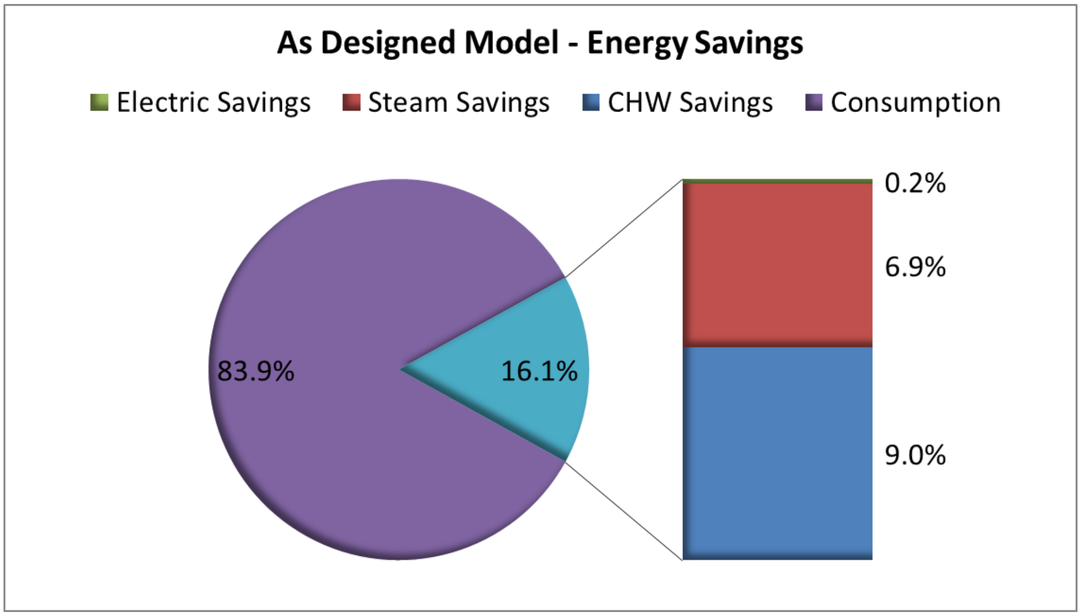


Figure 39: As-designed energy model savings

6.3 Energy Efficient Energy Model

Five additional energy savings opportunities are proposed to improve the energy efficiency from the original building design. The as-designed model was used as the baseline model when determining the energy savings for the additional EEMs. However, the *percent* savings reported from the EEMs are determined from the original baseline energy consumption.

6.3.1 EEM #2.1 – Zone Temperature Setback

The KEB currently operates under the same conditions during all hours of the day, meaning that the building is always in occupied mode and the zone thermostat setpoints do not change. Many commercial buildings have the opportunity to shut down the HVAC systems overnight and during the weekends to save energy. Since the KEB is almost always partially occupied, this action is not possible. However, there are many spaces in the KEB that are not usually occupied overnight and on the weekends. This EEM proposes that the thermostats have timed temperature setbacks in such spaces. Six space types were identified in Phase I and Fischell Addition as potential setback zones. Five different combinations of setback schedules were modeled for these space types using no setback, night setback, and night and weekends setback as the three options.

Table 12: KEB zone setback schedule options

NONE
NIGHT
NIGHT + WKD

Sch 1	Sch 2	Sch 3	Sch 4	Sch 5
classrooms	classrooms	classrooms	classrooms	classrooms
seminar rooms	seminar rooms	seminar rooms	seminar rooms	seminar rooms
general offices	general offices	general offices	general offices	general offices
grad/fac offices	grad/fac offices	grad/fac offices	grad/fac offices	grad/fac offices
labs	labs	labs	labs	labs
computer labs	computer labs	computer labs	computer labs	computer labs

Pacific Northwest National Laboratory (PNNL) suggests that 5-10°F is an acceptable range of temperature setbacks (Pacific Northwest National Laboratory). For the purpose of modeling this EEM, zone temperatures will be set back 8°F from 10 pm to 6 am. Schedule 4 was selected as the most likely scenario to be implemented in the KEB and thus was used in the energy savings summary for the building. With schedule 4, 2,500 MMBtu can be saved annually, equating to 3.9% savings from baseline and $58,100. Table 13 and Figure 40 summarize the energy savings from this EEM. Schedule 4 was also simulated from 10 pm to 5 am to show the effect that one less hour of setback has on savings. The low energy savings in Schedule 1 and Schedule 3 demonstrate that lab temperature setback is the driver in this EEM due to the high air flow to those zones.

Table 13: EEM #2.1 energy savings table

	Sch 1	Sch 2	Sch 3	Sch 4	Sch 5
Electric Savings [kBtu]	1,000	7,557	4,197	10,812	18,815
Steam Savings [kBtu]	359,018	1,918,530	547,089	2,107,164	3,088,174
CHW Savings [kBtu]	64,996	344,238	102,515	383,718	595,379
Total Savings [kBtu]	425,014	2,270,325	653,802	2,501,695	3,702,368
Percent Savings	0.65%	3.45%	0.99%	3.80%	5.63%
Dollar Savings	$9,900	$52,700	$15,100	$58,100	$85,700

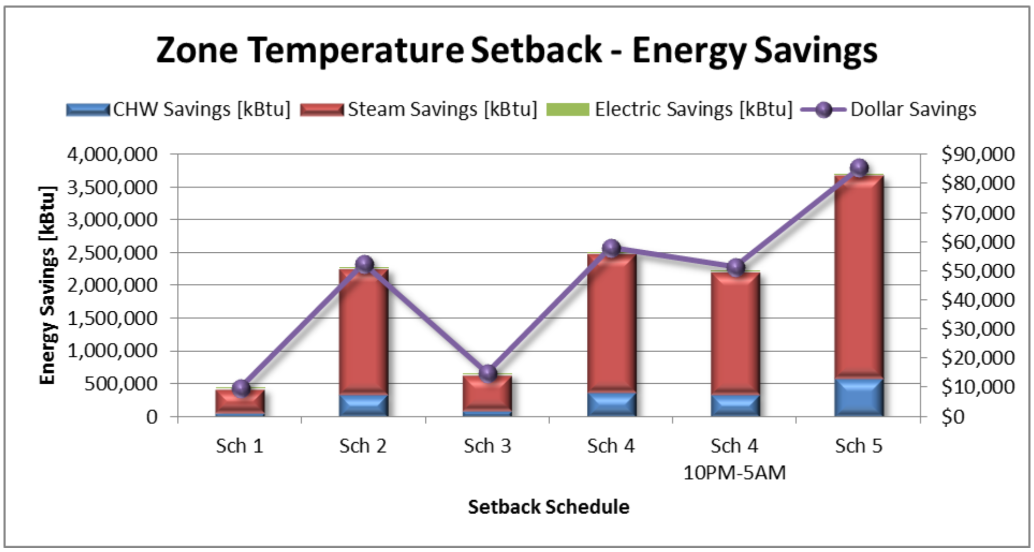


Figure 40: EEM #2.1 energy savings

An important consideration for this measure is the recovery time, or the time that it takes to bring each zone back to the occupied setpoint temperature in the morning. The energy model was used to determine the recovery time for each zone on the coldest night of the year, when the overnight temperature dropped to as low as 3.5°F. Figure 41 displays the heating recovery time for zones included in the night setback. The vertical axis represents the difference between zone temperature and thermostat setpoint. One hour after the zone thermostats are adjusted back to normal operating setpoint, the largest differential in the building is only 0.3°F.

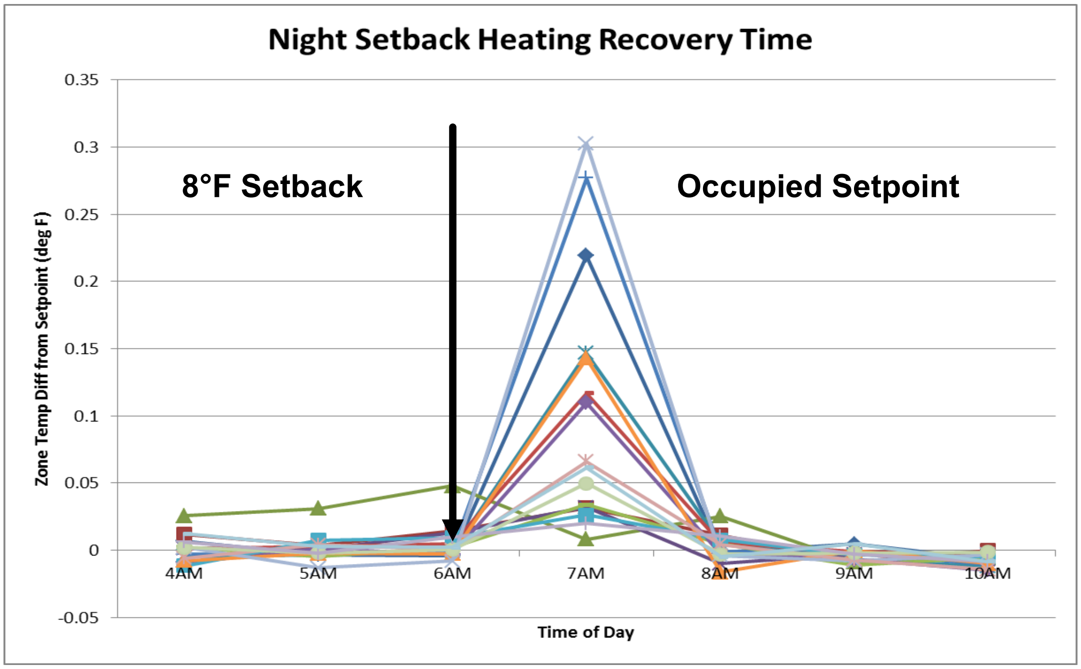


Figure 41: Night setback heating recovery time for all setback zones

6.3.2 EEM #2.2 – Increase Fan Coil Unit Setpoint Temperatures

The KEB contains 18 FCUs in Phase I of the facility. During the initial building walkthrough, a few of these small electrical and telecommunications rooms felt very cold. The temperature controls for the FCU units consist solely of a knob that can be set continuously from "cool" to "warm." The BMS confirmed the cold temperature in these zones and are shown in Figure 42.

FCU Summary

Tag	Service	Location	Zone Temp, °F
1	Elev Rm	1104	73.12
2	Server	2107B	62.86
3	IT Server	1206	70.01
4	Elev Rm	1224	68.42
5	UPS Rm	1208	60.31
6	Elec Rm	1123	70.51
7	Elec Rm	1223	60.66
8	Elec Rm	2123	51.43
9	Elec Rm	2223	65.52
10	Elec Rm	2123	56.29
11	Elec Rm	3223	56.53
12	Tel Rm	1117	71.60
13	Tel Rm	1229	77.19
14	Tel Rm	2117	80.59
15	Tel Rm	2229	66.98
16	Tel Rm	3117	67.95
17	Tel Rm	3229	65.28
18	Tel Rm	1230	69.0

Figure 42: Snapshot of FCU room temperatures in August

The average zone temperature for the FCU zones is 63.2°F. Excluding the UPS and server rooms, raising all zones to 75°F will save approximately 86,100 kBtu and $1,300 each year.

6.3.3 EEM #2.3 – Cleanroom Air Change Rate Reduction

One of the most important factors in cleanroom contamination control is air recirculation, or air change rate (ACR). Cleanroom ACRs are 5 to 50 times higher than for a general-purpose building. According to a cleanroom study sponsored by ASHRAE, over-supply of cleanroom filtered air is common practice and leads to significant energy waste. The recommended ACR guideline tables are based on old experience and were determined based solely on air cleanliness class with little scientific backing (Sun, 2010). Table 14 presents typical air flow designs for various cleanroom classes (Jaisinghani, 2003).

Table 14: Typical cleanroom ACRs for various classes

Cleanroom Class	Airflow Type	Air Changes/hr
1	Unidirectional	360-540
10	Unidirectional	300-540
100	Unidirectional	240-480
1,000	Mixed	150-240
10,000	Mixed	60-90
100,000	Mixed	5-48

Based on the cleanroom design documents and BMS, the ACRs for the KEB class 1,000, 10,000, and 100,000 cleanrooms are 106, 197, and 47, respectively. A 2005 KEB cleanroom performance evaluation completed by Air Filtration Management, Inc. (Bethlehem, PA) was used to document the particle concentrations in different sections of the cleanrooms. These data are plotted in Figure 43 and Figure 44. The blue dashed lines represent the cleanliness standards for each cleanroom class. The highest 1μm particle count in the class 1,000 cleanroom analysis is 80 particles/ft^3 and the acceptable limit is 240 particles/ft^3. The highest 1μm particle count in the class 10,000 cleanroom is 117 particles/ft^3 and the acceptable limit is 2,400 particles/ft^3. In the class 100,000 cleanroom, the maximum count at 1μm is 418 particles/ft^3 and the limit is 24,000 particles/ft^3. The test results clearly show that the KEB cleanroom is performing well above its design.

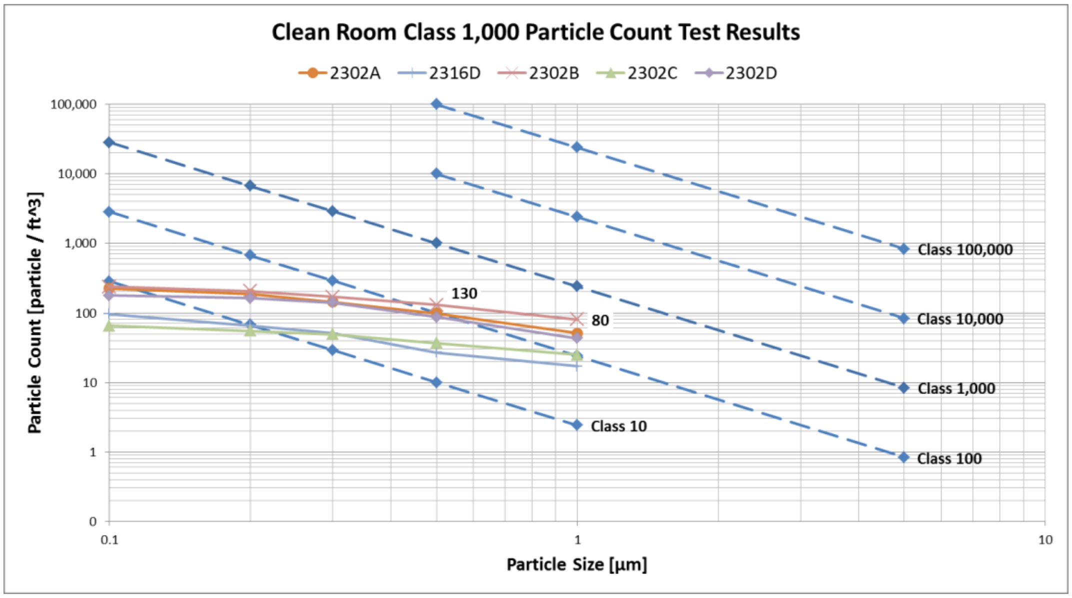


Figure 43: Cleanroom class 1,000 air quality performance testing

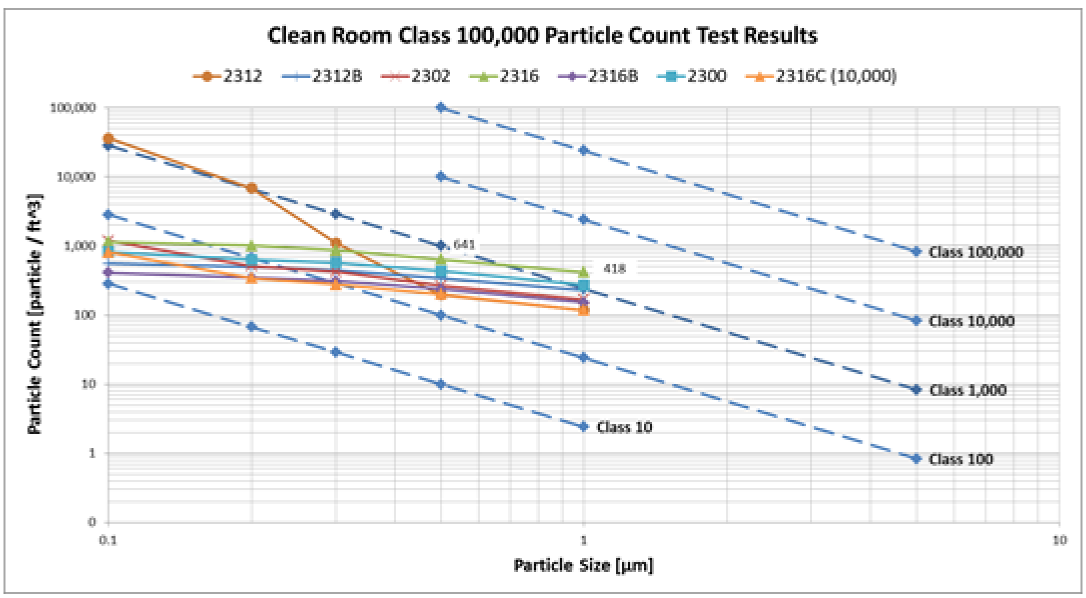


Figure 44: Cleanroom class 10,000 and 100,000 air quality performance testing

Sun et al., researchers from the cleanroom study discussed above, developed a numerical model that relates ACR to room particle concentration. Their model incorporates many variables including ACR, particle generation rate, particle deposition rate, filter efficiency, percentage of outside air in supply stream, impurity of outside air, and room air leakage rate. Figure 45 shows results from the research group's analysis. The relationship between particle concentration and ACR is on a logarithmic scale for various particle generation rates (Sun, 2010).

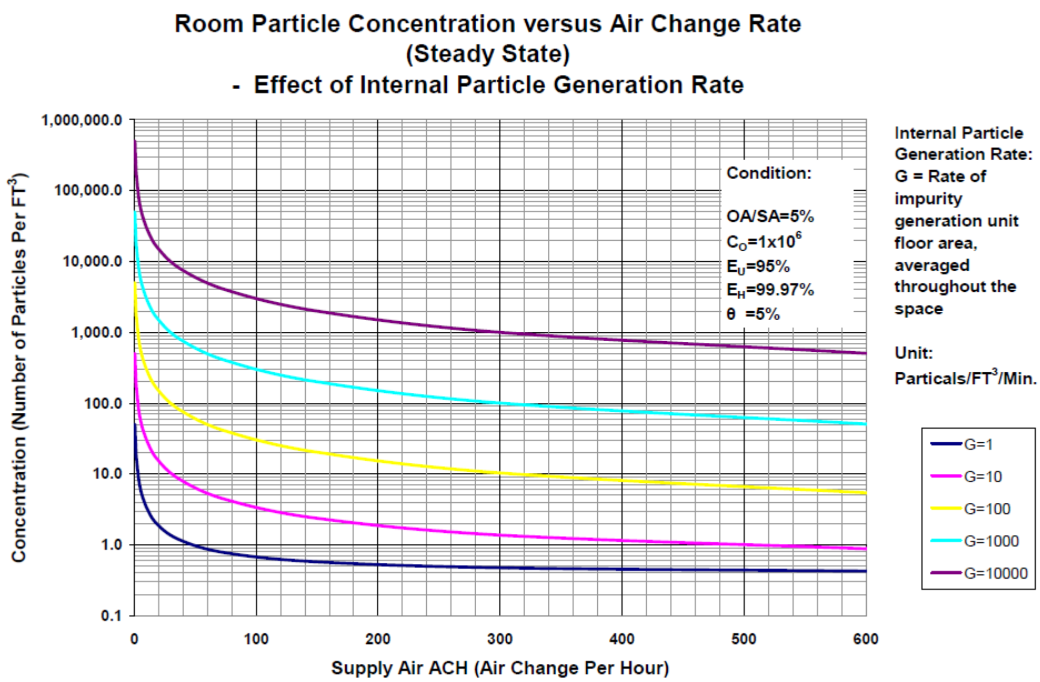
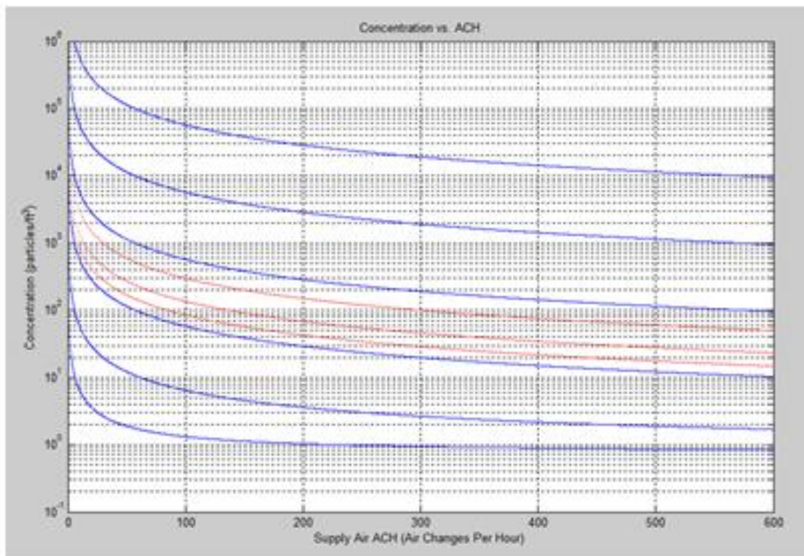


Figure 45: ACR cleanroom model developed by Sun et al

The results presented in the study by Sun et al were reproduced in this analysis and adapted to the KEB cleanroom conditions for all three cleanroom classes in order to determine the lowest acceptable ACR. The class 10,000 and 100,000 cleanrooms are served by the same system, so alterations to each space's ACR cannot be done independently. Figure 46 displays the results from the KEB cleanroom model. The blue lines represent the same particle generation rates from the ASHRAE study and the red lines represent the maximum particle generation rates of the KEB cleanroom classes. The values are displayed in the table beside the chart (G) and represent the 1 μm particle generation rate.



Class	G
1,000	147
10,000	522
100,000	237

Figure 46: KEB cleanroom ACR model

According to the KEB cleanroom model, the class 1,000 recirculation air flow can be reduced from 106 to 36.1 air changes/hr. Due to the high volatility of particle counts at lower ACRs as seen in the figure, the class 10,000 and 100,000 could not be solved numerically with a high level of confidence. It is safe to say that the ACR reduction in the class 1,000 cleanroom can be applied to the other two classes based on the particle count data. For this EEM, savings for various RAH fan air flow reductions were calculated and are shown in Figure 47. Based on fan affinity laws, reducing the fan air flow by a factor will reduce the fan power by the cube of that factor:

$$\frac{HP_2}{HP_1} = \left(\frac{N_2}{N_1}\right)^3$$

where HP is horsepower and N is fan speed (proportional to flow rate).

This relation is for ideal situations, but real air dynamics require a correction to the cube exponent. According to Lime Energy Consulting and Technical Services, there is no globally accepted exponent for savings calculations, and most engineers select a value between 2.1 and 2.9, based on individual experience (Vaillencourt). For this analysis 2.5 was used as the affinity law exponent. A 50% reduction in ACR provides high energy savings and maintains a safety factor for particle concentration in the cleanrooms. This reduction will save 691 MMBtu and $22,800 and is a 1% reduction from baseline energy consumption.

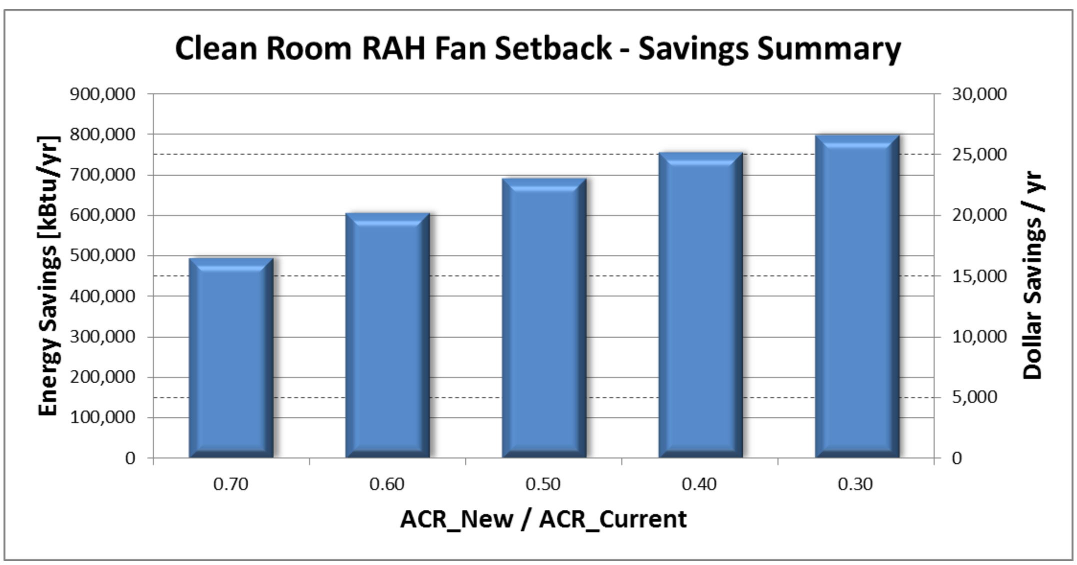


Figure 47: Cleanroom RAH fan ACR reduction savings

6.3.4 EEM #2.4 – AHU Supply Air Temperature Reset

The supply air temperature for all VAV with reheat systems in the KEB is 55°F year-round. This leads to very high heating loads in the VAV terminal reheat boxes during the winter. By adjusting the economizer control during the winter, 65°F SAT can be achieved with little added energy in the AHU and would greatly reduce the amount of hot water reheat needed to maintain zone temperature setpoints. To simulate this EEM, the AHUs' SATs and mixed air temperatures were both increased 10°F when the outdoor air temperature was below 45°F, a typical reset schedule according to Portland Energy Conservation (Portland Energy Conservation, Inc.). When implemented in the KEB, the SAT can be controlled with the BMS in real time using outdoor temperature, zone temperature drift, or even VAV box damper position. Annual savings from this EEM are 201 MMBtu and $46,300 and are displayed in Figure 48.

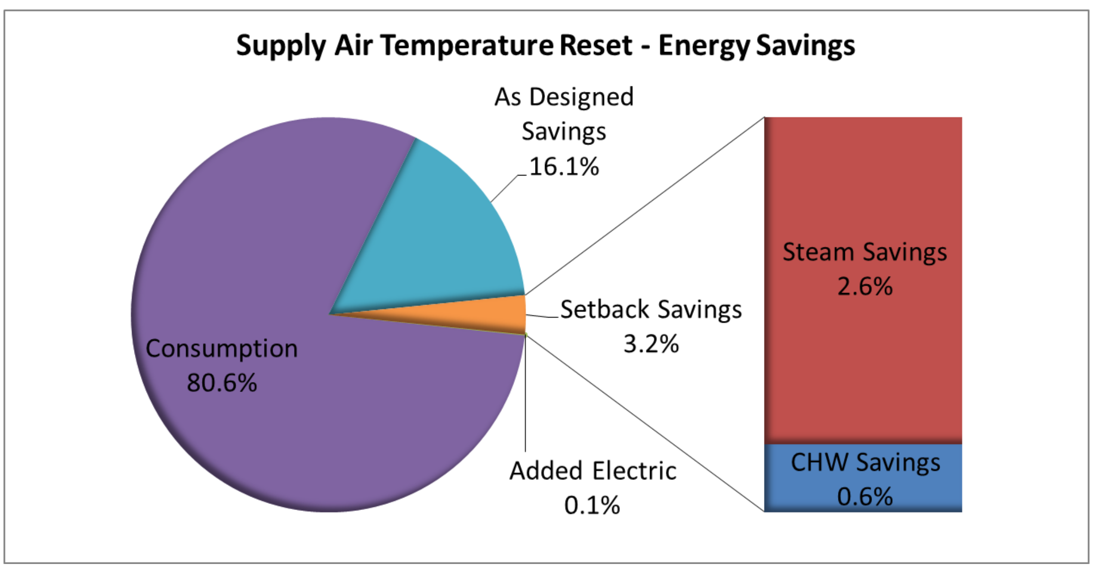


Figure 48: EEM #2.4 energy savings

The only factor that would prevent the implementation of SAT reset is the need for 55°F supply air by any zones in the winter time. The KEB facility operator explained that SAT reset was attempted in the past but the CATT Lab on the third floor became too hot due to intense space heat loads. The energy model confirmed this sentiment, as the temperature in the “computer lab” thermal zone, which includes the CATT Lab, regularly increased to above 80°F. By providing an independent, supplemental cooling system to the overheated zone, the EEM can safely be implemented.

A ductless variable refrigerant flow (VRF) system is proposed for any spaces that have trouble maintaining setpoint temperature post SAT reset. Although the CATT Lab will be moving out of the KEB, the following analysis demonstrates the benefit of a secondary cooling system for high space-load thermal zones. According to the E+ model, a 20 ton VRF system is needed to supplement the 65°F supply air in the winter in the computer lab thermal zone. After simulating the additional cooling in that zone, the number of annual hours above zone cooling setpoints was reduced to zero. Table 15 summarizes the energy savings and economic analysis, including simple payback period. The source for the cost estimate is Trane, who provided an equipment selection report, shown in Appendix A.4.

Table 15: EEM #2.4 economic analysis

EEM #2.4 - AHU Supply Air Temperature Reset	
Net Energy Savings (million kBtu)	2.01
Percent Energy Savings from Baseline	3.20%
Net Annual Dollar Savings	$46,300
EEM Upfront Cost Estimate	$102,900
Simple Payback Period	2.2

6.3.5 EEM #2.5 – Cleanroom Energy Recovery

According to the KEB BMS, the cleanrooms exhaust a constant flow of air at approximately 18,300 CFM. The MAHs draw in outdoor air to make up this airflow and maintain a positive pressure in the rooms. There are two exhaust systems that serve the cleanrooms: general exhaust and corrosive exhaust. KEB cleanroom managers state that the majority of exhaust air from the cleanroom comes from the corrosive exhaust system. Figure 49 shows an aerial view of the KEB roof including the MAH intake hoods and exhaust fan systems.

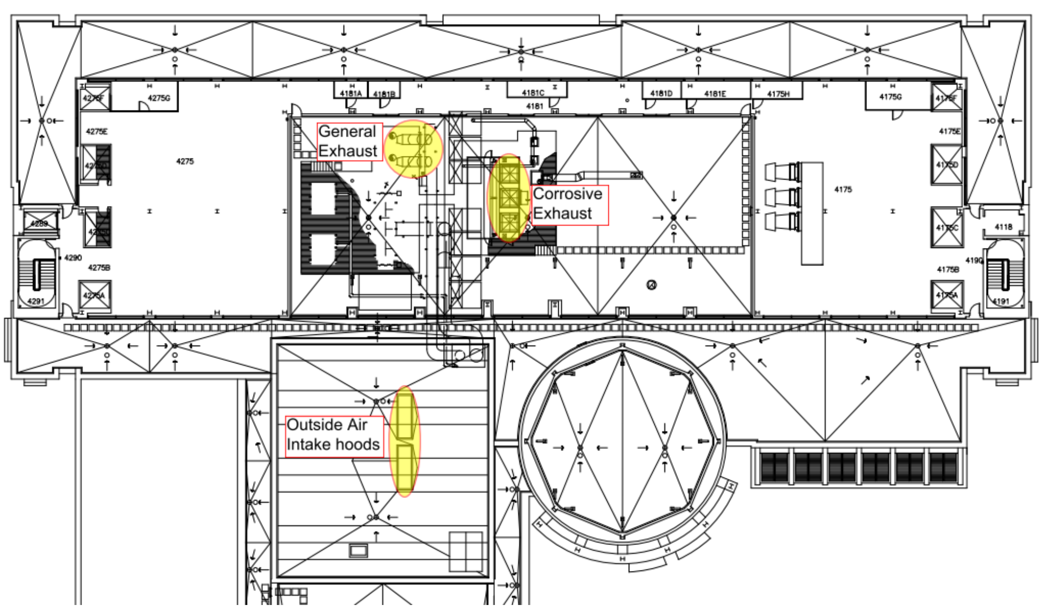


Figure 49: Aerial schematic view of KEB roof

Current operation does not utilize any form of energy recovery in the cleanrooms. With a recovery system, energy from exhaust air at approximately 68°F can be used to heat makeup air in the winter and cool makeup air in the summer. Due to the distance from the exhaust fans to makeup air intake, a run-around heat recovery system is the only option for cleanroom exhaust energy recovery. A typical coil energy recovery loop places extended, finned-tube water coils in supply and exhaust plenums and uses a closed glycol-water loop to transfer heat between them. Figure 50 (ASHRAE, 2000) and Figure 51 (Greenheck, 2012) show a vertical and horizontal view of a generic run-around energy recovery system.

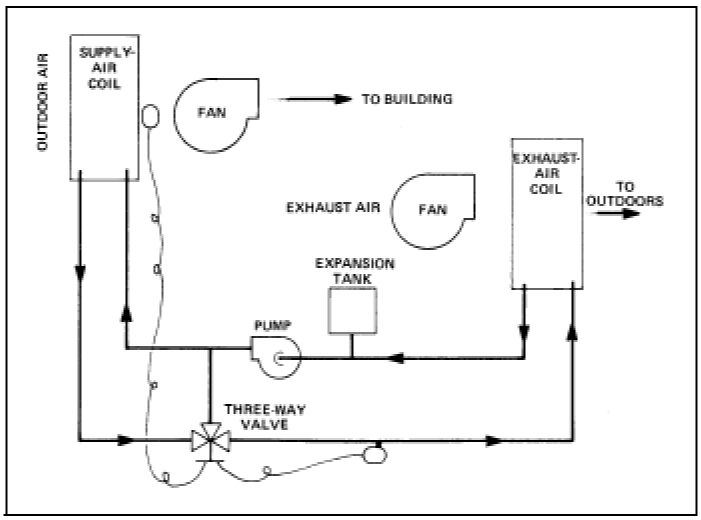


Figure 50: schematic of run-around energy recovery system

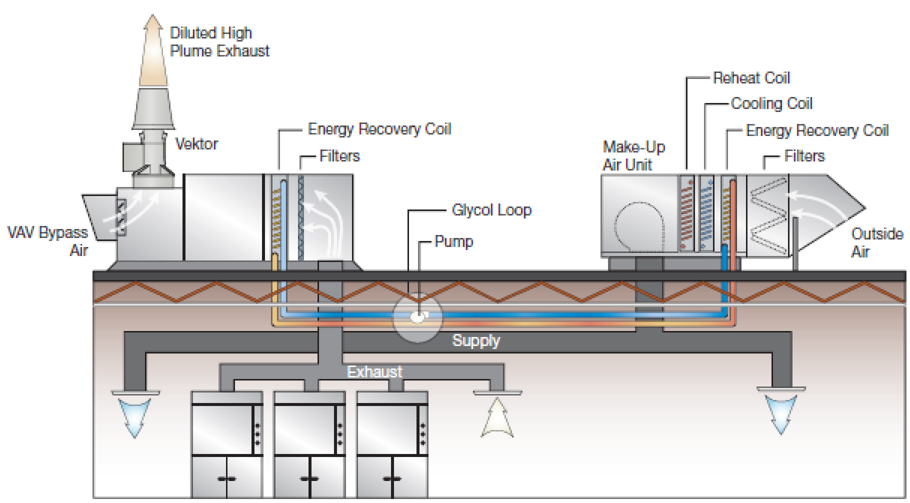


Figure 51: Cross-sectional view of run-around energy recovery system

Coil energy recovery systems are very flexible and well suited for renovation and industrial applications. Typical effectiveness values for run-around recovery systems range from 45%-65% (ASHRAE, 2000). Due to the corrosive nature of the exhaust air, application of a protective coating is required for the recovery coils. There are various companies that specialize in providing that service.

As a result of E+ energy recovery limitations, manual calculations in Microsoft Excel were performed to estimate energy savings. A *bin method* was used for outdoor temperature based on the TMY2 Baltimore weather file, as shown in Figure 52.

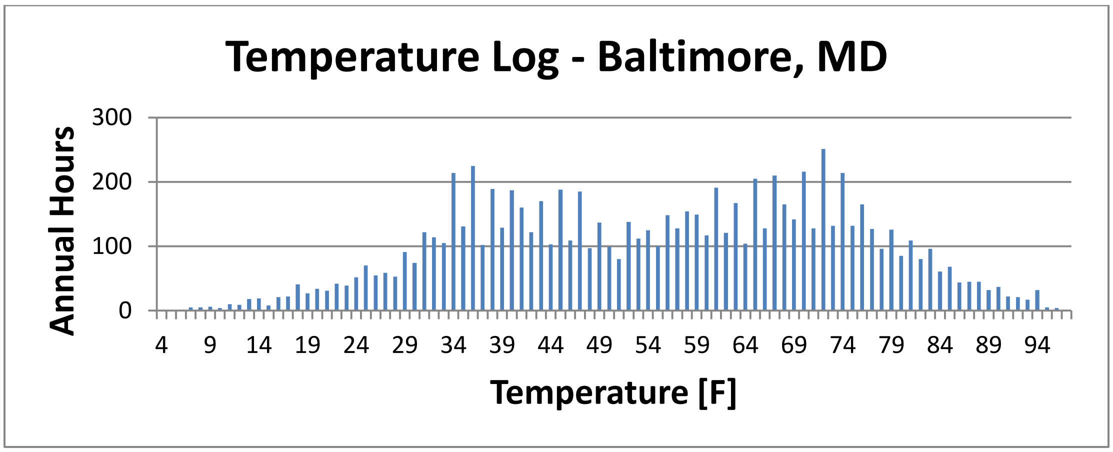


Figure 52: Binned temperature data for Baltimore, MD

Energy savings were calculated using a heating effectiveness of 55% and cooling effectiveness of 40%, as per equipment supplier recommendations (Aerofin, VA). Heat exchanger effectiveness determines the amount of heat transfer achieved as a percentage of the maximum heat transferred possible. The equation below represents the method used to calculate energy recovered from the exhaust air stream (ASHRAE, 2000). All values are known except T_4, the exiting exhaust air temperature.

$$\eta = \frac{Actual\ Energy\ Transfer}{Maximum\ possible\ energy\ transfer} = \frac{\dot{m}_{exhaust}(T_3 - T_4)}{\dot{m}_{min}(T_3 - T_1)}$$

where $\dot{m}$ represents mass flow rate
T_1 represents entering supply air
T_2 represents leaving supply air
T_3 represents entering exhaust air
T_4 represents leaving exhaust air

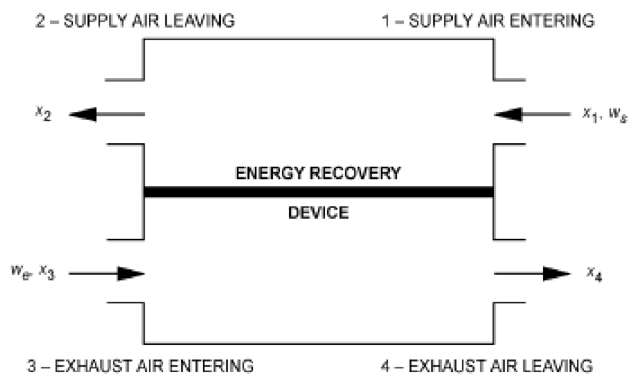


Figure 53: Air stream numbering convention

Although energy recovery is advertised as a “free” preconditioning of makeup air, there are significant energy costs associated with the method. The placement of recovery coils in the intake and exhaust plenums results in added pressure requirements for the MAH and exhaust fans, respectively. 0.8 in. w.c. was added to each plenum and associated energy costs were calculated using fan affinity laws. Moreover, the glycol-water pump uses energy to keep the heat transfer fluid recirculating between coils. A 3-HP pump was selected and used for additional pump energy. Energy savings are summarized in Figure 54, and Table 16 provides an economic summary of the EEM. Details of the cost estimate are provided in Appendix A.3. 1.8% of total building energy consumption can be reduced with a cleanroom exhaust air energy recovery system with an estimated investment cost of $190,000 and a simple payback of 5.7 years.

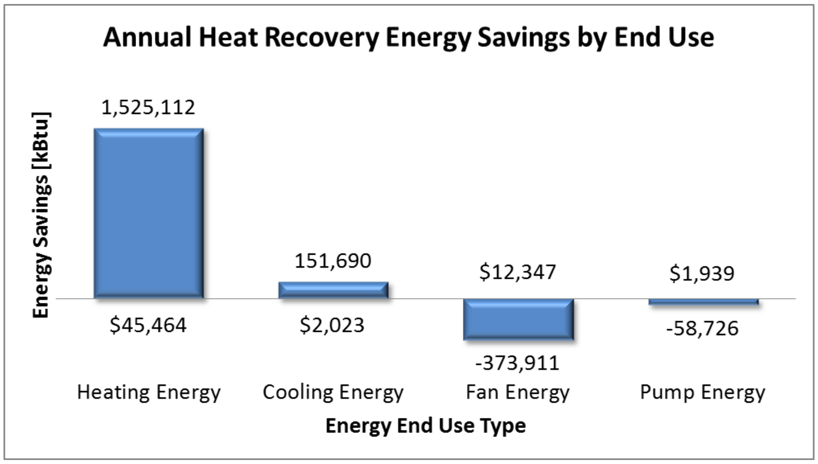


Figure 54: Cleanroom energy recovery energy savings summary

Table 16: Cleanroom energy recovery economic analysis

EEM #2.5 - Cleanroom Energy Recovery Summary	
Net Energy Savings (million kBtu)	1.24
Percent Energy Savings from Baseline	1.80%
Net Annual Dollar Savings	$33,200
EEM Upfront Cost Estimate	$190,000
Simple Payback Period	5.7

6.4 Energy Savings Summary

By implementing all suggested EEMs, an estimated 25.3% reduction in annual energy consumption can be realized. The resulting building EUI is 312.8 kBtu/ft^2-yr after the 16,760 MMBtu reduction. Using the auxiliary utility rates, expected annual utility savings are $341,500. Table 17 summarizes the energy savings for each EEM including the as-designed model and high efficiency model. Carbon dioxide emission reductions associated with each EEM were estimated using plant efficiencies and emission factors from the Climate Registry, a nonprofit organization that provides meaningful information to reduce greenhouse gas emissions (The Climate Registry, 2013). A summary of this calculation is shown in Appendix A.2. Figure 55 displays a savings summary for each individual EEM. The left vertical axis and bars show energy savings, and the right vertical axis and points show utility savings.

Table 17: KEB energy efficiency measure savings summary

EEM SUMMARY	Energy Savings [MMBtu]	Percent Energy Savings	Utility Savings [$]	$(CO_2)_e$ Emission Reductions [Metric Tons]
EEM #1.1 - Cleanroom Freeze Stat	5,139	7.8%	$99,000	509.5
EEM #1.2 - AHU Freeze Stat	3,718	5.7%	$71,400	369.2
EEM #1.3 - AHU Mixed Air Temp	912	2.0%	$10,200	104.3
As Designed Model	10,571	16.1%	$196,100	1,062.7
EEM #2.1 - Zone Temperature Setback	2,502	3.9%	$58,100	229.4
EEM #2.2 - Increase FCU Setpoint Temps	86	0.1%	$1,300	9.1
EEM #2.3 - Reduce Cleanroom ACR	691	1.0%	$22,825	48.9
EEM #2.4 - AHU SAT Reset	2,040	3.2%	$46,300	189.1
EEM #2.5 - Cleanroom Energy Recovery	1,244	1.8%	$33,200	121.0
High Efficiency Model	16,760	25.3%	$341,500	1,642.5

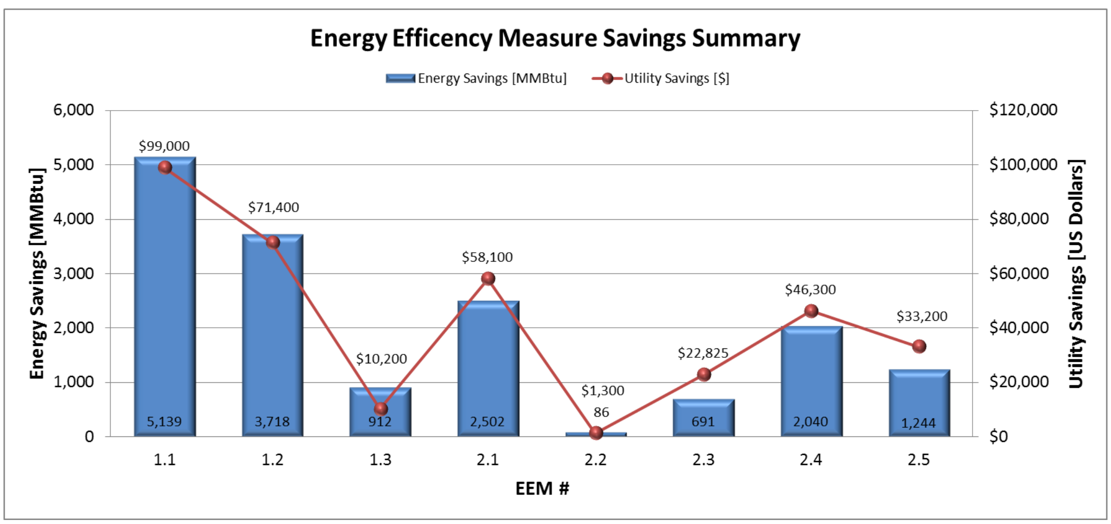


Figure 55: KEB energy efficiency measure savings summary

Chapter 7: Conclusions and Future Work

7.1 Conclusions

An accurate energy model of the Kim Engineering Building required upfront planning, selection of an energy modeling approach, and significant time and resources. Coordination between information sources, energy model development, and model performance validation and fine-tuning were the three main time-consuming and challenging tasks in the project. Once the baseline model was completed, “what-if” scenarios and EEMs were easy to simulate with little time investment. In this regard, the KEB E+ energy model can be very useful for future energy decisions regarding the KEB.

The baseline energy model showed a 5.4% deviation in annual energy usage from utility bills averaged from 2010-2012. Percent deviations for electric, steam, and chilled water energy consumption were 1.2%, 4.3%, and 8.3%, respectively (all under-estimates). According to the energy model, the cleanroom accounts for 50% of total building energy consumption, much greater than previous speculation. Based on the utility analysis and energy model, space conditioning accounts for about 78% of the building’s energy consumption. A significant portion of heating and cooling energy is a result of poor HVAC control strategies that can be solved rather easily. Simultaneous heating and cooling within KEB AHUs is a common practice in current operation. This work shows that improper building operation can result in tremendous energy and dollar losses over time. Inevitably, there are high cooling loads in the summer months due to cooling and dehumidification of makeup air in the hot and humid climate of College Park, MD. The cleanroom dehumidification requirements also lead to substantial reheating of supply air in the summer. VAV box zone reheat represents nearly half of total building heating energy, stemming from constant 55°F supply air temperature from the AHUs (recommendations provided in next section).

In the case of the KEB, high-investment measures are not necessary to ensure high energy savings. Based on the analysis and energy model developed during the project, annual energy consumption can be reduced by approximately 25% relying primarily on a shift towards "best-practice" building operation. Looking at all proposed measures as a whole, the simple payback period of the entire project is *less than one year*. This assumes that the CATT Lab is moving out of the KEB, fixing the freeze stat issues do not cost more than $100,000, changing controls strategies does not require financial investments, and the auxiliary utility rates are accurate. One of the most important conclusions drawn from this project is that significant retro-commissioning and retuning can be avoided in the future with proper planning and maintenance procedures in the present.

7.2 Recommendations

It is highly recommended that all three as-designed EEMs are implemented as soon as possible in the KEB. The poor operational strategy used in these measures costs the university nearly $200,000 every year. EEM #1.1 does require deeper consideration because the freeze stats in the MAHs must be fixed without affecting the performance and cleanliness of the cleanroom. The cleanroom HVAC system was designed with redundancy, and both MAHs have more than the capacity needed to individually serve the spaces. The difficulty with this EEM will be testing the system after the freeze stats are fixed or replaced.

UMD facilities management may want to determine, space by space, the possibility of night temperature setback in KEB laboratories. Although the labs are not typically occupied overnight, there is a possibility of sensitive lab equipment needing constant temperatures at all times. If any thermal zones have such lab equipment, they should not be included in the setback measure (EEM #2.1). In EEM #2.3 – Cleanroom ACR Reduction, it is crucial that the cleanroom is tested before and after ACR reduction. Significant time has passed since the last cleanroom performance verification, and an updated test should be conducted under current and proposed conditions to verify that the reduction maintains cleanliness requirements. It will also provide insight into a realistic relationship between KEB cleanroom ACR and particle concentration. When implementing EEM #2.4 – AHU SAT Reset, the SAT should be adjusted by 5°F and the data tracked one week, focusing mainly on zone temperatures to determine how aggressive the setback is. If there are minimal complaints from tenants and all zone setpoints are met by the time the building becomes occupied, the setback can be increased and new data tracked. This is a trial and error approach and results will change as the outdoor weather changes, especially during the shoulder months (Pacific Northwest National Laboratory). It is recommended that management obtains an official cost estimate for the cleanroom energy recovery system. Cleanroom energy recovery is the only measure requiring a significant investment, and the university should be confident in the cost of the system including planning, design, materials, equipment, installation, start-up, and maintenance.

Finally, it is important that the BMS is used to trend building performance data. The BMS can set up trends very easily, but this feature has gone unused. By trending information like zone temperature, airflow, economizer operation, and heating and cooling energy, building performance can be analyzed very quickly. Regular performance verifications should be scheduled using the trended data to ensure that there are no energy-wasting issues within the KEB operation. By doing this post-construction of the KEB, UMD could have saved nearly $1.6 million on utility costs.

7.3 Future Work

Although a comprehensive energy model and energy reduction study was completed for the KEB, not all energy-saving opportunities are captured in this report. There are a few topics that were not analyzed, including some investment EEMs. For example, humidification in the AHUs has been turned off by the building operator to save energy. The energy model can be used to determine how much energy the humidifiers use. Since humid air feels warmer, it may be more effective to turn the humidifiers back on and decrease zone heating setpoints by a degree or two, maintaining the same comfort level. Plug load energy reduction is not something heavily considered in this project. Many offices and labs have numerous computers that are left on overnight. Plug load reduction requires eager and active participation from building occupants and can become a successful energy conservation measure with proper culture change in the KEB.

There are a few deficiencies in the E+ modeling approach that can be modified or improved upon. To more accurately determine and model plug loads in the building, electric meters can be set up in various space types to gain electric consumption data representative of those spaces. This data can be used to more accurately input electric loads and schedules in the energy model, affecting electric consumption and heating and cooling loads. Due to necessary simplifications in HVAC systems within the energy model, fan energy consumption seems to have been somewhat overestimated. Improvements can be made by logging KEB fan energy consumption over a period of time and reflecting the data in the model. This logging may have already been accomplished by the commissioning agent, MBP. These enhancements are interrelated, since a reduced fan load will call for an increased plug load to maintain electric consumption. The most sensitive portion of the energy model is the cleanroom. Minor changes to temperature and humidity setpoints can negatively affect the simulation results. Improvements to the robustness of the model's cleanroom controls will make it possible to analyze temperature and humidity sensitivity in the cleanrooms.

The next phase of the project includes implementation of proposed EEMs with proper planning. Measuring energy savings caused by the EEMs and comparing those values to the predicted savings is an important process that should be carried out by either the sustainability department, FM, or a research group in continuation of this project. Verification of savings is crucial in determining the value of energy modeling as a tool for campus energy consumption and carbon footprint reduction. If successful, similar projects can be performed for other energy-intensive buildings across campus.

Appendices

A.1 Cleanroom ACR Matlab Model

```
% Cleanroom ACH Model
% Jared Levy
% 5/9/14

close all
clear all
clc
```

Symbolic Solver

```
syms m Co Eu Eh n theta G D ACR Cst
eq=((((1-Eu)*(1-Eh)*m*Co)+60*(G*(1-theta)/(ACR)))/(m+(Eu+Eh-Eu*Eh)*(1-m)))-Cst;
solve(eq,G)
% G = -(ACR*(Cst - (Co*m*(Eh - 1)*(Eu - 1))/(m - (m - 1)*...
% (Eh + Eu - Eh*Eu)))*(m - (m - 1)*(Eh + Eu - Eh*Eu)))/(60*(theta - 1))

solve(eq,ACR)
% ACR = -(G*(theta - 1))/((Cst*(m - (m - 1)*(Eh + Eu - Eh*Eu)))/60 - ...
% (Co*m*(Eh - 1)*(Eu - 1))/60)
```

```
ans =

-(ACR*(Cst - (Co*m*(Eh - 1)*(Eu - 1))/(m - (m - 1)*(Eh + Eu - Eh*Eu)))*(m - (m -
1)*(Eh + Eu - Eh*Eu)))/(60*(theta - 1))


ans =

-(G*(theta - 1))/((Cst*(m - (m - 1)*(Eh + Eu - Eh*Eu)))/60 - (Co*m*(Eh - 1)*(Eu -
1))/60)
```

Plot all ACR

```
close all
clear all

m=0.05; %Ratio of outside/supply
Co=10^6; %Impurity concentration in makeup air
Eu=0.95; %Filters' combined efficiency in AHU
Eh=0.9997; %HEPA filter efficiency in room
n=0.05; %Percentage of room leakage
theta=0.05; %Percentage of total particle generation deposited on surfaces
ACR=106; %Air change rate

i=0;
for G = [1 10 100 1000 10000 100000]
    i=i+1;
    for ACR= [1:.1:300]
        C=(((1-Eu)*(1-Eh)*m*Co)+60*(G*(1-theta)/(ACR)))/(m+(Eu+Eh-Eu*Eh)*(1-m));
        name1=semilogy(ACR,C,'b-');
        hold on
    end
    name2='G=1';
    hold on
end

axis([0 300 0.1 1000000]);
title('Concentration vs. ACH')
xlabel('Supply Air ACH (Air Changes Per Hour)')
ylabel('Concentration (particles/ft^3)')
grid on
```

Class 1,000

```
disp('****Class 1,000****')
% Limiting case is 2302B for 1um
% Particle count = 80

Cst=80;
ACR = 106;
G = -(ACR*(Cst - (Co*m*(Eh - 1)*(Eu - 1))/(m - (m - 1)*...
    (Eh + Eu - Eh*Eu)))*(m - (m - 1)*(Eh + Eu - Eh*Eu)))/(60*(theta - 1))
% G = 147.3751

for ACR= [1:.1:300]
    C=(((1-Eu)*(1-Eh)*m*Co)+60*(G*(1-theta)/(ACR)))/(m+(Eu+Eh-Eu*Eh)*(1-m));
    a7=semilogy(ACR,C,'b-');
    hold on
```

```
end
hold                                                                    on

for                    m                    =                  0.10:0.1:0.50
    for                    ACR                    =                  [1:.1:300]
        C=(((1-Eu)*(1-Eh)*m*Co)+60*(G*(1-theta)/(ACR)))/(m+(Eu+Eh-Eu*Eh)...
            *(1-m));
        semilogy(ACR,C,'m-');
        hold                                                            on
    end
end


Cst=240;
New_ACR_1k = -(G*(theta - 1))/((Cst*(m - (m - 1)*(Eh + Eu - Eh*Eu)))/60 - ...
    (Co*m*(Eh - 1)*(Eu - 1))/60)
```

```
****Class                                                        1,000****

G                                                                        =

  147.3751


New_ACR_1k                                                               =

   36.1309
```

Class 10,000

```
disp('****Class                                                  10,000****')
%               Limiting               case               is               1um
%               Particle               count              is               117

Cst=117;
ACR=256;
G   =   -(ACR*(Cst   -   (Co*m*(Eh   -   1)*(Eu   -   1))/(m   -   (m   -   1)*...
    (Eh  +  Eu  -  Eh*Eu)))*(m  -  (m  -  1)*(Eh  +  Eu  -  Eh*Eu)))/(60*(theta  -  1))

for                              ACR=                              [1:.1:300]
    C=(((1-Eu)*(1-Eh)*m*Co)+60*(G*(1-theta)/(ACR)))/(m+(Eu+Eh-Eu*Eh)*(1-m));
    a8=semilogy(ACR,C,'b-');
    hold                                                                on
end
hold                                                                    on

for                    m                    =                  0.10:0.1:0.50
```

```
    for ACR = [1:.1:300]
        C=(((1-Eu)*(1-Eh)*m*Co)+60*(G*(1-theta)/(ACR)))/(m+(Eu+Eh-Eu*Eh)...
            *(1-m));
        semilogy(ACR,C,'m-');
        hold on
    end
end

Cst=2400;
New_ACR_10k = -(G*(theta - 1))/((Cst*(m - (m - 1)*(Eh + Eu - Eh*Eu)))/60 - ...
    (Co*m*(Eh - 1)*(Eu - 1))/60)
```

```
****Class 10,000****

G =

  491.7855


New_ACR_10k =

   11.7166
```

Class 100,000

```
disp('****Class 100,000****')
% Limiting case is 1um
% Particle count is 419

Cst=419;
ACR=32.3;
G = -(ACR*(Cst - (Co*m*(Eh - 1)*(Eu - 1))/(m - (m - 1)*...
    (Eh + Eu - Eh*Eu)))*(m - (m - 1)*(Eh + Eu - Eh*Eu)))/(60*(theta - 1))

for ACR= [1:.1:300]
    C=(((1-Eu)*(1-Eh)*m*Co)+60*(G*(1-theta)/(ACR)))/(m+(Eu+Eh-Eu*Eh)*(1-m));
    a9=semilogy(ACR,C,'b-');
    hold on
end
hold on

for m = 0.10:0.1:0.50
    for ACR = [1:.1:300]
        C=(((1-Eu)*(1-Eh)*m*Co)+60*(G*(1-theta)/(ACR)))/(m+(Eu+Eh-Eu*Eh)...
            *(1-m));
        semilogy(ACR,C,'m-');
        hold on
```

```
    end
end

Cst=24000;
New_ACR_100k = -(G*(theta - 1))/((Cst*(m - (m - 1)*(Eh + Eu - Eh*Eu)))/60 - ...
    (Co*m*(Eh - 1)*(Eu - 1))/60)
```

```
****Class                                                          100,000****

G                                                                           =

  233.1816


New_ACR_100k                                                                =

    0.5540
```

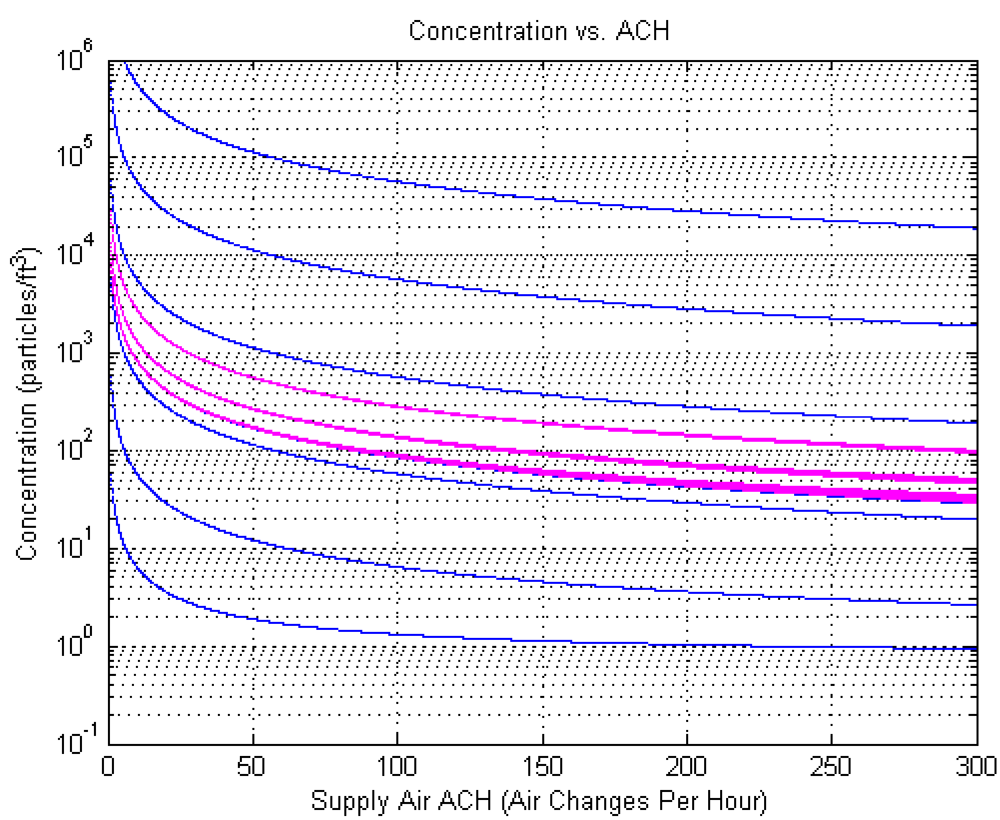


Figure 56: KEB particle concentration vs. ACR

A.2 EEM Greenhouse Gas Emission Reduction Calculation Summary

Table 18: GHG emission reduction calculations

	EEM #1.1	EEM #1.2	EEM #1.3	As-Designed	EEM #2.1	EEM #2.2	EEM #2.3	EEM #2.4	EEM #2.5	Total
Annual Cooling Savings (MMBtu)	2,549	1,857	1,097	5,905	384	74	0	361	152	6,856
Cooling COP	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Annual Cooling Steam Savings (MMBtu)	3,186	2,321	1,371	7,381	480	93	0	451	190	8,570
Annual Heating Steam Savings (MMBtu)	2,540	1,836	-215	4,554	2,107	6	0	1,727	1,525	10,466
Total Annual Site Steam Savings (MMBtu)	5,726	4,157	1,156	11,935	2,587	99	0	2,178	1,715	19,036
Steam Transmission Losses	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Annual CHP Plant Steam Savings (MMBtu)	7,158	5,197	1,445	14,919	3,234	123	0	2,723	2,144	23,795
Annual Electricity Savings (MMBtu)	49	25	30	112	11	6	691	-48	-433	-563
Annual CHP Plant Energy Production Savings (MMBtu)	7,207	5,222	1,475	15,031	3,245	129	691	2,675	1,711	23,232
Overall CHP Plant Efficiency	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Annual Natural Gas Savings (MMBtu)	9,609	6,962	1,967	20,041	4,326	172	921	3,566	2,281	30,976
CO2 Emissions Reduction (Metric Tons)	509.47	369.13	104.29	1,062.60	229.38	9.13	48.85	189.09	120.94	1,642.35
CH4 Emissions Reduction (Metric Tons)	0.05	0.04	0.01	0.11	0.02	0.00	0.00	0.02	0.01	0.16
N2O Emissions Reduction (Metric Tons)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2e Emissions Reduction (Metric Tons)	509.5	369.2	104.3	1,062.7	229.4	9.1	48.9	189.1	121.0	1,642.5

A.3 Energy Recovery Cost Estimate

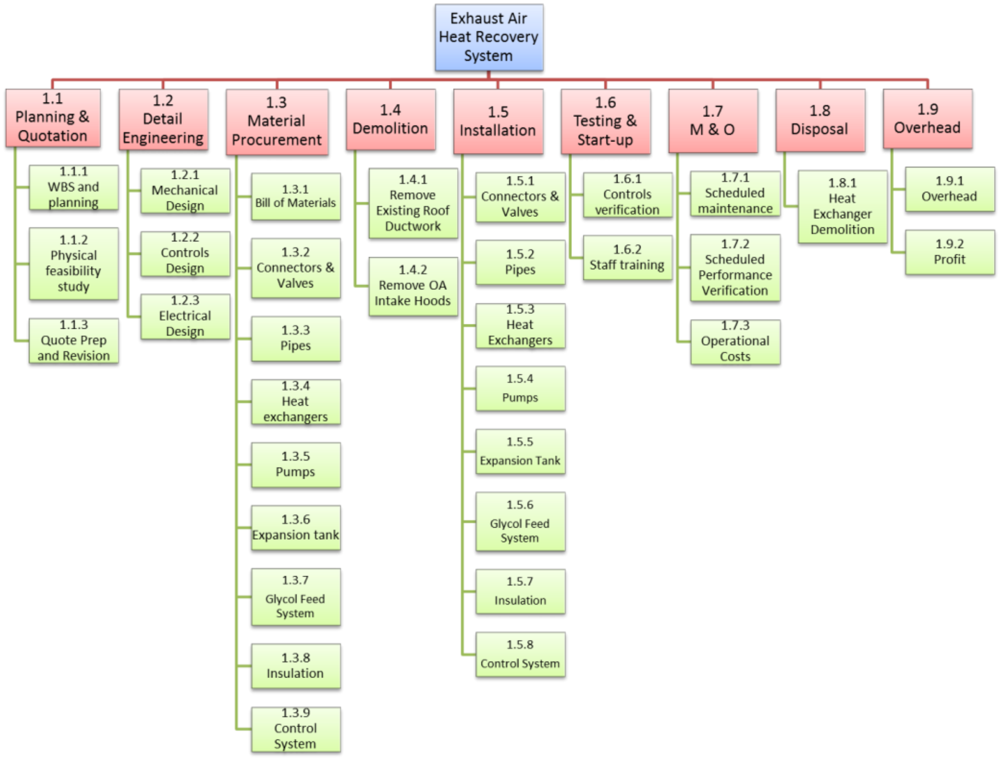


Figure 57: Energy recovery system top-level work breakdown structure (WBS)

Table 19: Cleanroom energy recovery cost estimate overview

		Labor Cost			Materials Cost			Total Cost		
		Low	Middle	High	Low	Middle	High	Low	Middle	High
1.1 Planning & Quotation		$4,060	$4,511	$4,962	$0	$0	$0	$4,060	$4,511	$4,962
1.1.1	WBS and Planning	$1,421	$1,579	$1,737	$0	$0	$0	$1,421	$1,579	$1,737
1.1.2	Physical Feasibility Study	$1,015	$1,128	$1,240	$0	$0	$0	$1,015	$1,128	$1,240
1.1.3	Quote Preperation and Revision	$1,624	$1,804	$1,985	$0	$0	$0	$1,624	$1,804	$1,985
1.2 Detail Engineering		$52,520	$58,355	$64,191	$0	$0	$0	$52,520	$58,355	$64,191
1.2.1	Mechanical Design	$18,594	$20,660	$22,726	$0	$0	$0	$18,594	$20,660	$22,726
1.2.2	Controls Design	$17,528	$19,475	$21,423	$0	$0	$0	$17,528	$19,475	$21,423
1.2.3	Electrical Design	$16,398	$18,220	$20,042	$0	$0	$0	$16,398	$18,220	$20,042
1.3 Material Procurement		$2,772	$3,080	$3,388	$55,913	$85,533	$119,834	$58,685	$88,613	$123,222
1.3.1	Bill of Materials	$2,772	$3,080	$3,388	$0	$0	$0	$2,772	$3,080	$3,388
1.3.2	Connectors, valves	$0	$0	$0	$2,717	$9,849	$22,844	$2,717	$9,849	$22,844
1.3.3	Pipes	$0	$0	$0	$11,685	$26,216	$39,908	$11,685	$26,216	$39,908
1.3.4	Heat Exchangers	$0	$0	$0	$25,000	$30,000	$35,000	$25,000	$30,000	$35,000
1.3.5	Pumps	$0	$0	$0	$3,982	$4,207	$4,633	$3,982	$4,207	$4,633
1.3.6	Expansion tank	$0	$0	$0	$217	$326	$435	$217	$326	$435
1.3.7	Glycol Feed System	$0	$0	$0	$3,472	$4,827	$5,157	$3,472	$4,827	$5,157
1.3.8	Insulation	$0	$0	$0	$346	$670	$1,477	$346	$670	$1,477
1.3.9	Control System	$0	$0	$0	$8,494	$9,438	$10,381	$8,494	$9,438	$10,381
1.4 Demolition		$178	$356	$507	$0	$0	$0	$178	$356	$507
1.4.1	Remove existing roof ductwork	$78	$156	$207	$0	$0	$0	$78	$156	$207
1.4.2	Remove OA intake hoods	$100	$200	$300	$0	$0	$0	$100	$200	$300
1.5 Installation		$10,764	$15,684	$19,696	$0	$0	$0	$10,764	$15,684	$19,696
1.5.1	Connectors, valves	$976	$3,110	$5,189	$0	$0	$0	$976	$3,110	$5,189
1.5.2	Pipes	$3,240	$4,899	$5,679	$0	$0	$0	$3,240	$4,899	$5,679
1.5.3	Heat Exchangers	$852	$1,301	$1,750	$0	$0	$0	$852	$1,301	$1,750
1.5.4	Pumps	$810	$894	$944	$0	$0	$0	$810	$894	$944
1.5.5	Expansion tank	$47	$58	$70	$0	$0	$0	$47	$58	$70
1.5.6	Glycol Feed System	$105	$105	$105	$0	$0	$0	$105	$105	$105
1.5.7	Insulation	$836	$986	$1,195	$0	$0	$0	$836	$986	$1,195
1.5.8	Control System	$3,898	$4,331	$4,764	$0	$0	$0	$3,898	$4,331	$4,764
1.6 Testing and Start Up		$2,359	$3,810	$5,580	$0	$0	$0	$2,359	$3,810	$5,580
1.6.1	Controls verification	$1,590	$2,544	$3,657	$0	$0	$0	$1,590	$2,544	$3,657
1.6.2	Staff training	$769	$1,266	$1,923	$0	$0	$0	$769	$1,266	$1,923
1.9 Overhead & Profit		$5,033	$6,860	$8,533	$5,591	$8,553	$11,983	$10,624	$15,413	$20,517
1.9.1	Overhead	$3,020	$4,116	$5,120	$0	$0	$0	$3,020	$4,116	$5,120
1.9.2	Profit	$2,013	$2,744	$3,413	$5,591	$8,553	$11,983	$7,605	$11,297	$15,397
TOTALS		$77,685	$92,656	$106,857	$61,504	$94,086	$131,817	$139,189	$186,742	$238,674

AEROFIN
Heat Transfer Products

Date: 5/2/2014
Job Name:
System ID:
Quote Number:

COIL INFORMATION	EXHAUST COIL	SUPPLY COIL	
Coil Type	W	W	
Fin Thickness & Material	0.0075 Aluminum Wave	0.0075 Aluminum Wave	
Circuiting	Full	Full	
Tube Wall Thickness & Material	0.020 Copper	0.020 Copper	INCH
Number In Face:	1	1	
Fin Height	54.00	42.00	INCH
Fin Length	96.00	88.00	INCH
Tube Face	36	28	
Fins Per Inch	10.00	10.00	
Rows	6.00	6.00	
Connection Size & Qty.	(1) 3" Threaded	(1) 2.5" Threaded	
Weight - Dry	760	604	Pounds
Dwg Number	CA-W-100	CA-W-100	
Header Info	Standard Non-Ferrous with Brazed Joints	Standard Carbon Stl with Brazed Joints	
Casing Info	1-1/2" Leg with Galvanized Casings	1-1/2" Leg with Galvanized Casings	
Miscellaneous			

PERFORMANCE V	Total Heat Recovered 493.20 MBH	Efficiency - 36 %	
Air Side			
Elevation / Pressure	Sea Level	Sea Level	FT
Pressure	29.92	29.92	IN HG
Air Flow	18,300.0	13,000.0	SCFM
System Face Area	36.00	25.70	FT^2
Face Velocity	508.3	506.5	FPM
Entering Air Temp. DB/WB	69.0 / 43.0	0.0 / 0.0	°F
Leaving Air Temp. DB/WB	44.0 / 0.0	35.2 / 0.0	°F
Total / Sensible Heat Load	493.2 / 493.2	493.2 / 0.0	MBH
Outside Fouling	0.0000	0.0000	HR-FT^2-°F/BTU
Fluid Side 30% Propylene Glycol			
Entering Fluid Temp	36.73	46.20	°F
Leaving Fluid Temp	46.25	36.70	°F
Fluid Flow Rate	110.00	110.00	GPM
Tube Velocity	3.25	4.17	FPS
Inside Fouling	0.0000	0.0000	HR-FT^2-°F/BTU
Turbulators	No	No	
Losses			
Air Pressure Drop	0.80	0.74	IN H2O
Fluid Pressure Drop	12.07	20.40	FT H2O
Notes	51,47	51	

47 Leaving wet bulb temp. is below 32 F (0 C). Contact Home Office.
51 Outside the scope of AHRI standard 410.

Version: 3.5.5 um test.hrc Page 1 of 1 DB Ver: DLL Ver:

Figure 58: Aerofin energy recovery coil selection

A.4 Trane Variable Refrigerant Flow System (20 Ton) Selection Report

TRANE

Project Report

Name :
Tel. :
E-mail :
Address :

UMD-Academic Research Bldg
05-15-2014

Name : Jared Levy
Tel. :
E-mail :
Address :

1 Total Load Profile

1.1 Building1

Dept	Fl.	Room	Area		Load per unit area		Required Capacity			Sum of capacity			Model	Qty	Nominal Capacity			Outdoor	Model	Nominal Capacity		Combi. Ratio	
			CAD	SALES	Cooling	Heating	Cooling		Heating	Cooling		Heating			Cooling		Heating			Cooling	Heating	Cooling	Heating
							TC	SHC	TC	TC	SHC	TC			TC	SHC	TC			TC	TC		
			sq.ft	sq.ft	BTU/h/sq.ft	BTU/h/sq.ft	BTU/h	BTU/h	BTU/h	BTU/h	BTU/h	BTU/h			BTU/h	BTU/h	BTU/h	-	-	BTU/h	BTU/h	%	%
Building1	1F									18000 0	12930 0	202000	4TVC0024B100NB 4TVC0036B100NB	6 1	24000 36000	17100 26700	27000 40000	CU-1	4TVR0240B400NB	24000 0	27000 0	75	75

2 Piping & Wiring

2.1 CU-1

2.1.1 Detail Load Profile

1) Design condition: USA, Dist. of Columbia, Washington, Cooling 95.0/78.0, Heating 5.0/.0

2) Load profile

Building			Unit		Liquid	Gas	H.P.Gas	Airflow	Nominal Capacity			Simulated Capacity			Combi. Ratio	
Dept	Fl.	Room	Name	Model name					Cooling		Heating	Cooling		Heating	Cooling	Heating
									TC	SHC	TC	TC	SHC	TC		
-	-	-	-	-	in	in	in	CFM	BTU/h	BTU/h	BTU/h	BTU/h	BTU/h	BTU/h	%	%
Building1	Roof		CU-1	4TVR0240B400NB	5/8"	1 1/8"	1 1/8"	18364.32	240000		270000	142700		173700	75.00	74.81
	1F		Rm 3105	4TVC0024B100NB	1/4"	1/2"		565.05	24000	17100	27000	19000	14900	23200		
			Rm 3107	4TVC0024B100NB	1/4"	1/2"		565.05	24000	17100	27000	19000	14900	23200		
			Rm 3109	4TVC0024B100NB	1/4"	1/2"		565.05	24000	17100	27000	19000	14900	23200		
			Rm 3111	4TVC0024B100NB	1/4"	1/2"		565.05	24000	17100	27000	19000	14900	23200		
			Rm 2111-1	4TVC0024B100NB	1/4"	1/2"		565.05	24000	17100	27000	19000	14900	23200		
			Rm 2111-2	4TVC0024B100NB	1/4"	1/2"		565.05	24000	17100	27000	19000	14900	23200		
			Rm 2107	4TVC0036B100NB	3/8"	5/8"		776.96	36000	26700	40000	28500	22100	34600		

2.1.2 Control

1) This data is for reference only. Verify local, state, and national electric codes. Trane does not guarantee this data.

2) Configuration

Building			Unit		Transmission wires	Power wires	Breaker Fuse	Main Address		RMC Address		Accessories	
Dept	Fl.	Room	Name	Model name								Optional accessories	Basic accessories
-	-	-	-	-	in2	in2	A						
Building1	Roof		CU-1	4TVR0240B400NB	AWG~	~							
	1F		Rm 3105	4TVC0024B100NB	AWG 18~16	AWG 16~14		0	0	0	0	TVCTRLTWRWE10T	TVEPANPC4NUSET
			Rm 3107	4TVC0024B100NB	AWG 18~16	AWG 16~14		0	1	0	0	TVCTRLTWRWE10T	TVEPANPC4NUSET
			Rm 3109	4TVC0024B100NB	AWG 18~16	AWG 16~14		0	2	0	0	TVCTRLTWRWE10T	TVEPANPC4NUSET
			Rm 3111	4TVC0024B100NB	AWG 18~16	AWG 16~14		0	3	0	0	TVCTRLTWRWE10T	TVEPANPC4NUSET
			Rm 2107	4TVC0036B100NB	AWG 18~16	AWG 16~14		0	4	0	0	TVCTRLTWRWE10T	TVEPANPC4NUSET
			Rm 2111-1	4TVC0024B100NB	AWG 18~16	AWG 16~14		0	5	0	0	TVCTRLTWRWE10T	TVEPANPC4NUSET
			Rm 2111-2	4TVC0024B100NB	AWG 18~16	AWG 16~14		0	6	0	0		TVEPANPC4NUSET

2.1.3 Equipment list

1) Equipment list

Categories	Model name		Qty	Categories	Model name		Qty
VRF	4TVR0240B400NB	4TVR0120B400NB	2	Y-Joint		4TDK3100B0000A	1
4 WAY CASSETTE		4TVC0024B100NB	6			4YDK3419B0336A	1
		4TVC0036B100NB	1			4YDK3100B0468A	1
4 WAY CASSETTE PANEL		TVEPANPC4NUSET	7	Mode Change Unit		4MCUCUY6NCE000	1
WIRED REMOTE CONTROLLER		TVCTRLTWRWE10T	6			4MCUCUY4NCE000	1
Y-Joint		4TDK3819B0000A	1				

2) Piping length

Length as pipe diameter		1/4"	3/8"	1/2"	5/8"	3/4"	7/8"	1"	1 1/8"	1 1/4"	1 3/8"	1 1/2"	1 5/8"	1 3/4"	1 7/8"	2"	2 1/8"
1. Liquid piping	ft	179.99	54.99	31.56	50.00												
2. Gas piping	ft			179.99	54.99				81.56								
3. High pressure gas piping	ft				25.00		31.56		50.00								

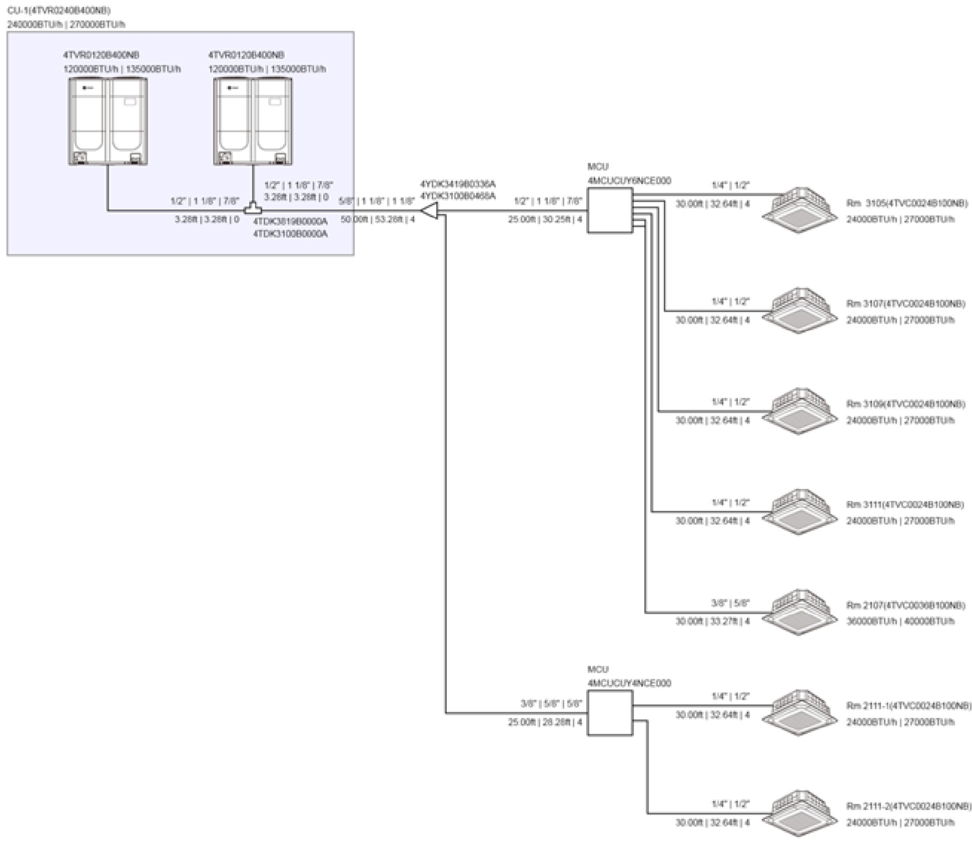
Restriction of pipe length		Restriction (Based on Installation manual)	Actual piping length	Equivalent piping length
1. Total piping length	ft	3280.84	319.52	
2. Maximum piping length	ft	656.17	110.73	124.34
3. Main pipe length	ft		50.00	
4. Piping length between the first branch and the farthest indoor unit	ft	147.64/0.00	56.46	
5. Level difference between outdoor and indoor unit(Max) (OD above ID unit / OD below ID unit)	ft	164.04/131.23	3.28	
6. Level difference between indoor units	ft	49.21		

3) Basic and additional refrigerant amount

Basic refrigerant charge amount : 32.62 lbs

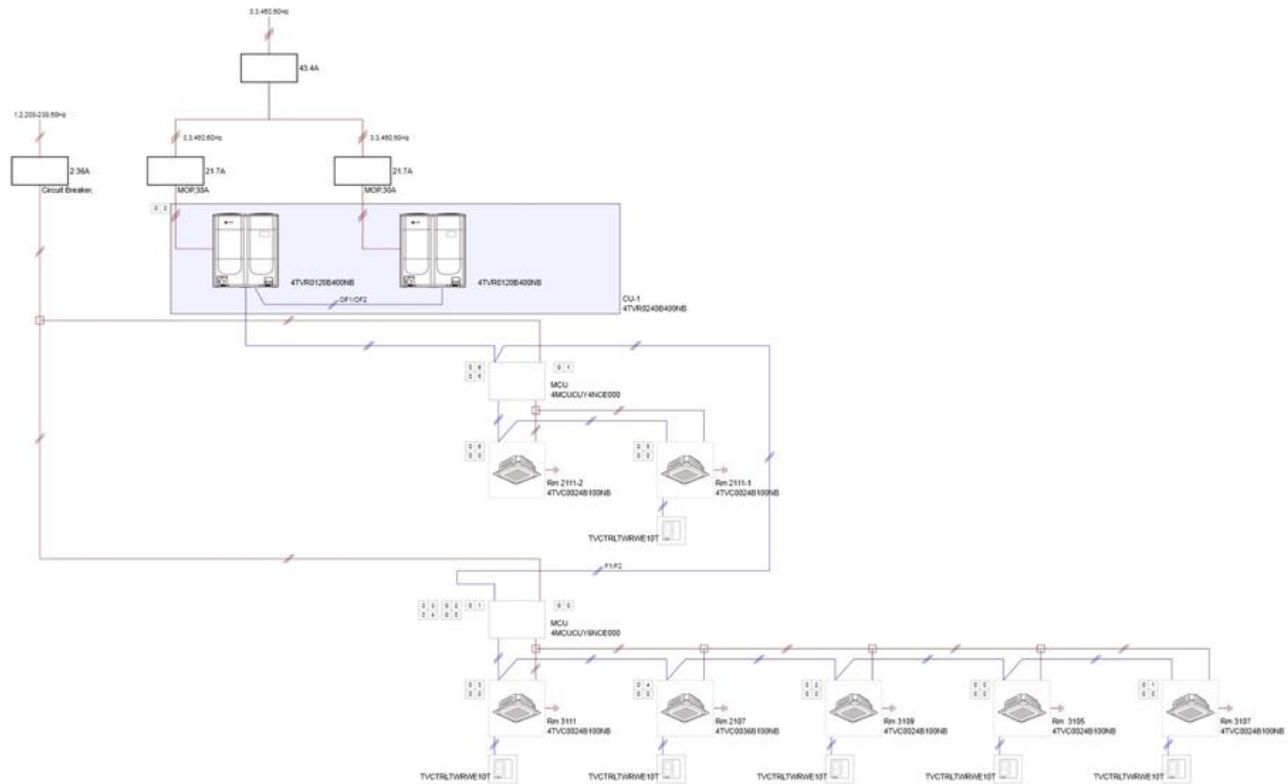
Additional refrigerant amount : 23.13 lbs

2.1.4 Piping



- The system configuration may be different from the actual installation conditions, refer to the installation manual.

2.1.5 Wiring



- The system configuration may be different from the actual installation conditions, refer to the installation manual.

3.1 VRF

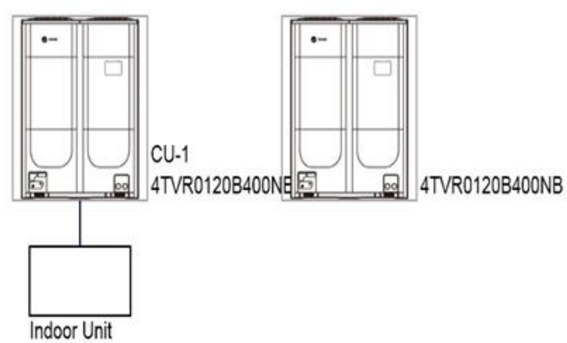
3.1.1 Outdoor units

Model name				4TVR0240B400NB		
Power supply			ø, #, V, Hz	3,3,460,60Hz		
Mode			-	HEAT RECOVERY		
Performance	TON		TON	20.00		
	Capacity(Nominal)	Cooling	kW	70.3371		
			BTU/h	240000		
		Cooling 114.8°F	kW	-		
			BTU/h	N/A		
		Heating	kW	79.1292		
			BTU/h	270000		
	-4 °F	Heating(Low ambient temp.)	kW	-		
			BTU/h	N/A		
Power	Power Input(Nominal)	Cooling	kW	17.4084		
		Heating	kW	18.0825		
	Power Input (at specific)		kW	N/A		
	Power Input(Nominal)	Cooling	A	25		
		Heating	A	26		
	Max. Current Input		A	43.4		
	Circuit Breaker		A	-		
COP	Cooling		-	4.04		
	Heating		-	4.38		
Compressor	Type		-	SSC Scrollx2		
	Output		kW × n	6.1252x2		
Fan	Type		-	Propeller		
	Output		W	620x4		
	Number of Units		EA	2		
	Air Flow Rate		CFM	9182.16x2		
	External Static Pressure	Max.	W.G.	0.314959400619778		
Piping Connections	Liquid Pipe		ø,In(mm)	5/8"(15.88)		
	Gas Pipe		ø,In(mm)	1 1/8"(28.58)		
	Discharge Gas Pipe		ø,In(mm)	1 1/8"(28.58)		
	Oil Equalizing Pipe		ø,In(mm)	N/A(N/A)		
Field Wiring	Power Source Wire		In2	-		
	Transmission Cable		In2	AWG/		
Refrigerant	Type		-	R410A		
	Factory Charging		lbs	16.31x2		
Sound	Sound pressure		dB(A)	-		
External Dimension	Net Weight		lbs	626.11x2		
	Shipping Weight		lbs	668.00x2		
	Net Dimensions (WxHxD)		In	(50.98x66.73x30.12)x2		
	Shipping Dimensions (WxHxD)		In	(53.66x74.29x32.76)x2		
Operating Temp. Range	Cooling		F	23.00~120.00		
	Heating		F	-4.00~75.00		

3.1.2 Indoor units

Model				4TVC0024B100NB	4TVC0036B100NB			
Power supply			ø, #, V, Hz	1,2,208-230,60Hz	1,2,208-230,60Hz			
Performance	Capacity(Nominal)	Cooling	kW	7.0337	10.5506			
			BTU/h	24000	36000			
		Cooling (SHC)	kW	5.0115	7.825			
			BTU/h	17100	26700			
		Heating	kW	7.9129	11.7228			
			BTU/h	27000	40000			
Power	Power Input(Nominal)	Cooling	W	40	75			
		Heating		40	75			
	Current Input	Cooling	A	0.3	0.56			
		Heating		0.3	0.56			
Fan	Motor	Type	-	Turbo Fan	Turbo Fan			
		Output	W					
		Number of unit	EA	1	1			
	Air Flow Rate	H/M/L (UL)	CFM	618.03/565.05/494.42	847.58/776.95/706.32			
	External Pressure	Min / Std / Max	W.G.	-	-			
Piping Connections	Liquid Pipe		ø,in(mm)	1/4"(6.35)	3/8"(9.52)			
	Gas Pipe		ø,in(mm)	1/2"(12.7)	5/8"(15.88)			
	Drain Pipe		ø,mm	VP25 (OD 32,ID 25)	VP25 (OD 32,ID 25)			
Field Wiring	Power Source Wire		in2	AWG 16~14	AWG 16~14			
	Transmission Cable		in2	AWG 18/16	AWG 18/16			
Refrigerant	Type		-	R410A	R410A			
	Control Method		-	EEV INCLUDED	EEV INCLUDED			
Sound	Sound pressure	High / Low	dBA	36/34	40/33			
Dimensions	Net Weight		lbs	55.11	63.93			
	Shipping Weight		lbs	68.34	77.16			
	Net Dimensions (WxHxD)		in	33.07x8.03x33.07	33.07x11.33x33.07			
	Shipping Dimensions (WxHxD)		in	35.35x10.82x35.35	35.35x14.05x35.35			
Panel Size	Panel model		-	TVEPANPC4NUSET	TVEPANPC4NUSET			
	Panel Net Weight		lbs	14.77	14.77			
	Shipping Weight		lbs	19.62	19.62			
	Net Dimensions (WxHxD)		in	37.40x1.18x37.40	37.40x1.18x37.40			
	Shipping Dimensions (WxHxD)		in	41.02x3.66x41.02	41.02x3.66x41.02			

4 Controller



- The system configuration may be different from the actual installation conditions, refer to the installation manual.

5 Total Equipment List

Index	Model	Qty.	Remark(Categories)	Unit Price	Amount
Outdoor unit	4TVR0120B400NB	2	VRF	0	0
Indoor unit	4TVC0024B100NB	6	4 WAY CASSETTE	0	0
	4TVC0036B100NB	1	4 WAY CASSETTE	0	0
Piping	4MCUCUY6NCE000	1	Mode Change Unit	0	0
	4MCUCUY4NCE000	1	Mode Change Unit	0	0
	4TDK3819B0000A	1	Y-Joint	0	0
	4TDK3100B0000A	1	Y-Joint	0	0
	4YDK3419B0336A	1	Y-Joint	0	0
	4YDK3100B0468A	1	Y-Joint	0	0
Control System	TVCTRLTCMA300T	1	Touch Screen Controller	0	0
Optional accessories	TVCTRLTWRWE10T	6	WIRED REMOTE CONTROLLER	0	0
Basic accessories	TVEPANPC4NUSET	7	4 WAY CASSETTE PANEL	0	0
Ref. Pipe	1/4"(6.35)	179.99	ft	0	0
	3/8"(9.52)	54.99	ft	0	0
	1/2"(12.70)	211.55	ft	0	0
	5/8"(15.88)	129.99	ft	0	0
	7/8"(22.22)	31.56	ft	0	0
	1 1/8"(28.58)	131.56	ft	0	0
Additional Ref. Quantity	R410A	23.13	lbs	0	0
		Total			0

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