MEASURING WHOLE-BUILDING HVAC SYSTEM ENERGY EFFICIENCY

A Thesis

by

LINYAN WANG

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Chair of Committee,	David E. Claridge
Committee Members,	Charles H. Culp
	Michael B. Pate
Head of Department,	Andreas A. Polycarpou

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ABSTRACT

Usually, the chiller and boiler efficiencies are the primary measures that are considered with respect to building HVAC systems efficiency. However, during operation, several other components consume energy as part of the HVAC system, such as pumps and fans. If a complete building HVAC system efficiency measure would like to be identified, it is necessary to combine all relevant energy uses. This paper defines such an index, called the Building Systems Load/Energy Ratio, which is the ratio of the building systems total load to the total energy input provided by all the HVAC systems components. The building systems total load is composed of the envelope load, the load from internal gains, and the ventilation air load on the secondary systems. The total energy input contains chillers, boilers, pumps and fans on both the air-side and the water-side. Hourly energy efficiency for both heating and cooling are calculated separately when there is heating or cooling load generated in a building.

A building on the Texas A&M University West Campus was selected as the case study to illustrate the methodology. This structure is supplied with electricity, chilled water and heating hot water by the West Campus plants. WinAM software was used to simulate the building energy performance during the period of 9/1/2012 to 8/31/2013, in order to provide the detailed report of hourly HVAC systems operation condition. After combining equations with the WinAM report details, the hourly building load and hourly total energy input was obtained.

As a result, the annual cooling efficiency is 2.09 Btu-Load/Btu-Input (1.69kW/ton), the monthly cooling efficiency varies from 1.45 to 2.68 Btu-Load/Btu-Input, and the hourly cooling efficiency ranges from 0.23 to 3.77 Btu-Load/Btu-Input. The annual heating efficiency is 0.52 Btu-Load/Btu-Input, the monthly heating efficiency varies from 0.06 to 0.6 Btu-Load/Btu-Input, and the hourly heating efficiency ranges from 0.01 to 0.69 Btu-Load/Btu-Input. Since the building is divided by lab and office areas and each area has its interior and exterior zones, there are four kinds of cooling load combinations and three kinds of heating load combinations within whole year. Under each condition of load combination, the analysis of the efficiency values mainly focuses on the chiller plant cooling energy use, plant heating energy use, heating and cooling load, plant cooling efficiency, and the outside air temperature.

DEDICATION

To my family

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NOMENCLATURE

HVAC	Heating, Ventilation and Air-Conditioning
SDVAV	Single Duct Variable Air Volume System
OAHU	Outside Air Handler Unit
AHU	Air Handler Unit
CHW	Chilled Water
HHW	Heating Hot Water
OA	Outside Air
FY13	Fiscal Year 2013
Q_{BSL}	Building Systems Loads
$Q_{BSL,in}$	Building Systems Loads for Interior Zone
$Q_{BSL,ex}$	Building Systems Loads for Exterior Zone
A_{in}	Building Interior Zone Area
$A_{Lab,in}$	Lab Interior Zone Area
$A_{Office,in}$	Office Interior Zone Area
A_{ex}	Building Exterior Zone Area
E_{BS}	Building Systems Energy Inputs
C_{BS}	Building Systems Energy Inputs Cost
Q_{LEnv}	Building Envelop Load
$q_{LEnv,in}$	Building Envelop Load for Interior Zone Per Square Feet
$q_{LEnv,ex}$	Building Envelop Load for Exterior Zone Per Square Feet

Q_{LGain}	Building Internal Gains
$q_{LGain,in}$	Building Internal Gains for Interior Zone Per Square Feet
$q_{LGain,ex}$	Building Internal Gains for Exterior Zone Per Square Feet
Q_{LVent}	Building Ventilation Air Load
$q_{LVent,in}$	Building Ventilation Air Load for Interior Zone Per Square Feet
$q_{LVent,ex}$	Building Ventilation Air Load for Exterior Zone Per Square Feet
$C_{B,Fan}$	Building Fans Energy Consumption
$C_{B,CHWPump}$	Building Chilled Water Pump Energy Consumption Cost
$C_{B,HHWPump}$	Building Heating Hot Water Pump Energy Consumption Cost
$C_{CHWPump}$	Plant Chilled Water Pump Energy Consumption Cost
$C_{HHWPump}$	Plant Heating Hot Water Pump Energy Consumption Cost
C_{CTFan}	Plant Cooling Tower Fans Energy Consumption Cost
C_{CWPump}	Plant Condensing Water Pump Energy Consumption Cost
$C_{Chiller}$	Chiller Plant Cooling Energy Consumption Cost
C_{Boiler}	Boiler Plant Heating Energy Consumption Cost
E_i	Energy Inputs by a Component i
P_i	Unit Cost for a Kind of Fuel i
$R_{PC,E/L}$	Plant Cooling Energy/Load Ratio
R_{PH}	Plant Heating Efficiency
E_{CHW}	Chiller Plant Cooling Energy Use for a Building
C_{PC}	Chiller Plant Cooling Energy Consumption Cost
E_{HHW}	Boiler Plant Heating Energy Use for a Building

C_{PH}	Boiler Plant Heating Energy Consumption Cost
$E_{S,V}$	Building Sensible Ventilation Load
$E_{L,V}$	Building Latent Ventilation Load
V_{OA}	Outside Air Flow Volume
$V_{OA,in}$	Outside Air Flow Rate for Interior Zone
$V_{OA,ex}$	Outside Air Flow Rate for Exterior Zone
T_{OA}	Outside Air Temperature
T_{RA}	Return Air Temperature
w_{OA}	Outside Air Humidity Ratio
w_{RA}	Return Air Humidity Ratio
CUP	Central Utility Plant
SUP1	Satellite Utility Plant 1
SUP2	Satellite Utility Plant 2
SUP3	Satellite Utility Plant 3
$q_{V,in}$	Ventilation Load for Interior Zone Per Square Feet
$q_{V,ex}$	Ventilation Load for Exterior Zone Per Square Feet
$q_{S,V,in}$	Sensible Ventilation Load for Interior Zone Per Square Feet
$q_{S,V,ex}$	Sensible Ventilation Load for Exterior Zone Per Square Feet
$q_{L,V,in}$	Latent Ventilation Load for Interior Zone Per Square Feet
$q_{L,V,ex}$	Latent Ventilation Load for Exterior Zone per Square Feet
$V_{Office,in}$	Office Interior Zone Air Flow Rate
$V_{Lab,in}$	Lab Interior Zone Air Flow Rate

$T_{Office, in, Supply}$	Office Interior Zone Supply Air Temperature
$T_{Lab, in, Supply}$	Lab Interior Zone Supply Air Temperature
$T_{Office, CL}$	Office Cooling Coil Leaving Air Temperature
$T_{Lab, CL}$	Lab Cooling Coil Leaving Air Temperature
PLR	Ratio of Flow at Part Load to Design Rated Flow
NG	Natural Gas
ELE	Electricity
WC	West Campus

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1. INTRODUCTION

1.1 Background

The buildings sector consumes 40% of the total energy usage in the United States, including 22% (21.62 Quadrillion Btu/year) by residential buildings and 19% (18.02 Quadrillion Btu/year) by commercial buildings (EIA, 2012). The projected growth rate for 2011 – 2040 of 0.5% per year (about 3.1 Quadrillion Btu) for the commercial building sector is higher than any other end-use sector (EIA, 2013). In a commercial building, HVAC systems typically consume around 30% of the energy, with typical space heating use of 5%, cooling of 14% and 12% for ventilation (EIA, 2012). Hence, efficient HVAC system performance is important in achieving an efficient building to save energy, reduce emissions and obtain cost savings without sacrificing thermal comfort and good indoor environmental quality.

There are many ways of achieving HVAC systems with high energy efficiency in a building. For instance, obtaining a LEED platinum rating for a new building with the design of an efficient HVAC system, or implementing Continuous Commissioning® to optimize an existing building's HVAC systems (Liu et al. 2002) using an energy performance model. These efforts may provide efficient HVAC systems, and detailed cost savings relative to less efficient systems or operation may be determined, but this still provides no measure of the efficiency for the entire HVAC system in meeting the heating and cooling loads present in the building. Therefore, after implementing these measures, it is still unknown whether there is potential for further improvement in the energy efficiency of the systems in a particular building.

There are a number of common efficiency measures related to the building HVAC systems. Usually, the chiller and boiler efficiencies are the primary measures considered when mentioning building HVAC efficiency. However, during operation, several other components consume energy as part of the entire HVAC system, like pumps and fans. It is necessary to consider all of these components together if a complete building HVAC systems efficiency is to be identified. However, no measure of complete system efficiency has come into significant usage in the market. This thesis will present a new measure to quantify complete HVAC systems energy efficiency as a comprehensive measure to guide the further building commissioning or energy retrofit programs.

1.2 Purpose and Significance

The thesis will introduce a measure of complete HVAC systems efficiency called the Building Systems Load/Energy Ratio, or LER, which is the ratio of building systems total load divided by total energy input. The LER is computed by dividing the thermal load generated in a building by all of the energy input required by the HVAC components summed together to meet this load. This measure will provide an absolute indication of the efficiency with which a system meets the heating and cooling loads present in a particular building. Experience shows that the efficiency of systems varies under different weather conditions, occupancy schedules, etc., but the LER will provide a common basis for comparing how well different systems meet a particular set of loads. It may be possible to use the LER to estimate the potential for efficiency improvement in a building once there is sufficient experience with its use.

The total energy input mentioned above includes input to many different components, like chillers, boilers, pumps and fans. The LER will help to highlight the differences in the contribution of each of these components to total system efficiency when comparing two different HVAC systems.

2. LITERATURE REVIEW

The literature review chapter describes existing energy efficiency indexes and the energy performance tools used to evaluate how much energy should be required to meet specific cooling or heating loads in a building. These are presented to familiarize engineers and others with the diverse energy efficiency indexes currently available.

2.1 Common Energy Efficiency Index

Several important measures of HVAC equipment and system efficiency are widely used. Furnaces and boilers are typically rated using some form of fuel efficiency, often based on the higher or lower heating value.

2.1.1 Coefficient of Performance

The most fundamental way used to describe the efficiency of cooling equipment and heat pumps is the Coefficient of Performance or COP since "efficiency" is generally understood to have a value less than unity, while the COP of most HVAC cooling equipment is larger than unity. The COP is the ratio of the net refrigerating or heating provided (in Watts) to the power input (in Watts) at any given set of rating conditions expressed in Watts/Watts (AHRI, 2011).

2.1.2 Energy Efficiency Ratio

Energy Efficiency Ratio (EER) is the ratio of the cooling capacity (in Btu/h) to the power input (in Watts). National appliance standards require room air conditioners to have an EER rating of 8 to 9 or greater, depending on the type and capacity (DOE, 2012a).

2.1.3 Seasonal Energy Efficiency Rating

The Seasonal Energy Efficiency Rating (SEER) is the ratio of total cooling provided divided by the total electric energy input (expressed as Btu/Wh) during a test cycle designed to approximate average annual performance. The test cycle is specified in ANSI/ASHRAE Standard 37 (ANSI/ASHRAE, 2007). SEER ratings for air conditioning and air-source heat pump systems manufactured today range from 13 SEER to 24 SEER, with the highest numbers indicating the most efficient units that offer the most energy savings year after year (AHRI, 2014).

2.1.4 Integrated Part-Load Value

The term Integrated Part-Load Value, or IPLV, is used to signify the cooling efficiency related to a typical (hypothetical) season rather than a single rated condition. The IPLV is computed by determining the weighted average efficiency at part-load capacities specified by an accepted standard using the same condensing temperature typically for each part-load condition and not include cycling or load/unload losses. The units should be confirmed when the term IPLV is used since the units of IPLV are not consistent in the literature. Therefore, ASHRAE Standard 90.1 uses IPLV to report seasonal cooling efficiencies for both seasonal COPs (unitless) and seasonal EERs (Btu/Wh), depending on the equipment capacity category. Seasonal efficiencies for large chillers are reported by most chiller manufacturers as IPLV with the units of kW/ton. Depending on how a cooling system loads or unloads, the IPLV can be between 5% and 50% higher than the EER at the standard rated condition. IPLV can be expressed by Eq. 1.

$$\text{IPLV} = \frac{1}{\frac{0.01}{\text{A}} + \frac{0.42}{\text{B}} + \frac{0.45}{\text{C}} + \frac{0.12}{\text{D}}} \tag{1}$$

where A = Power Input per Capacity, kW/ton at 100%, B = Power Input per Capacity, kW/ton at 75%, C = Power Input per Capacity, kW/ton at 50%, D = Power Input per Capacity, kW/ton at 25% (AHRI, 2011).

2.1.5 Annual Fuel Utilization Efficiency

Annual Fuel Utilization Efficiency (AFUE) is the ratio of heat output compared to the total fossil fuel energy consumed by a furnace or boiler over a test cycle as specified in ANSI/ASHRAE Standard 103 (ANSI/ASHRAE, 2009). The minimum allowed AFUE rating for a non-condensing fossil-fueled, warm-air furnace is currently 78% for almost all types of furnaces. AFUE doesn't include the heat losses of a duct system or piping, which can be as much as 35% of the energy for total output when ducts are located in partially conditioned or unconditioned space (DOE, 2012b).

2.1.6 Heating Seasonal Performance Factor

Heating Seasonal Performance Factor (HSPF) is the total heating output of a heat pump (in Btu) during its normal use period for heating divided by the total electrical energy input (in Watt-hours) over a test cycle as specified in ANSI/ASHRAE Standard 37 (ANSI/ASHRAE, 2007). HSPF is used only for heat pump equipment with typical unit size less than 65,000 Btu/hr (DOE, 2014).

2.2 Building Energy Efficiency Index

Some papers put forward several indexes that can measure the building energy efficiency to a certain extent for different occasions.

2.2.1 Energy Use Intensity

Energy use intensity, or EUI being expressed as kWh/ft^2, is the preferred unit of analysis for commercial end-use demand forecasting (Eto, 1990) to reflect a rate of energy use and work as a type of energy benchmark to be widely used in building energy analysis. For commercial buildings, the EUI is also often commonly expressed in units of Btu/ft^2. EUIs attempt to normalize energy use relative to building floor area to indicate inefficient buildings or systems where improvements can be made when wide differences occur between building EUIs.

2.2.2 HVAC Power Density

In a format similar to the lighting power density (LPD), the HVAC power density (HvacPD) is expressed in terms of power input per unit area for the entire HVAC system. The development process of HvacPD begins by computing the required specific design cooling (q_c) and heating (q_h) loads for energy efficient buildings. These values are divided by the system energy efficiency ratio (EER) for cooling called cooling power density (CPD) and the thermal efficiency values for fossil fuel equipment (η_t) for heating called heating input density (HID) to arrive at HvacPD values.

$$\mathrm{CPD}\ [{}^{W_e}/_{ft^2}] = \frac{q_c}{A}\left[{}^{Btu}/_{h \cdot ft^2}\right] \div \mathrm{EER}[{}^{Btu}/_{W \cdot h}] \tag{2}$$

$$\mathrm{HID}\left[{}^{Btu}/_{h \cdot ft^2}\right] = \frac{q_h}{A} \div \eta_t \tag{3}$$

The CPD present the electrical demand requirement per unit, including the input for all HVAC systems components (chillers, fans, pumps). The HID expresses the heating requirement per unit floor area. Once the building type and climate type are identified, HvacPD can be applied as a preliminary index to measure the HVAC systems energy demand for a complex building. It is directly identifies the impact of all system components upon the net efficiency of the building HVAC system (Kavanaugh et al., 2006) at design conditions.

2.2.3 System Performance Ratio

Goel et al. (2014) introduce the System Performance Ratio (SPR), which is defined as the ratio of annual system load to the annual system energy consumption, similar to a whole system COP. Cooling system performance ratio (C-SPR), heating system performance ratio (H-SPR), and total system performance ratio (T-SPR) are separately calculated to provide an independent evaluation of the cooling, heating and integrated HVAC systems.

$$\mathrm{SPR_{Heating}} = \frac{\text{Ideal annual heating load}}{\mathrm{E_{Heating}} + \mathrm{E_{Fan,Heating}} + \mathrm{E_{Pump,Heating}}} \quad (4)$$

$$\mathrm{SPR_{Cooling}} = \frac{\text{Ideal annual cooling load}}{\mathrm{E_{Cooling}} + \mathrm{E_{Fan,Cooling}} + \mathrm{E_{Pump,Cooling}} + \mathrm{E_{Heat,Rejection}}} \quad (5)$$

$$\mathrm{SPR_{Total}} = \frac{\text{Ideal annual heating load} + \text{Ideal annual cooling load}}{\mathrm{E_{Heating}} + \mathrm{E_{Cooling}} + \mathrm{E_{Fan}} + \mathrm{E_{Pump}} + \mathrm{E_{Heat,Rejection}}} \quad (6)$$

Where the $E_{Heating}$ is the heating coil energy use, $E_{Fan,Heating}$ is the fan energy use during heating mode, $E_{Pump,Heating}$ is the pump energy use in the case of hydronic systems, $E_{Cooling}$ is the cooling coil energy use, $E_{Fan,Cooling}$ is the fan energy use during cooling mode,

$E_{Pump,Cooling}$ is the pump energy use in the case of hydronic systems, and $E_{Heat,Rejection}$ is the energy use for heat rejection in the cooling tower.

A special HVAC system type available in EnergyPlus, called the Ideal Loads system, can be used to simulate, in order to determine the base annual heating, cooling, and total loads for each building. A higher value indicates less heating and cooling energy use to meet the loads to represent a more efficient HVAC system. SPR provides a single evaluation criteria to address all of the HVAC system's components in a building, which includes mechanical ventilation, equipment full and part load performance and distribution system effectiveness. However, most engineers and building operators are not familiar with what constitutes good or poor efficiency values for a system using gas for heating and electricity for cooling. The $SPR_{Cooling}$ and $SPR_{Heating}$ values deal with this problem, but do not consider the impact of simultaneous heating and cooling on system efficiency.

2.2.4 Multizone Efficiency Index

Kreider and Rabl (1994) proposed the Multizone Efficiency Index (MEI), which accounts for the inefficiency of the HVAC systems caused by simultaneous heating and cooling for different zones. The MEI is calculated separately for heating and cooling: heating MEI is the ratio of the annual heating energy required by the ideal one-zone systems to the observed annual heating energy, and cooling MEI is the ratio of the annual cooling energy required by the ideal one-zone systems to the observed annual cooling energy. The highest possible value of the MEI is unity. When the MEI is small, the overconsumption is great because of the simultaneous heating and cooling. The MEI does not evaluate the efficiency of the individual heating and cooling systems.

2.2.5 Energy Delivery Efficiency

Reddy et al. (1994) introduced an energy delivery efficiency (EDE) index, which is calculated as the absolute value of measured thermodynamic minimum energy use (the difference between measured cooling and heating energy) divided by actual energy use. The EDE methodology pointed out that the 1-zone model is an upper limit, and that the efficiency of a two zone model, would constitute a more realistic energy standard to evaluate the efficiency of actual HVAC systems. This methodology was applied to two institutional buildings in the Texas LoanSTAR program (Claridge et al., 1991) with measured energy data for both pre-retrofit and post-retrofit time periods. The final EDE plots showed the improvement of the energy efficiency after the building retrofit program. The values of EDE reflect a more complete HVAC system efficiency than the common measures mentioned before since both heating and cooling are considered in EDE.

The mathematical treatment considered only sensible heat flows, but was expanded by Reddy et al. (1998) to cover supply air latent effects as well as the influence of economizer operation. The EDE approach is a diagnostic tool to evaluate HVAC retrofit performance and operation and maintenance measures.

2.2.6 Energy Efficiency Index for Buildings

González et al. (2010) proposed the energy efficiency index for buildings (EEIB) as the basis for a common framework of a certification scheme. EEIB is calculated as a ratio of the performance (in terms of energy consumption) of the actual building (AB) under certification or study, and that of a reference building (RB) (Eq. 7). Both RB and AB should belong to the same type of building and have the same floor space since the energy use of a building is significantly dependent on the function (residential, hospital, education, office). The energy consumption of the RB, must represent a reference based on the energy use of the whole set of buildings of the same type. Thus, EEIB can express a higher or lower performance of the AB in comparison with a standardized performance level in that type of building. The Spanish energy certification of new buildings defines seven bands of values of the energy certification index from less than 0.4 to greater than 2.0.

$$EEI_B = \frac{C_{AB}}{C_{RB}} \tag{7}$$

Where C_{AB} and C_{RB} are the energy consumption with the units of kWh/year.

2.2.7 System Coefficient of Performance

Yan et al. (2012) proposed the system coefficient of performance (SCOP), which is an indicator to assess the overall energy efficiency of an HVAC system. SCOP is defined as the ratio between the total refrigerating loads to the total consumption of the HVAC system. Since obtaining an accurate value of SCOP by modelling components is complicated and time-consuming, a simplified linear regression model (Eq. 8) is adopted to calculate the partial load efficiency of an HVAC system.

$$SCOP = SCOP_{full} \times (PLR)^{C1} \tag{8}$$

where $SCOP_{full}$ and C_1 are the two regression coefficients being identified using short-term measurement data for a particular HVAC system. PLR is the part load ratio that reflects the degree of deviation of partial load operation conditions from the full load conditions.

SCOP is estimated using system-level regression models in which the entire HVAC system is viewed as a whole and the performance is considered to be only determined by the part load ratio of the chiller. As a result, the energy performance can only be examined at the system level while the component performance cannot be provided.

And then, C. Yan et al. (2015) developed SCOP calculated using component-level HVAC models by which the energy performance of both the entire HVAC system and individual components can be provided for the use of detailed diagnosis.

$$\mathrm{SCOP} = \frac{\mathrm{CL_{Supply}}}{\mathrm{E_{HVAC}}} = \frac{\mathrm{CL_{Supply}}}{\mathrm{E_{Chiller}} + \mathrm{E_{Pump}} + \mathrm{E_{Fan}}} \tag{9}$$

where $E_{chiller}$, E_{Pump} and E_{Fan} are the energy consumption of chiller, pumps and fans respectively, and CL_{Suppy} is the actual cooling load at the supply side.

2.3 Building Energy Performance Tools

Several building energy performance tools have been developed by government organizations with the aim of helping the public be aware of their building's degree of energy efficiency.

2.3.1 Building Energy Asset Score

The Building Energy Asset Score, being developed by Pacific Northwest National Laboratory for the Department of Energy (DOE), aims to help assess the physical characteristics and structural energy efficiency of new and existing commercial buildings.

The energy asset scoring tool is a web-based application with a simplified user interface built on a centralized simulation engine – Energy Plus - in order to reduce the implementation cost and increase standardization compared with an approach that requires users to build their own energy models. There are two levels of rating application – the simple level and the advanced level, based on the collection of the variable types needed. The variables obtained determine the different degrees of accuracy for the preliminary analysis of building physical characteristics and guidance in finding improvement of potential areas for identifying cost-effective retrofit opportunities. The Asset Score is generated by simulating building performance under a standard set of typical operation and occupancy conditions. By focusing only on a building's physical characteristics and removing occupancy and operational variations, the system allows consistent comparisons between differently operated buildings. With this tool, users can enter building information online to obtain a standard Asset Sore Report and feedback on areas and options for energy efficiency improvements. There are four sections for a standard Asset Score Report – scores (current score and potential score after all recommended upgrades are made) based on source energy use intensities (EUIs), buildings systems evaluations, a list of improvement areas and options, and building assets (a detailed list of building characteristics that contribute to a building's Asset Score) (Wang et al., 2013).

2.3.2 ENERGY STAR Portfolio Manager

The ENERGY STAR Portfolio Manager is an energy measure and tracking tool for existing commercial buildings served as a web-based application. It was developed by the U.S. Environment Protection Agency (EPA) to assist in evaluating and tracking a facility's energy consumption, help identify underperforming facilities, generate an ENERGY STAR score (from 1-100), track energy savings from implementation of energy efficiency measures, and evaluate potential energy saving measures for a facility (Roskoski et. al, 2011).

2.3.3 Leadership in Energy and Environmental Design

The Leadership in Energy and Environmental Design (LEED) green building certification system was developed in 2000 by the United States Green Building Council (USGBC). LEED is now accepted as a popular tool to guide and evaluate green buildings throughout their life-cycle. The LEED version 3 (released in 2009) still works for most building projects, even though the LEED version 4 has been launched. The LEED (version 3) certification systems is composed of five main categories, including Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, and Indoor Environmental Quality. Under each category, there are various credits needed to achieve a particular LEED rating, with each credit assigned certain point values from 10 to 35. Two additional categories, Innovation and Regional Priority, provide 10 more points as bonus. There are 100 total points possible for the five main categories. The final score for each building is determined by the sum of the points earned from these credits. There are 4 grades based on the total points earned: Certified (40-49 points), Silver (50-59 points), Gold (60-79 points), and Platinum (more than 80 points). The LEED system enables rating the energy efficiency and environmental performance of the entire building based on the final score (Suzer, 2015).

2.3.4 Building Energy Quotient

The Building Energy Quotient (bEQ) is a building energy performance labeling program developed by ASHRAE. There are two separate workbooks, including one evaluation of As Designed potential for new construction and the other assessing In Operation performance for existing buildings. The rating score is expressed by Eqs. 10 - 11.

$$\text{Rating Score for Existing Building} = \left(\frac{\text{EUI}_{\text{metered}}}{\text{EUI}_{\text{median}}}\right) \times 100 \tag{10}$$

$$\text{Rating Score for New Construction} = \left(\frac{\text{EUI}_{\text{baseline}}}{\text{EUI}_{\text{median}}}\right) \times 100 \tag{11}$$

where the $EUI_{metered}$ is the measured energy use index for an existing building, the $EUI_{baseline}$ is the energy use index value obtained from the building energy modeling for new construction, and the EUI_{median} is the normalized median energy use index based on ENERGY STAR Portfolio Manager. It is easy to use a Building Energy Quotient Dashboard to check the building energy efficiency, where a lower rating score means better efficiency and a higher score represents worse efficiency.

The As Designed evaluation uses a baseline median EUI from modeling a building's energy performance with standardized inputs, in order to evaluate the building's potential energy use independent of operational and occupancy variables. The In Operation assessment uses the measured EUI from an energy audit and offers specific building energy saving measures with estimated costs and payback information that can improve a building's energy performance. It focuses on the building's measured energy use for the preceding 12 to 18 months.

2.4 Summary of Literature Review

The existing indexes related to building energy system efficiency are described above. Each index has its own focus for different target clients, which leads to different strengths and weaknesses. The common energy efficiency indexes such as COP are based on testing in a laboratory, which is different from normal operating conditions. A whole building EUI can indicate the overall building efficiency as an integrated system, but it is inadequate to fully understand the individual effect of building subsystems. Since the HVAC Power Density is based on peak load demand, part load efficiencies, the impact of system controls and similar factors are not reflected in the value. The SPR doesn't reflect the efficiency variation during a year since SPR only presents an average value. The MEI focuses on the inefficiency of HVAC systems instead of the efficiency, due to the simultaneous heating and cooling. The EEIB cannot present an absolute building systems efficiency value since it relies on the consumption of the reference building. Although the energy efficiency of the entire cooling system can be measured by the SCOP, the heating systems still need to be considered owing to the heating energy use impacts the efficiency of the entire HVAC systems. The EDE is limited to the thermal efficiency of the airside sub-system. The energy use of the water-side and the plant must be considered in a measure of complete HVAC system efficiency. The building energy performance tools give an integrated score to measure the entire building systems energy efficiency with consideration of all the components. However, the final score is only a simple combination of the different components without reflecting the actual HVAC systems energy efficiency. An efficiency measure for the complete building HVAC systems which considers both heating and cooling together, as well as the water-side and air-side on the real condition would be desirable. The impact of the energy input components, like fans and pumps, would then be evident under different operating conditions.

3. METHODOLOGY

This section will define the load/energy ratio and describe the calculation method of both total building load and total energy input. It will then give a detailed application using the WinAM simulation program and describe the approach for analyzing the results.

3.1 Definition

The overall building systems load/energy ratio LER methodology defines an index that measures the energy efficiency of the entire HVAC system in a specific building. It can also be used to define the efficiency of the complete heating system or the complete cooling system. The load/energy ratio LER can be expressed in terms of the different sources of energy (E_{BS}) required to meet the corresponding positive or negative loads (Q_{BSL}) of the entire building (Eq. 12).

$$\mathrm{LER} = \mathrm{Q_{BSL}}/\mathrm{E_{BS}} \tag{12}$$

The total building systems load, Q_{BSL}, is defined as the sum of the envelope load (Q_{LEnv}), the load from internal gains (Q_{LGain}) and the ventilation air load on the secondary systems (Q_{LVent}) (Eq. 13).

$$\mathrm{Q_{BSL}} = \mathrm{Q_{LEnv}} + \mathrm{Q_{LGain}} + \mathrm{Q_{LVent}} \tag{13}$$

It differs from the common definition of building load that includes only the envelope and internal gains. The envelope load includes the radiation from the sun and the thermal conduction through walls, windows, roofs, and doors. The load from internal gains includes the lighting loads, plug loads, the sensible and latent loads from people, the equipment loads from electrical/mechanical components and office appliances. The ventilation air load on the secondary system includes the sensible and latent loads from the outside ventilation air. This total load represents cooling load when it is positive and heating load when it is negative for an interior zone or exterior zone.

The total energy input (E_{BS}) can be obtained by first obtaining the combination of all the energy input costs (C_{BS}), so the different fuels are uniformly handled on the basis of cost when multiple fuels are used. The total energy input cost includes air-side and water-side costs as well as boiler/tower/chiller costs. The air-side cost includes the energy consumption of the fan motors in the air handler units and any return fans present ($C_{B,Fan}$). The water-side cost includes the building cooling ($C_{B,CHWPump}$) and heating pumps ($C_{B,HHWPump}$) as well as the primary and secondary chilled water ($C_{CHWPump}$) and heating hot water pumps ($C_{HHWPump}$). The chiller/tower/boiler cost includes the chiller compressor ($C_{Chiller}$), the cooling tower fans (C_{CTFan}), condensing water pumps (C_{CWPump}), and boiler (C_{Boiler}) energy (Eq. 14).

$$\begin{gathered} C_{BS} = C_{B,Fan} + C_{B,CHWPump} + C_{B,HHWPump} + C_{Chiller} + C_{CTFan} + \\ C_{CWPump} + C_{CHWPump} + C_{HHWPump} + C_{Boiler} \end{gathered} \tag{14}$$

where all quantities are expressed in monetary units (e.g. $). Each cost component is the product of the energy required by a component (E_i) and the unit cost of the fuel (P_i) used by that component (Eq. 15).

$$C_i = E_i \times P_i \tag{15}$$

Then the equivalent energy input can be determined for a single energy source (Eq. 16) in computing the load/energy ratio.

$$E_{BS} = C_{BS}/P_i \tag{16}$$

where P_i is the unit price of the electricity (P_{ELE}), natural gas (P_{NG}) or other fuel in terms of which the load/energy ratio will be expressed. This formula includes the cost of the electricity used to meet building heating loads when a boiler is used, and the reheat that may be present in a system when in the cooling mode.

3.2 Methodology Adjustments

The energy/load ratio will normally be calculated using the entire building load and total energy input for each building. However, campus buildings used for the case study in this paper are served by a central plants group and it is impossible to separate the plant energy consumption used to supply a specific building. Hence the methodology will be adjusted for use with central plants as follows:

When the building has cooling energy input, the chiller plant cooling energy input for each building will be obtained using the chiller plant average cooling energy/load ratio ($R_{PC,\,E/L}$) and the chiller plant cooling energy use (E_{CHW}).

$$\begin{aligned} C_{Chiller} + C_{CTFan} + C_{CTPump} + C_{CHWPump} &= C_{PC} \\ &= R_{PC,E/L} \times E_{CHW} \times P_{ELE} \end{aligned} \tag{17}$$

where C_{PC} is the chiller plant cooling energy consumption cost.

When the building has heating energy input or uses reheat, the boiler plant heating energy input for each building will be obtained using the boiler plant average heating efficiency (R_{PH}) and the boiler plant heating energy use (E_{HHW}).

$$C_{HHWPump} + C_{Boiler} = C_{PH} = E_{HHW}/R_{PH} \times P_{NG} \quad (18)$$

where C_{PH} is the boiler plant heating energy consumption cost, the E_{HHW} is the plant heating hot water usage.

It is common to see a building that has a heating load for one area and a cooling load for another area at the same time. That situation requires the building HVAC systems to provide both heating and cooling energy at the same time. We can use the total building load and total energy input to get a single load/energy ratio easily. However, separating the whole system into cooling and heating energy efficiency can help us recognize the system's actual efficiency when different building loads are generated. Another reason for computing them separately is that the heating energy efficiency must be less than unity (unless using a heat pump) while the cooling efficiency is commonly greater than unity. As a result, the cooling and heating load and energy input were separated and individual calculations made for the case study presented later. The final results still present the interaction between cooling and heating at the systems level.

Since it is desired to obtain both cooling and heating efficiency values, the total energy input needs to be separated based on when cooling load is generated or heating load is generated. The group of equations 12 to 18 still can be used, but each term is evaluated only for the cooling portion or the heating portion.

4. APPLICATION

The load/energy ratio methodology described in the previous section may be used to determine the overall energy efficiency of the complete HVAC system in a specific building. A campus building was selected as a case study to illustrate the methodology. The building has daily heating and cooling data for the heating hot water and chilled water that are supplied by the West Campus central plants, as well as hourly electricity consumption data to use for energy model calibration. The hourly energy data for chillers, boilers and auxiliaries from the central plants were used for the plants cooling energy input and plants heating energy input.

Hourly values of the different Energy/Load Ratios are obtained by first calibrating a WinAM simulation model to the measured energy consumption data for the building and then using the simulated values of the loads and the energy inputs to the HVAC system to provide a close approximation of the actual Energy/Load Ratios for the building.

4.1 General Building Description

The Office of the Texas State Chemist (shown in Figure 1) was selected as the case study building. It was constructed in 2006 and is located on the West Campus of Texas A&M University in College Station, Texas. It is a one-story building with a total conditioned area of 19,132 ft^2. It is a typical educational building and consists primarily of laboratories and offices. The building is generally occupied on weekdays from 6:00 AM to 6:00 PM, but also has some occupancy later in the evening and on weekends. Both the lab and office areas are divided into interior and exterior zones to simply distribute the area's building load.

Figure 1   Office of the Texas State Chemist (Energy Systems Laboratory, 2013)

The building HVAC systems are running 24/7. The building lab area is served by an outside air unit (OAHU-1). OAHU-1 is a single duct variable air volume unit with DDC. It supplies conditioned outside air to the office AHU (AHU-2, 900 CFM) and to the lab areas through eighteen Lab-Trac terminals with reheat and eight constant air volume (CAV) terminal boxes with reheat. The building office wing is served by a single duct variable air volume (VAV) DDC air handling unit (AHU-2). There are ten parallel fan powered boxes with reheat, one series fan powered box with reheat, and one cooling only VAV terminal box serving the building office areas. The outside air of AHU-2 is supplied from the outside air handling unit (OAHU-1) through a VAV terminal box. The HVAC system information for both buildings is listed in Table 1. The schematic diagram of the two air handler units are presented in Figure 2 and Figure 3.

Table 1 Building HVAC Systems Information

UNIT	Design Max Supply (cfm)	Design Max OA (cfm)	Service area	Type
OAHU-1	32000	32000	Lab/Office	SDVAV
AHU-2	8000	1760	Office	SDVAV

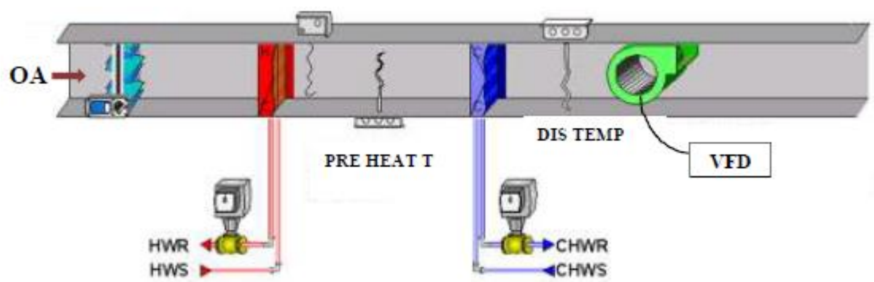


Figure 2 Outside Air Handling Unit (OAHU-1) Schematic Diagram (Energy Systems Laboratory, 2013)

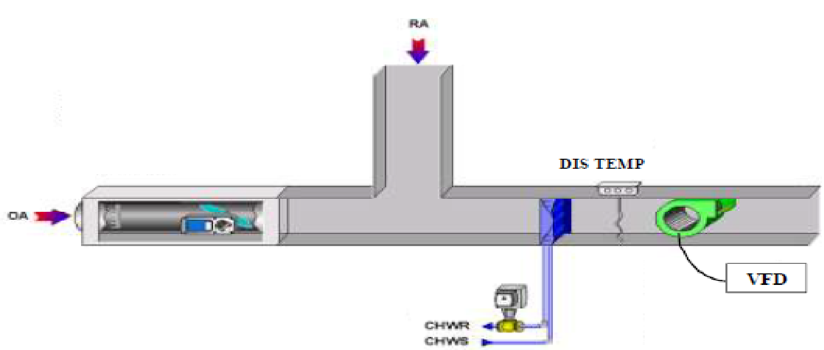


Figure 3 Office Air Handling Unit (AHU-2) Schematic Diagram (Energy Systems Laboratory, 2013)

The building pumping system consists of a chilled water (CHW) loop and a heating hot water loop. The CHW system has two 10 HP, 470 GPM, and 50 ft head DDC controlled variable speed pumps. The heating hot water loop has two 5 HP, 200 GPM, and 57 ft head DDC controlled variable speed pumps.

Table 2 shows the monthly measured energy use of electricity, chilled water and heating hot water for the Office of the Texas State Chemist.

Table 2 Building Monthly Actual Energy Use of Electricity, CHW and HHW

Month	**Measured ELE Use**	**Measured CHW Use**	**Measured HHW Use**
	kWh	**mmBtu**	**mmBtu**
Sep-12	52974	543	63
Oct-12	55458	356	93
Nov-12	51472	170	118
Dec-12	51150	164	179
Jan-13	55025	162	214
Feb-13	50663	110	125
Mar-13	56135	178	143
Apr-13	55005	261	104
May-13	56831	531	116
Jun-13	54270	744	88
Jul-13	56728	783	94
Aug-13	55066	732	77

4.2 Data Used for Case Study

The load/energy ratio was computed during the fiscal year 2013, which runs from September 1, 2012 through August 31, 2013. The load/energy ratio sometimes depends on energy prices. If the prices of the different energy sources used by a building fluctuate significantly relative to each other, this will influence individual values of the index. Hence the price for electricity and natural gas are fixed by using the annual average value in this paper. The price values are provided by the Utilities & Energy Services group and are as shown in Table 3.

Table 3 Utility Rates – Direct Cost Portion (Sakurai, 2014)

Name	Unit	FY13
Electricity	$/kWh	0.055
Natural Gas	$/mmBtu	5.511

4.3 Central Plant Description

Central plants supply chilled water and heating hot water to virtually all of the campus buildings at Texas A&M University. The four plants on the campus are the Central Utility Plant (CUP), Satellite Utility Plant 1 (SUP1), Satellite Utility Plant 2 (SUP2), and Satellite Utility Plant 3 (SUP3). Both the CUP and SUP3 serve the Main Campus, while SUP1 and SUP2 serve the West Campus. Wellborn Road separates the West Campus from Main Campus. In this paper, only the West Campus plants (SUP1, SUP2) were considered since the selected building studied is located on West Campus. The West Campus plants have fewer chillers and more complete data than the main campus plants, which is the main reason for selecting a West Campus building. The West Campus central plant information is listed in Table 4. The power of chillers, chilled water pumps, cooling tower fans and condensing water pumps are listed in Table 5 to Table 8.

Table 4 West Campus Central Plant Information

Plant	Chillers (Number)	Chilled Water Pumps (Number)	Cooling Towers (Number)
SUP1	6	3	7
SUP2	5	4	5

Table 5 Chiller Power of Each Plant at Rated Conditions

Plant	Chiller Number	Power (kW)
SUP1	CHLR101	598
	CHLR102	598
	CHLR103	1492
	CHLR104	1476
	CHLR105	1476
	CHLR106	1476
SUP2	CHLR201	804
	CHLR202	883
	CHLR203	804
	CHLR204	1391
	CHLR205	1391

Table 6 Chilled Water Pump Power of Each Plant at Rated Conditions

Plant	Chilled Water Pump	Power (kW)
SUP1	CHWP101	447
	CHWP102	447
	CHWP103	447
SUP2	CHWP201	149
	CHWP202	149
	CHWP203	224
	CHWP204	224

Table 7 Cooling Tower Fan Power of Each Plant at Rated Conditions

Plant	Cooling Tower Fan	Power (kW)
SUP1	CT101	45
	CT102	45
	CT103A	45
	CT103B	45
	CT104	93
	CT105	93
	CT106	93
SUP2	CT201	56
	CT202	56
	CT203	56
	CT204	75
	CT205	75

Table 8 Condensing Water Pump Power of Each Plant at Rated Condition

Plant	Condensing Water Pump	Power (kW)
SUP1	CWP101	75
	CWP102	75
	CWP103A	56
	CWP103B	56
	CWP104	186
	CWP105	186
	CWP106	186
SUP2	CWP201	93
	CWP202	93
	CWP203	93
	CWP204	149
	CWP205	149

Based on the section on Methodology Adjustments, the hourly entire plant average cooling energy/load ratio ($R_{PC, E/L}$) and heating efficiency (η_{PH}) are two important variables that need to be obtained. After logging onto the campus utility central systems, the hourly individual energy inputs for chillers, boilers, chilled water pumps, condensing water pumps, cooling tower fans, and heating hot water pumps were downloaded for the period from September 1, 2012 through August 31, 2013, as well as the hourly chiller tonnage provided to the campus buildings. The total natural gas usage can be obtained by the monthly natural gas bills from the Utilities & Energy Services group to determine the amount of boiler plant energy input. The hourly chiller plant cooling energy/load ratio is the ratio of the hourly total chiller plant cooling energy input divided by the hourly chiller tonnage provided, whereas the hourly total chiller plant cooling energy input is the sum of the energy input to the chillers, chilled water pumps, condensing water pumps and cooling tower fans. The monthly boiler plant heating efficiency is the ratio of the monthly boiler plant heating energy provided over the boiler plant heating energy input, where the boiler plant heating energy input is the sum of the natural gas usage and the heating hot water pumps energy input. Here the heating hot water pumps electricity input needs to be changed into the energy input in units of MMBtu by dividing the pumping electricity cost by the natural gas price. The monthly boiler plant heating efficiency can be considered as an average value for each period within a month, so it is used as an hourly heating efficiency value in that month.

The West Campus monthly chiller plant energy efficiency values and boiler plant energy efficiency values are listed in Table 9 and Table 10.

Table 9 West Campus Chiller Plant Energy Input, Output and Cooling Efficiency

Month	WC Plant Cooling Provided	WC Plant Auxiliary Energy Use	Tonnage [tons]	WC Plant Cooling Efficiency
	kWh	kWh	tons	kW/ton
Sep-12	3279754	1276511	5741708	0.79
Oct-12	2374239	1071762	4408262	0.78
Nov-12	1558946	898978	3229691	0.76
Dec-12	1405435	701540	2714215	0.78
Jan-13	1202798	631933	2369851	0.77
Feb-13	1117839	511356	2115013	0.77
Mar-13	1361512	712460	2648494	0.78
Apr-13	1844649	877167	3670438	0.74
May-13	2825533	1176935	5151561	0.78
Jun-13	3745494	1421066	6589788	0.78
Jul-13	3907338	1528602	7238808	0.75
Aug-13	3503915	1349655	6595672	0.74

Table 10 West Campus Boiler Plant Energy Input, Output and Heating Efficiency

Month	WC Plant Heating Energy Provided	WC Plant Pumps Energy Use	WC Plant NG Supplied	WC Plant Heating Efficiency
	mmBtu	mmBtu	mmBtu	
Sep-12	12445	760	14,260	0.83
Oct-12	15995	755	18,780	0.82
Nov-12	18992	1303	23,259	0.77
Dec-12	24539	1185	30,117	0.78
Jan-13	26428	1261	32,201	0.79
Feb-13	20494	1002	24,337	0.81
Mar-13	20780	1064	24,783	0.80
Apr-13	17857	977	21,697	0.79
May-13	15629	899	19,177	0.78
Jun-13	12482	775	16,012	0.74
Jul-13	12950	785	16,602	0.74
Aug-13	12368	673	14,478	0.82

4.4 Building Energy Modeling

Creating an energy model for the selected building by using an energy simulation tool is the beginning in ascertaining the details of building HVAC systems. In this study, WinAM – a quick energy simulation software program (shown in Figure 4) was used to simulate the building energy performance. WinAM was developed by the Energy Systems Laboratory (ESL) at the Texas A&M Engineering Experiment Station to rapidly calibrate a simulation and estimate the savings from energy conservation measures to an existing building. It started as an implementation of the ASHRAE Simplified Energy Analysis Procedure, and still uses the basic structure of a simple envelope analysis and more complete primary and secondary systems analysis used in the original procedure. It allows engineers to simulate an existing building's current operation, calibrate the simulation, and then determine the energy and financial savings of applying the Continuous Commissioning® process. Unlike most building energy modeling tools (eQUEST, DOE-2 etc), WinAM is designed for the purposes of modeling existing buildings and estimating savings from energy conservation measures. There are four steps required to complete the energy model: (1) Collect the detailed site information for a specific building; (2) Put all of the parameter values into the WinAM model; (3) Upload the weather and measured energy consumption data to the model; (4) Calibrate the model inputs so that the model output reasonably matches the measured data. As a result, the detailed hourly, daily, and monthly data for HVAC systems variables are listed in the report.

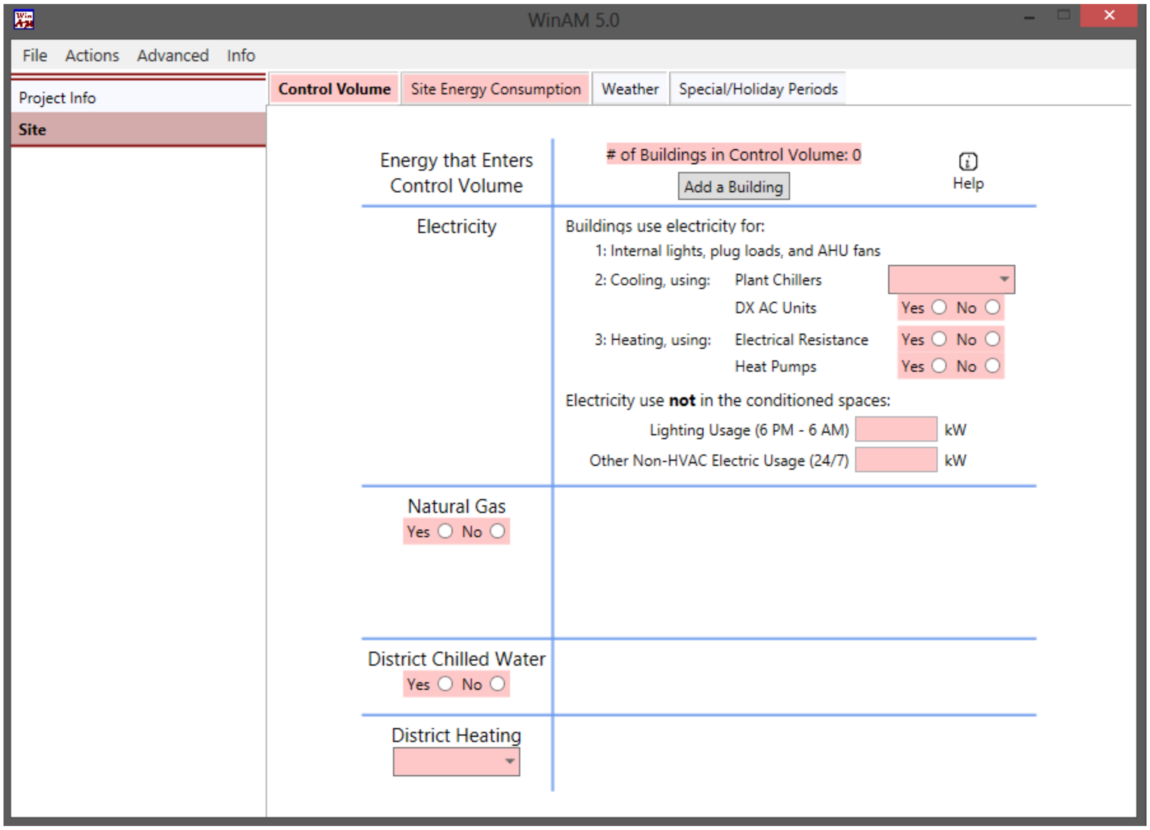


Figure 4 WinAM Interface

According to the HVAC systems information presented before, there are three kinds of AHUs that are listed in the WinAM program to represent the whole systems. One SDVAV system services the offices, and one SDVAV system and one SDCAV system service the labs since there are both VAV terminal boxes and CAV terminal boxes. The basic building and HVAC systems information needs to be inputted, including the parameters related to the structure, control schedule, air-control, fans, coil setpoint, peak loads and load schedules. The details of the data inputted are listed in Table 11 through Table 13.

Table 11 Details of AHU-2 Serving the Office Space

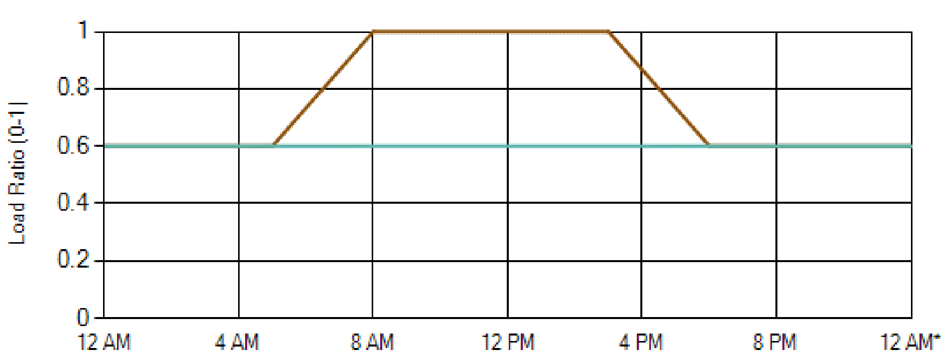
Item	Inputs			
Systems	Single Duct Variable Air Volume With Reheat			
Structure	Conditioned Floor Area: 7452 ft^2	Interior Zone: 63%	Exterior Window+Wall Area: 3401 ft^2	Window: 22%
	Roof Area: 7425 ft^2	Exterior Walls: 0.12 Btu/ft^2·h·°F	Exterior Windows: 0.9 Btu/ft^2·h·°F	Roof: 0.05 Btu/ft^2·h·°F
Control Schedule	7 days/24 hours			
Air Control	Space T Set point: Cooling-75°F, heating-70°F	Minimum Primary Flow: 0.4 cfm/ft^2	Minimum OA: 22%	
Fans	Supply Fan Design Total Pressure: 3.5 in H_2O	Design Flow Rate: 1 cfm/ft^2	Variable Frequency Drive	Static Pressure Control Method: Demand Based - Demand Curve Exponent: n=2.5
Coil Setpoints	Cooling Constant Set Point: 55°F	Reheat Constant Set Point: 40 °F		
Peak Loads	Peak Lighting+Peak Usage:2 W/ft2	Peak Occupancy: 100ft^2/person	Sensible Heat Per Person: 250 Btu/h	Latent Heat Per Person: 200 Btu/h
Load Schedules				

Table 12 Details of OAHU-1 with Variable Volume Terminal Boxes Serving the Lab Space

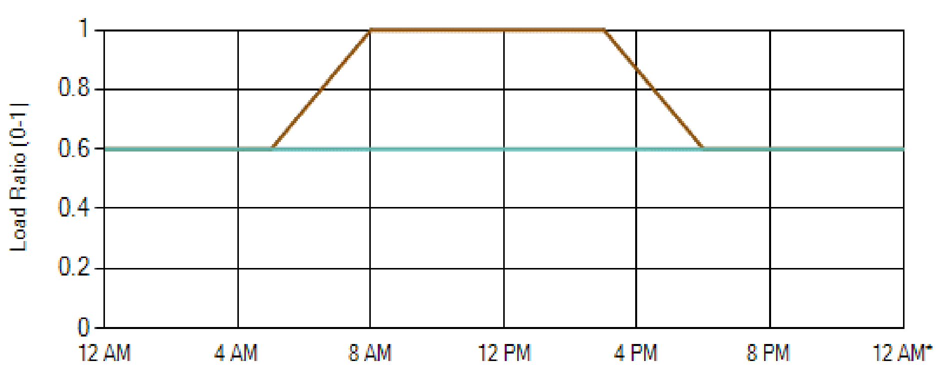
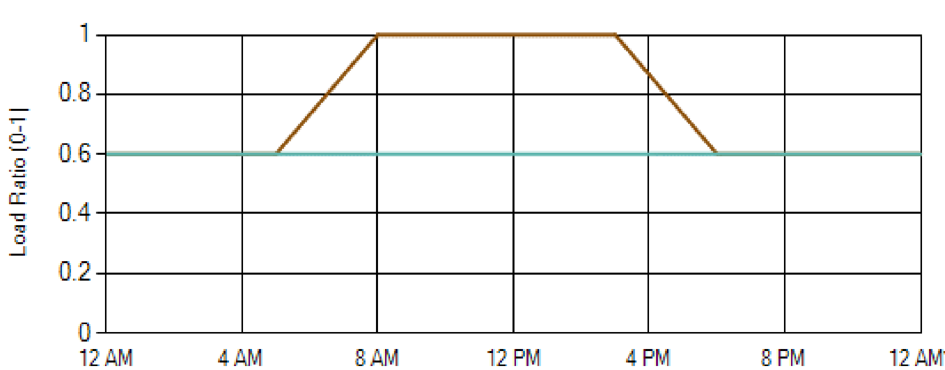
Item	Inputs			
Systems	Single Duct Variable Air Volume With Reheat			
Structure	Conditioned Floor Area: 9774 ft^2	Interior Zone: 43%	Exterior Window+Wall Area: 3308 ft^2	Window: 12%
	Roof Area: 9774 ft^2	Exterior Walls: 0.12 Btu/ft^2·h·°F	Exterior Windows: 0.9 Btu/ft^2·h·°F	Roof: 0.05 Btu/ft^2·h·°F
Control Schedule	7 days/24 hours			
Air Control	Space T Set point: 74°F	Minimum Primary Flow: 0.8 cfm/ft^2	Minimum OA: 100%	
Fans	Supply Fan Design Total Pressure: 3.8 in H2O	Design Flow Rate: 2.7 cfm/ft^2	Variable Frequency Drive	Static Pressure Control Method: Demand Based - Demand Curve Exponent: n=2.5
Coil Setpoints	Cooling Constant Set Point: 53°F	Reheat Constant Set Point: 40 °F		
Peak Loads	Peak Lighting+Peak Usage:2 W/ft2	Peak Occupancy: 150ft^2/person	Sensible Heat Per Person: 250 Btu/h	Latent Heat Per Person: 200 Btu/h
Load Schedules				

Table 13 Details of OAHU-1 with Constant Volume Terminal Boxes Serving the Lab and Providing OA to the Offices

Item	Inputs			
Systems	Single Duct Constant Air Volume With Reheat			
Structure	Conditioned Floor Area: 1906 ft^2	Interior Zone: 43%	Exterior Window+Wall Area: 645 ft^2	Window: 12%
	Roof Area: 1906 ft^2	Exterior Walls: 0.12 Btu/ft^2·h·°F	Exterior Windows: 0.9 Btu/ft^2·h·°F	Roof: 0.05 Btu/ft^2·h·°F
Control Schedule	7 days/24 hours			
Air Control	Space T Set point: 74°F		Minimum OA: 100%	
Fans	Supply Fan Design Total Pressure: 4.6 in H2O	Design Flow Rate: 2.7 cfm/ft2	Variable Frequency Drive	Static Pressure Control Method: Demand Based - Demand Curve Exponent: n=2.5
Coil Setpoints	Cooling Constant Set Point: 53°F		Reheat Constant Set Point: 40 °F	
Peak Loads	Peak Lighting+Peak Usage: 2 W/ft2	Peak Occupancy: 150ft^2/person	Sensible Heat Per Person: 250 Btu/h	Latent Heat Per Person: 200 Btu/h
Load Schedules				

After uploading the weather data and the measured daily energy consumption for electricity, chilled water and heating hot water, the total error can be used to check the model accuracy. Figure 5 presents the relationship between predicted and measured consumption, as well as the total error.

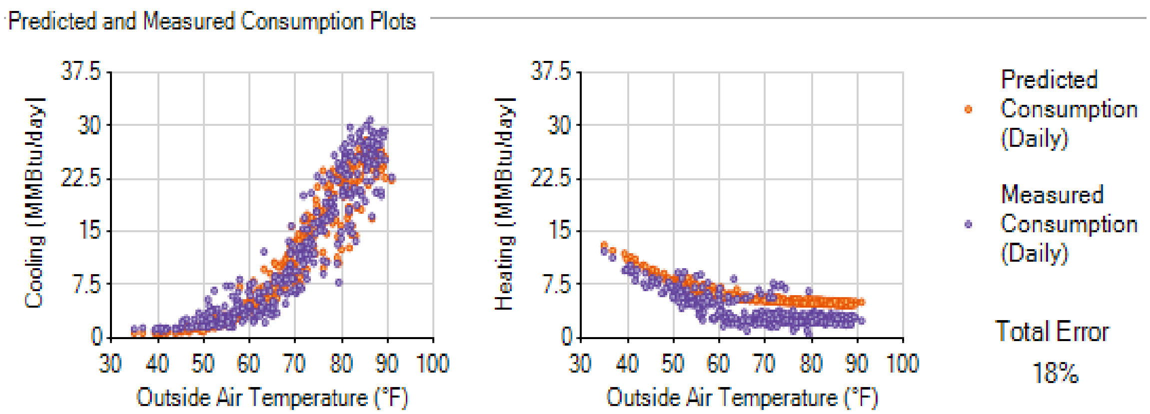


Figure 5 Plots of Predicted and Measured Consumption with Total Error before Calibration

The total error was 18% after simulation. The original model should be updated by calibration since the predicted and measured energy data for cooling and heating differed significantly. The calibration process included a total of four changes to decrease the total error as shown in Table 14.

Table 14 Input Changes during Calibration

No.	Item	Before calibration	After calibration	Total error before calibration	Total error after calibration
1	Other Non-HVAC ELE Usage (kWh)	0	25	18%	15%
2	Space T Set Point (Lab VAV, Lab CAV) (°F)	74	72	15%	12%
3	Peak Lighting + Plug Usage (Lab VAV, Lab CAV) (W/ft^2)	2	3	12%	11%
4	Peak Occupancy (Lab VAV, Lab CAV) (ft^2/person)	150	100	11%	10%

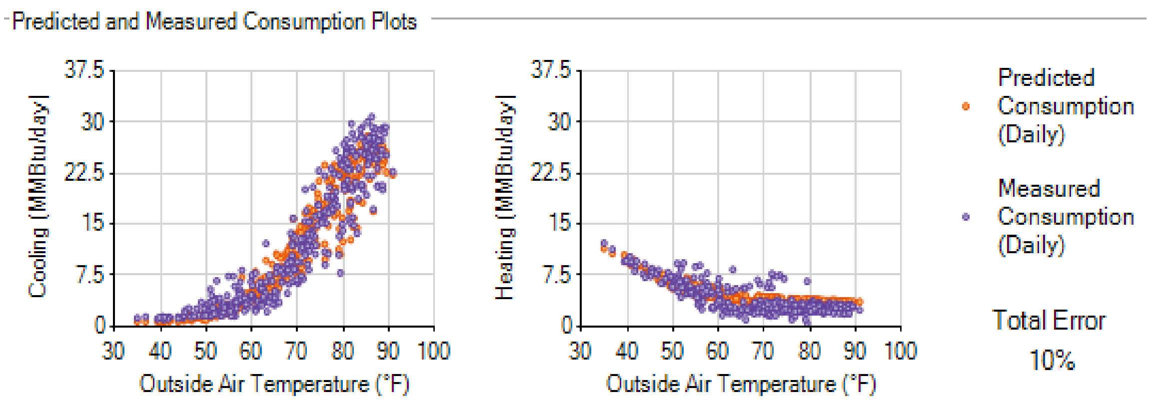


Figure 6 Plots of Predicted and Measured Consumption with Total Error after Calibration

After calibration was completed, this version of the building energy performance model was used since the total error was reduced to a reasonable value. It is clear from the Figure 6 that the predicted consumption largely overlaps the measured use for both cooling and heating.

Here are the monthly modeled energy use of electricity, chilled water and heating hot water for office and lab areas shown in Table 15 and Table 16.

Table 15 Monthly Modeled Energy Use of Electricity, CHW and HHW for Office

Month	Total Electric Usage kWh	Total Chilled Water Usage MMBtu	Total Hot Water Usage MMBtu
Sep-12	7927	62	3
Oct-12	8298	50	8
Nov-12	8007	38	11
Dec-12	8168	36	16
Jan-13	8287	33	18
Feb-13	7438	30	13
Mar-13	8168	37	13
Apr-13	8007	43	9
May-13	8305	58	5
Jun-13	7942	70	3
Jul-13	8349	72	2
Aug-13	8306	76	2

Table 16 Monthly Modeled Energy Use of Electricity, CHW and HHW for Lab

Month	Total Electric Usage kWh	Total Chilled Water Usage MMBtu	Total Hot Water Usage MMBtu
Sep-12	20676	511	102
Oct-12	21692	326	116
Nov-12	20956	159	126
Dec-12	21411	146	165
Jan-13	21692	105	175
Feb-13	19484	83	127
Mar-13	21411	140	140
Apr-13	20956	243	119
May-13	21692	451	110
Jun-13	20676	624	99
Jul-13	21692	633	101
Aug-13	21552	662	100

4.5 Building Load Calculation

After completing the energy performance simulation, there are several sheets of the details of the output variables that are created according to the different input for three types of AHUs created in WinAM program. Each sheet can list the hourly, daily or monthly data values for the specific HVAC systems, including energy usage, temperature/humidity ratio for different points, and sensible/latent loads. From these sheets, other important variables can be obtained, including the outside air flow, temperature of outside air and return air, and humidity ratio of outside air and return air for both interior zones and exterior zones. Combining Eqs. 19 - 24 with the values of these parameters, the building cooling and heating load can be determined.

The ventilation sensible and latent loads for the interior and exterior zones are:

$$q_{S,V,in}[Btu/ft^2] = 1.08 \times V_{OA,in} \times (T_{OA} - T_{RA}) \tag{19}$$

$$q_{S,V,ex}[Btu/ft^2] = 1.08 \times V_{OA,ex} \times (T_{OA} - T_{RA}) \tag{20}$$

$$q_{L,V,in}[Btu/ft^2] = 4840 \times V_{OA,in} \times (w_{OA} - w_{RA}) \tag{21}$$

$$q_{L,V,ex}[Btu/ft^2] = 4840 \times V_{OA,ex} \times (w_{OA} - w_{RA}) \tag{22}$$

$$q_{V,in}[Btu/ft^2] = q_{S,V,in} + q_{L,V,in} \tag{23}$$

$$q_{V,ex}[Btu/ft^2] = q_{S,V,ex} + q_{L,V,ex} \tag{24}$$

Where $q_{S,V,in}$ is the interior zone sensible ventilation load, $q_{S,V,ex}$ is the exterior zone sensible ventilation load, $q_{L,V,in}$ is the interior zone latent ventilation load, and $q_{L,V,ex}$ is the exterior zone latent ventilation load.

Based on the definition of the building's total load, the total load for the interior zone and the exterior zone of labs and offices are presented by Eqs. 25 - 26.

$$Q_{ESL,in}[mmBtu] = \frac{(q_{LEnv,in} + q_{LGain,in} + q_{LVent,in}) \times A_{in}}{10^6} \quad (25)$$

$$Q_{ESL,ex}[mmBtu] = \frac{(q_{LEnv,ex} + q_{LGain,ex} + q_{LVent,ex}) \times A_{ex}}{10^6} \quad (26)$$

Where A_{ex} is the exterior zone area, and A_{in} is the interior zone area, $q_{LEnv,in}$ is the interior zone envelop load, $q_{LGain,in}$ is the interior zone internal gains, $q_{LEnv,ex}$ is the exterior zone envelope load, and $q_{LGain,ex}$ is the exterior zone internal gain. It is cooling load when the load value is positive, while the negative means it is heating load.

The above result is used for one kind of area with interior and exterior zones. So both the office and lab cooling and heating loads can be determined using the same calculation method. The monthly value is shown in Table 17 and Table 18.

Table 17 Monthly Cooling Load for Office and Lab

Month	**Office Cooling Load** mmBtu	**Lab Cooling Load** mmBtu
Sep-12	59	402
Oct-12	44	232
Nov-12	30	88
Dec-12	27	83
Jan-13	24	58
Feb-13	22	31
Mar-13	29	69
Apr-13	36	160
May-13	53	347
Jun-13	67	516
Jul-13	69	523
Aug-13	72	553

Table 18 Monthly Heating Load for Office and Lab

Month	Office Heating Load	Lab Heating Load
	mmBtu	mmBtu
Sep-12	0.0	0.1
Oct-12	0.8	27.3
Nov-12	2.0	57.2
Dec-12	5.1	103.9
Jan-13	6.2	129.0
Feb-13	2.7	75.3
Mar-13	2.7	70.4
Apr-13	1.2	38.9
May-13	0.4	13.1
Jun-13	0.0	0.0
Jul-13	0.0	0.0
Aug-13	0.0	0.0

According to the results of the load calculation, there are four cooling/heating load combinations for cooling efficiency and three kinds of heating/cooling load combinations for heating efficiency listed in Table 19 and Table 20.

Table 19 Types of Building Cooling/Heating Load Combinations for Cooling Efficiency

Hours	Office	Lab
6061	Cooling	Cooling
846	Cooling	Heating
1749	Cooling for Interior zone, Heating for exterior zone	Heating
104	Cooling	Cooling for Interior zone, Heating for exterior zone

Table 20 Types of Building Heating/Cooling Load Combinations for Heating Efficiency

Hours	Office	Lab
846	Cooling	Heating
1749	Cooling for Interior zone, Heating for exterior zone	Heating
104	Cooling	Cooling for Interior zone, Heating for exterior zone

The cooling load and heating load from different kinds of load combinations are identified in Table 21 – Table 22, and Eqs. 27 - 28.

Table 21 Cooling Load under Different Load Combinations

Load Combination	Office cooling load	Lab cooling load
Office-Cooling, Lab-Cooling	Office interior zone cooling load + Office exterior zone cooling load	Lab interior zone cooling load + Lab exterior zone cooling load
Office-Cooling, Lab-Heating	Office interior zone cooling load + Office exterior zone cooling load	0
Office - Cooling/Heating, Lab-Heating	Office interior zone cooling load	0
Office-Cooling, Lab-Cooling/Heating	Office interior zone cooling load + Office exterior zone cooling load	Lab interior zone cooling load

$$\text{Cooling load} = \text{Office cooling load} + \text{Lab cooling load} \qquad (27)$$

Table 22 Heating Load under Different Load Combinations

Item	Office heating load	Lab heating load
Office-Cooling, Lab-Cooling	0	0
Office-Cooling, Lab-Heating	0	Lab interior zone heating load + Lab exterior zone heating load
Office - Cooling/Heating, Lab-Heating	Office exterior zone heating load	Lab interior zone heating load + Lab exterior zone heating load
Office-Cooling, Lab-Cooling/Heating	0	Lab exterior zone heating load

$$\text{Heating load} = \text{Lab heating load} + \text{Office heating load} \tag{28}$$

4.6 Energy Input Calculation

The detailed sheets from the WinAM building model also can provide data in terms of energy inputs, including the cooling energy use, heating energy use, building fan energy use and building pump energy use. However, each energy usage value is the sum of the energy usage for both the interior and the exterior zones. It is necessary to separate them to a cooling part and a heating part when the interior zone needs cooling and the exterior zone needs heating during certain hours.

Based on the tables of cooling load combinations and heating load combinations, the cooling energy use, heating energy use, building fan's energy use, and building pump's energy use are separated so that reheat energy is counted as part of the energy used to meet the cooling loads by the system and cooling energy supplied to a zone in which there is a heating load is counted as part of the energy used to meet the heating load by the system. The specific combinations and equations used for different heating/cooling load combinations are computed according to the equation given below. The suffixes 'C' and 'H' are used to separate the energy usage for the cooling part or the heating part. Table 23 and Table 24 show the cooling and heating energy use under cooling load combinations.

Table 23 Cooling Energy Use under Different Cooling Load Combinations

Item	**(Office cooling use)** $_C$	**(Lab cooling use)** $_C$
Office-Cooling, Lab-Cooling	Office cooling use	Lab cooling use
Office-Cooling, Lab-Heating	Office cooling use	0
Office - Cooling/Heating, Lab-Heating	$\text{Office cooling use} \times \frac{Office\ interior\ zone\ air\ flow\ rate}{Office\ air\ flow\ rate}$	0
Office-Cooling, Lab-Cooling/Heating	Office cooling use	$\text{Lab cooling use} \times \frac{Lab\ interior\ zone\ air\ flow\ rate}{Lab\ air\ flow\ rate}$

$$(\text{Total cooling use})_C = (\text{Lab cooling use})_C + (\text{Office cooling use})_C \tag{29}$$

Table 24 Heating Energy Use under Different Cooling Load Combinations

Item	**(Office HHW use)** $_C$	**(Lab HHW use)** $_C$
Office-Cooling, Lab-Cooling	Office HHW use	Lab HHW use
Office-Cooling, Lab-Heating	Office HHW use	0
Office - Cooling/Heating, Lab-Heating	Office reheat use for interior zone	0
Office-Cooling, Lab-Cooling/Heating	Office HHW use	Lab reheat use for interior zone

$$\text{Office reheat use for interior zone [mmBtu]} = \frac{1.08 \times V_{Office,in} \times (T_{Office,in,Supply} - T_{Office,CL}) \times A_{Office,in}}{10^6} \quad (30)$$

$$\text{Lab reheat use for interior zone [mmBtu]} = \frac{1.08 \times V_{Lab,in} \times (T_{Lab,in,Supply} - T_{Lab,CL}) \times A_{Lab,in}}{10^6} \quad (31)$$

where $V_{Office,in}$ is the office interior zone air flow rate, $V_{Lab,in}$ is the lab interior zone air flow rate, $T_{Office,in,Supply}$ is the office interior zone supply air temperature, $T_{Lab,in,Supply}$ is the lab interior zone supply air temperature, $T_{Office,CL}$ is the office cooling coil leaving air temperature, $T_{Lab,CL}$ is the lab cooling coil leaving air temperature, $A_{Office,in}$ is the office interior zone area, and $A_{Lab,in}$ is the lab interior zone area.

$$(\text{Total HHW use})_C = (\text{Lab HHW use})_C + (\text{Office HHW use})_C \quad (32)$$

Table 25 shows the building fan energy use under cooling load combinations.

Table 25 Building Fan Energy Use under Different Cooling Load Combinations

Item	**(Office fan ELE) $_C$**	**(Lab fan ELE) $_C$**
Office-Cooling, Lab-Cooling	Office fan ELE	Lab fan ELE
Office-Cooling, Lab-Heating	Office fan ELE	0
Office - Cooling/Heating, Lab-Heating	$\text{Office cooling use} \times \frac{Office\ interior\ zone\ air\ flow\ rate}{Office\ air\ flow\ rate}$	0
Office-Cooling, Lab-Cooling/Heating	Office fan ELE	$\text{Lab cooling use} \times \frac{Lab\ interior\ zone\ air\ flow\ rate}{Lab\ air\ flow\ rate}$

$$(\text{Bldg CHW pump ELE})_C = \text{Bldg CHW pump ELE} \times \frac{(\text{Total cooling use})_c}{\text{Total cooling use}} \quad (33)$$

$$(\text{Bldg HHW pump ELE})_C = \text{Bldg HHW pump ELE} \times \frac{(\text{Total HHW use})_c}{\text{Total HHW use}} \quad (34)$$

$$(\text{Total building HVAC ELE})_C = \; = (\text{Lab fan ELE})_C + (\text{Office fan ELE})_C + (\text{Building CHW pump ELE})_C + (\text{Building HHW pump ELE})_C \quad (35)$$

$$(\text{Chiller plant ELE})_C = \text{Plant cooling efficiency [kW/ton]} \times (\text{Total cooling use})_C \quad (36)$$

$$(\text{Total HVAC ELE})_C = (\text{Chiller plant ELE})_C + (\text{Total building HVAC ELE})_C \quad (37)$$

$$(\text{Total NG use})_C = \frac{(\text{Total HHW use})_C}{\text{Plant heating efficiency}} \quad (38)$$

Table 26 and Table 27 show the cooling and heating energy use under heating load combinations.

Table 26 Cooling Energy Use under Different Heating Load Combinations

Item	**(Office cooling use)$_H$**	**(Lab cooling use)$_H$**
Office-Cooling, Lab-Heating	0	Lab cooling use
Office - Cooling/Heating, Lab-Heating	$\text{Office cooling use} \times \frac{Office\ exterior\ zone\ air\ flow\ rate}{Office\ air\ flow\ rate}$	Lab cooling use
Office-Cooling, Lab-Cooling/Heating	0	$\text{Lab cooling use} \times \frac{Lab\ exterior\ zone\ air\ flow\ rate}{Lab\ air\ flow\ rate}$

$$(\text{Total cooling use})_H = (\text{Lab cooling use})_H + (\text{Office cooling use})_H \tag{39}$$

Table 27 Heating Energy Use under Different Heating Load Combinations

Item	**(Office HHW use)$_H$**	**(Lab HHW use)$_H$**
Office-Cooling, Lab-Heating	0	Lab HHW use
Office - Cooling/Heating, Lab-Heating	Office HHW use - Office reheat use for interior zone	Lab HHW use
Office-Cooling, Lab-Cooling/Heating	0	Lab HHW use - Lab reheat use for interior zone

$$(\text{Total HHW use})_H = (\text{Lab HHW use})_H + (\text{Office HHW use})_H \tag{40}$$

Table 28 shows the building fan energy use under heating load combinations.

Table 28 Building Fan Energy Use under Different Heating Load Combinations

Item	**(office fan ELE)$_H$**	**(Lab fan ELE)$_H$**
Office-Cooling, Lab-Heating	0	Lab fan ELE
Office - Cooling/Heating, Lab-Heating	Office cooling use $\times \frac{Office\ exterior\ zone\ air\ flow\ rate}{Office\ air\ flow\ rate}$	Lab fan ELE
Office-Cooling, Lab-Cooling/Heating	0	Lab cooling use $\times \frac{Lab\ exterior\ zone\ air\ flow\ rate}{Lab\ air\ flow\ rate}$

$$(\text{Bldg CHW pump ELE})_H = \text{Bldg CHW pump ELE} \times \frac{(\text{Total cooling use})_H}{\text{Total cooling use}} \quad (41)$$

$$(\text{Bldg HHW pump ELE})_H = \text{Bldg HHW pump ELE} \times \frac{(\text{Total HHW use})_H}{\text{Total HHW use}} \quad (42)$$

$$(\text{Total building HVAC ELE})_H = (\text{Lab fan ELE})_H + (\text{Office fan ELE})_H + (\text{building CHW pump ELE})_H + (\text{building HHW pump ELE})_H \quad (43)$$

$$(\text{Chiller Plant ELE})_H = \text{Chiller plant efficiency [kW/ton]} \times (\text{Total cooling use})_H \quad (44)$$

$$(\text{Total HVAC ELE})_\text{H} = (\text{Chiller plant ELE})_\text{H} + (\text{Total building HVAC ELE})_\text{H} \quad (45)$$

$$(\text{Total NG use})_\text{H} = \frac{(\text{Total HHW use})_\text{H}}{\text{Plant heating efficiency}} \quad (46)$$

4.7 Cooling and Heating Load/Energy Ratio Calculations

The cooling and heating load/energy ratios need to be separated to get individual efficiency values classified with the four different cooling/heating load combinations for cooling efficiency and three different heating/cooling load combinations for heating efficiency. There are four different cooling/heating load combinations for cooling efficiency to be separated in order to illustrate the calculation method. The lab and office heating energy consumption is based on the modeled value to separate the heating and reheat energy use to simplify the way of calculation.

Based on the method introduced before, the cooling load/energy ratio can be obtained by Eqs. 47 - 52.

$$(\text{HVAC ELE cost})_\text{C} = (\text{Total HVAC ELE})_\text{C} \times \$0.055/\text{kWh} \quad (47)$$

$$(\text{NG use cost})_\text{C} = (\text{Total NG use})_\text{C} \times \$5.511/\text{mmBtu} \quad (48)$$

$$(\text{Total cost})_\text{C} = (\text{HVAC ELE cost})_\text{C} + (\text{NG use cost})_\text{C} \quad (49)$$

$$(\text{Total equivalent cooling ELE})_\text{C} = \frac{(\text{Total cost})_\text{C}}{\$0.055/\text{kWh}} \quad (50)$$

$$\text{Cooling kW/ton} = \frac{(\text{Total equivalent cooling ELE})_\text{C}\ [\text{kWh}]}{\text{Total cooling load } [\text{ton} \cdot \text{h}]} \quad (51)$$

$$\text{Cooling COP} = \frac{12/3.412}{\text{Cooling kW/ton}} \text{[Btu-Load/Btu-Input]} \tag{52}$$

Where \$0.055/kWh is the price of electricity, \$5.511/mmBtu is the price of natural gas. The Cooling kW/ton is a way to express the cooling efficiency with the unit of kW/ton similar to the chiller plant kW/ton, the Cooling COP is another way to express the cooling efficiency with the unit of Btu-Load/Btu-Input.

The heating load/energy ratio can be obtained by Eqs. 53 - 57.

$$(\text{HVAC ELE cost})_{\text{H}} = (\text{Total HVAC ELE})_{\text{H}} \times \$0.055/\text{kWh} \tag{53}$$

$$(\text{NG use cost})_{\text{H}} = (\text{Total NG use})_{\text{H}} \times \$5.511/\text{mmBtu} \tag{54}$$

$$(\text{Total cost})_{\text{H}} = (\text{HVAC ELE cost})_{\text{H}} + (\text{NG use cost})_{\text{H}} \tag{55}$$

$$(\text{Total equivalent HHW use})_{\text{H}} = \frac{(\text{Total cost})_{\text{H}}}{\$5.511/\text{mmBtu}} \tag{56}$$

$$\text{Heating efficiency} = \frac{\text{Total heating Load}}{(\text{Total equivalent HHW use})_{\text{H}}} \text{[Btu-Load/Btu-Input]} \tag{57}$$

4.8 Cooling Efficiency Results and Analysis

After applying the method above to do the calculation of the cooling load and energy input for cooling, the hourly cooling load/energy ratio can be obtained. It can also been expressed in terms of monthly and annual values to see the long-term results. The annual cooling efficiency is 2.09 Btu-Load/Btu-Input (or 1.69 kW/ton) and the monthly cooling efficiency values are shown in Table 29 and Figure 7. Cooling efficiency is expressed in terms of cooling COP (Btu-Load/Btu-Input) and cooling kW/ton below since both of these measures are widely used measures of equipment efficiency.

Table 29   Monthly System Cooling Efficiency

Month	Basic Total Cooling Load	Total Equivalent Cooling ELE for Cooling	Cooling kW/ton	Cooling COP
	mmBtu	kWh	kW/ton	Btu-Load/Btu-Input
Sep-12	460	62639	1.63	2.15
Oct-12	275	40752	1.78	1.98
Nov-12	118	21582	2.20	1.60
Dec-12	109	20444	2.24	1.57
Jan-13	82	15482	2.26	1.55
Feb-13	54	11963	2.68	1.31
Mar-13	98	19607	2.40	1.47
Apr-13	196	31318	1.92	1.83
May-13	400	55434	1.66	2.11
Jun-13	583	75333	1.55	2.27
Jul-13	592	74482	1.51	2.33
Aug-13	625	75429	1.45	2.43

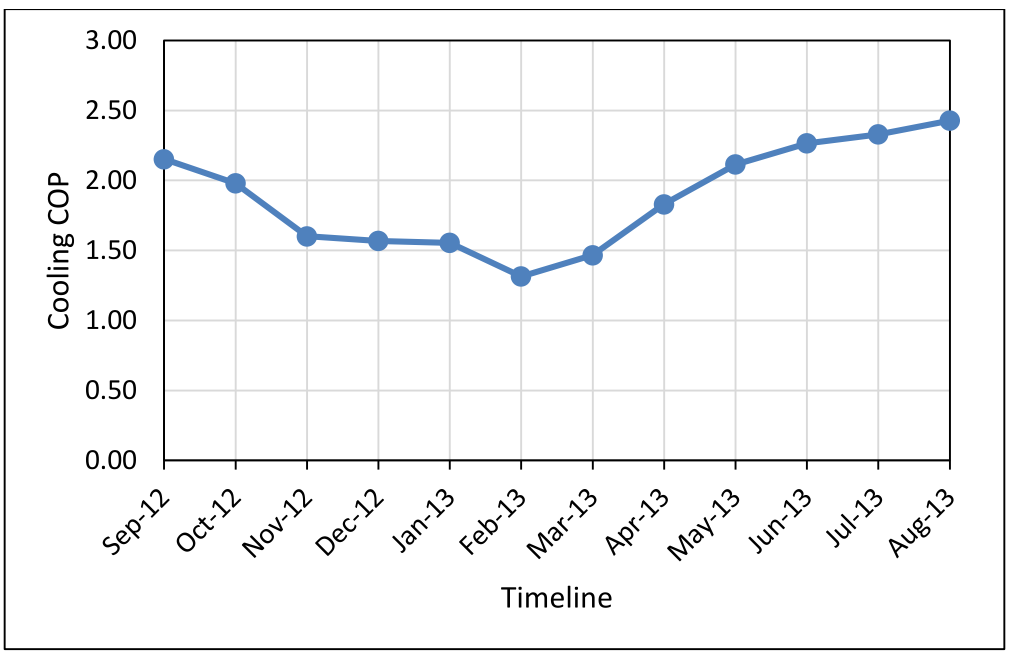


Figure 7   Monthly System Cooling COP

These results show that monthly system cooling COP varies by slightly more than a factor of two from 1.31 in January to 2.43 in August (2.68 kW/ton to 1.45 kW/ton). Monthly values are 2.0 or larger from May through September when cooling loads are larger and less than 2.0 during the months when cooling loads are smaller. The annual cooling COP of 2.09 reflects this fact since the average of the monthly COP values is less than 2.0. However, examining hourly cooling system COP values (not shown) shows that they vary by more than an order of magnitude from a low of 0.23 to 3.77. On some days, cooling system COP varies by a relatively small amount, and on others by more than an order of magnitude.

The cooling system performance will now be examined in more detail for several short periods when different combinations of zone heating and cooling loads are present in an attempt to determine the major factors that contribute to the wide variation in system COP.

4.8.1 Cooling Efficiency when Both Lab and Office Need Cooling

When both the lab and office need cooling, the values of system cooling COP shown in Figure 8 vary from 0.3 to 3 Btu-Load/Btu-Input during the 9/1/2012- 8/31/2013 observation period. In the summer period (May to September), the majority of the cooling COP values fall within a narrow range from 2 to 2.8 Btu-Load/Btu-Input, except for several days with much lower values. In the winter period (October to April), the cooling COP values vary more noticeably from 0.3 to 2.6 Btu-Load/Btu-Input.

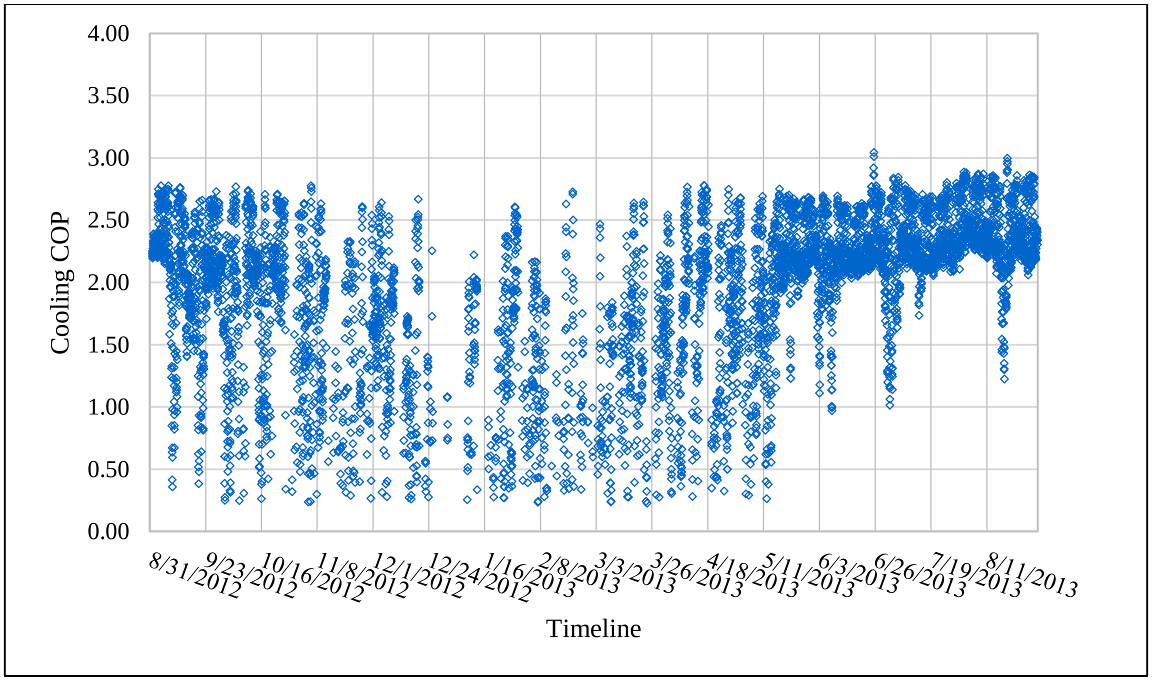


Figure 8 HVAC Cooling COP when Both Lab and Office Need Cooling

The period 7/8/2013-7/12/2013 is selected for a more detailed examination on an hourly basis since these days show a small range of cooling efficiency values in the summer period. The top line in Figure 9 shows that the cooling COPs range from 2.1 to 2.7 Btu-Load/Btu-Input during this period. The bottom portion of the figure shows the hourly breakdown of the total equivalent cooling electricity between the chiller plant, fans, pumps and boiler plant.

For these conditions, the fans and pumps account for about 20% of the equivalent electric input while the chiller plant accounts for somewhat more than 60% of the input and the boiler plant accounts for 15% or more, even under these hot summer conditions. The diurnal COP can be seen to increase when the boiler portion decreases and vice versa.

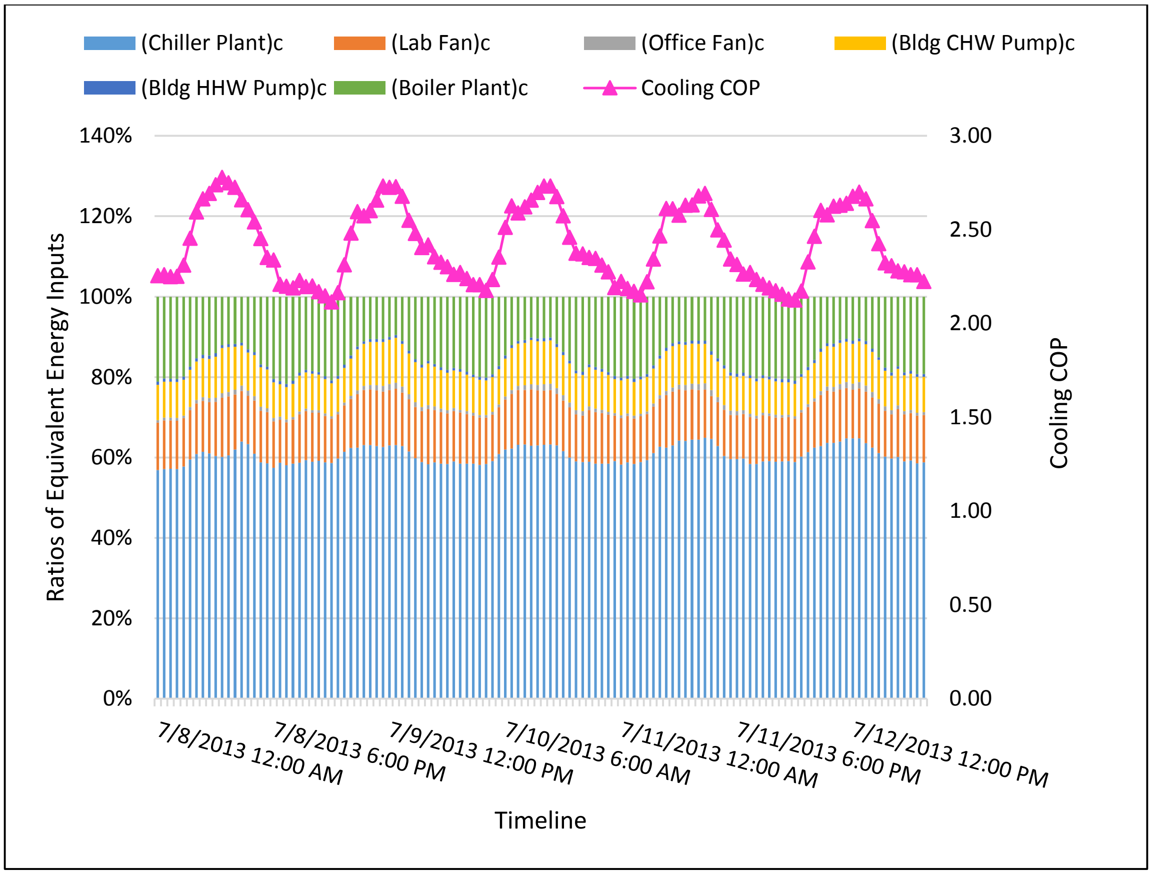


Figure 9 Cooling COP and Ratios of Equivalent Energy Inputs during 7/8/2013-7/12/2013

Figure 10 shows the same basic information shown in Figure 9 except that the system efficiency is expressed in kW/ton instead of COP.

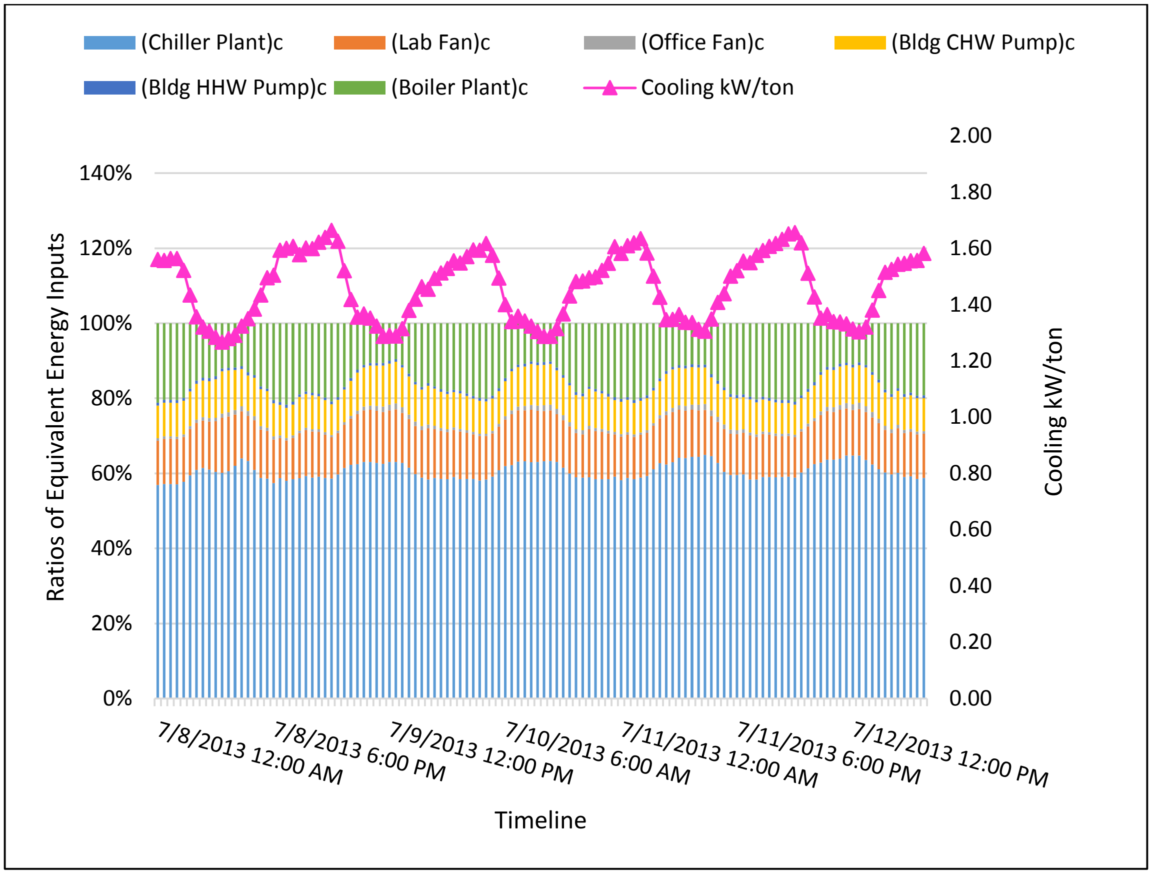


Figure 10 Cooling kW/ton and Ratios of Equivalent Energy Inputs during 7/8/2013-7/12/2013

The top line in Figure 11 shows the hourly variation in the cooling load in MMBtu/hr while the bottom portion of the figure shows the equivalent energy inputs in kW. The peak load is about 40% higher than the lowest load, corresponding to variation of approximately 0.3 MMBtu/hr while the total equivalent energy peak input is only 25% greater than the minimum input.

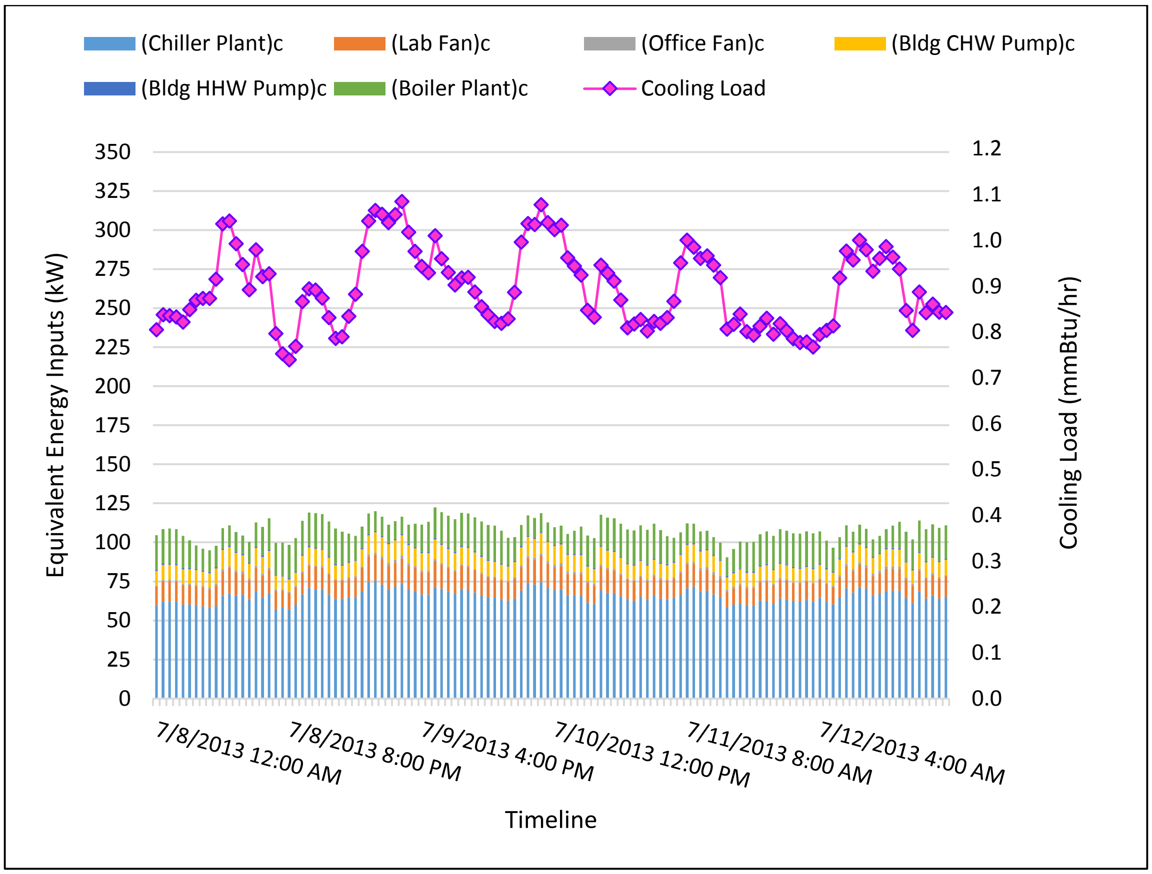


Figure 11 Cooling Load and Equivalent Energy Inputs during 7/8/2013-7/12/2013

Figure 12 shows the chiller plant kW/ton, the cooling system kW/ton and the cooling load. The plot very dramatically shows that the variation in system kW/ton is virtually all due to system performance and not to plant performance.

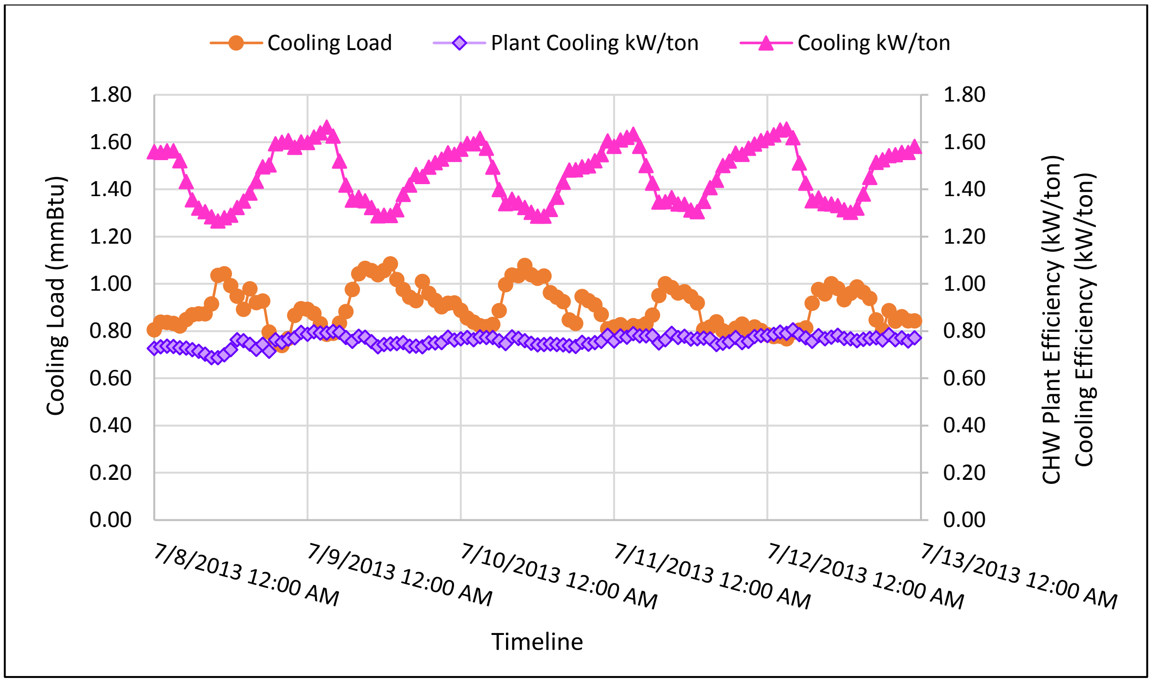


Figure 12 Cooling Load, Chiller Plant kW/ton and Cooling kW/ton during 7/8/2013-7/12/2013

The period 3/12/2013-3/15/2013 is selected for more detailed analysis of a period when both lab and office need cooling and there is a significant range of cooling efficiency values over a short period of time. The pink line in Figure 13 shows that the cooling COPs range from about 0.3 to 2.4 Btu-Load/Btu-Input during this period. The colorized columns of the figure show the hourly breakdown of the total equivalent cooling electricity between the chiller plant, fans, pumps and boiler plant. For these conditions, the fans and pumps account for about 12% of the equivalent electric input while the chiller plant accounts for somewhat more than 35% of the input and the boiler plant accounts for as much as 53%. The diurnal COP can be seen to increase when the boiler portion decreases and vice versa.

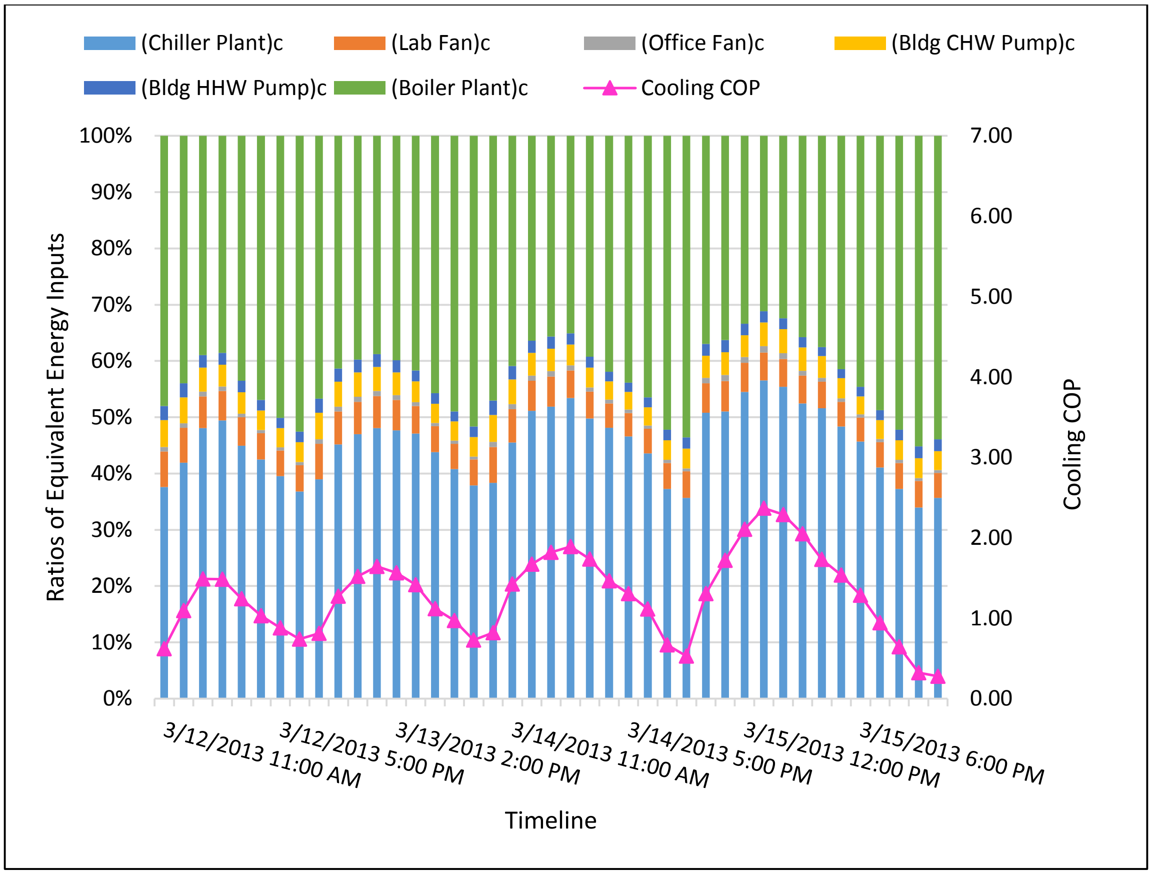


Figure 13 Cooling COP and Ratios of Equivalent Energy Inputs during 3/12/2013-3/15/2013

Figure 14 shows the same basic information shown in Figure 13 except that the system efficiency is again expressed in kW/ton instead of COP.

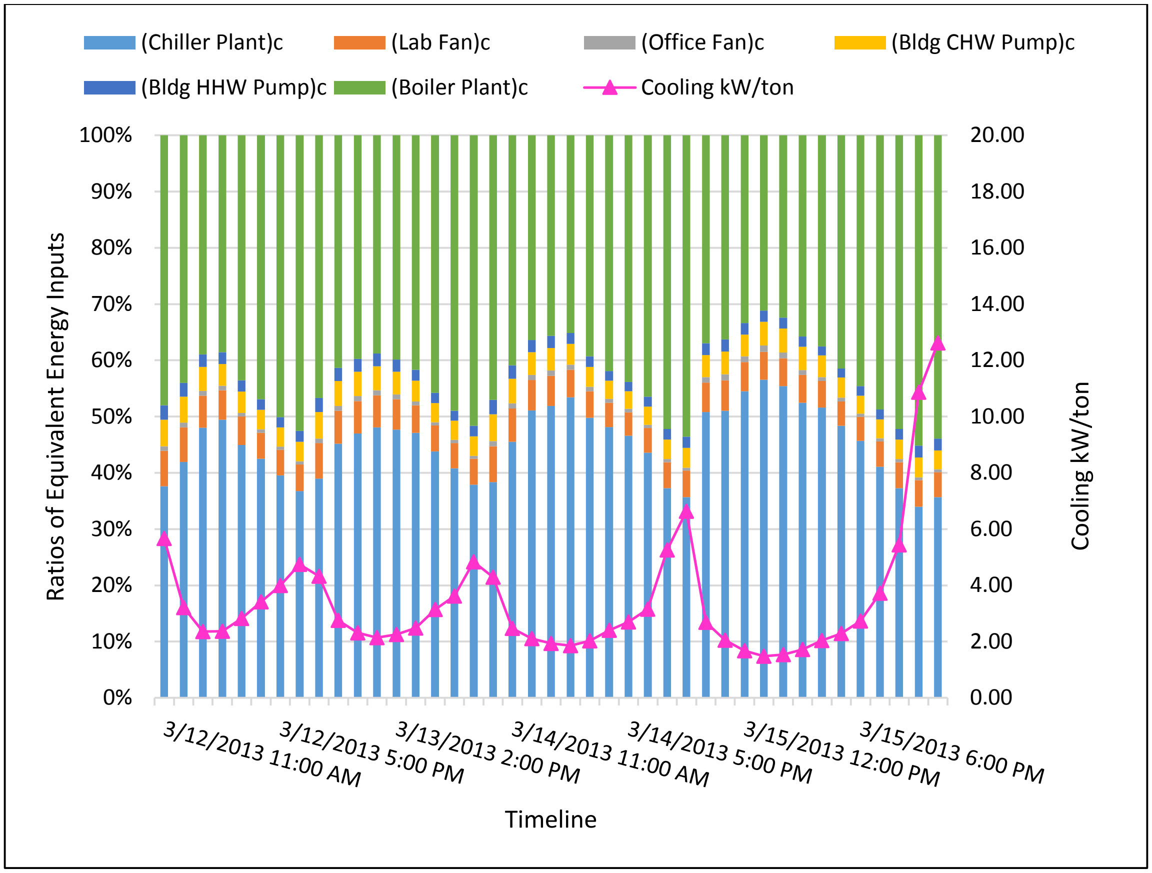


Figure 14 Cooling kW/ton and Ratios of Equivalent Energy Inputs during 3/12/2013-3/15/2013

The line in Figure 15 shows the hourly variation in the cooling load in MMBtu/hr while the bottom bars in the figure show the equivalent energy inputs in kW. The peak load is almost eight times greater than the lowest load, corresponding to variation of approximately 0.29 MMBtu/hr while the total equivalent energy peak input is only 36% greater than the minimum input.

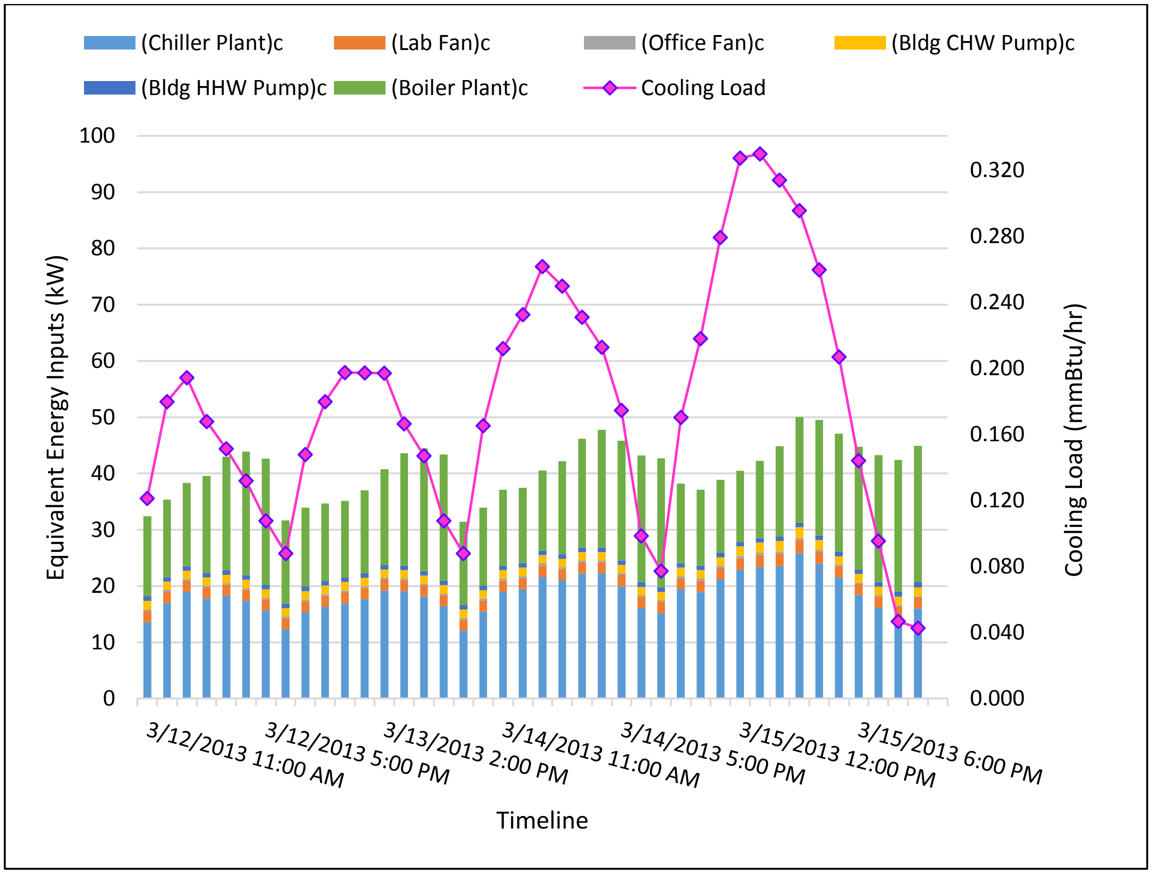


Figure 15 Cooling Load and Equivalent Energy Inputs during 3/12/2013-3/15/2013

Figure 16 shows the chiller plant kW/ton, the cooling system kW/ton and the cooling load. The plot again shows very dramatically that the variation in system kW/ton is virtually all due to system performance and not to plant performance.

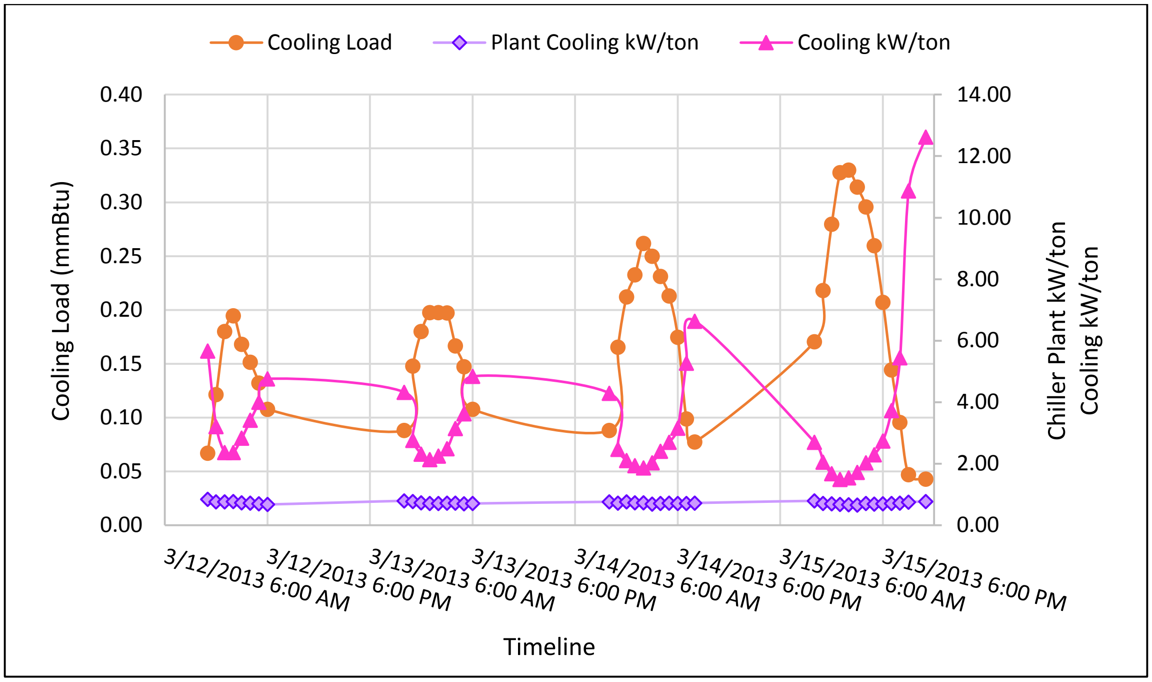


Figure 16 Cooling Load, Chiller Plant kW/ton and Cooling kW/ton during 3/12/2013-3/15/2013

When observing the Figures of Cooling COP and Ratios of Equivalent Energy Inputs for the two periods selected under the conditions when both lab and office need cooling, the big difference is the ratios of equivalent energy inputs from the chiller plant and the boiler plant. The cooling efficiency is low if there is more boiler plant energy input and less chiller plant cooling energy input, and it reaches higher values when the boiler plant heating energy use is less and chiller plant cooling energy use is more.

4.8.2 Cooling Efficiency when Lab Needs Heating and Office Needs Cooling

When the lab needs heating and the office needs cooling, the values of cooling COP vary widely from 0.9 to 3.5 Btu-Load/Btu-Input as shown in Figure 17. There are more values in the range from 0.9 to 2 Btu-Load/Btu-Input, and fewer values larger than 2.0 Btu-Load/Btu-Input. These conditions all occur during the period of September 2012 - May 2013.

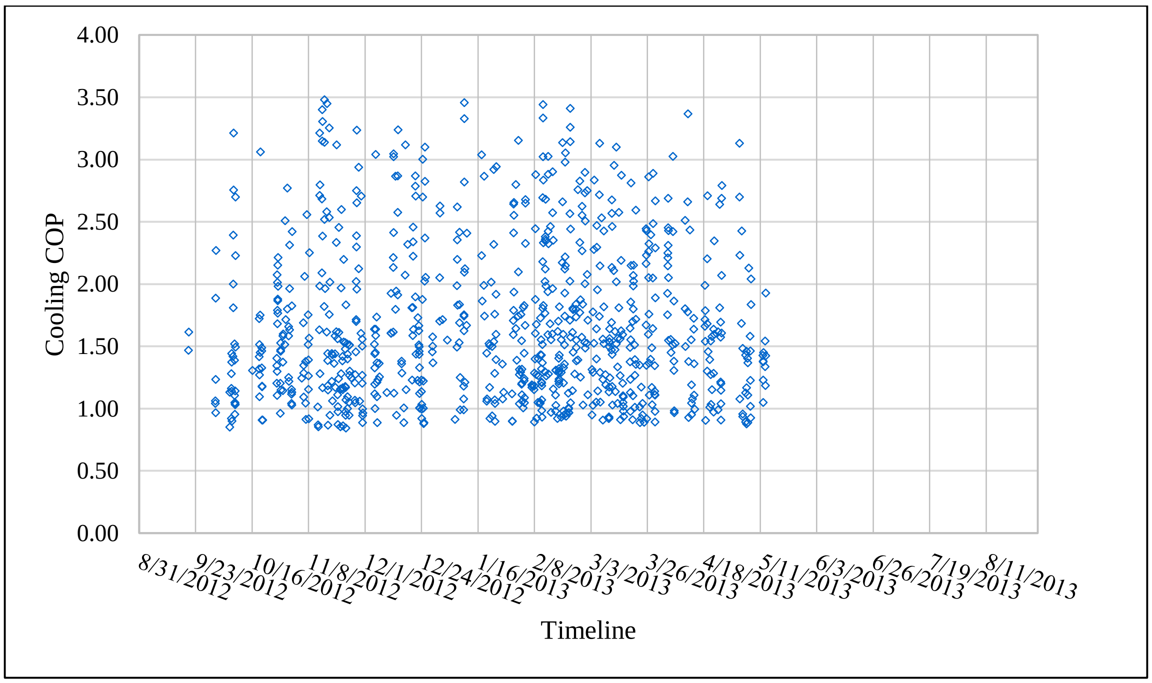


Figure 17 HVAC Cooling COP when Lab Needs Heating and Office Needs Cooling

The period 2/19/2013-2/20/2013 is used for analysis of conditions when the lab needs heating and the office needs cooling since this period showed a wide range of cooling efficiency values. The pink line in Figure 18 shows that the cooling COPs range from 0.9 to 3.0 Btu-Load/Btu-Input during this period. The colorized columns of the figure shows the hourly breakdown of the total equivalent cooling electricity between the chiller plant, fans, pumps and boiler plant. For these conditions, the fans and pumps generally account for 10-20% of the equivalent electric input while the chiller plant accounts for about 40-65% of the input and the boiler plant accounts for 15 - 50%. The system COP can be seen to increase when the boiler portion decreases and vice versa.

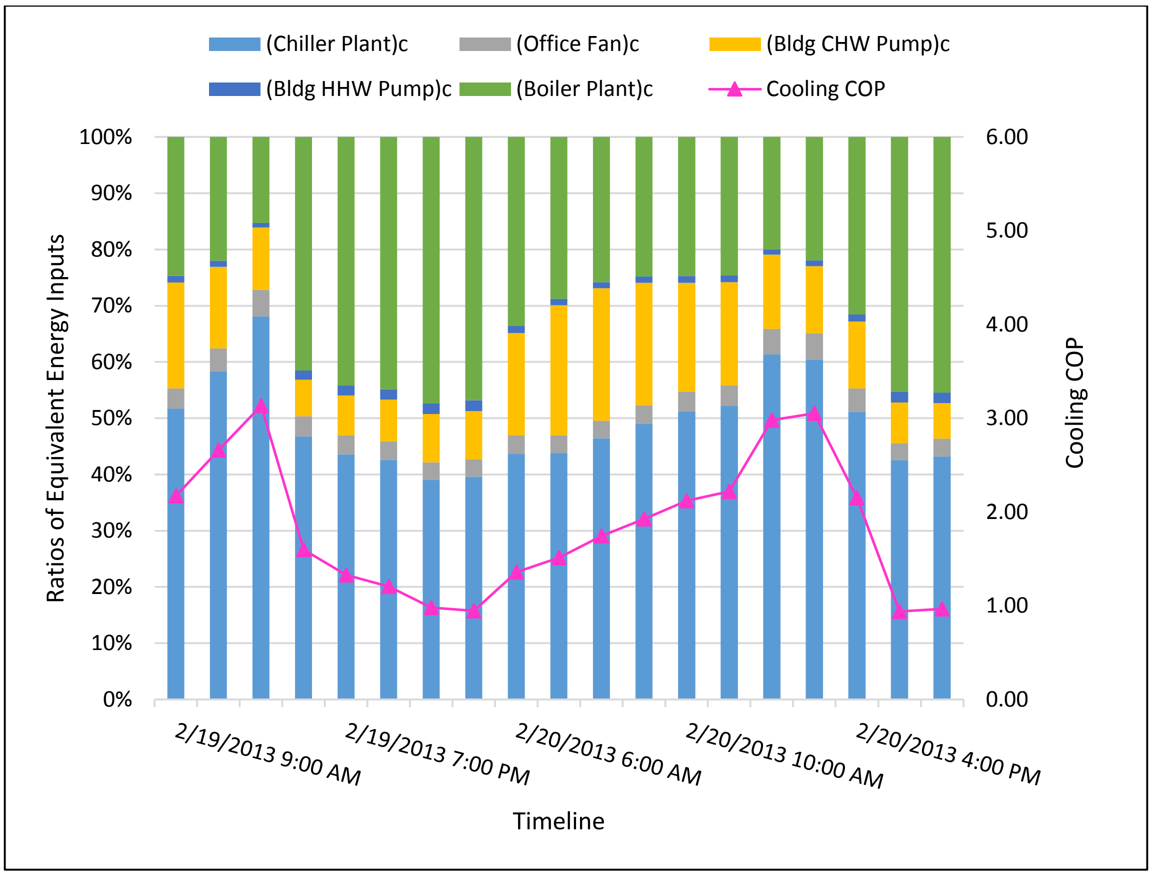


Figure 18   Cooling COP and Ratios of Equivalent Energy Inputs during 2/19/2013-2/20/2013

Figure 19 shows the same basic information shown in Figure 18 except that the system efficiency is expressed in kW/ton instead of COP.

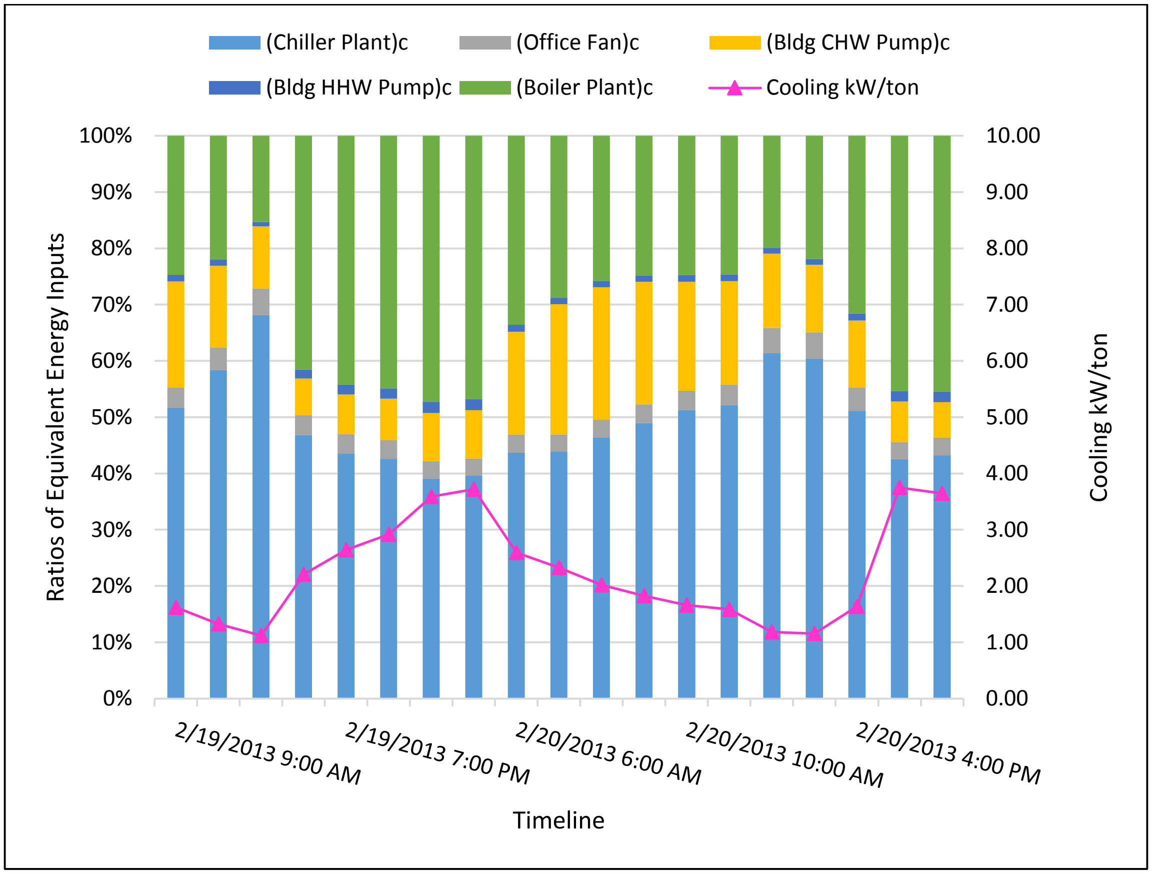


Figure 19 Cooling kW/ton and Ratios of Equivalent Energy Inputs during 2/19/2013-2/20/2013

The top line in Figure 20 shows the hourly variation in the cooling load in MMBtu/hr while the bottom portion of the figure shows the equivalent energy inputs in kW. The peak cooling load is about 2.5 times as large as the lowest load, but the peak cooling load during this period is only 5% of the peak summer cooling load. Even at these low loads, the total equivalent energy peak input is only 34% greater than the minimum input.

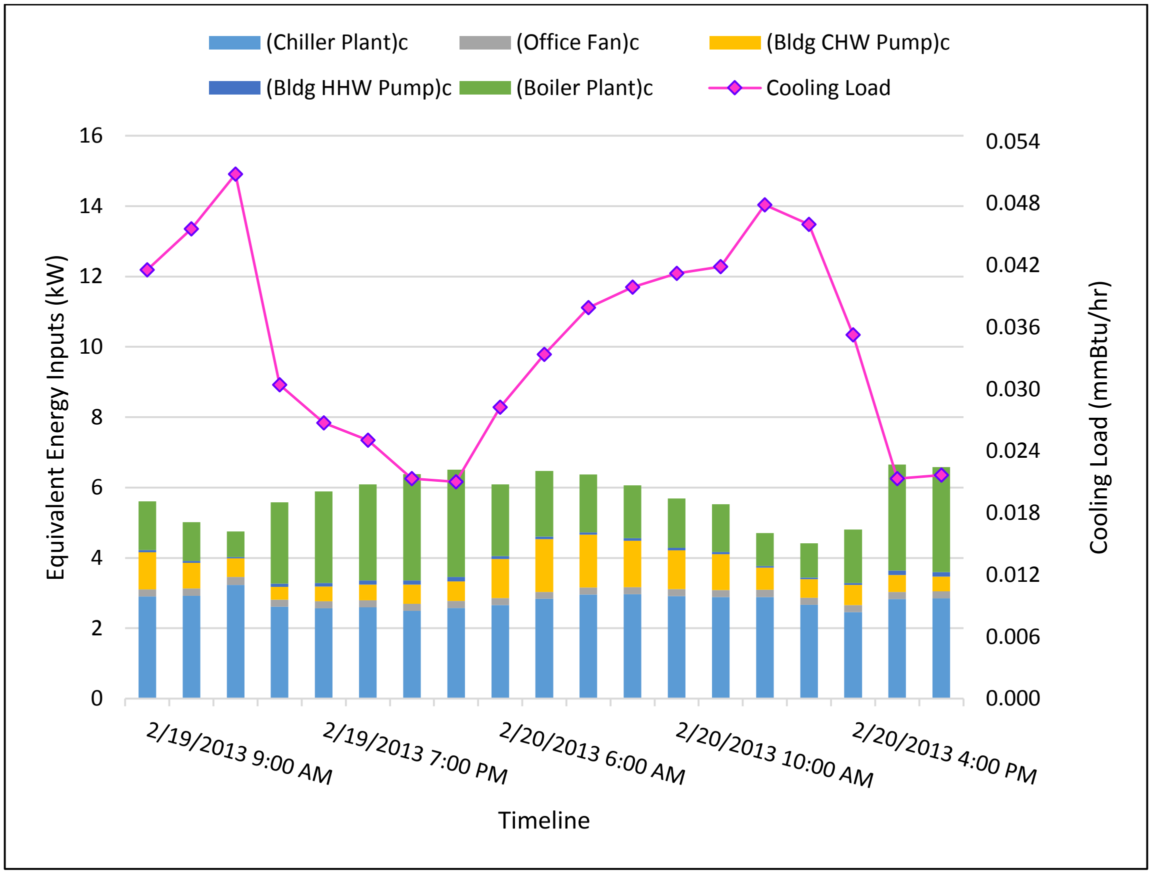


Figure 20 Cooling Load and Equivalent Energy Inputs during 2/19/2013-2/20/2013

Figure 21 shows the chiller plant kW/ton, the cooling system kW/ton and the cooling load. Again, this plot very dramatically shows that the variation in system kW/ton is virtually all due to system performance and not to plant performance. It may also be noted that the presence of cooling loads in the office and heating loads in the lab occurs only during some hours during this 1-2 day period.

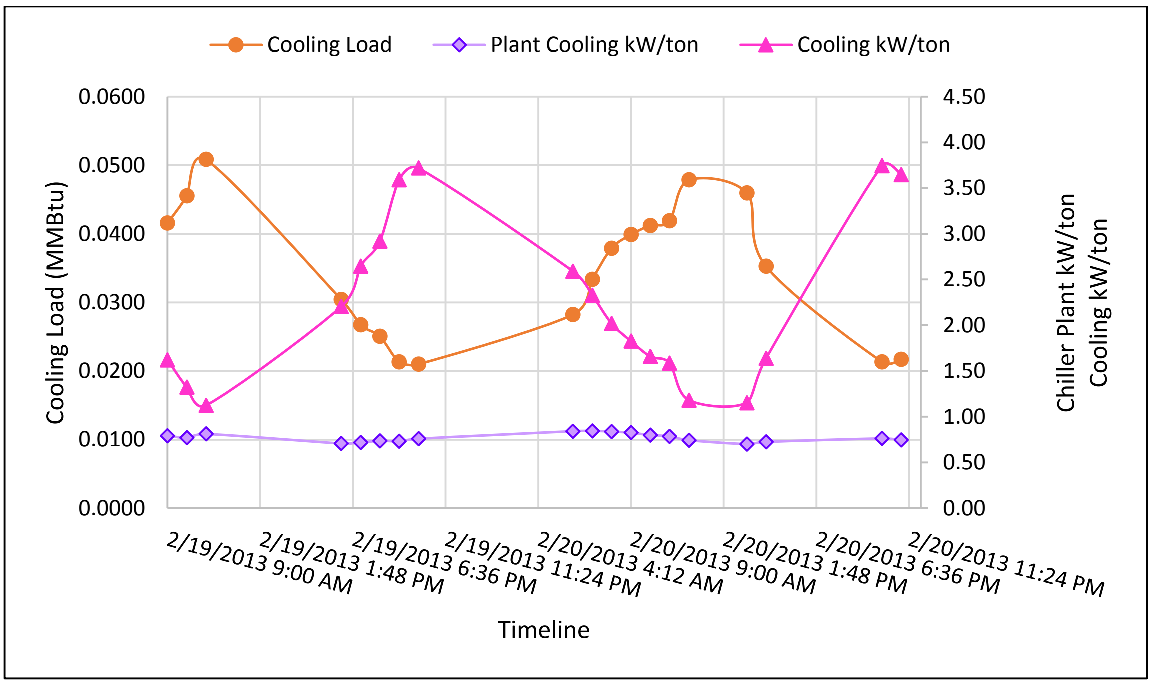


Figure 21 Cooling Load, Chiller Plant kW/ton and Cooling kW/ton during 2/19/2013-2/20/2013

The period from 2/2/2013 to 2/3/2013 is used to examine days when there is a more limited range of cooling efficiency values. The pink line in Figure 22 shows that the cooling COPs range from 1 to 1.8 Btu-Load/Btu-Input during this period. The colorized columns of the figure show the hourly breakdown of the total equivalent cooling electricity between the chiller plant, fans, pumps and boiler plant. For these conditions, the fans and pumps account for about 15% of the equivalent electric input while the chiller plant accounts for 40 - 50% of the input and the boiler plant accounts for about 40 - 50%. The system COP can again be seen to increase when the boiler portion decreases and vice versa, with the more limited range of COP due to the more limited change in the chiller and boiler contributions

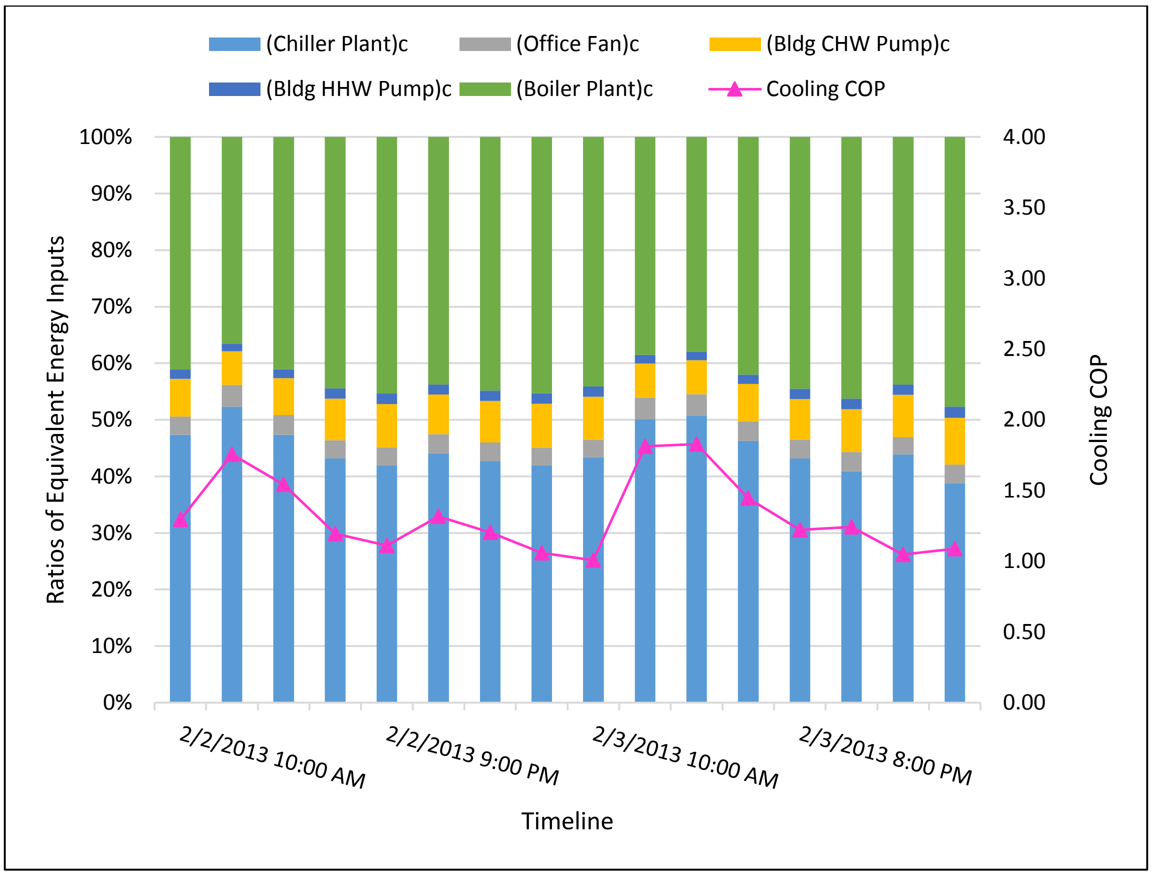


Figure 22 Cooling COP and Ratios of Equivalent Energy Inputs during 2/2/2013-2/3/2013

Figure 23 shows the same basic information shown in Figure 22 except that the system efficiency is expressed in kW/ton instead of COP.

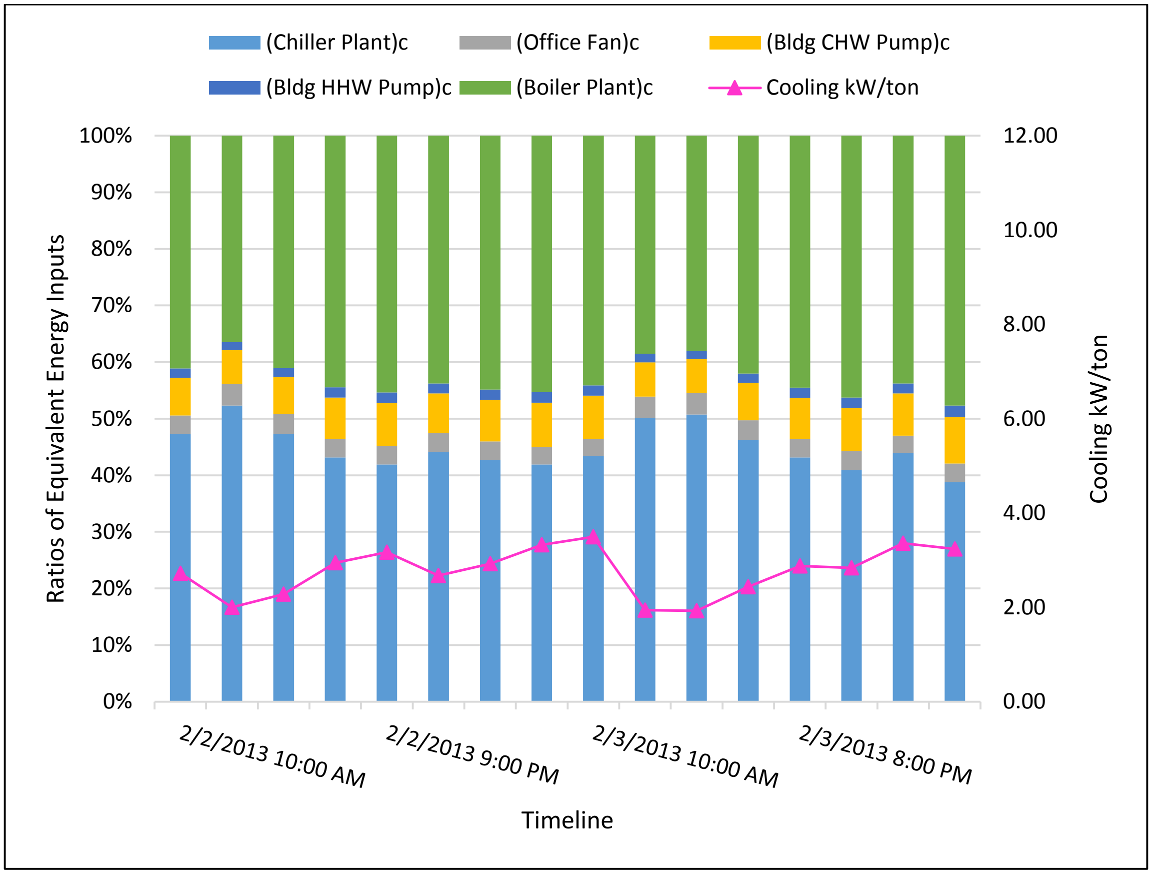


Figure 23 Cooling kW/ton and Ratios of Equivalent Energy Inputs during 2/2/2013-2/3/2013

The top line in Figure 24 shows the hourly variation in the cooling load in MMBtu/hr while the bottom portion of the figure shows the equivalent energy inputs in kW. The peak cooling load during this period is only 3-4% of the peak summer load and the total equivalent energy peak input is only 18% greater than the minimum input.

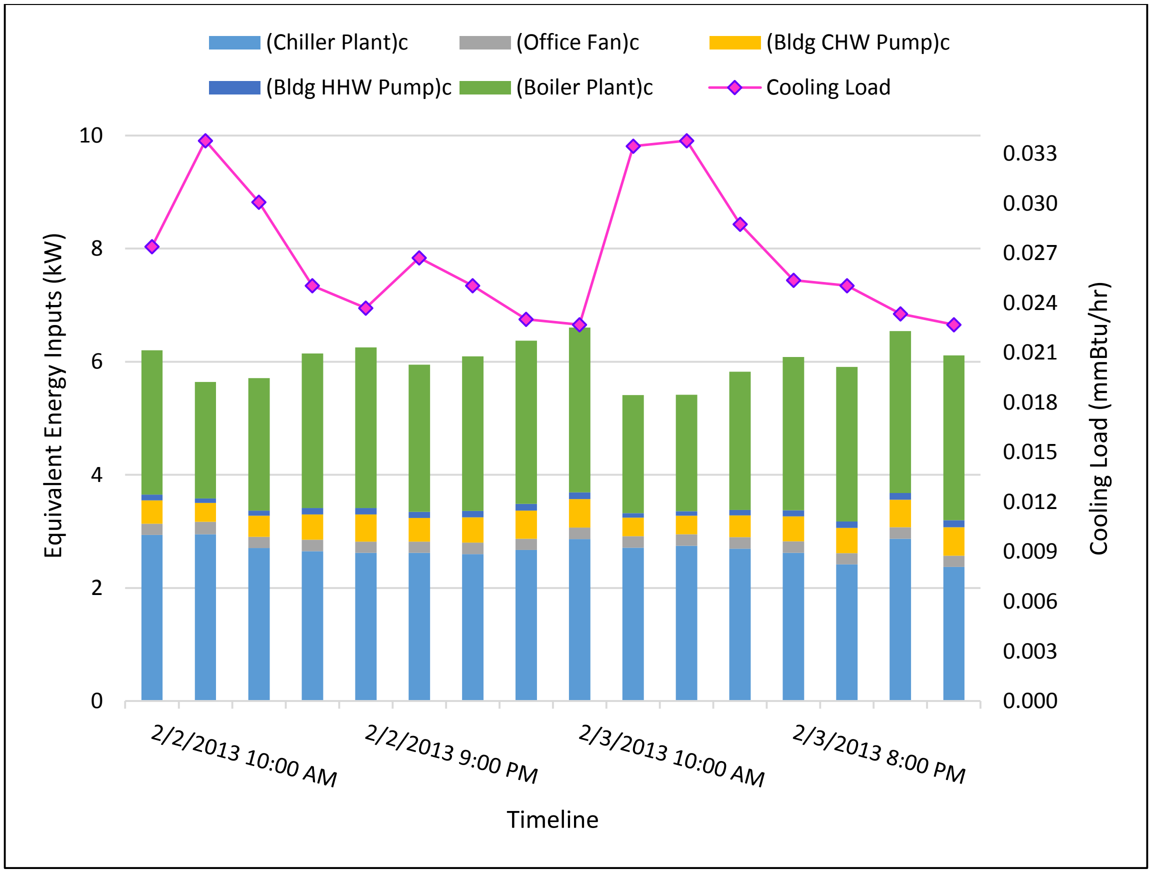


Figure 24 Cooling Load and Equivalent Energy Inputs during 2/2/2013-2/3/2013

Figure 25 shows the chiller plant kW/ton, the cooling system kW/ton and the cooling load. It may again be observed that the variation in system kW/ton is primarily due to system performance and not to plant performance.

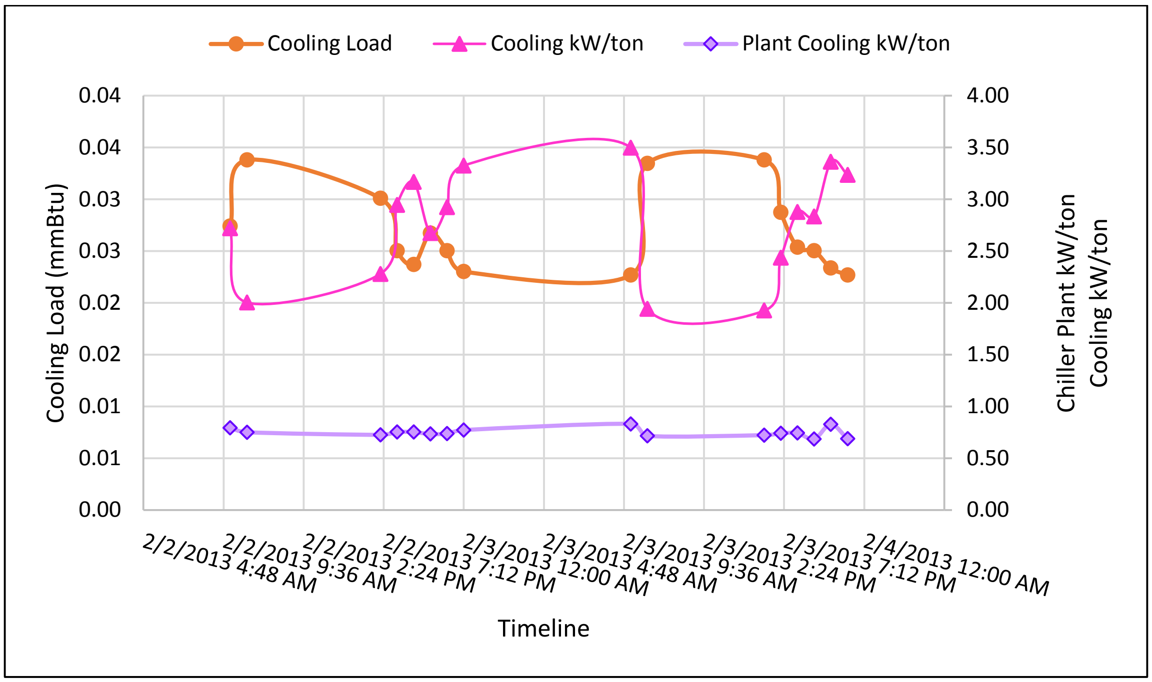


Figure 25 Cooling Load, Chiller Plant kW/ton and Cooling kW/ton during 2/2/2013-2/3/2013

When observing the Figures of Cooling COP and Ratios of Equivalent Energy Inputs for the two periods selected when the lab needs heating and the office needs cooling, it is again true that cooling COP variation is due to the variation of the ratios of equivalent energy inputs from chiller plant and boiler plant. The cooling efficiency values have a wide range if there is a great variation of boiler plant heating energy input ratio and chiller plant cooling energy input ratio, and the same is true in the reverse.

4.8.3 Cooling Efficiency when Lab Needs Heating and Office Needs Cooling for Interior Zone and Heating for Exterior Zone

When the lab needs heating, and when the office needs cooling for the interior zone and heating for the exterior zone, the cooling COP values range from 0.4 to 3.8 Btu-Load/Btu-Input as shown in Figure 26. The observed cooling COPs tend to divide into two groups, one with COP less than 2 Btu-Load/Btu-Input and the other generally above 2.5 Btu-Load/Btu-Input. These values all occur during the period from October 2012 to May 2013.

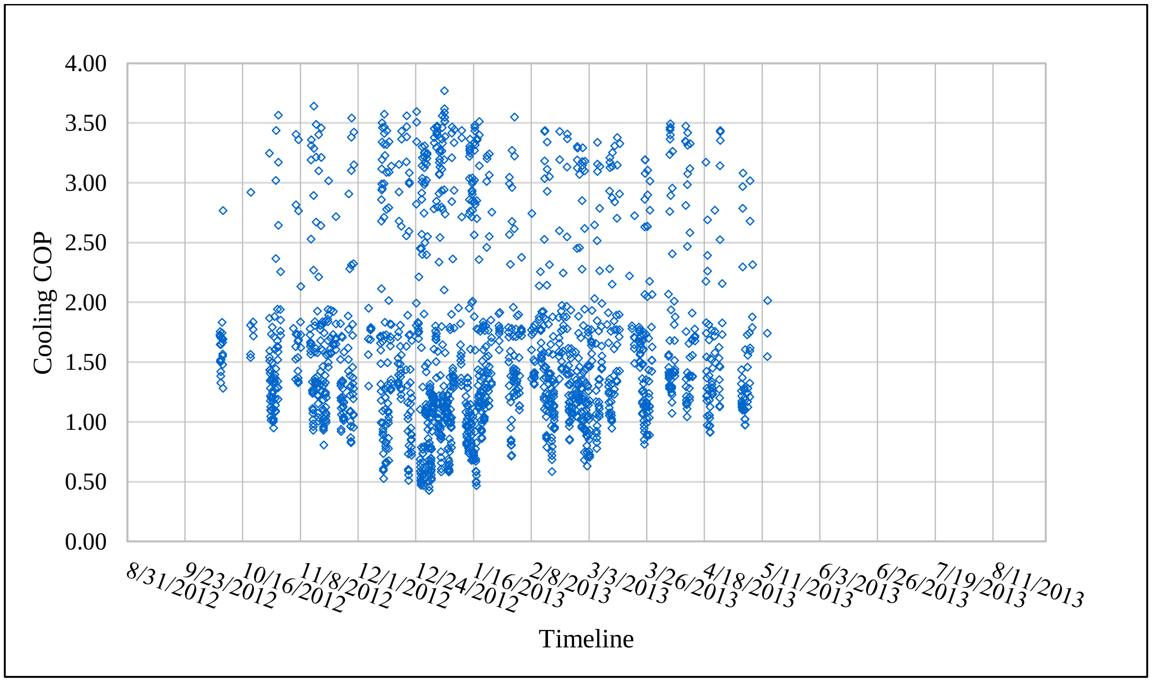


Figure 26 HVAC Cooling COP - Lab Needs Heating and Office Needs Cooling and Heating

For the period with cooling only in the interior offices, the period from 12/26/2012 to12/27/2012 is selected for analysis since the range of cooling efficiency values for this period is large. The pink line in Figure 27 shows that the cooling COPs range from 0.5 to 3.3 Btu-Load/Btu-Input during this period. The colorized columns of the figure show the hourly breakdown of the total equivalent cooling electricity between the chiller plant, fans, pumps and boiler plant. For these conditions, the fans and pumps account for more 20-40% of the equivalent electric input while the chiller plant accounts for 35-65% of the input while the boiler plant accounts for 0 - 36%. The diurnal COP can be seen to increase when the boiler portion decreases and vice versa.

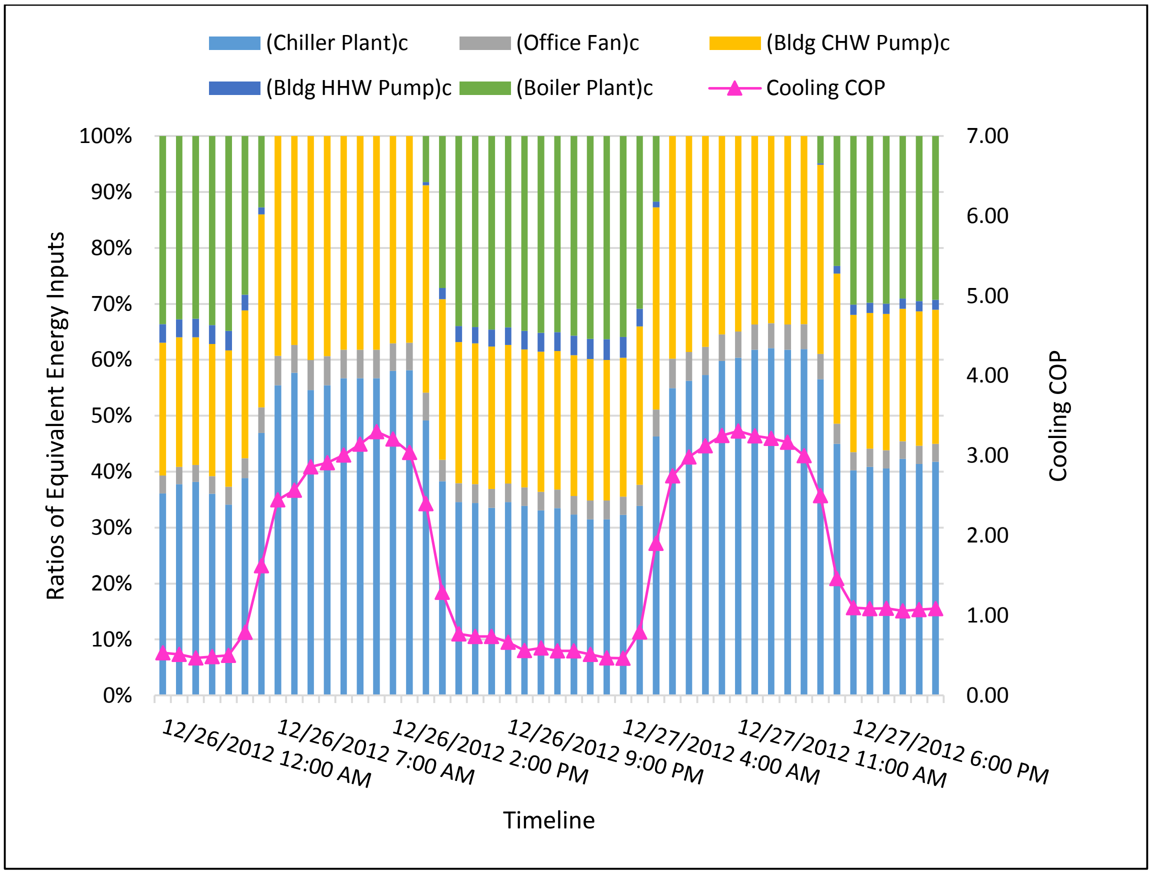


Figure 27 Cooling COP and Equivalent Ratios of Energy Inputs during 12/26/2012-12/27/2012

Figure 28 shows the same basic information shown in Figure 27 except that the system efficiency is expressed in kW/ton instead of COP.

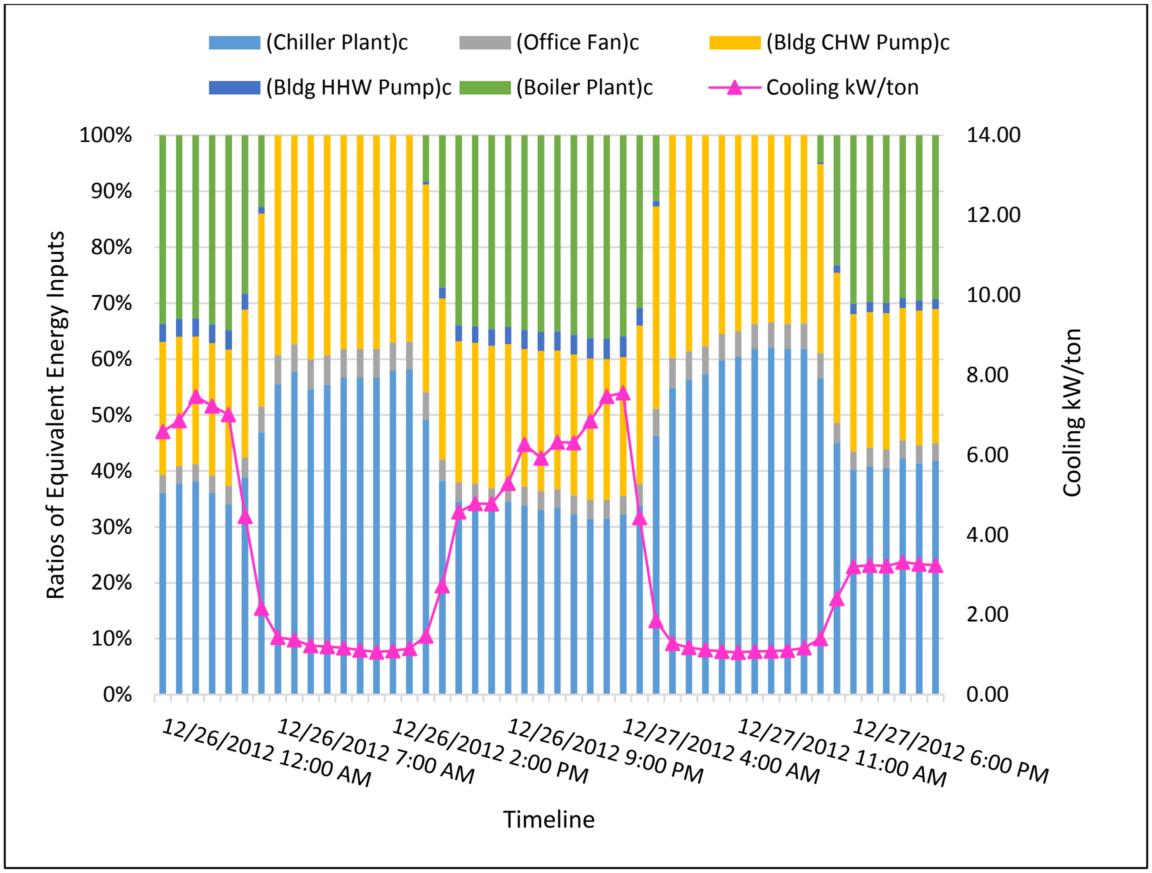


Figure 28 Cooling kW/ton and Equivalent Ratios of Energy Inputs during 12/26/2012-12/27/2012

The line in Figure 29 shows the hourly variation in the cooling load in MMBtu/hr while the bars in the figure show the equivalent energy inputs in kW. The peak load is more than four times the lowest load, but the peak load is only 3% of the summer peak cooling load. As the cooling load goes up, the total equivalent energy input goes down at the higher loads when no heating is used.

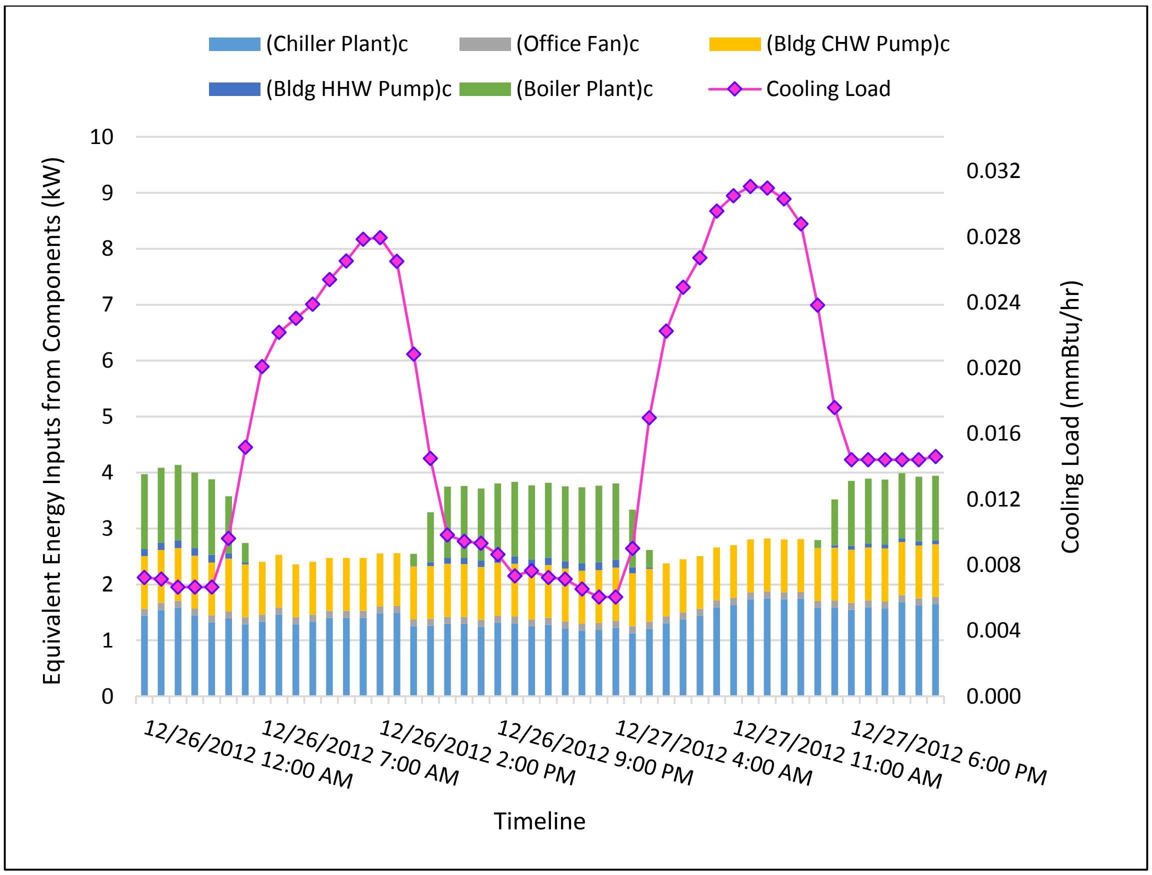


Figure 29 Cooling Load and Equivalent Energy Inputs during 12/26/2012-12/27/2012

Figure 30 shows the chiller plant kW/ton, the cooling system kW/ton and the cooling load. As seen in every previous case, the plot shows that the variation in system kW/ton is virtually all due to system performance and not to plant performance.

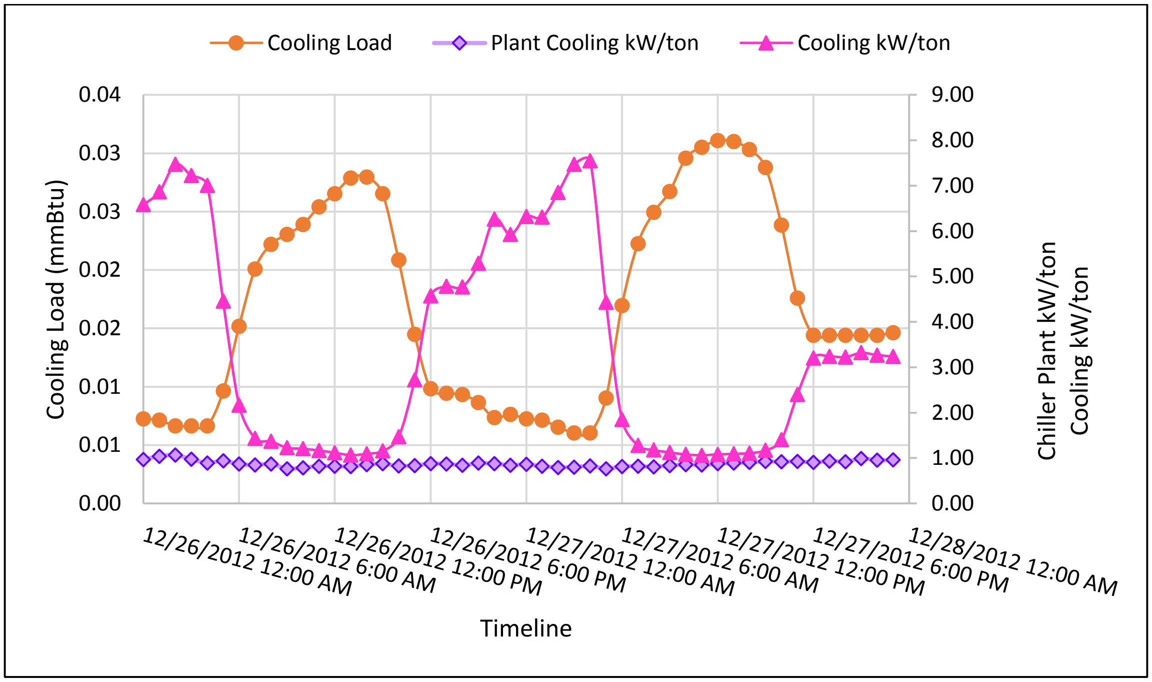


Figure 30 Cooling Load, Chiller Plant kW/ton and Cooling kW/ton during 12/26/2012-12/27/2012

The other data set analyzed for this case with cooling only in the interior offices is the period from 12/29/2012 to 12/30/2012. The data from this period shows a small range of cooling efficiency values during the winter period. The pink line in Figure 31 shows that the cooling COPs range from 0.4 to 1.3 Btu-Load/Btu-Input during this period. The colorized columns of the figure show the hourly breakdown of the total equivalent cooling electricity between the chiller plant, fans, pumps and boiler plant. For these conditions, the fans and pumps account for about 30% of the equivalent electric input while the boiler plant accounts for 30% to almost 40% of the input and the chiller plant accounts for about 35% - 40%, even under these cold winter conditions. The diurnal COP can be seen to increase when the boiler portion decreases and vice versa. It is noteworthy that the boiler portion of the energy input is a remarkably stable fraction of the total.

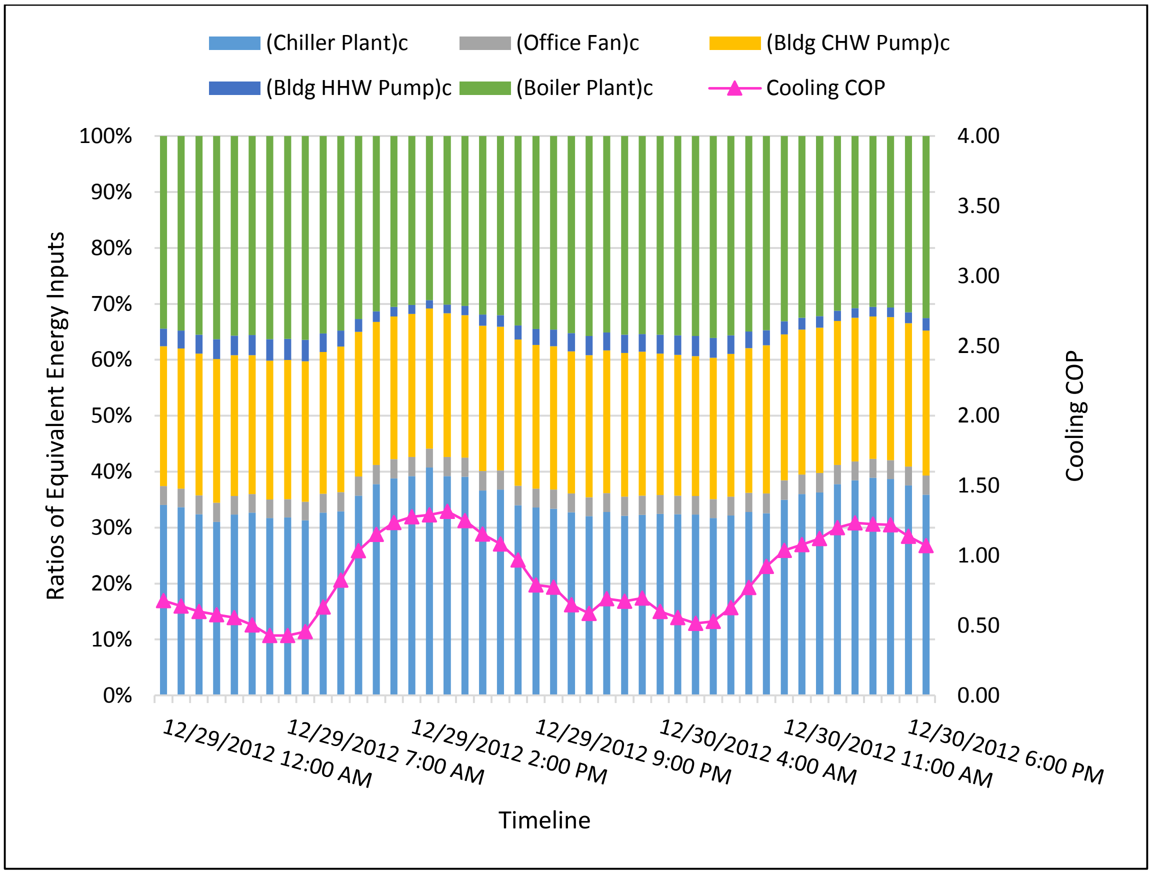


Figure 31 Cooling COP and Ratios of Equivalent Energy Inputs during 12/29/2012-12/30/2012

Figure 32 shows the same basic information shown in Figure 31 except that the system efficiency is expressed in kW/ton instead of COP.

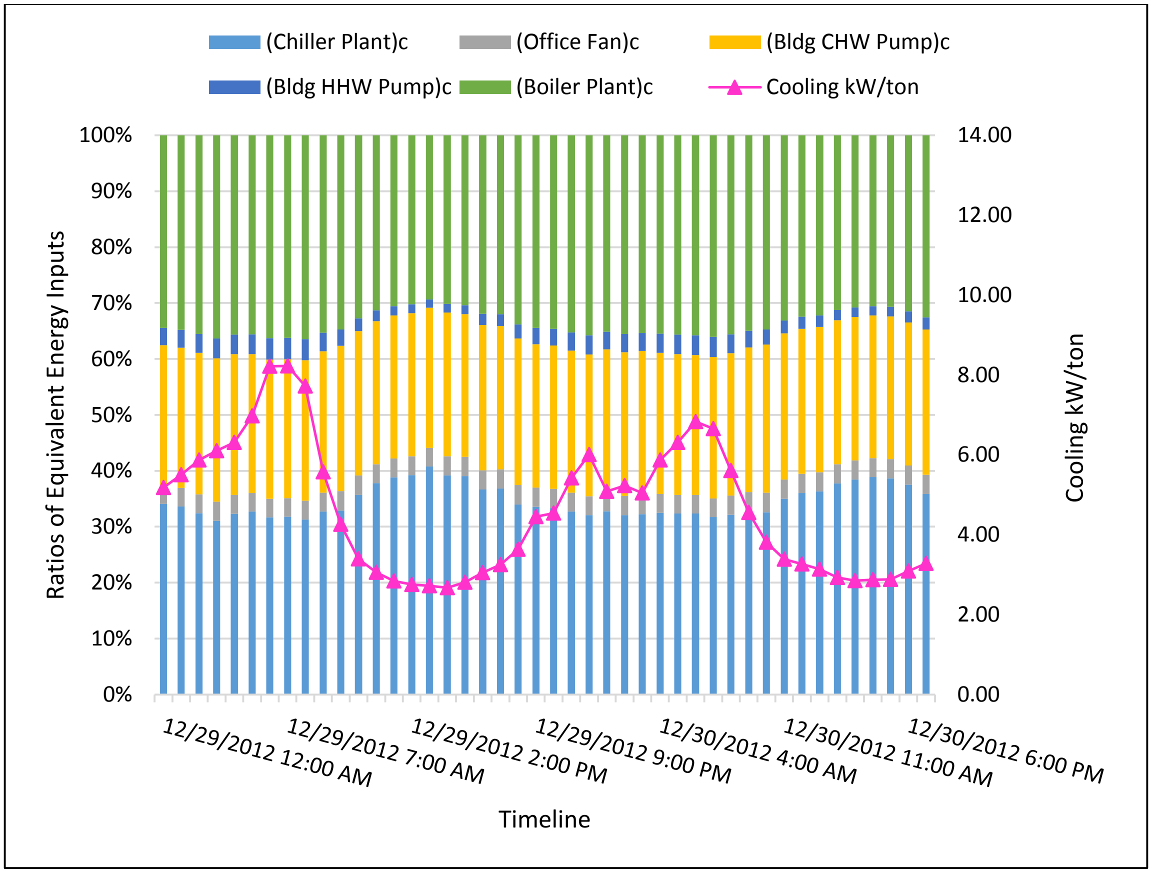


Figure 32 Cooling kW/ton and Ratios of Equivalent Energy Inputs during 12/29/2012-12/30/2012

The line in Figure 33 shows the hourly variation in the cooling load in MMBtu/hr while the bars show the equivalent energy inputs in kW. The peak load in this case is less than 2% of the summer peak and the peak cooling load is about three times the lowest load. This large fractional variation in cooling load is accompanied by variation in the total equivalent energy input of only 6%.

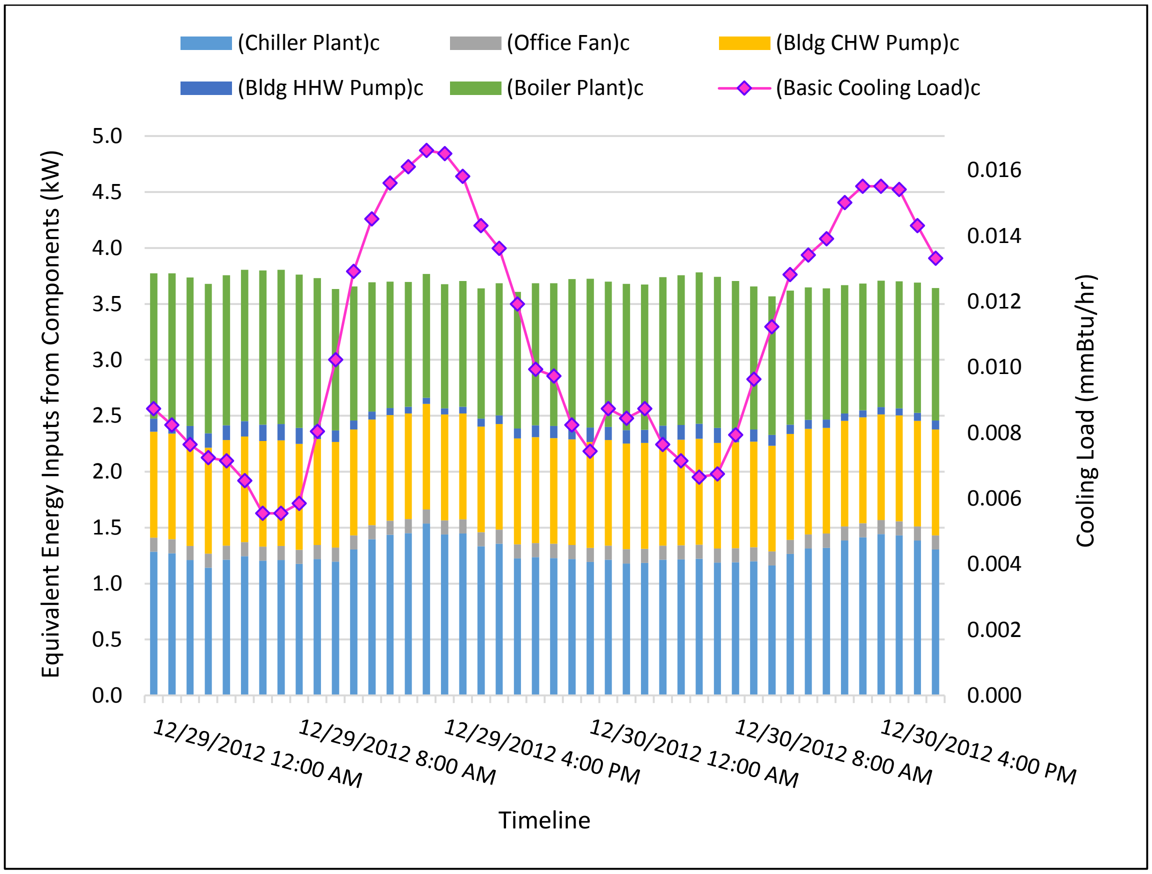


Figure 33 Cooling Load and Equivalent Energy Inputs from 12/29/2012-12/30/2012

Figure 34 shows the chiller plant kW/ton, the cooling system kW/ton and the cooling load. The figure shows that the system kW/ton varies from about 2.5 to 8 while the plant kW/ton is almost less than 1.0 at all times. In this case, the variation in system COP occurs due to variation in the cooling load while the total energy input to meet the small (in absolute terms) cooling load remains almost constant.

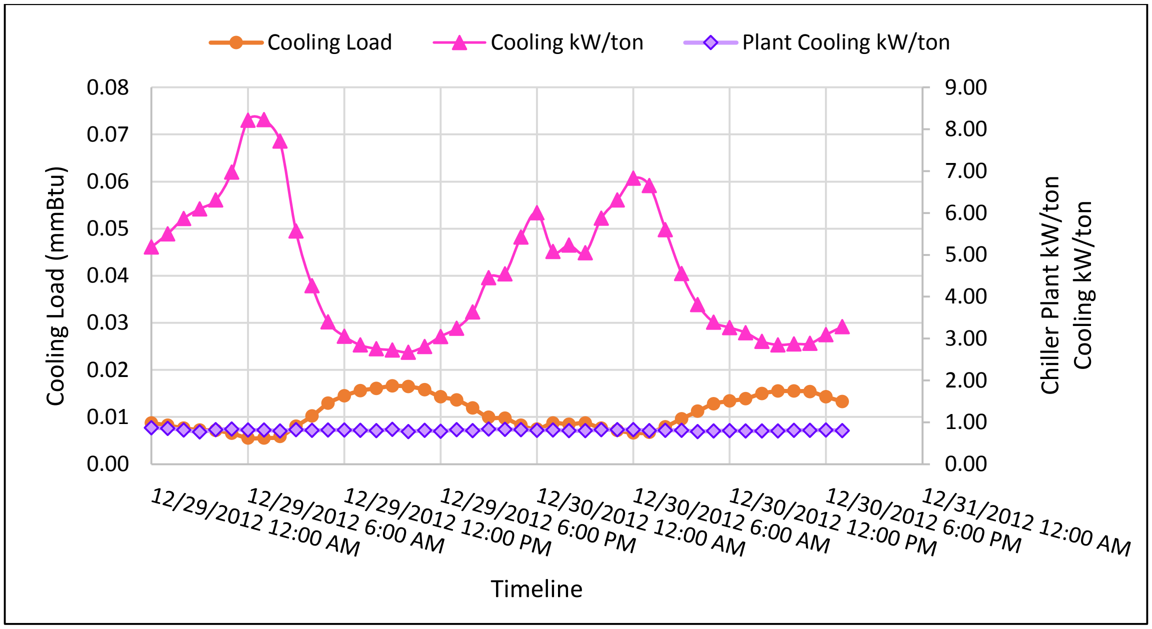


Figure 34 Cooling Load, Chiller Plant kW/ton and Cooling kW/ton from 12/26/2012-12/27/2012

When observing the Figures of Cooling COP and Ratios of Equivalent Energy Inputs for the two periods selected under the condition that the lab needs heating and the office needs cooling for the interior zone and heating for the exterior zone, one period has variation in COP because of the variation of the equivalent boiler plant heating energy inputs and the other differs from all the other periods examined since the variation in cooling COP occurs because the total energy input is almost constant while the very small cooling load changes by a factor of three!

4.8.4 Cooling Efficiency when Lab Needs Cooling for the Interior Zone and Heating for the Exterior Zone and the Office Needs Cooling

When the office needs cooling while the lab needs cooling for the interior zone and heating for the exterior zone, the observed system cooling COP values range from 0.3 to 1.1 Btu-Load/Btu-Input as shown in Figure 35. The values can be further divided into two parts: a group clustering near COP=1 Btu-Load/Btu-Input and a cluster of lower values near 0.5 Btu-Load/Btu-Input. These values occur during the period from September 2012 to May 2013.

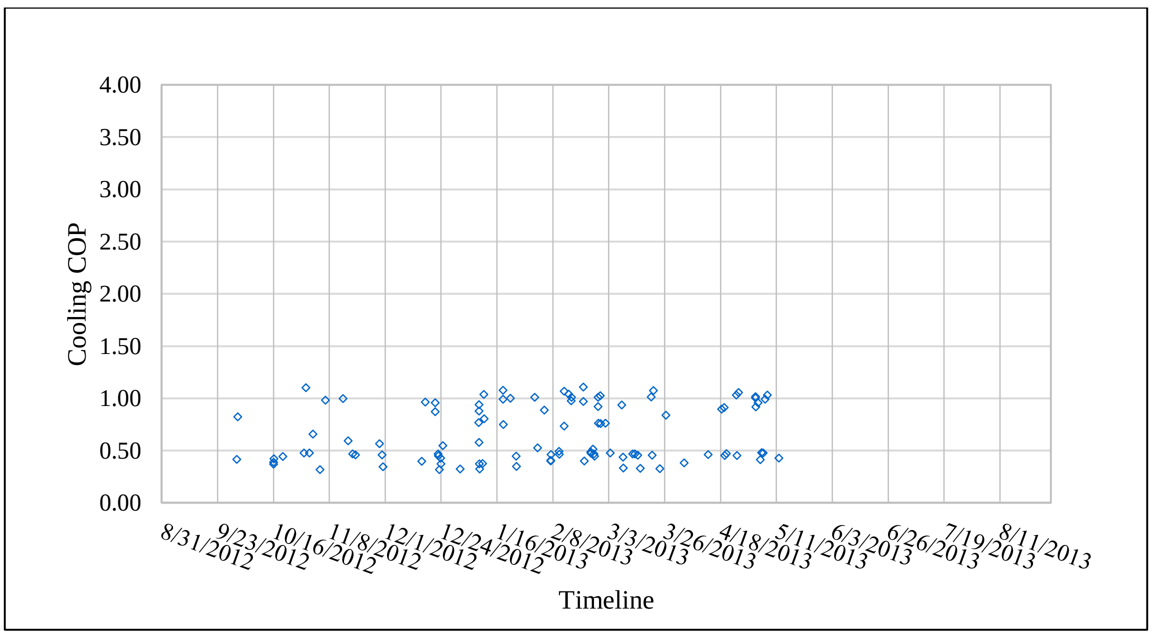


Figure 35 HVAC Cooling COP - Office Needs Cooling and Lab Needs Cooling and Heating

For this case, one period where the COP values cluster near 1 and another period where they cluster near 0.5 are examined.

The first period from 2/12/2013 to 2/20/2013 has system COP values near 1 Btu-Load/Btu-Input. The pink line in Figure 36 shows that the cooling COPs range from 0.7 to 1.1 Btu-Load/Btu-Input during this period. The colorized columns of the figure show the hourly breakdown of the total equivalent cooling electricity between the chiller plant, fans, pumps and boiler plant.

For these conditions, the fans and pumps account for about 20% of the equivalent electric input while the chiller plant accounts for about 40% of the input and the boiler plant accounts for about 40%. The only point where the COP goes out of the range 1.0 – 1.1 dips due to a small decrease in cooling input and a corresponding increase in heating input.

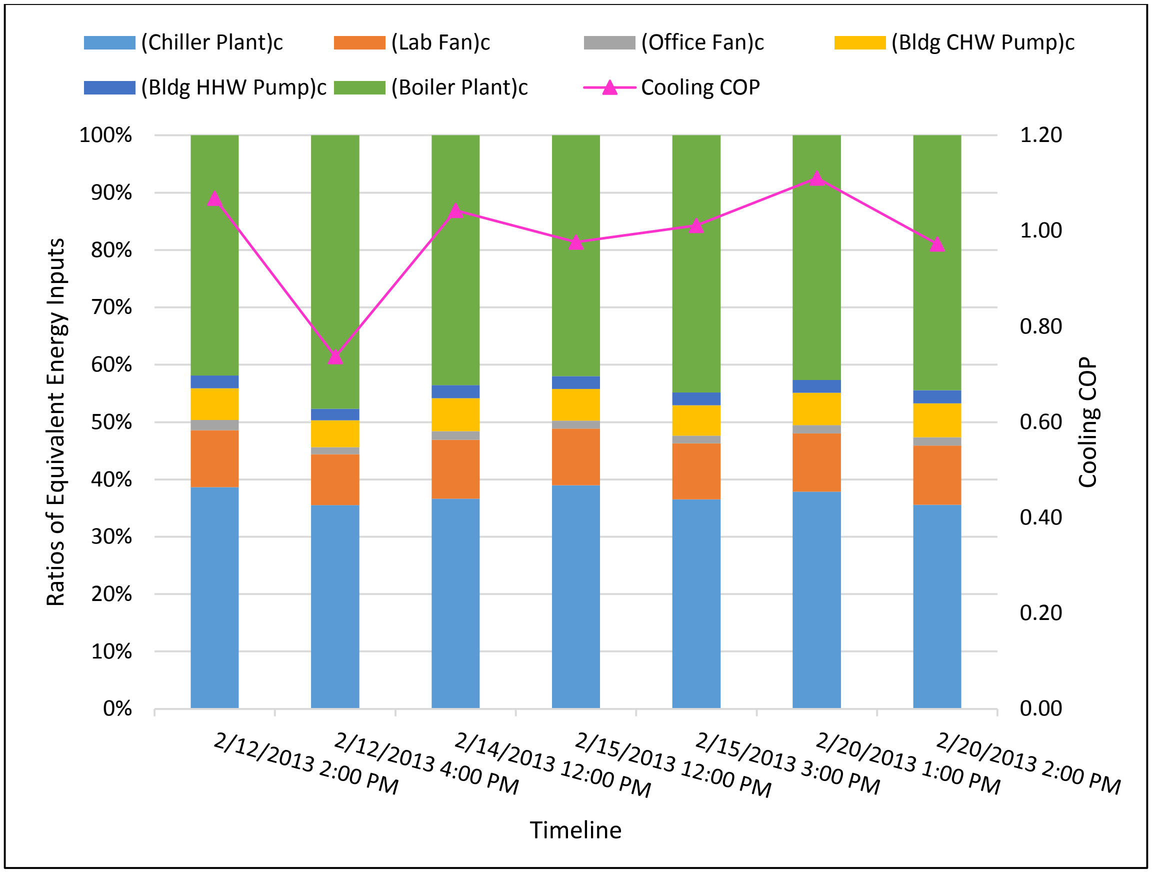


Figure 36 Cooling COP and Equivalent Ratios of Energy Inputs from 2/12/2013-2/20/2013

Figure 37 shows the same basic information shown in Figure 36 except that the system efficiency is expressed in kW/ton instead of COP.

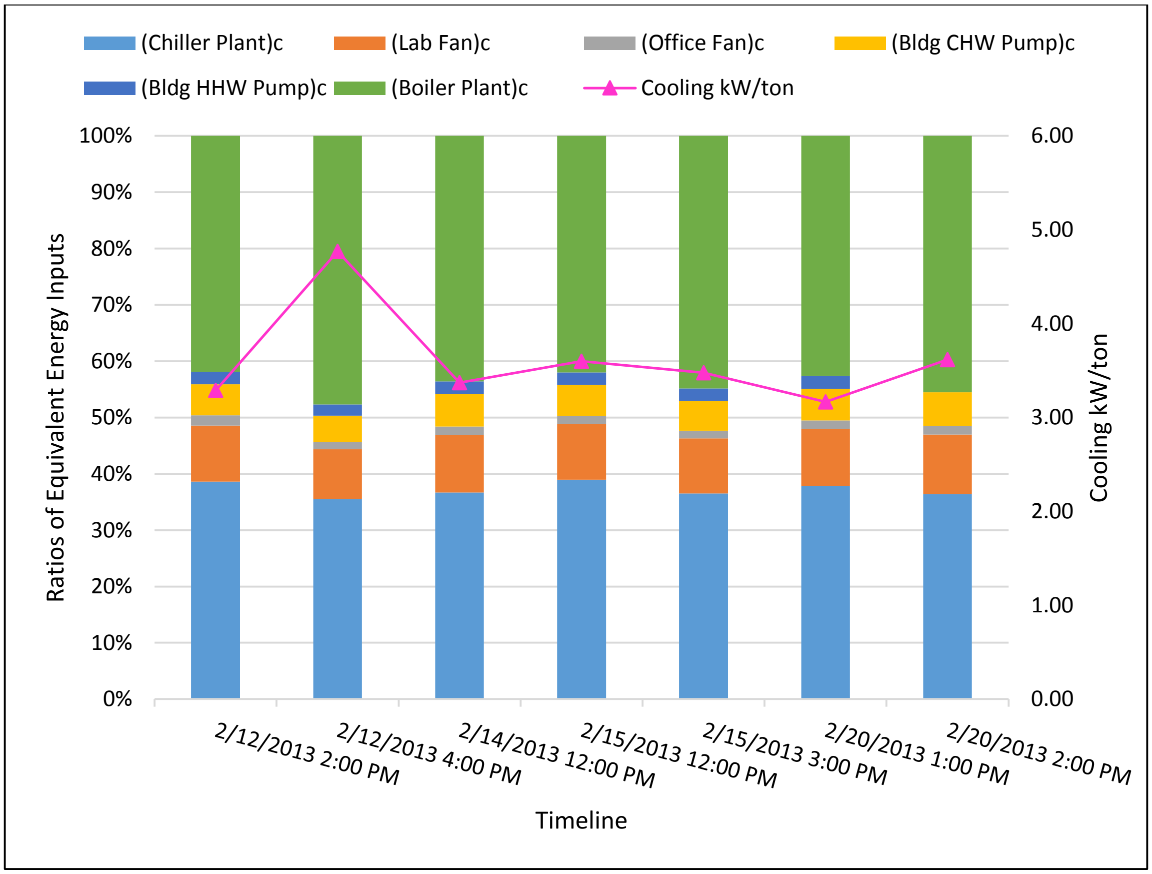


Figure 37 Cooling kW/ton and Equivalent Ratios of Energy Inputs from 2/12/2013-2/20/2013

The line in Figure 38 shows the hourly variation in the cooling load in MMBtu/hr while the bars show the equivalent energy inputs in kW. The peak load in this case is about 6% of the summer peak and the values are very similar except for one point where the load drops to about 80% of the other values.

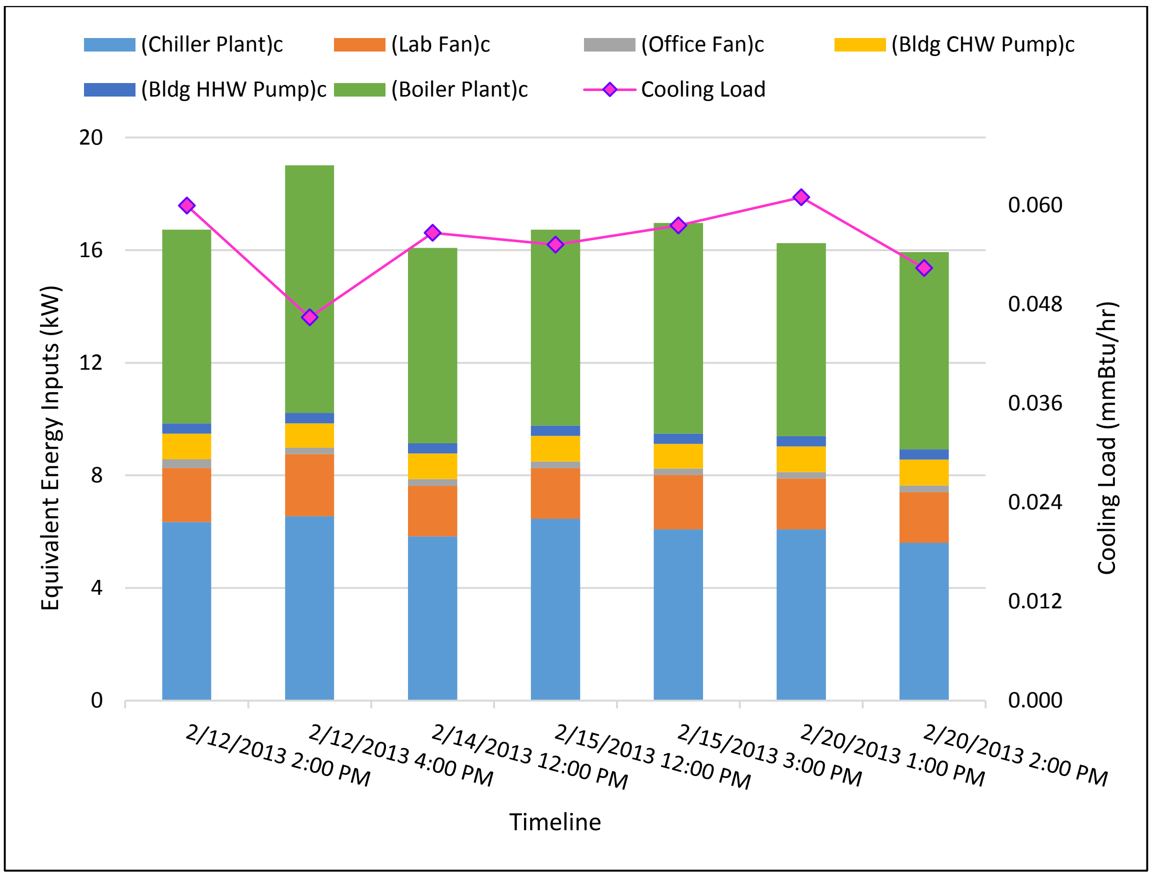


Figure 38 Cooling Load and Equivalent Energy Inputs from Components from 2/12/2013-2/20/2013

Figure 39 shows the chiller plant kW/ton, the cooling system kW/ton and the cooling load. The plot again shows that the variation in system kW/ton is virtually all due to system performance and not to plant performance.

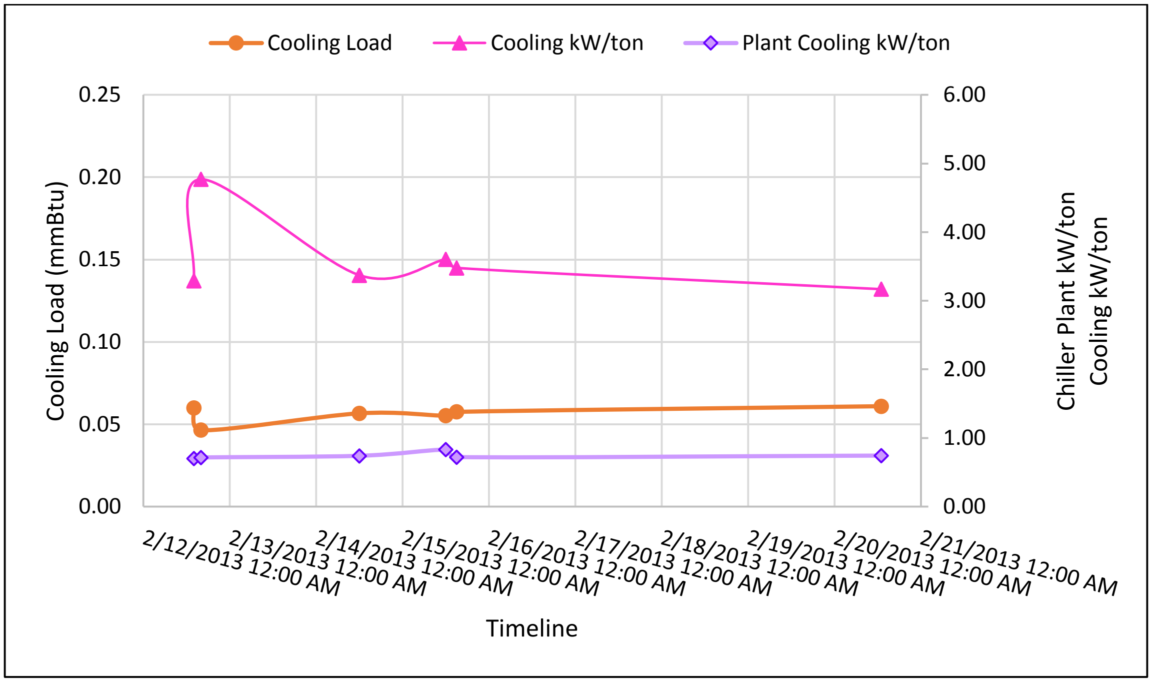


Figure 39 Cooling Load, Chiller Plant kW/ton and Cooling kW/ton from 2/12/2013-2/20/2013

The period 11/15/2012-12/16/2012 is used for analysis for the case where the system cooling efficiency values focus on 0.5 Btu-Load/Btu-Input. The pink line in Figure 40 shows that the cooling COPs range from 0.35 to 0.6 Btu-Load/Btu-Input during this period. The colorized columns of the figure show the hourly breakdown of the total equivalent cooling electricity between the chiller plant, fans, pumps and boiler plant. For these very low COP values, the fans and pumps account for about 15% of the equivalent electric input while the chiller plant accounts for about 30 - 35% of the input while the boiler plant accounts for about 50 - 55%. .

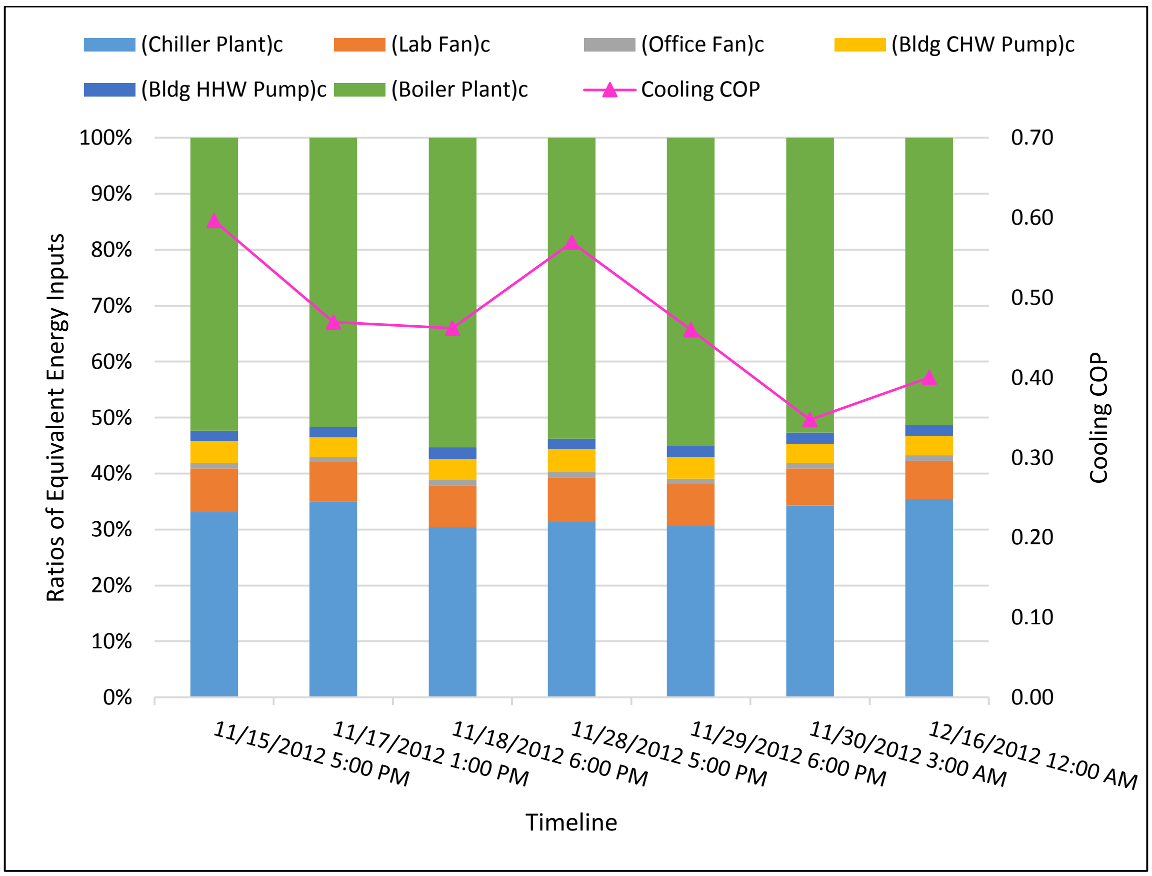


Figure 40 Cooling COP and Equivalent Ratios of Energy Inputs from 11/15/2012-12/16/2012

Figure 41 shows the same basic information shown in Figure 40 except that the system efficiency is expressed in kW/ton instead of COP.

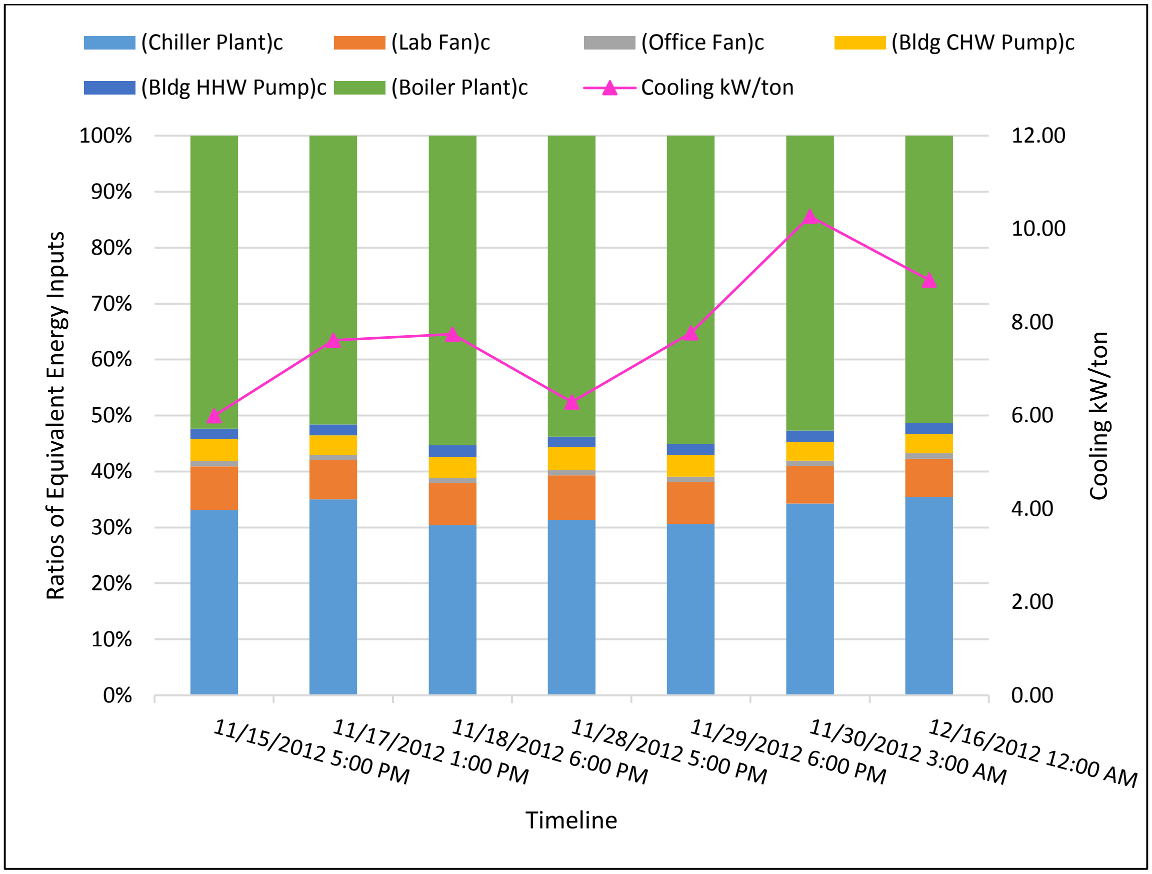


Figure 41 Cooling kW/ton and Equivalent Ratios of Energy Inputs from 11/15/2012-12/16/2012

The line in Figure 42 shows the hourly variation in the cooling load in MMBtu/hr while the bars in the figure show the equivalent energy inputs in kW. The cooling load varies between about 3% and 4% of the peak summer load.

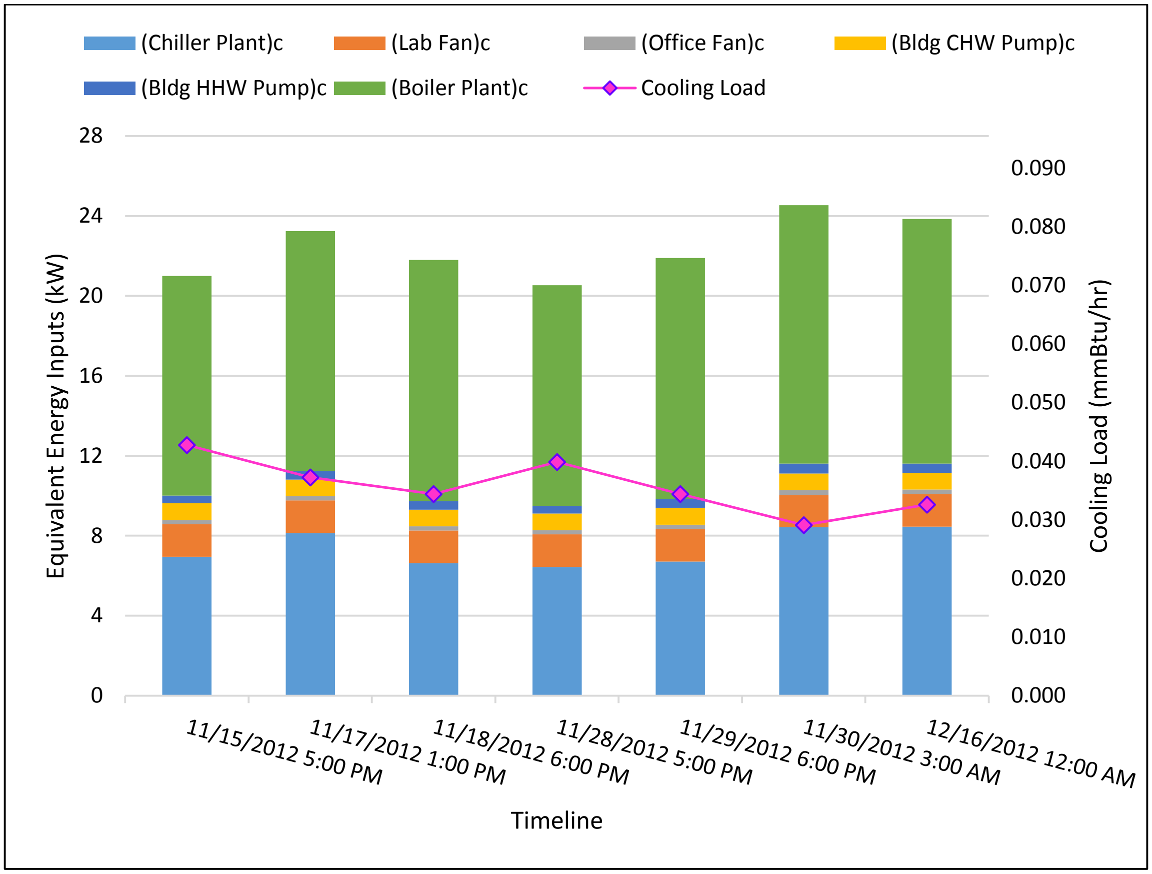


Figure 42 Cooling Load and Equivalent Energy Inputs from 11/15/2012-12/16/2012

Figure 43 shows the chiller plant kW/ton, the cooling system kW/ton and the cooling load. This plot shows the system kW/ton is 6 – 10 times the plant kW/ton and again, the plant kW/ton is almost constant.

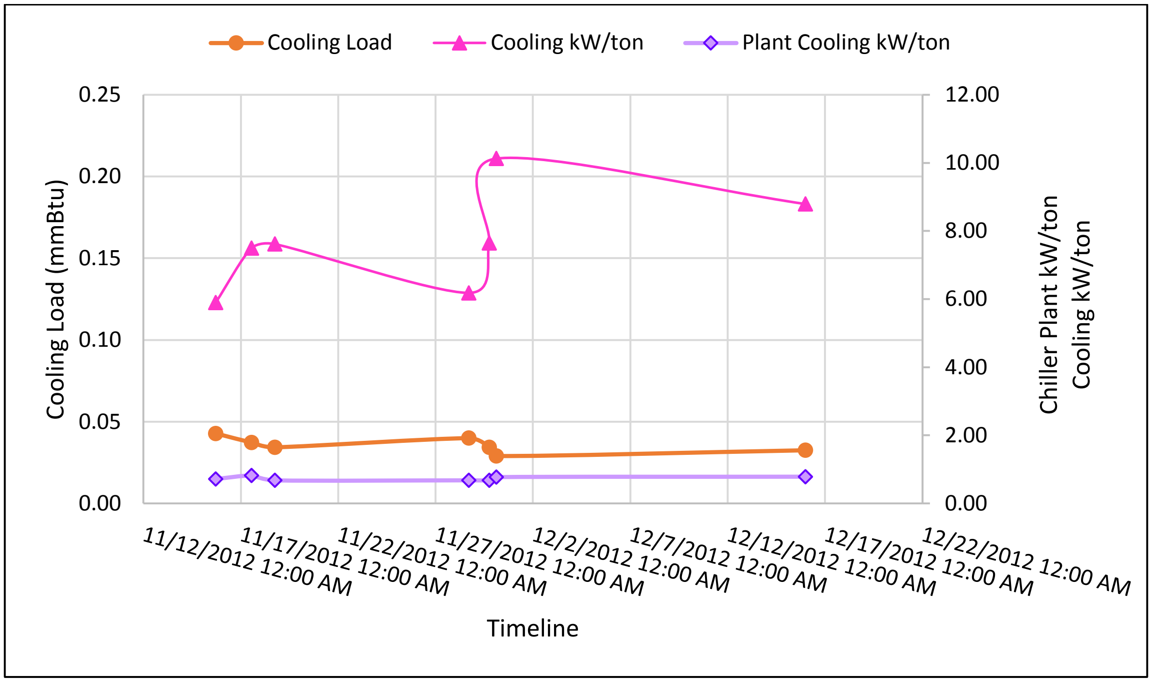


Figure 43 Cooling Load, Chiller Plant kW/ton and Cooling kW/ton from 11/15/2012-12/16/2012

When observing the Figures of Cooling COP and Ratios of Equivalent Energy Inputs for the two periods selected under the condition that the office needs cooling and the lab needs cooling for the interior zone and heating for the exterior zone, it may be observed that the heating and cooling energy inputs are both substantial with relatively small variation and the cooling loads are all quite small.

The Figures of the Cooling Load, Chiller Plant kW/ton and Cooling COP present both the chiller plant cooling efficiency and the entire HVAC system cooling efficiency, as well as the building cooling load. The primary difference between the two efficiencies clusters is that the cooling loads for the COP=1 cluster are almost two times as large as those for the COP=0.5 cluster.

4.9 Heating Efficiency Results and Analysis

After applying the method to do the calculation of heating load and energy input for heating, the hourly heating efficiency can be obtained. It can also been expressed by monthly values or the annual value to see the long-term results. The annual heating efficiency is 0.52 Btu-Load/Btu-Input and the monthly heating efficiency values are listed in the Table 30 and shown in Figure 44.

Table 30 Monthly System Heating Efficiency

Month	**Basic Total Heating Load**	**Total Equivalent NG for Heating**	**Heating Efficiency**
	mmBtu	**mmBtu**	**Btu-Load/Btu-Input**
Sep-12	0.05	0.95	0.06
Oct-12	28.14	64.37	0.44
Nov-12	59.14	128.57	0.46
Dec-12	108.93	194.03	0.56
Jan-13	135.21	226.14	0.60
Feb-13	78.03	160.96	0.48
Mar-13	73.08	148.44	0.49
Apr-13	40.12	80.92	0.50
May-13	13.50	32.19	0.42
Jun-13	0.00	0.00	NA
Jul-13	0.00	0.00	NA
Aug-13	0.00	0.00	NA

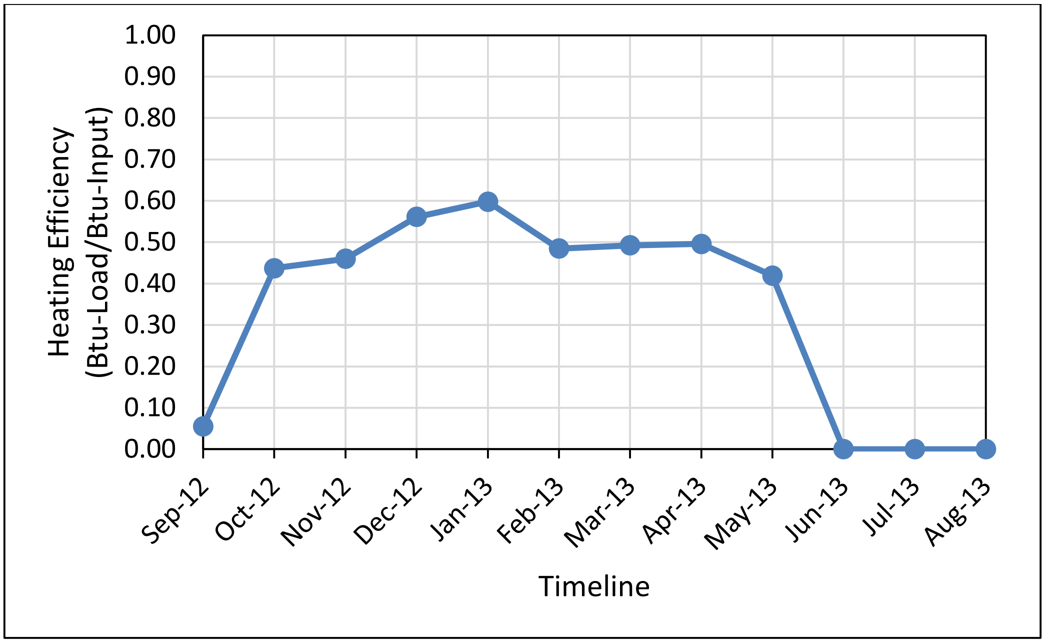


Figure 44 Monthly System Heating Efficiency

These results show that monthly system heating efficiency varies widely from 0.06 in September to 0.6 in December. Monthly values are larger than 0.4 from October 2012 through May 2013 when heating loads are larger and less than 0.4 only in September when heating loads are smaller. There is no heating efficiency from June through August since there is no heating load during this period. Hourly system heating efficiency values (not shown) vary significantly from a low of 0.01 to 0.69. On some days, system heating efficiency varies by a relatively small amount, and on others by more than an order of magnitude. The heating system performance will now be examined in more detail for several short periods when different combinations of zone heating and cooling loads are present in an attempt to determine the major factors that contribute to the wide variation in system heating efficiency.

Three different heating load combinations are examined in the following sections.

4.9.1 Heating Efficiency when Lab Needs Heating and Office Needs Cooling

When the lab needs heating and the office needs cooling, the heating efficiency has a wide range from 0.03 to 0.8 Btu-Load/Btu-Input as shown in Figure 45. A large portion of the values are less than 0.4 Btu-Load/Btu-Input. The heating efficiency values shown occur during the period from September 2012 to May 2013.

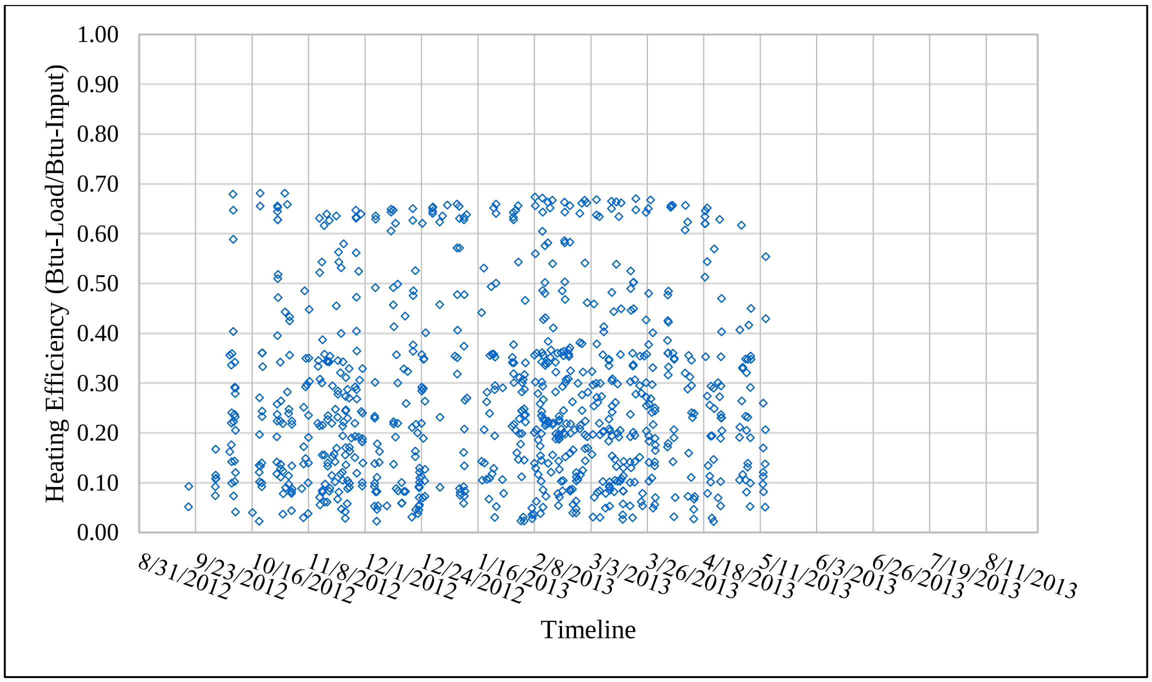


Figure 45 HVA Heating Efficiency when Office Needs Cooling and Lab Needs Heating

The first period examined in detail is from 11/11/2012 to 11/15/2012 with a wide range of heating efficiency values during each of these days. The red line in Figure 46 shows that the heating efficiency values range from 0.06 to 0.6 Btu-Load/Btu-Input during this period. The colorized columns of the figure show the hourly breakdown of the total equivalent heating natural gas between the chiller plant, fans, pumps and boiler plant. For these conditions, the fans and pumps account for about 15% of the equivalent natural gas while the boiler plant accounts for about 60 - 85% of the input while the chiller plant input ranges from 0 to about 25%. The diurnal heating efficiency can be seen to decrease when the chiller portion increases and vice versa.

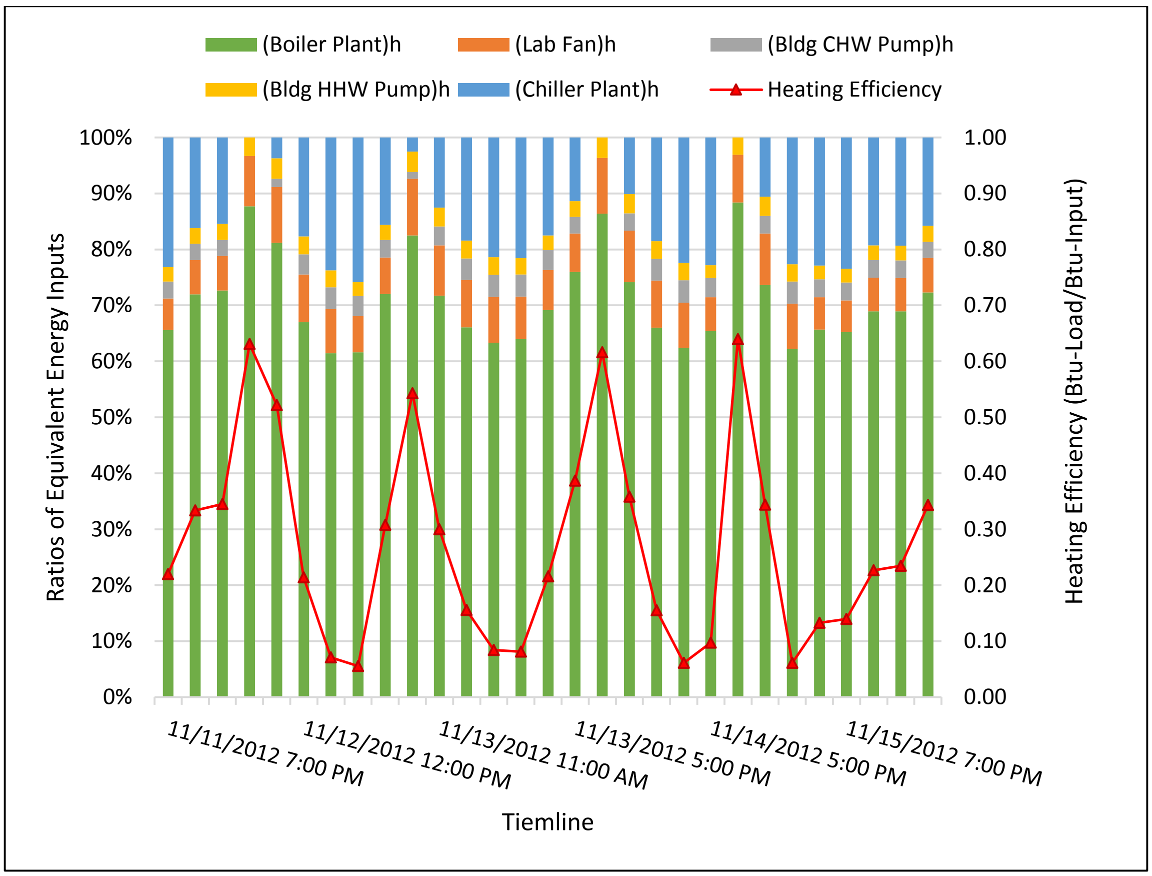


Figure 46 Heating Efficiency and Ratios of Equivalent Energy Inputs from 11/11/2012-11/15/2012

The line in Figure 47 shows the hourly variation in the heating load in MMBtu/hr while the bars in the figure show the equivalent energy inputs in MMBtu/hr. The peak load of 0.15 MMBtu/hr is about 15 times the lowest load while the total equivalent energy peak input is only 1.75 times the minimum input.

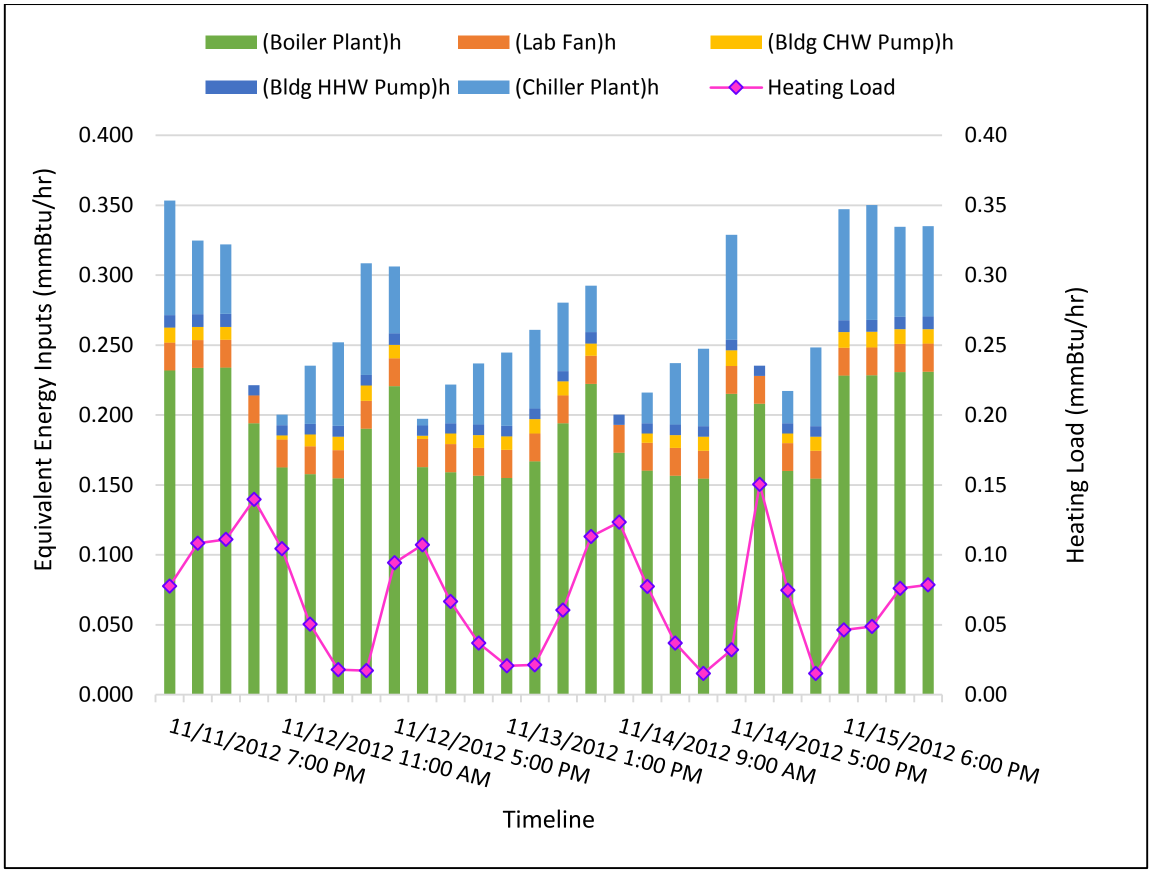


Figure 47 Heating Load and Equivalent Energy Inputs during 11/11/2012-11/15/2012

Figure 48 shows the heating load, the heating efficiency, outside air temperature, and chiller plant cooling energy use. The heating efficiency was generally higher when the heating load was higher, and lower when the heating load was lower. The heating load increased at lower outside air temperatures as expected. When the heating loads were small, some cooling was used by the system, further lowering system efficiency.

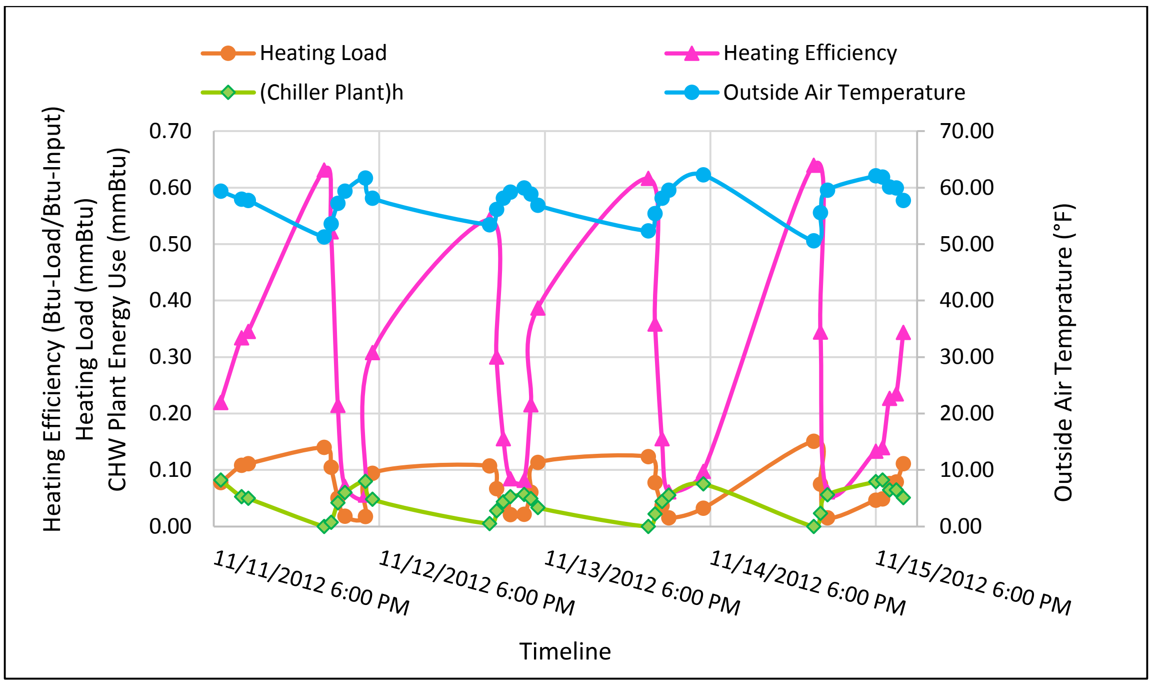


Figure 48 Outside Air Temperature, Heating Load, Chiller Plant Cooling Energy Input and Heating Efficiency from 11/11/2012-11/15/2012

4.9.2 Heating Efficiency when Lab Needs Heating and Office Needs Cooling for Interior Zone and Heating for Exterior Zone

When the lab needs heating and the office needs cooling for the interior zone and heating for the exterior zone, the heating efficiency values range from 0.1 to 0.7 Btu-Load/Btu-Input as shown in Figure 49. One group of the values fall within a narrow range between 0.6 and 0.7 Btu-Load/Btu-Input, whereas another group of the values generally lies between 0. 3 and 0.6 Btu-Load/Btu-Input. Several points are less than 0.3 Btu-Load/Btu-Input due to a high cooling energy input with a low heating load when outside air temperature is high. The heating efficiency values shown occur from October 2012 to May 2013.

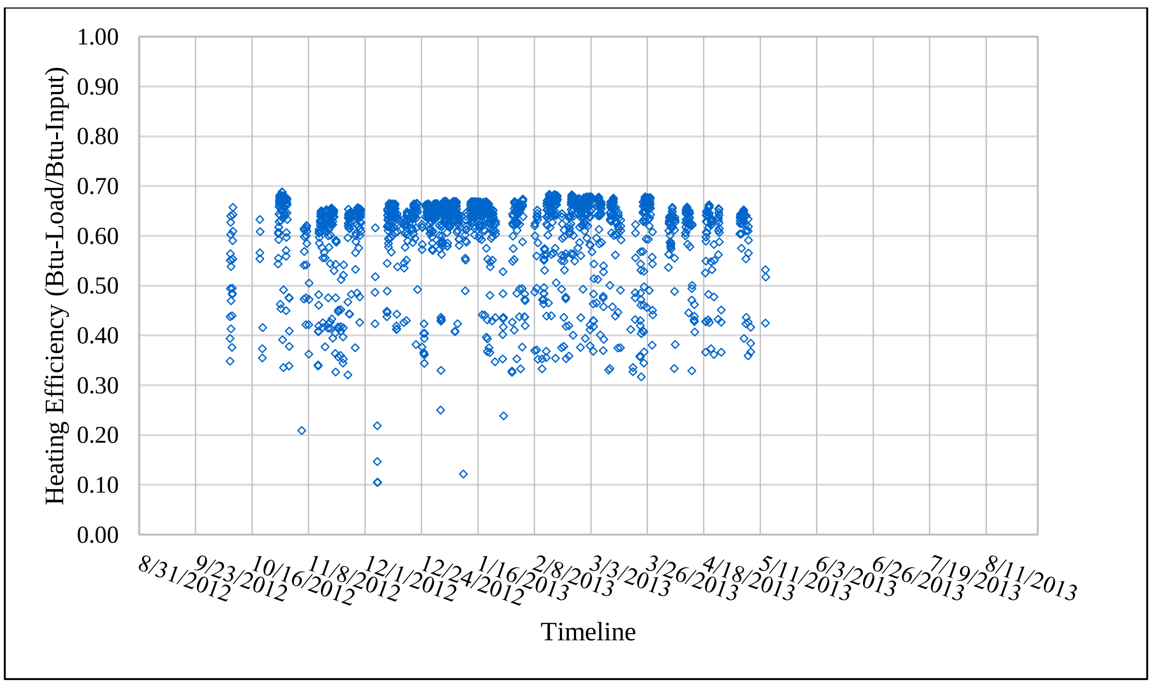


Figure 49 HVAC Heating Efficiency when Office Needs Cooling and Heating and Lab Needs Heating

The period from 10/27/2012 to10/29/2012 is selected for analysis since these days have a wide range of heating efficiency values. The red line in Figure 50 shows that the heating efficiency values range from 0.3 to 0.7 Btu-Load/Btu-Input during this period. The colorized columns of the figure show the hourly breakdown of the total equivalent heating natural gas between the chiller plant, fans, pumps and boiler plant. For these conditions, the fans and pumps account for about 15% of the equivalent natural gas input while the boiler plant accounts for 70 - 85% of the input and the chiller plant accounts for about 0 - 15%. The diurnal heating efficiency can be seen to decrease when the chiller portion increases and vice versa.

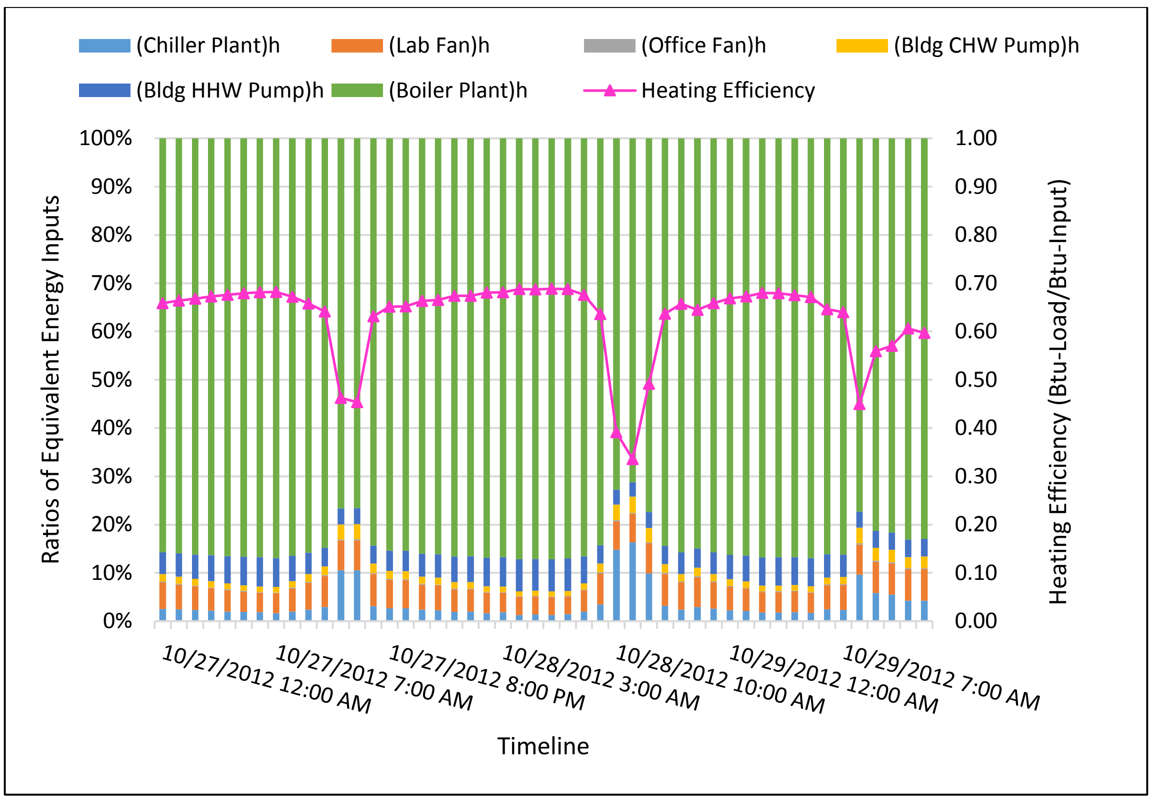


Figure 50   Heating Efficiency and Ratios of Equivalent Energy Inputs from 10/27/2012-10/29/2012

The line in Figure 51 shows the hourly variation in the cooling load in MMBtu/hr while the columns show the equivalent energy inputs in MMBtu/hr. The peak load is about three times the lowest load, while the total equivalent energy peak input is less than twice the minimum input. The peak load in this case is more than twice the peak shown in Figure 47 when the office required no heating.

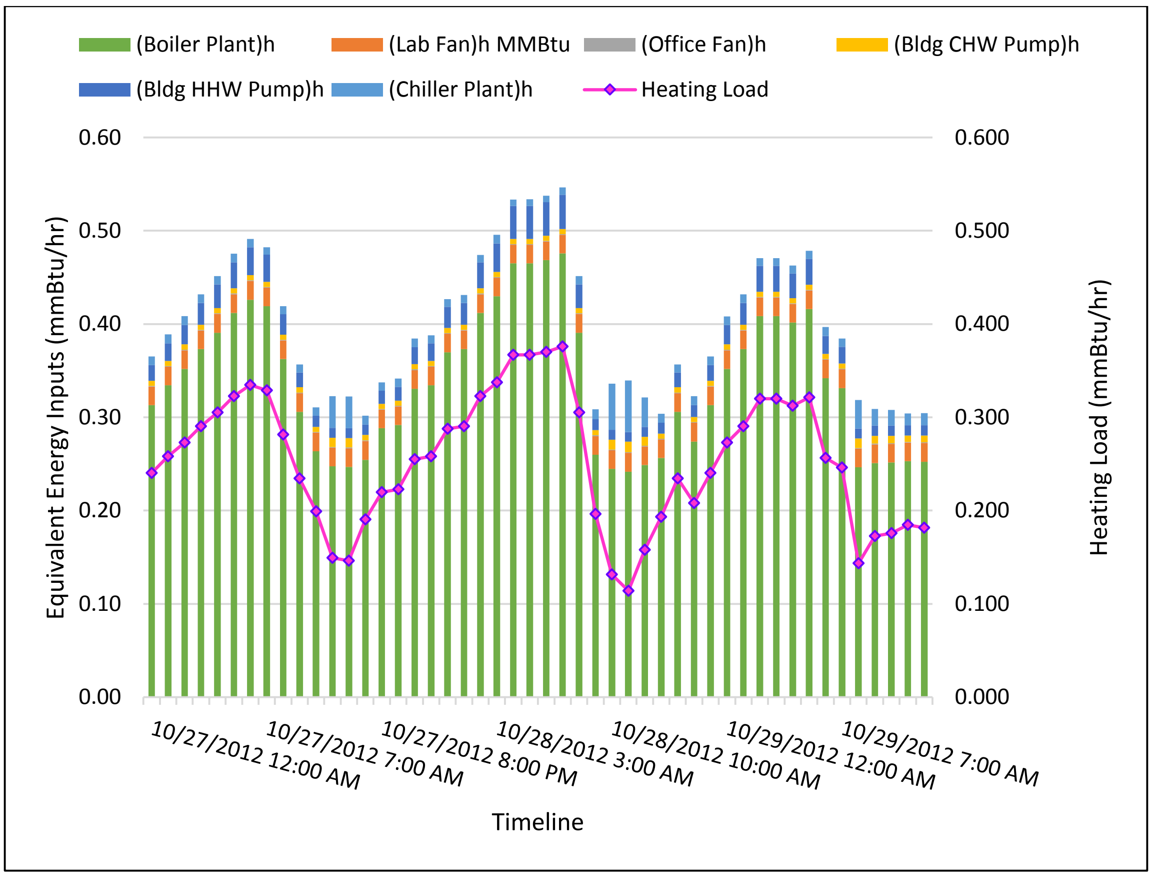


Figure 51 Heating Load and Equivalent Energy Inputs during 10/27/2012-10/29/2012

Figure 52 shows heating efficiency and outside air temperature. The plot shows clearly that the system heating efficiency decreases when the outside air temperature increases and vice versa, though this is undoubtedly due to the higher heating loads at lower temperatures.

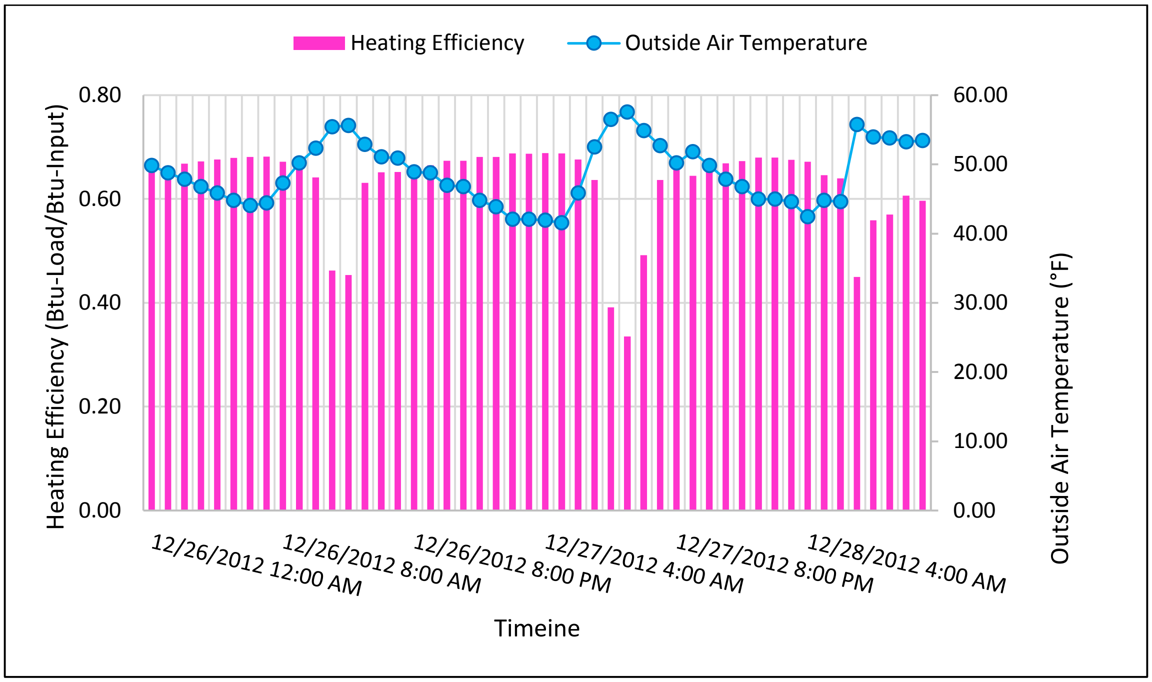


Figure 52 Heating Efficiency and Outside Air Temperature from 10/27/2012-10/29/2012

Figure 53 shows outside air temperature, heating load and ratio of equivalent boiler plant heating energy input. The plot shows clearly that when the outside air temperature is higher, both the equivalent boiler plant heating energy ratio and the heating load are lower, and vice versa.

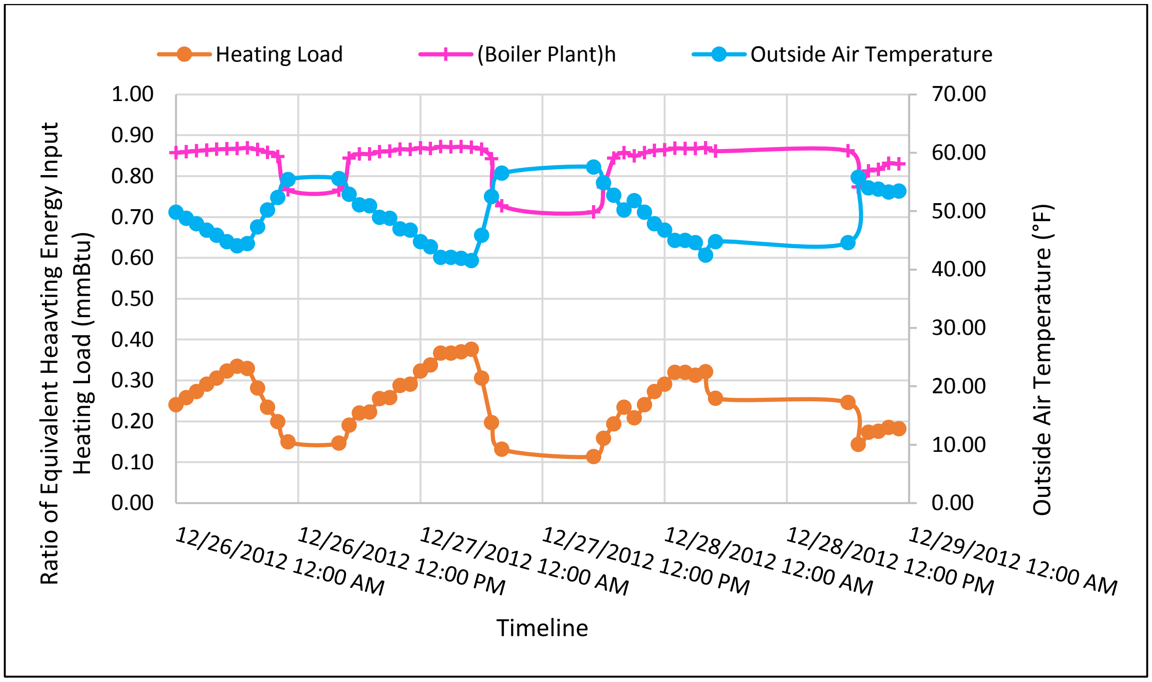


Figure 53 Outside Air Temperature, Heating Load and Ratio of Equivalent Boiler Plant Heating Energy Input from 10/27/2012-10/29/2012

4.9.3 Heating Efficiency when Lab Needs Cooling for Interior Zone and Heating for Exterior Zone and Office Needs Cooling

When the lab needs cooling for the interior zone and heating for the exterior zone and when the office needs cooling, the heating efficiency values are less than 0.1 Btu-Load/Btu-Input as shown in Figure 54. These conditions occur during the period of September 2012 to May 2013.

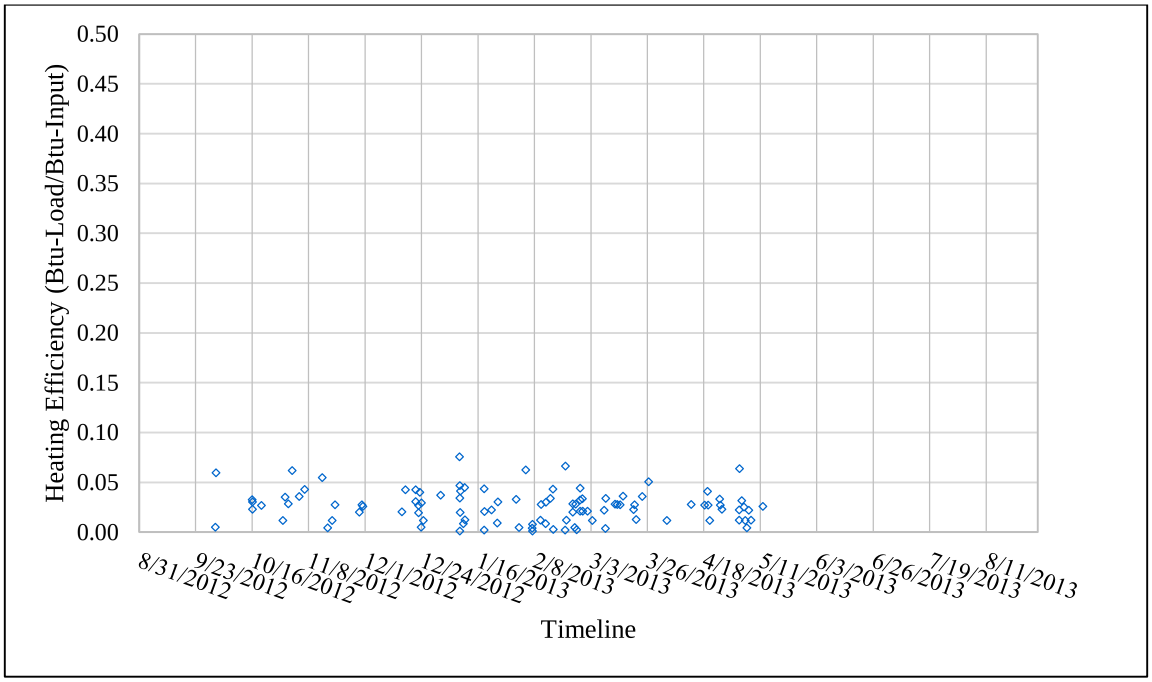


Figure 54 HVAC Heating Efficiency when Office Needs Cooling and Lab Needs Cooling and Heating

All of these heating efficiency values are analyzed for this cooling and heating load combination. The red line in Figure 55 shows that the heating efficiency values are less than 0.1 Btu-Load/Btu-Input during this period. The colorized columns of the figure show the hourly breakdown of the total equivalent heating natural gas between the chiller plant, fans, pumps and boiler plant. For these conditions, there is always input from the chiller plant, ranging from about 20 – 30%. The fans and pumps account for about 15% of the equivalent natural gas input while the boiler plant accounts for about 50 - 55% of the input. The diurnal heating efficiency can be seen to decrease when the chiller portion increases and vice versa.

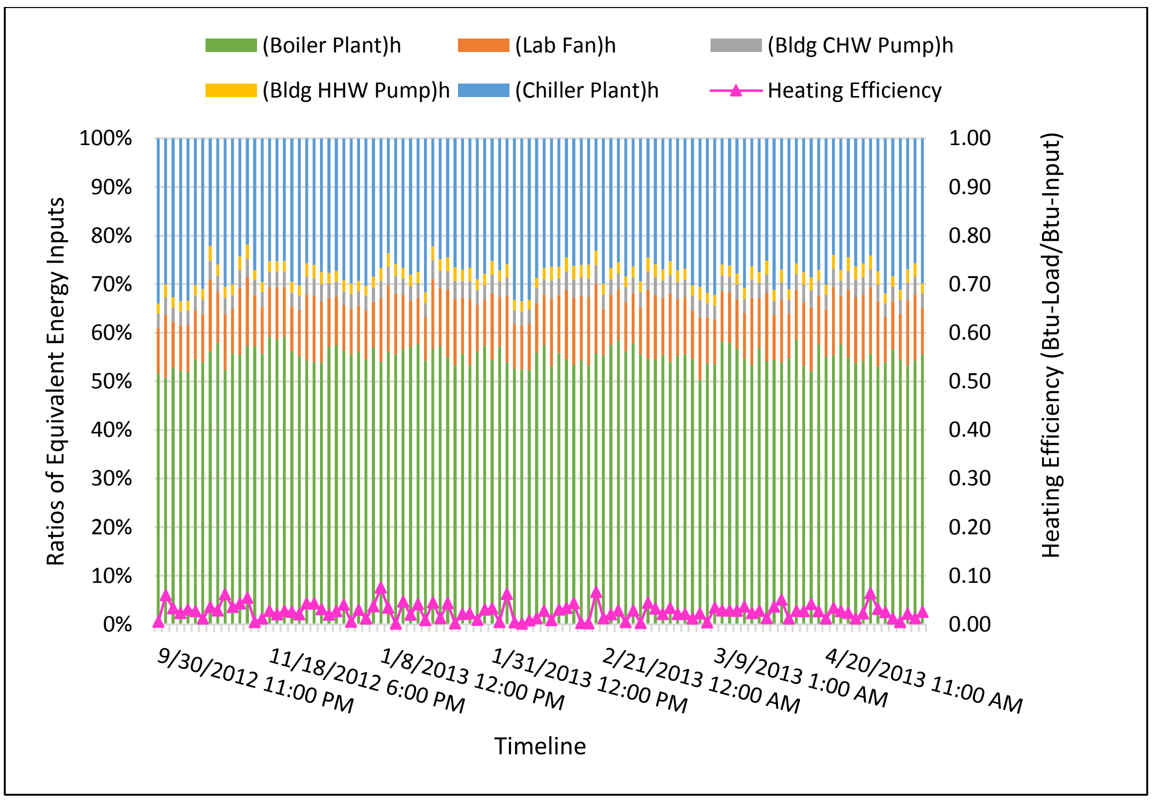


Figure 55   Heating Efficiency and Ratios of Equivalent Energy Inputs from 9/30/2012-5/5/2013 when only the lab exterior zone needs heating

The line in Figure 56 shows the hourly variation in the cooling load in MMBtu/hr while the columns show the equivalent energy inputs in MMBtu/hr. The peak load is more 10 times the lowest load, but even the peak is just over 10 kBtu/hr, which may be compared with a peak of almost 400 kBtu/hr in Figure 53. The total equivalent energy peak input is only 1.5 times the minimum input.

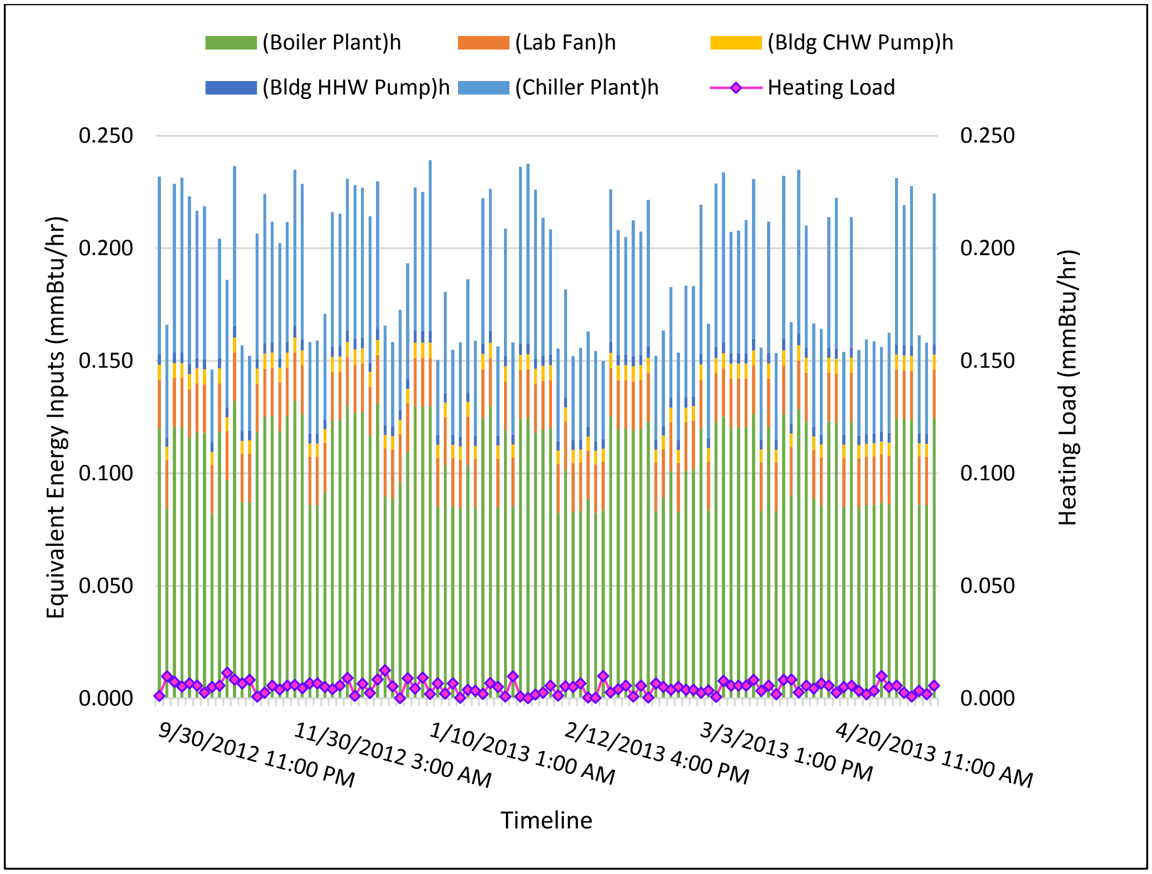


Figure 56 Heating Load and Equivalent Energy Inputs from 9/30/2012-5/5/2013

Figure 57 shows heating efficiency and outside air temperature. The plot shows clearly that the system heating efficiency decreases when the outside air temperature increases and vice versa, but again, this is load related.

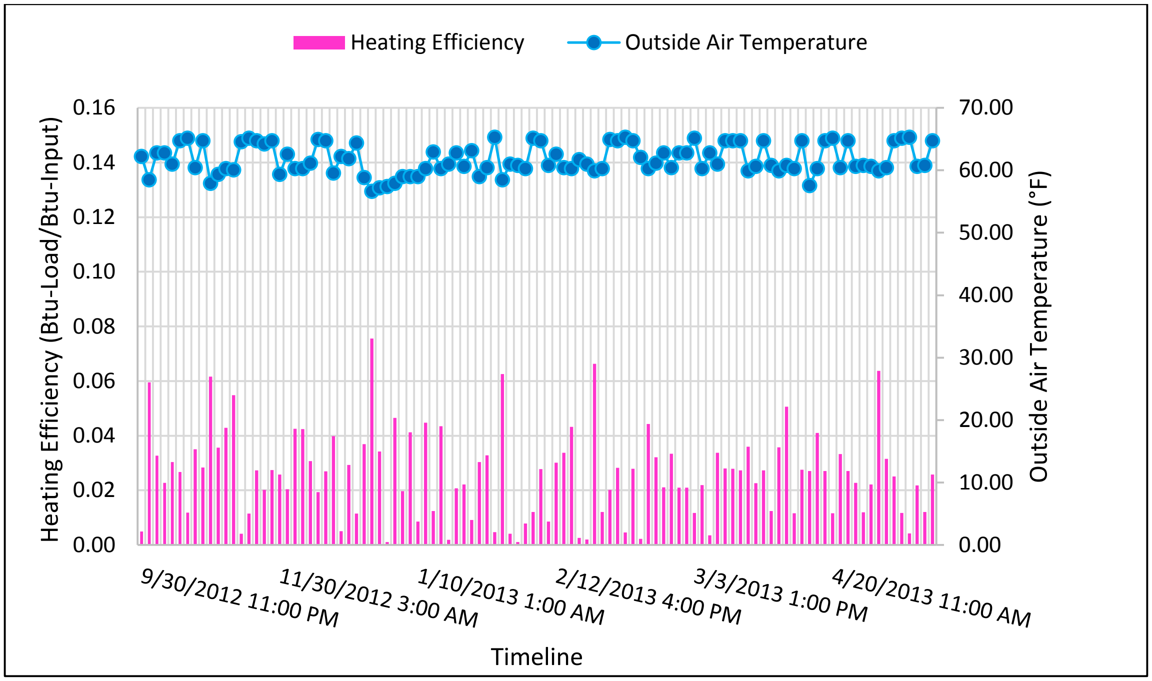


Figure 57 Heating Efficiency and Outside Air Temperature from 9/30/2012-5/5/2013

Figure 58 shows heating load, ratio of boiler plant equivalent energy input and outside air temperature. The plot shows clearly that when only the lab exterior zone needs heating the outside air temperature values range from 56 °F to 66 °F, the ratios of boiler plant heating energy input values range from 50% to 60%, and the heating load is less than 0.015 MMBtu. They are the reason that the heating efficiency values are less than 0.1 Btu-Load/Btu-Input.

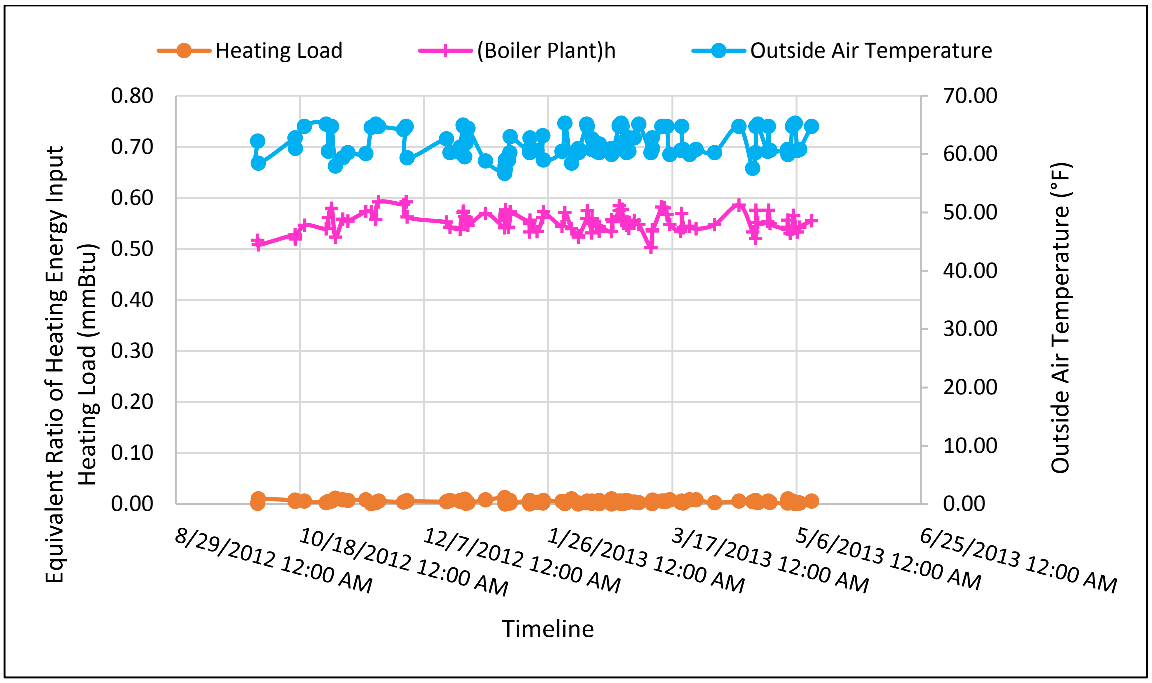


Figure 58 Outside Air Temperature, Heating Load and Ratio of Equivalent Boiler Plant Heating Energy Input from 9/30/2012-5/5/2013

5. SUMMARY

Because of the high energy consumption consumed by the HVAC systems in a commercial building, a new index is needed to measure the complete HVAC systems energy efficiency and guide the further building commissioning or energy retrofit programs. To this end, the concept of the load/energy ratio was proposed in this thesis. The load/energy ratio is the ratio of the total building load divided by the total equivalent energy input. The building systems total load is composed of the envelope load, the load from internal gains and the ventilation air load on the secondary systems. The total energy input contains the chiller plant cooling energy use, building fans and pumps energy input, and the boiler plant heating energy use. The cooling and heating energy efficiency were separately calculated to describe the extent of energy efficiency on the conditions of supplying cooling or heating by the entire HVAC systems.

The Office of the State Chemist was selected as a case study building served by two West Campus plants. This building has two different areas – labs served by SDVAV systems with 100% outside air, and offices served by SDVAV systems. Each area is divided into an interior zone and an exterior zone to distribute the area's load more simply. The fiscal year 2013 from September 1st 2012 to August 31th 2013 was the period for the case study.

The annual cooling COP is 2.09 Btu-Load/Btu-Input or 1.69kW/ton, and the monthly cooling COP varies from 1.31 to 2.43 Btu-Load/Btu-Input. The hourly cooling efficiency ranges from 0.3 to 3 Btu-Load/Btu-Input when both the lab and the office need cooling over the course of the whole year. It ranges from 0.9 to 3.5 Btu-Load/Btu-Input when the lab needs heating and the office needs cooling, according to the data from September 2012 to May 2013. When the lab needs heating and the office needs cooling for the interior zone and heating for the exterior zone, cooling efficiency ranges from 0.4 to 3.8 Btu-Load/Btu-Input, as indicated by the data from October 2012 to May 2013. Lastly, when the office needs cooling and the lab needs cooling for the interior zone and heating for the exterior zone, the cooling efficiency values range from 0.3 to 1.1 Btu-Load/Btu-Input, according to data from September 2012 to May 2013.

The annual heating efficiency is 0.52 Btu-Load/Btu-Input, and the monthly heating efficiency varies from 0.06 to 0.6 Btu-Load/Btu-Input. The hourly heating efficiency values fluctuate from 0.03 to 0.8 Btu-Load/Btu-Input when the lab needs heating and the office needs cooling, as indicated by data collected from September 2012 to May 2013. It ranges from 0.1 to 0.7 Btu-Load/Btu-Input when the lab needs heating and the office needs cooling for the interior zone and heating for the exterior zone, based on data from October 2012 to May 2013. The heating efficiency values are less than 0.1 Btu-Load/Btu-Input when the lab needs cooling for the interior zone and heating for the exterior zone and when the office needs cooling, according to data gathered from September 2012 to May 2013.

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APPENDIX

Building Load/Energy Ratio Calculation Process.xlsx

Chiller Plant Energy Use Data of Satellite Utility Plant 1.xlsx

Chiller Plant Energy Use Data of Satellite Utility Plant 2.xlsx

Chiller Plant Energy Use Data of West Campus Plant.xlsx

Boiler Plant Energy Use Data of West Campus Plant.xlsx

WinAM Energy Performance Model for Office of Texas State Chemist.wam

Weather Data for WinAM Energy Performance Model.xlsx

Energy Consumption Data for WinAM Energy Performance Model.xlsx

WinAM Report for the Office of the Texas State Chemist.xlsx