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Energy efficiency enhancements to a low energy high performance building

by

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Program of Study Committee:
Michael B. Pate, Co-major Professor
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List of Nomenclature

ΔP	Differential pressure
ARI	Air Conditioning and Refrigeration Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
COP	Coefficient of Performance
C_v	Loss coefficient for valves
DAQ	Data acquisition
DC	Discretionary communal
DOAS	Dedicated outside air system
DOE	Department of Energy
DOE-2	Building energy simulation software program
DP	Discretionary personal
EAEAT	Exhaust air entering air temperature
EALAT	Exhaust air leaving air temperature
EIA	Energy Information Administration
ERV	Energy recovery ventilator
EUI	Energy use intensity
GSHP	Ground source heat pump
HVAC	Heating, ventilating, and air conditioning
HVAC&R	Heating, ventilating, air conditioning, and refrigeration
IAMU	Iowa Association of Municipal Utilities
IESNA	Illuminating Engineering Society of North America
LEED	Leadership in Energy and Environmental Design
LON	LonWorks communication protocol
N	Nondiscretionary

NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
OAEAT	Outside air entering air temperature
OALAT	Outside air leaving air temperature
PID	Proportional, integral, differential
PT	Pressure, temperature
Q	Flow rate
RTD	Resistance temperature detector
SHGC	Solar heat gain coefficient
TMY	Typical Meteorological Year
USGBC	United States Green Building Council
VAV	Variable air volume
VFD	Variable frequency drive
VOC	Volatile organic compound
VT	Visual transmittance

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Abstract

This report discusses energy efficiency enhancements made to a low energy, high performance office building. The building studied is the Iowa Association of Municipal Utilities' headquarters located in Ankeny, Iowa, just north of Des Moines. Monitoring the energy use of the building for over six years has revealed that it has an average annual site energy use of 29,300 Btu/ft^2. This is 68% less energy than that used by the average U.S. office building and 74% less energy than the average office building in climate zone 2, the location of Ankeny.

Three areas of energy use were chosen for improvement: the ground source heat pump system's circulating pump, the energy recovery ventilator's defrost heater, and general office equipment (computers, refrigerators, coffee pot, etc.) during periods when the building is unoccupied. Before the improvements, the three items contributed to 38% of the building's annual energy use. The table below summarizes the energy use of each item before improvements were made, and the savings resulting from the improvements. The improvements have the potential of saving up to 27% of the building's annual energy use. The circulating pump's energy savings were achieved by switching it from a constant speed pump to a variable speed pump by equipping it with a variable frequency drive and installing shutoff valves on the heat pumps. Energy savings for the defrost heater were realized by decreasing its set point from an unreasonable 46 ^{o}F to a recommended 5 ^{o}F. The savings for the general equipment can be achieved if employees turn off all unnecessary equipment when the building is unoccupied.

	Before Changes		**After Changes**			
Annual Building Energy: 107,300 kWh	**Annual Energy (kWh)**	**% of Total Building Energy**	**Annual Energy (kWh)**	**Cost Savings**	**% Savings**	**% Savings of Building Energy**
Circulating Pump	18200	17%	3100 to 4100	\$920 to \$990	77% to 83%	13% to 14%
Defrost Heater	5100	5%	360	\$260	93%	4%
Unoccuped Period General Equipment	17400	16%	8100*	\$600*	53%*	9%*
*Savings potential if all discretionary equipment is turned off during unoccupied periods						

Chapter 1. Introduction

There is a large movement among the building design, construction, and operation and maintenance communities to make buildings ‘green’. This movement is rooted in the assertion that human activities are damaging the natural environment to an extent that the environment will not be able to provide for the needs of future generations. The movement to design and construct green buildings, also referred to as sustainable buildings, seeks to reduce the impact buildings have on the environment, and hence make buildings more sustainable. The United States Green Building Council, a prominent organization within the green building movement, has established five areas in which to measure the sustainability of buildings: (USGBC, 2007)

1. Sustainable site development
2. Water savings
3. Energy efficiency
4. Materials selection
5. Indoor environmental quality

The large amount of pollution created and natural systems disrupted during the production and use of energy, especially energy derived from fossil fuels, makes energy efficiency a key element of making buildings more sustainable. Besides sustainability, energy efficiency is important because of the growing global demand for limited energy sources and the corresponding rising price of energy. Investing in energy efficiency will provide savings throughout the life of a building.

In 2005, buildings in the United States used over 39 Quads of primary energy, and contributed to 40% of the U.S.’ total primary energy use (DOE 2007). Of this 40% of U.S. primary energy use, commercial buildings used over 7 Quads or 18%, and residential buildings used over 8 Quads or 22%. The U.S. Department of Energy predicts that U.S. building energy use will continue to rise over the next two decades, reaching 48

Quads by 2020 and 53 Quads by 2030 (DOE 2007). Currently U.S. building energy use contributes 39% of the U.S.'s carbon emissions and 9% of the world's total carbon emissions (DOE 2007).

1.1. Problem Definition

The energy use of a building is determined by three main phases in its life: the design of the building, the implementation of the design (construction and commissioning), and the occupancy of the building. During the design phase, many elements that will greatly affect a building's energy use are determined. Some of these elements are the building orientation, type and quantity of fenestrations, and the type and efficiency of mechanical systems. Without a design that takes energy efficiency into account, it is almost impossible for a building to be a low energy building. Ideally, a building would be constructed exactly as the architects and engineers specified, but many practical reasons prevent this from happening. Changes made to the design during implementation, and the quality of construction will affect the energy use of a building. If insulation is installed poorly or a daylighting system is commissioned incorrectly, the intended energy savings from these items will not be realized. Finally, in the occupancy phase, the occupancy level, the type and quantity of equipment used, the behavior of the occupants, and physical changes to the building, will affect the energy use of the building.

This study uses the Iowa Association of Municipal Utilities' (IAMU) office building as a case study to examine how the energy use of a low energy building can be reduced. Design of the IAMU's office building began in 1997, and it became occupied in June 2000. From the beginning of design, the organization's leaders desired a building with low environmental impacts, including low energy use. Monitoring of the building has shown that it maintains high indoor environmental quality and is indeed a low energy building. The building was one of the American Institute of Architects' National Committee on the Environment's Top Ten Green Projects in the U.S. in 2002. The building was also rated among the top 10% most efficient commercial buildings in the U.S. when it received an Energy Star rating of 93. The low energy use of the building is due largely to the integrated design approach and the use of energy modeling to determine cost effective energy efficiency features in the building. The building's design process has been documented by McDougall et al. (2006), and the results from monitoring the energy use and indoor environmental quality of the building are presented by Klaassen et al. (2006).

During the design of the IAMU building, emphasis was placed on implementing energy efficiency measures that would save the largest amount of energy and have the largest paybacks. The building energy monitoring has shown that these energy efficiency measures have succeeded in greatly reducing the energy use of the building. The building uses 55% less energy compared to an energy simulation, using DOE-2, of the building without any of the efficiency measures (Winkelmann et al 1993). While attention was placed on implementing efficiency measures for the biggest energy uses, many smaller energy uses were not considered for efficiency measures. Energy monitoring has shown that these ignored energy uses, which would be insignificant in a building without any efficiency measures, contribute a significant proportion of the IAMU building's total energy use. Because these energy uses did not receive efficiency measures in the original building design, they present opportunities to significantly further reduce the building's energy use. The energy uses fall into all three building phases in which energy use is determined: system design, design implementation, and occupancy.

1.2. Goals and Objectives

This report has two main goals. First, it will document energy uses of a low energy building for which attention was not paid to efficiency in the design of the building, implementation of the design, or occupancy phase of the building. These energy uses present areas for further reduction in building energy use through energy efficiency enhancements. The second goal is to implement energy efficiency enhancements to reduce the energy use of an already low energy building. The goals will be met through the use of the IAMU building as a case study. The report will meet the goals through the following objectives:

1. Give an overview of the current work being done in low energy buildings through a literature review.
2. Document that the IAMU building is a low energy building by:
    a. Presenting how a focus on energy efficiency by the design team led to a building with energy efficiency integrated into all of its systems.
    b. Presenting building monitoring data that reveal that the IAMU building uses significantly less energy than typical office buildings.
3. Identify three systems within the building where energy efficiency improvements can be made. Each energy use will correspond to one of the three building phases within which building energy use is determined.
    a. Provide complete description of system
    b. Present monitored energy performance data for system
    c. Make changes to systems to improve energy performance
    d. Document changes in energy performance.

1.3. Report Organization

In Chapter 2 a review of literature on topics related to low energy buildings is presented. Section 2.2 gives statistics on the energy use of buildings in the United States. These statistics include the historical amount of primary energy U.S. buildings use, the distribution of commercial building energy use among end uses, the average energy use index for different types of commercial buildings, and the contribution U.S. building energy use makes to green house gas emissions. Section 2.3 presents the definitions of several phrases frequently used to describe low energy buildings. These phrases include ‘good design’, ‘high performance building’, and ‘sustainable building’. Following this, section 2.4 discusses several definitions of a ‘zero energy building’ and explores the technical feasibility of this type of building. Section 2.5 outlines designing and optimizing a low energy building, and then discusses monitoring buildings to determine their performance level. Finally, in section 2.6, several case studies of low energy buildings from the literature are presented.

Chapter 3 introduces the reader to the IAMU office building and the design features that make it a low energy building. Section 3.2 discusses the integrated design of the building, section 3.3 discusses the major building systems, and section 3.4 discusses the cost premiums associated with the original energy efficiency design features. Chapter 4 presents information on the monitoring of the energy performance and indoor environmental quality of the IAMU building. Section 4.2 contains an overview of the data acquisition system, and section 4.3 discusses the building monitoring strategy. Then in section 4.4 energy performance of the building from six years of monitoring is presented.

The experimental section is contained in Chapter 5. This chapter discusses three areas where the energy performance of the building could be improved, and the steps taken to make those improvements. Section 5.2 discusses the energy performance of the ground source heat pump system circulating pump’s energy use, section 5.3 discusses the energy use of the energy recovery ventilator’s defrost heater, and section 5.4 discusses the energy use of the building’s general equipment when the building is unoccupied. Section 5.2 has four subsections: the first gives an overview of the operation of the GSHP system, the second describes the performance and energy use of the system, the third describes changes made to the system, and the fourth describes the energy savings resulting from the changes. Sections 5.3 and 5.4 contain three subsections each: the first describes the operation of the systems, the second describes the performance and energy use of the systems, and the third describes changes made to the systems and the resulting energy savings. Finally, Chapter 6 contains a conclusion to the energy efficiency enhancements made to the IAMU building.

Chapter 2. Literature Review

2.1. Introduction

This literature review covers issues related to low energy buildings on the whole building level. The review covers building energy statistics, definitions associated with low energy buildings, the design of low energy buildings, and case studies of monitored low energy buildings. Section 2.2 lays the background for discussing low energy buildings by outlining some pertinent statistics on the energy use and carbon emissions of buildings in the U.S. Section 2.3 goes on to define several terms frequently used in literature to describe low energy buildings and clarifies how the terms are related to low energy buildings. These terms include ‘High Performance Building’, ‘Sustainable Building’, and ‘Green Building’. In section 2.4 the concept of a net zero energy building is introduced, and four different definitions that emphasize different methods of meeting net zero energy are outlined. This section also contains information on the technological feasibility of constructing net zero energy commercial buildings. Section 2.5 contains guidelines on the design and optimization of low energy buildings, and procedures for monitoring and reporting the energy use of buildings. Finally in section 2.6 seven low energy building case studies are discussed. The case studies offer insights into different types of low energy buildings, their design, the type of technology used in them, and the problems encountered in them.

2.2. United States’ Building Energy Use Statistics

Buildings have a profound impact on our world by providing the shelter and conditioned environment needed for most human activities to take place. Large amounts of energy are used by buildings for lighting, space heating and cooling, and ventilation to provide a healthy comfortable indoor environment. Considerable additional energy is used for the activities that occur within the buildings including the operation of computers and appliances, refrigeration, heating of water, etc. In 2005, as shown in

Table 2.1, buildings in the U.S. used 39.7 Quads of primary energy, or 40% of the U.S.'s primary energy. In 2005 commercial building accounted for 18% of U.S. primary energy use and residential buildings accounted for 22% of U.S. primary energy use. Since 1980 the primary energy used by U.S. buildings has grown 50% from 26.4 Quads to 39.7 Quads. It is predicted that by 2030 U.S. building primary energy use will grow an additional 34% from 39.7 Quads to 53.3 Quads. Table 2.1 also show that between 1980 and 2005 the percentage of primary energy used by residential buildings has increased only slightly from 20% to 22%, and it is predicted it will drop back to 20% by 2030. In contrast the percentage of primary energy used by commercial buildings has increased from 14% to 18% between 1980 and 2005, and is predicted to increase to 20% by 2030.

Table 2.1. U.S. commercial and residential building primary energy use (DOE 2007).

Year	Building Primary Energy Use (Quads)	% U.S. Primary Energy Used by All Buildings	% U.S. Primary Energy Used by Residential Buildings	% U.S. Primary Energy Used by Comercial Buildings
1980	26.4	34%	20%	14%
1990	30.4	36%	20%	16%
2000	37.7	38%	21%	17%
2005	**39.7**	**40%**	**22%**	**18%**
2010	42.5	40%	22%	18%
2020	48.0	41%	21%	19%
2030	53.3	41%	20%	20%

The breakdown of primary energy to end uses in commercial buildings in the U.S. is shown in Table 2.2. The largest category of energy consumption is lighting at 26% of commercial building primary energy use, followed by space heating at 14%, and space cooling at 13%. Ventilation uses another 6% of the primary energy. The 'other' category, which makes up 13% of the primary energy use, includes service station equipment, ATMs, telecommunications equipment, medical equipment, pumps, emergency electric generators, combined heat and power, and manufacturing in commercial buildings. Electronics use 6% of commercial building primary energy, refrigeration uses 4%, computers use 3%, and cooking uses 2%. The 'adjust to SEDS' category' is an adjustment the Energy Information Agency (EIA) uses to remove discrepancies between data sources.

Table 2.2. Commercial building primary energy end uses (DOE 2007).

Energy Use	Amount (Quad)	Percent
Space heating	2.5	14%
Lighting	4.6	26%
Space Cooling	2.3	13%
Water Heating	1.2	7%
Electronics	1.1	6%
Refrigeration	0.7	4%
Cooking	0.4	2%
Ventilation	1.1	6%
Computers	0.6	3%
Other	2.4	13%
Adjust to SEDS	1.0	5%
Total	**17.9**	100%

The amount of energy a building uses per unit floor area, or energy use intensity (EUI), is a useful metric for comparing the energy use of different buildings. Table 2.3 contains EUI's for thirteen different commercial building types averaged over the entire U.S. and averaged over climate zone 2, which contains Ankeny, IA. Climate Zone 2 is defined by the National Oceanic and Atmospheric Administration (NOAA) as the area of the U.S. that has historically (1971-2000) had fewer than 2000 cooling degree days and between 5,500 and 7,000 heating degree days. For most of the categories Climate Zone 2's EUIs are higher than the national average. For commercial office buildings the national average EUI is 92.9 kBtu/ft^2, while the EUI for commercial office buildings in Climate Zone 2 is 114.9 kBtu/ft^2, 24% higher than the national average. The EUI of office buildings is slightly higher the average EUI for all commercial building types (row 1 of Table 2.3) when compared on both the national and climate zone 2 levels.

Table 2.3. Comparison of the 2003 energy use intensity for various commercial buildings between the average for the U.S. and Climate Zone 2 (EIA 2006).

Principle Building Activity	**United States Energy Use Index (kBtu/ft^2)**	**Climate Zone 2* (Contains Ankeny, IA) Energy Use Index (kBtu/ft^2)**
All Buildings	90.1	102.6
Education	83.1	85.2
Food Service	258.3	238.7
Inpatient Healthcare	249.2	283.3
Outpatient Healthcare	94.6	101.5
Lodging	100.0	132.1
Retail (non-malls)	73.9	73.5
Enclosed and Strip Malls	102.2	114.3
Office	**92.9**	**114.9**
Public Assembly	93.9	90.8
Relitious worship	43.5	46.9
Serrvice	77.0	71.2
Warehouse and Storage	45.2	76.1
*Defined by NOAA as historically (1971-2000) having fewer than 2000 CDD and 5,500 HDD		

The use of electricity generated through the burning of fossil fuels such as coal, natural gas, or oil, or the burning of these fossil fuels at the building site releases carbon dioxide, a known greenhouse gas and contributor to global warming. Through the use of electricity produced by burning fossil fuels or the direct burning of fossil fuels onsite, U.S. commercial and residential buildings release 630.3 million metric tons of carbon annually into the atmosphere (DOE 2007). This accounts for 39% of U.S. carbon emissions and 9% of annual global carbon emissions (DOE 2007). It is projected that by the year 2030 U.S. building carbon emissions will grow to 885.4 million metric tons annually, but the contribution to global emissions will decrease slightly to 8% as other areas of carbon emission throughout the world increase at a faster rate (DOE 2007).

2.3. Definitions of ‘High Performance Building’, ‘Green Building’, and ‘Sustainable Building’

In literature there are many references to ‘high performance’ buildings, ‘green’ buildings, and ‘sustainable’ building. Frequently these terms are used interchangeably or without any reference to their exact meaning. This section discusses the meaning of each phrase. Section 2.3.1 defines ‘good’ design—what all building designers should strive for. Section 2.3.2 discusses ‘high performance’ buildings and section 2.3.3 discusses ‘green’ and ‘sustainable’ buildings.

2.3.1. Definition of ‘Good’ Design

Because of the pervasiveness of buildings in human activity it is important that they are designed well. The ASHRAE GreenGuide outlines five qualifications of good building design (ASHRAE 2006). A good design should be considered the minimum goal of all building designs. The first qualification is for the building to meet the needs of the owners and occupants. This is the most basic requirement; no matter what features a building has, if it doesn’t meet the needs of the owner and occupants the design cannot be qualified as good. Second the building must meet all applicable building codes and standards. These represent minimum requirements of the building necessary for human health and safety, and for reducing the building’s environmental impact. Third the building must provide good indoor environmental quality including thermal comfort, indoor air quality, acoustical comfort, and visual comfort. Fourth a well designed building will be “compatible with and respectful of the characteristics, history, and culture of the immediate surroundings” (ASHRAE 2006). A building should always be appropriate for its surroundings; an otherwise well designed barn would not be compatible with downtown Manhattan. Finally, the ASHRAE GreenGuide specifies that a building have the emotional impact on a viewer that the designers intended (ASHRAE 2006).

2.3.2. Definition of ‘High Performance’ Building

In literature the exact meaning of a ‘high performance’ building is unclear. In the most generic definition a ‘high performance’ building is a building that meets the five qualification of good design in exceptional ways. A key characteristic of a high performance building is that all of its systems work together to compliment each others’ operation. It is difficult for a building to meet the good design criteria, let alone the high performance building criteria if the building systems (siting, envelope, lighting, mechanical systems, etc.) have not been specifically designed to complement each other. There are no official qualifications for the way in which a high performance building must exceptionally meet the prerequisites of good design, but some commonly used qualifications are: the building uses significantly less energy than other buildings with comparable services; the building restores or protects the natural environment of the building site; the building has an exceptional indoor environment; or the building has exceptional emotional impact on the viewer. The performance of a high performance can be quantified as reduced energy consumption, reduced energy cost, reduced resource inputs, reduced waste outputs, high level of occupant comfort, and reliable building operation.

2.3.3. Definition of ‘Sustainable’ and ‘Green’ Building

With electric lighting, mechanical heating, cooling, and ventilation, and air purification systems, buildings can be designed to operate completely independent of the outside environment. Under most circumstances designing a building to be independent of the outside environment would be a poor design decision; the building would use more energy and resources than necessary, cost more to operate than necessary, and disconnect the occupants from the outdoor environment. With the growing human population and our increased pressure on the natural systems of the world, it is important that the environment be considered when designing buildings. In the book Natural Capitalism

Hawken et al. (1999) establish the concept of natural capital as one of four necessary types of capital required by the economy (the three others are human capital, financial capital, and manufactured capital). Natural capital consists of natural resources, living systems, and ecosystem services. Ecosystem services consist of such processes as the water cycle and the carbon cycle. It is generally accepted that through human activities natural capital is being depleted at rates that will cause resource shortages and disruptions in major ecosystem services in the future. Resource shortages and decreased ecosystem services will compromise the ability of future generations to survive. Our current rate of resource use and damage to the environment must be reduced to a sustainable level—a level that will allow us to meet our current needs, but will leave enough natural capital for future generations to meet their needs. The concept of sustainability can be applied to building design to decrease the use of natural capital in buildings. Throughout their life buildings use considerable natural capital: resources are used and ecosystems displaced when a building is constructed, the building uses energy and more resources throughout its life, and at the end of a building's life it must be disposed of. Many steps can be taken during the design of a building to reduce the rate of natural capital use throughout its lifecycle. Frequently the term 'green' is used to give the connotation of a connection to nature to buildings (ASHRAE 2006). 'Green' is essentially a synonym of sustainable, but it is frequently used more loosely than the term sustainable.

The United States Green Building Council (USGBC) has established the Leadership in Energy and Environmental Design (LEED) rating system to encourage building designs that increase the sustainability of the building over its entire life cycle. LEED measures the sustainability of buildings in five areas (USGBC, 2007):

1. Sustainable site development
2. Water savings
3. Energy efficiency

4. Materials selection
5. Indoor environmental quality

Sustainable site development seeks to have as minimal impact on the natural biome of the building site as possible if the site is a greenfield. If the site has been disturbed, the project may restore the area around the building to a natural site. Sustainable site development may include planting native plants, minimizing runoff using permeable paving systems or wetlands, and the reduction of light pollution from site lighting. Efficient water use includes reducing or eliminating the need to water landscaping, using innovate waste water management systems, and reducing the water use within the building. Energy efficiency is important to reduce the emissions and pollution associated with energy production. A sustainable building will draw on the resources freely available at the building site to reduce its use of natural capital—it may use daylighting instead of relying entirely on electric lighting, passive solar heating may be incorporated to reduce the energy use of the heating system, or natural ventilation could be utilized to reduce the reliance on mechanical cooling. When local resources are insufficient to meet the building's needs the most efficient lighting, heating, cooling, and ventilation equipment should be employed. Materials selection in sustainable buildings seeks to use materials reused from other buildings, recycled materials, materials obtained locally, and fast growing renewable materials. Finally, sustainable buildings must provide good indoor environmental quality. While good indoor environmental quality is not unique to sustainable buildings, it is part of the good design of all buildings, a focus on sustainability can affect how good indoor environmental quality is achieved. The sustainable design guidelines of LEED place a large emphasis on using low emitting materials, controlling air pollutants, and providing daylighting and views to achieve good indoor environmental quality (USGBC, 2005).

Typically a sustainable or green building should also meet the five requirements of good design, but currently green design features are not considered necessity for a good design (ASHRAE 2006). Because of the growing concern over the sustainability of current building practices, sustainable design may become one of the requirements of good design. A building that meets the five criteria of a well designed building plus the requirements for being a sustainable building would also be considered a high performance building. Energy use is considered one of the largest factors affecting the sustainability of a building, and the LEED sustainable building rating system allocates 10 out of 69 points to energy efficiency, three points to on site renewable energy, one point to enhanced commissioning of building systems, one point for measurement and verification of the actual building energy use, and one point for purchasing green power from the grid (USGBC 2005). A large amount of work has focused on the energy efficiency aspects of sustainable and high performance buildings, and the remaining sections of the literature review focuses on this work.

2.4. Net Zero Energy Building

A net zero energy building is a subset of high performance buildings that utilizes energy efficient systems to greatly reduce its energy use and has renewable energy sources to meet its remaining energy needs. The U.S. DOE has a goal of making net zero energy commercial and residential buildings marketable. Section 2.4.1 discusses the different definitions of a net zero energy building and section 2.4.2 discusses the technical potential for net zero energy commercial buildings.

2.4.1. Definitions of Net Zero Energy Buildings

A net zero energy building relies on both onsite renewable energy sources and a connection to the electrical grid for its energy needs. The primary source of energy for a net zero energy building is its onsite renewable source, but when this source is insufficient the building can draw power from the electrical grid. When the building uses less energy than is produced onsite, the surplus power is fed back into the electrical grid. A net zero energy building is achieved when the amount of energy drawn from the grid equals the amount of onsite renewable energy fed back into the electrical grid.

Although the concept of a net zero energy building is straight forward there is some disagreement on the precise definition of a net zero energy building. Torcellini et al. (2006b) outline four definitions for a net zero energy building: net zero site energy, net zero source energy, net zero energy cost, and net zero energy emissions. Each definition emphasizes different strategies and energy sources for achieving a net zero energy building. Torcellini et al. also layout a hierarchy of steps that should be taken to achieve a net zero energy building. The first step is to prevent the consumption of energy by designing an energy efficient building. Second, renewable energy sources within the building footprint, such as photovoltaic panels on the roof or façade should be taken advantage of. Third, renewable energy sources on the building site should be used, such as a wind turbine or photovoltaic panels not placed on the building. Renewable energy sources in the building footprint are preferred because the energy producing system should be able to stay in place for the entire life of the building whereas renewable energy sources outside of the building footprint my be displaced by future development. The fourth level in the hierarchy is renewable energy sources available away from the building site that are brought to the building to produce electricity or heat. This includes all types of biofuels that are harvested, processed, and shipped to the building. The last and least desirable level of the hierarchy is purchasing electricity generated off site from renewable sources such as hydro or wind. In a region where hydro power dominates the supply, all electricity purchased is essentially renewable. Elsewhere, customers can pay an extra fee to assure that their electrical energy is supplied by a renewable source.

The definition of a zero energy building should encourage the building owner to implement as many energy efficiency features as possible to reduce energy use (Torcellini et al., 2006b). If the definition of a zero energy building can be met by purchasing energy from a renewable source such as a hydroelectric plant, the building owner will not be motivated to build and maintain energy efficient buildings. A net zero site energy building treats all energy sources the same, therefore one energy unit of natural gas used at the building must be offset by one unit of electricity produced on site and one unit of purchased electricity must be offset by one unit of electricity produced on site. Because a site net zero building makes up all energy use one-to-one, they encourage the use of many energy efficient features (Torcellini et al., 2006b).

A net zero source energy building considers the amount of energy required at the energy source (power plant for electricity and gas pumping station for natural gas) to deliver one unit of energy use by a customer. Dreu and Torcellini (2006) determined that on a national average one unit of site electricity is equal to 3.37 units of source energy, and one unit of site natural gas is equal to 1.12 units of source energy. Therefore one unit of site produced exported electricity will make up for 3.37 units of site natural gas energy use. This ratio makes it easier to achieve a net zero source building when large amounts of natural gas are used.

A net zero energy cost building is achieved when the value of the exported site generated energy is equal to the value of the energy purchased for the building. This is the most difficult net zero energy definition to meet because electricity is usually purchased by power companies at a much lower price than the price they sell electricity to the building owner (Torcellini et al, 2006b). Demand charges, fees, and taxes make achieving a net zero energy cost building even more difficult. A net zero energy emissions building exports as much emissions free energy as energy purchased from emissions emitting sources. The accounting for a net zero energy emissions building is difficult because the electricity purchased from the grid is generated using multiple methods with varying amounts of emissions—some regions may have a large contribution from hydro and nuclear plants while other regions may have a large contribution from fossil fuel burning plants (Torcellini et al, 2006b)

2.4.2. Technical Potential of Zero Energy Buildings

The Department of Energy's Building Technologies Program has the goal of making net-zero energy buildings marketable by the year 2025. To assist this goal the National Renewable Energy Lab (NREL) examined the technological feasibility of constructing net-site zero energy commercial buildings (Griffith et al. 2006). The study does not consider the economic feasibility of net-zero energy commercial buildings, but considers the proportion of commercial buildings that could potentially be net-zero using technology available today and technological improvements predicted to occur by the year 2025. Fully utilizing today's technology, 22% of commercial buildings could be net-zero, and based on projected technology improvement in 2025, 64% of commercial buildings could be net-zero (Griffith et al. 2006). The projected technological improvements include doubling the efficiency of rooftop photovoltaic panels, increasing inverter efficiency, reducing lighting power density by 50% below Standard 90.1-2004 (ASHRAE 2004b), increasing chiller COP from 6.0 to 6.5, increasing heating efficiency from 95% to 97%, small decreases in fan static pressure, and other HVAC improvements (Griffith et al. 2006). By further reducing lighting power density to 75% below Standard 90.1-2004 or by reducing plug loads 25% below the other scenarios, the number of zero-energy buildings in 2025 would increase to about 70% (Griffith et al. 2006).

2.5. Low Energy Building Design and Monitoring

Designing a low energy or zero energy building takes a greater level of effort and organization than designing traditional buildings. Even if a building is designed to be low energy, it my not perform as such. Therefore it is important to monitor buildings' energy performance to find and correct discrepancies between the intended operation and the actual operation. Monitoring also allows a building's energy performance to be compared to other buildings' performance. Section 2.5.1 contains guidelines for the design of low energy buildings, section 2.5.2 outlines several methods for the optimization of the design of low energy buildings. Section 2.5.3 discusses monitoring the energy performance of a building and making comparisons between buildings.

2.5.1. Design Guidelines

There are many guidelines available to assist in the design of low energy buildings. The following list of best practices for designing low- and zero-energy buildings was developed by NREL after monitoring the performance of six high performance buildings. These best practices are general guidelines and should be used by building owners, architects, engineers, and anyone else involved in the design of buildings to assist in the construction of high performance low energy buildings (Torcellini et al. 2006a):

1. A whole-building design process should be used to design low energy buildings:
    a. Set specific measurable energy goals to guide design.
    b. Include all project participants from the start of design.
    c. Use building energy simulation software to model building energy use throughout design, construction, and occupancy to guide informed decision making.
    d. The building envelope should eliminate as much of the heating, cooling, and lighting loads as possible, and the mechanical and lighting systems should then be designed to make up the rest of the loads.

    e. Update the building simulation as changes are made so that energy impacts of changes can be evaluated.
2. Perform a post occupancy evaluation of the building's energy performance to determine if the building systems are working harmoniously together.
3. Obtain standard metrics on the building to determine performance of systems and overall building.
4. Design envelope and lighting system to take advantage of as much daylighting as possible:
    a. Use daylighting in all occupied areas adjacent to an exterior wall or ceiling.
    b. Prevent glare in daylighting design.
    c. Integrate electric lights into daylighting system by using automatic, continuously dimming daylighting controls.
    d. The building interior should maximize daylighting distribution.
    e. Commission daylighting system, and determine energy savings.
5. Energy recovery ventilators should have economizers.
6. Evaporative cooling should be used in dry climates.
7. Natural ventilation design guidelines:
    a. Natural ventilation should rely on stack effect—winds shift and require numerous cross-paths for reliable ventilation.
    b. Use separate supply and relief dampers with automatic HVAC controls for natural ventilation rather than relying on occupants to open and close windows.
    c. Avoid enclosed spaces that are difficult to ventilate naturally.
    d. Do not use natural ventilation as replacement for HVAC system economizers.

8. Use demand-responsive controls to mange demand.
9. Avoid parasitic energy draws.

ASHRAE (2004) has published several Advanced Energy Design Guides, including one for small office buildings that provide standard practices for designing a building that should reduce the energy use of a new building 30% below ASHRAE 90.1-1999. The guides divide the United States into eight climatic zones and provide a table of standard design features that will reduce the energy consumption of a building in each zone. The guide contains recommendations for the building envelope, lighting, HVAC equipment and systems, and water heating. Unlike the best practices guidelines presented above, the Advanced Energy Guides are very specific and offer such information as the R-value of insulation and efficiency of mechanical equipment needed to achieve 30% energy savings. The guides stress that for the measures to be effective, energy efficiency must be a priority form the beginning of the design and an integrated design approach should be utilized.

The ASHRAE GreenGuide gives general recommendation on the design, construction, and operation of sustainable buildings. It covers all areas related to sustainability, not just energy efficiency. The book is written primarily for HVAC&R engineers, but also contains green building information on fire protection, storm water management, lighting, and architectural features that affect energy use. This book also emphasizes that coordination is required between all parties involved in the design, construction, and commissioning of the building to ensure that the green building goals are met (ASHRAE 2006).

2.5.2. Design Optimization

The many energy efficiency design guidelines available to design professionals allow a range of low energy design solutions to be developed. Frequently a trial-and-error method is used in conjunction with building energy simulation to determine which design features to incorporate into a building. In the design of the Iowa Association of Municipal Utilities' (IAMU) office building, The Weidt Group (1998) used DOE-2.1E to simulate the energy use of a base case building built according to ASHRAE Standard 90.1-(1993 lighting standards). They then simulated 84 different energy efficiency measures individually to determine their impact on the energy use on the base case building simulation, their incremental implementation cost, and their expected payback period. The owner and design team then met to form three alternative bundles of energy efficiency measures from the list of 84. The first bundle contained the features most likely to be included in the building, the second contained all the features of the first plus additional desired items, and the third bundle was a variation of the first two. The Weidt Group then used DOE-2.1E to evaluate the energy performance of each of the three bundles before the final bundle selection was made.

This method of energy analysis is lengthy and labor intensive because the designer must run a separate building energy simulation for each energy efficiency feature and then run more simulations once the efficiency enhancement bundles are determined. The labor intensiveness of this design method severely limits its ability to optimize the energy efficiency of the building. Only a fraction of possible energy efficiency options can be evaluated in the initial development of alternatives, and then only a handful of energy efficiency bundles can be evaluated. It is unlikely that the small sample of bundles would determine the optimum design of the building. To facilitate the design of high performance buildings Charron and Athienitis (2006) suggest the use of genetic algorithms used in conjunction with a building energy simulation program. Genetic algorithms allow a large variety of alternatives to be tested, and they work well for finding optimal solutions. Various building parameters such as orientation, amount of glazing, insulation levels, and shading, can be varied by the genetic algorithm to produce a large number of solutions. Figure 2.1 shows the results of using a genetic algorithm to design a community hall in the United Kingdom (Coley and Schukat 2002). The genetic algorithm developed many different building designs that use significantly less energy than the typical community hall in the UK. This variety allows for design flexibility. Coley and Schukat reported that two of the better designs had similar energy use, but one relied on large amounts of insulation and few windows to achieve energy savings, and the second had a large amount of glazing to permit passive solar heating to achieve energy savings.

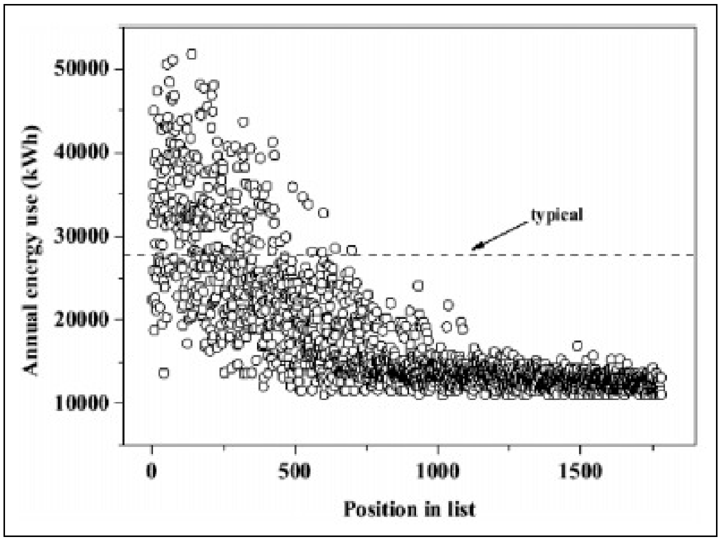


Figure 2.1. Energy efficiency design optimization for a community hall (Colley and Schukat 2002).

Optimization strategies have also been applied to residential single family homes. As part of the US Department of Energy's Building America program Anderson, Christensen, and Horowitz (2006) used a sequential search method called BEopt with a building energy simulation program to determine the least-cost path to achieving zero energy homes. Because most construction materials and configurations are available only in discrete forms, the optimization routine utilized discrete rather than continuous variables. For example, wall constructions, glass types, and furnaces all appear only in discrete forms. The optimization routine searches all categories of discrete variables at each sequential step in energy savings to determine the most cost-effective combination of energy improvements. The program determines cost-effectiveness based on the combined annual cost of energy and the mortgage used to finance the energy improvements. The most cost-effective point at each level of energy savings make up the least-cost path to zero energy homes, which is shown by the green line in Figure 2.2. Point 1 in the figure is the base case home that has no energy efficiency improvements. From point 1 energy efficiency upgrades are employed until the minimum annual cost is reached at point 2. Energy improvements are added to the home until point 3 is reached—the point where the marginal cost of additional energy improvements is equal to the cost of producing renewable energy onsite. From point 3 additional onsite generating equipment such as photovoltaic panels are added until net zero energy is reached at point 4. At point 4 the annual energy cost is zero, and the mortgage for financing the energy improvements makes up the entire annual cost.

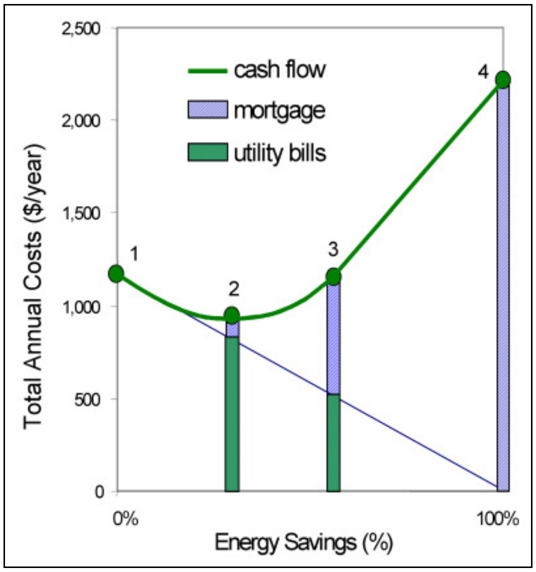


Figure 2.2. Least cost path to net zero energy home (Anderson, Christensen, and Horowitz 2006).

The exact shape of the curve and the energy savings where points 2 and 3 occur are dependent on many of the cost and construction assumptions of the model and the climate where the house is located. The researchers found that for the 5 main climate zones of the lower 48 states of the U.S. the minimum annual cost point (point 2) was reached between an energy savings of 27% and 39%. The switch from energy efficiency enhancements to renewable onsite generation (point 3) occurred between 50% and 60% energy savings. The least cost-curve is useful for determining the potential of energy improvements and onsite generation technologies for saving energy in new houses.

This general optimization procedure for determining the least cost path to net zero energy is useful for residential homes because the majority of homes have very similar features and construction practices. Applying a similar general optimization procedure to commercial buildings would not be practical because of the wide variety in commercial buildings. For useful results this optimization routine would need to be applied to many different categories of commercial buildings such as retail, office, warehouse, hospital, etc. Even so, the diversity among these groups is so great that a new least cost path many need to be developed for each new building under development.

2.5.3. Building Monitoring and Comparisons

In an effort to better understand the attributes of energy efficient buildings and the design practices that result in energy efficient buildings, a large amount of research has been devoted to monitoring the energy use and the indoor environment of buildings that have been designed to be high performance buildings. These monitoring projects focus on tracking the main energy uses in the buildings—lighting, HVAC, and equipment loads, and the energy production of any onsite renewable energy source such as photovoltaic panels—to determine energy savings of the buildings compared to equivalent buildings built according to the contemporary energy code. In addition to monitoring energy use and production, key building performance metrics such as light level, temperature, and humidity level are monitored to verify that the building systems are operating satisfactorily.

To determine the energy savings of a high performance building, a year long building energy simulation of the as built building should be compared to the energy simulation of a base case building using TMY weather data (Torcellini, et al. 2006). The base case building is the same as the as-built building, except its features minimally meet the applicable energy code. If the building under study has been monitored for a year, and weather data is available from the building site or from a nearby weather station, this weather data will provide more accurate simulation results than TMY weather data. Using the actual weather data and the actual occupancy, lighting, and equipment schedules will allow the as-built simulation to be tuned so that it predicts the same energy use as was measured in the actual building. Comparing a base case simulation to an as-built simulation allows difficult to know inputs to be remain constant between simulations and removes uncertainty from the calculation of energy savings (Torcellini, et al. 2006).

A standard set of building performance metrics is necessary to allow the comparison of a monitored building to energy simulation results or to other monitored buildings. Without a standard set of metrics a plethora of metrics developed for different programs make performance comparisons between buildings difficult. The Performance Metrics Project performed by the U.S. Department of Energy is an effort to standardize the metrics by which the performance of commercial buildings is reported (Barely, et al. 2005). Attention was paid to making the metrics applicable to a large variety of building configurations and scopes of monitoring projects. The project only developed metrics needed for energy performance quantification. The report by Barely, et al. specifies the procedure for determining 45 energy performance metrics shown in Table 2.4. The metrics are divided into two tiers. The first tier provides a quick summary of a building's energy performance and relies on the electric utility meter to provide energy usage data. The second tier uses a data acquisition system to monitor energy use of specific pieces of equipment and provides a much more detailed energy performance report. All 45 of the metrics would not be used in the second tier; only the metrics that apply to the systems included in the building and metrics that answer the questions of the researcher would be used. ASHRAE Standard 105-2007, "Standard Methods of Measuring, Expressing, and Comparing Building Energy Performance", also contains metrics to compare the energy performance of a building (ASHRAE 2007). While past versions of the standard have given guidelines for determining the energy performance of a building, they were not designed to compare the energy performance of different buildings. The updated standard outlines how to measure the energy performance of a building, how to compare the energy performance of buildings, and provides minimum requirements for reporting building energy performance and making comparisons.

Table 2.4 Building energy performance metrics (Barley et al. 2005).

Air Distribution Energy Use	HVAC Energy Use
Building Electrical Demand	Indoor Zone Temperature
Building Electrical Demand Intensity	Installed Lighting Energy Use
Building Energy Use	Net Facility Electrical Demand
Building Energy Use Intensity	Net Facility Energy Use
Building Lighting Energy Use	Net Facility Load Factor
Building Purchased Energy Cost	Net Facility Purchased Energy Cost
Building Purchased Energy Cost Intensity	Other Building Energy Use
Cogeneration Electrical Energy Output	Other Facility Electrical Energy Production
Cogenerational Fuel Use	Other HVAC Energy Use
Cogeneration Losses	Outdoor Ambient Temperature
Cogeneration Thermal Energy Output	Outdoor Energy Use
Cold Storage Transfer	People-Mover Energy Use
Cooling Energy Use	Plug-in Lighting Energy Use
DHW Energy Use	Plug Loads Energy Use
DHW System Efficiency	Process Energy Use
DHW Load	Produced Energy Storage Transfer
Electrical Generation System Losses	PV Energy Production
Façade Lighting Energy Use	Thermal Energy Production
Facility Energy Production	Total Facility Electrical Demand
Functional Area	Total Facility Energy Use
Gross Interior Floor Area	Wind Energy Production
Heating Energy Use	

2.6. Low Energy Building Case Studies

This section reviews seven case studies of energy efficient commercial and residential buildings that have been monitored and reported in the literature. For each building a description of important energy features, key energy performance metrics, and important lessons learned from the building are given. By reviewing these buildings, strategies that do and don't work for reducing the energy consumption can be learned. Areas of further research in the development of low energy buildings can also be determined from reviewing case studies. Information on a large number of additional low energy buildings can be obtained from the High Performance Building Database maintained by the U.S. Department of Energy. The database can be found at: http://www.eere.energy.gov/buildings/database/.

2.6.1. Science House

Steinbock, Eijad, and McDougal (2006) describe the design of a net zero site energy interpretive building at the Science Museum of Minnesota in St. Paul. The designers were faced with determining the amount of building that could be built to meet the building use requirements, produce all it own power, and remain within a fixed budget. To facilitate the conceptual design of the building, a spreadsheet was used to compare building alternatives. Using this tool a continuum of designs emerged with the extremes being a large, totally daylit, unconditioned space that would only be open during warm daylit hours; and a small, electrically lit, conditioned building that did not use energy efficiency features. The designers focused on designing a building that maximized the use of solar energy for daylighting, passive solar heating, and photovoltaic electricity production. DOE 2.1E was used to model a baseline code compliant building, and a range of energy efficiency features that could be implemented in the building. Then after energy efficiency features were chosen, a predicted building energy use simulation was created. After the building was completed a monitoring system was installed to monitor the energy use and determine if the building was meeting its net-zero energy goal. During the first winter of operation the monitoring system quickly alerted the researchers that the heat pumps were not operating and emergency electrical resistance elements were heating the building. The malfunction was fixed and the heat pumps operated properly for the rest of the winter. The monitoring system also confirmed that building was indeed producing more energy than it consumed during its first year of operation. The building used an average of 22,385 Btu/ft^{2}·yr, while it produced 30,864 Btu/ft^{2}·yr. The excess energy was sold back to the utility grid.

2.6.2. U.S.-China Demonstration Building

Xu et al. (2006) discuss the design and energy performance of a nine story office building in Beijing China that was constructed as a joint effort between China's Ministry of Science and Technology and the United States Department of Energy. The building is a demonstration of energy efficiency measures that can be incorporated into the majority of Chinese commercial buildings. China provided the land and paid for the base construction of the building and the U.S. Department of Energy paid for the additional cost to implement the energy efficiency design features. The building obtained a LEED Gold rating, and received ten out of ten points for energy efficiency by reducing predicted energy use by 60% below an equivalent building designed to meet ASHRAE 90.1. The design focused on reducing the energy use of the lighting and cooling systems. To decrease the amount of interior zones and increase the potential for daylighting, the building has a cross shape with most of the windows on the south and north sides. The other energy efficiency features include light-colored walls and roof, recessed windows, high efficiency lighting with a lighting power density of 0.37 W/ft^{2}, low-e windows, bi-level lighting for daylighting control, reduced window height, staged chillers, improved chiller efficiency, and an economizer. In addition to these energy efficiency measures the building has a 15 kW photovoltaic system, a 215 ft^2 solar hot water heater, and an ice thermal energy storage system to take advantage of lower off peak electricity costs. The building was designed to use 60% less energy than a building built to ASHRAE 90.1-1999, but examining the utility bills of the first eight months of operation show that the building is using much more electricity than predicted, particularly much more electricity for cooling than predicted. The monthly electrical use was up to three times higher than the predicted energy use and the monthly cooling electrical energy use was up to five times higher than predicted. The authors site two main reasons for the increased energy use: the building was occupied by twice as many people as was used in the energy simulation, and occupants left operable windows open when the building was being mechanically cooled. Despite the unpredicted high electrical use, the building appears to use less energy than other comparable Chinese commercial buildings. There are no comprehensive statistics for Chinese building energy use, but this building has a 40% and 50% lower electricity cost per unit area than two comparable multistory office buildings built in Beijing within the last decade.

2.6.3. Jack Evans Police Headquarters

Reilly, Kraft, and Olgyay (2006) describe the energy performance of the Jack Evans Police headquarters built by the city of Dallas in 2003. Among the goals the City of Dallas set for the building were: construct the building within a budget of $140/$ft^2$, achieve LEED Silver certification, and have a simple payback of ten years on all energy efficiency and green feature premiums. To achieve LEED Silver certification many features of the building went beyond the minimum prescribed by ASHRAE Standard 90.1-1999 and the building demonstrated a 46% energy savings compared to an equivalent built to the ASHRAE 90.1-1999 standards. The insulation in the steel framed walls was increased from R-13 to R-19 batts, triple-glazed windows instead of single-glazed windows were installed, and lighting power density was decreased from 1.3 W/ft^2

to 0.99 W/ft^2. To save additional lighting energy, occupancy sensors were installed throughout the building and daylighting dimming controls were installed in the perimeter zones. The HVAC system is a conventional VAV with electric reheat system, but the two 400 ton and one 200 ton chillers are controlled to optimize efficiency at part loads. Energy recovery enthalpy wheels are used to precondition the incoming ventilation air. The energy recovery ventilators reduced the peak cooling load by 200 tons, and saved $100,000 in initial costs. The 24-hour seven-day-a-week occupied police headquarters had an energy use intensity of 76 kBtu/ft^2 in its first year of operation compared to the average of 136.9 kBtu/ft^2 for southern climate continually occupied office buildings (EIA 1999). The lighting and cooling systems realize the main energy savings of the building. Comparing a DOE-2.2 model of an equivalent nominally ASHRAE 90.1-1999 compliant building to a model of the actual building, the lighting system saves 2,000,000 kWh/yr, and the cooling system saves 800,000 kWh/yr, for a combined cost savings of $200,000 at $0.08/kWh.

2.6.4. Zuckerman Building

Designing a building to be high performance does not guarantee that it will be high performance. Because each building is unique, and designers are likely using innovative techniques to improve the energy performance of their buildings, it is especially important to monitor the actual energy use of buildings to identify any deficiencies in their operation. One of the recommendations set out by Torcellini et al. (2006a) in their list of best practices for designing low energy buildings includes a post-occupancy review to determine if the building is operating as intended. If it is not operating as intended, corrections can be made to improve performance. Turner and Tovey (2006) outline the energy performance of the Zuckerman Institute for Connective Environmental Research building on the campus of the University of East Anglia in Norwich, UK that was designed to be a low energy building, but was using much more energy than expected. The main part of the building has a high thermal mass and is conditioned by a hollow core ventilation system. Ventilation air is supplied by a regenerative heat exchanger that precools or preheats the incoming air by recovering heat or coolness from the exhaust air. An air handling unit than distributes air to each floor of the building where heating coils, supplied with heat from the campus combined heat and power plant, heat the air if necessary. The air is distributed to diffusers through the hollow core concrete slabs. During the summer the nights are cool, and the ventilation system is run during the night to precool the hollow concrete slabs. Then during the day the regenerative heat exchanger precools the incoming air and the precooled hollow concrete slabs further cool the incoming air. No additional cooling is required. In the winter the regenerative heat exchanger preheats the incoming air which is further heated by the hollow core concrete slabs which absorb solar heat and heat from the building interior. Additional heat can be added to the air by the heating coils before it enters the hollow core concrete slabs. Monitoring of the system reveled that the system was using 84% more heating energy per unit floor area than a similarly constructed but less insulated building on campus. It was found that the control system caused the building to switch between heating and cooling modes multiple times per day, and the thermal mass advantages of the building were not being utilized. After adjusting the control strategy of the hollow core ventilation system, the heating energy use decreased by 57%, and it is now on a comparable level with the similar building on campus.

2.6.5. BigHorn Home Improvement Center

Deru et al. (2006) describe the energy performance of the BigHorn Home Improvement Center, one of the first retail centers in the U.S. designed to incorporate energy efficiency and sustainable design features. Using DOE-2.1 energy simulation software, it was determined that the as built retail center uses 36% less energy than an equivalent building built to ASHRAE Standard 90.1-1989. During the design a DOE-2.1

model of the base building built according to ASHRAE 90.1 was developed. Then, to determine which factors affected the energy use the most, different heat loads and losses were removed from the building—heat loss through the envelope, solar gain, infiltration, etc. This analysis focused energy efficiency design on the factors that had the greatest effects on the building's annual energy use. The largest portion of the energy savings comes from the lighting system. Daylighting is incorporated throughout the retail, office, and warehouse areas of the building. The use of daylighting reduced the installed lighting power density 28% below ASHRAE 90.1-2001 levels. Lighting energy use is further reduced through the use of occupancy sensors and daylighting controls. Overall the building realizes a 81% lighting energy savings. The cool climate, reduction of lighting heating loads, and a high level of envelope insulation, allows the building's cooling load and ventilation needs to be meet by natural ventilation. The building automation system opens windows when the building requires cooling. Heating is accomplishes through hydronic radiant floors, gas-fired radiant heaters, and a transpired solar collector. A rooftop integrated photovoltaic system was installed, but problems with the inverters limited its operation. The photovoltaic panels provided 2.5% of the building's annual energy use, but this could be increased to 8% if the problems with the inverters were fixed. The photovoltaic system rarely reduces the peak electrical demand because peak demand usually occurs in the evening when the indoor lights go to full power and the exterior lights turn on.

2.6.6. Montreal Retail Store

Another high performance retail building is described by Genest and Minea (2006). The building is located in Montreal, Canada, and it uses 71% percent less energy than an equivalent code compliant building. Among its energy efficiency features are a high performance envelope, daylighting and daylighting controls, liquid ground source heat pumps for radiant floor heating and cooling, a hybrid ventilation system, passive geothermal cooling, and a building automation system based integrated HVAC control system. During the cooling season ventilation air is cooled by passing it through underground tunnels as long as the dry-bulb temperature is below 80°F and the wet-bulb temperature is below 65°F. If either of these temperatures are exceeded the dedicated outside air system (DOAS) takes over ventilation. The DOAS contains an enthalpy wheel to pretreat incoming air, while additional cooling or heating is supplied by the working fluid form the ground source heat pump system. Heating and cooling of the building is accomplished by radiant floor slabs, with the temperature set point automatically adjusted according to the weather forecast. The geothermal heat pump system has four operational modes. In heating mode the heat pumps extract heat from the working fluid circulating in the ground loops and heat the indoor working fluid circulating in the radiant floor slabs, unit heaters, and the DOAS. In natural ventilation mode, the geothermal heat pump system is off and cooling is provided solely by the underground air cooling system. In geothermal free cooling mode the heat pumps are turned off and working fluid is circulated directly between the ground loops and the radiant floor slabs, unit heaters, and the DOAS. In mechanical cooling mode, the heat pumps extract heat from the working fluid circulating within the building and transfer it to the fluid circulating in the ground loop. Because of the complex control system of the ground source heat pump system, significant commissioning was undertaken to optimize its operation.

2.6.7. Energy Star Homes

Building practices differ greatly between commercial and residential construction, but many of the same principles for energy efficiency remain the same between both types of buildings. Proper building siting to maximize use of solar energy, a well insulated envelope with high performance windows, efficient mechanical systems, and efficient appliances and equipment are important in both commercial and residential construction. Henderson et al. (2006) document the energy performance of two homes built in Carbondale, CO as part of the U.S. Department of Energy's Build America Program. The first house, H1, was built to achieve a target Energy Star ratting of 88-89, and the second house, H2, was built to achieve an energy star rating of 94-95. Both homes have very high performance envelopes with R-53 insulation in the attic, R-20.8 insulation in the wall cavities and R-5 foam board insulation on the exterior walls, highly insulated rim joists and foundation, and low-e windows. The home with an Energy Star rating of 94-95 has premium mechanical systems including a gas fired solar assisted boiler for radiant floor heating and domestic hot water heating, a 1.6 kW rooftop photovoltaic array, and a heat recovery ventilator. Measurements show that both homes are realizing greater energy savings than predicted, although energy performance improvements can be made to some systems. During the first months of monitoring, the photovoltaic panels produced 64% of the electricity used in the second house. The premium systems in H2 prevent it from being a cost-effective home in today's market. All the energy efficiency measures in H1 have been cost effective in other homes, and it is likely that H1 would be cost-effective home to build.

Chapter 3. The IAMU's Headquarters

3.1. IAMU Introduction

The Iowa Association of Municipal Utilities' (IAMU) administrative headquarters in Ankeny Iowa, shown in Figure 3.1, is a leading example of a low energy high performance building. Since the 12,500 ft^2 office building opened in June 2000, the building has continually demonstrated that it is one of the most energy efficient office buildings in the country. The building's average Energy Use Index (EUI) over six years (2002-2007) is 29,300 $BTU/ft^2 \cdot year$. Thus the building uses nearly 55% less energy than it would if it had been built to the contemporary Iowa energy code: ANSI/ASHRAE/IESNA 90.1-1989. The building received an Energy Star rating of 93, which places it among the top 10% most energy efficient buildings in the United States. Among the design features that make the IAMU building energy efficient are a high performance building envelope, the use of daylighting with dimmable fluorescent lights as supplemental lighting, a ground source heat pump HVAC system, and an energy recovery ventilator (ERV).

Figure 3.1. The south side of the IAMU facility; the south wing is in the right side of the picture and the north wing is in the left side of the picture. (John Burnet, IAMU)

The goal of the IAMU is to support and strengthen Iowa’s municipal utilities, and the association provides training and centralized services to the more than 550 municipal gas, electric, water, and telecommunication services in the state of Iowa. From the inception of the building design in 1997, the IAMU leaders were committed to constructing an energy efficient and environmentally sound facility. Besides housing administrative office space, the building contains a boardroom seating 30 people and an auditorium seating 76 people for educational sessions. A twelve acre field on the grounds is used for training utility workers in the use of electric, gas, water, and telecommunication equipment, and a maintenance shed is used for additional indoor training. The landscaping surrounding the building and training field consist of native Iowa tall grass prairie, oak trees, and marshland. Figure 3.2 shows the sign at the entrance to the IAMU’s property and the native flowering prairie behind the sign. The prairie and marsh control soil erosion by allowing storm water to permeate into the ground. The IAMU’s headquarters acts as a working demonstration of an environmentally friendly, high performance, economically built building to all who come to the facility for training. Visitors are able to see first hand effective use of daylighting, feel the thermal comfort of a geothermal heat pump HVAC system combined with a high performance building envelope, and see the functional and aesthetic use of native tall grass prairie plantings. In keeping with its roots in the utilities industry, the building was built using utilitarian design features, but use of an open floor plan, abundant daylighting, views to the outside and natural wood finishes provide a pleasant work environment. All this was accomplished within an economical construction budget of $\$116/\text{ft}^2$.

Figure 3.2. IAMU entrance sign with flowering prairie in background. (John Burnet, IAMU)

Figure 3.3, containing the floor plan of the IAMU, shows that the building consists of two wings, with one wing, the "north wing", located just northwest of the second, "south wing". The wings are connected by an entry way containing the receptionist's desk and restrooms. The north wing contains private offices along its north and south offices, with open offices in the central area. A small meeting room is located at the west end of the wing and the boardroom is in the northeast corner of the wing. A small kitchen is located in the southeast corner of the wing. The south wing contains private offices along the north side and an open office area in the east end. An Auditorium is located on the south side of the south wing with an adjacent lobby area in the west end.

Figure 3.3. The IAMU floor plan. (RDG Planning and Design)

3.2. Integrated Building Design

To develop a high performance building it is necessary to use an integrated design approach, in which all the components of the building are viewed as interconnected. The initial design phase brought together a variety of parties not typically involved in building design in twelve daylong design charettes. These parties included traditional design professionals, IAMU member utilities, the Iowa Energy Center, the Polk County Conservation Board, Polk County Soil and Water Conservation Districts, Prairie Restoration specialists, Dark Sky Association, and local materials suppliers (Klaassen et. al, 2006). As described by McDougall, et al (2006), the design team determined five guiding goals for the IAUM facility:

1. **Minimize Building Energy Use.** Energy, through its production, distribution, and use was determined to be the most environmentally

damaging aspect of the building. A goal to reduce building energy use to 40% below a conventional office building was set.

2. **Minimize Construction Materials**. The building should be only as big as functionality demands.
3. **Use Materials with Low Embodied Energy.** Energy used in manufacture and transportation of materials should be minimized.
4. **Build a Healthy Environment.** The building should incorporate as much daylight as possible, give occupants control over the indoor environment, and avoid the use of volatile organic compounds.
5. **Expanded Design Team**. As mentioned above the design team included many non-traditional members**.**

To facilitate informed design decisions to minimize the energy use of the building, building energy simulations were performed using the DOE-2.1E energy simulation program (Winkelman et al. 1993). The building was first modeled as if it was constructed to conform to the contemporary Iowa energy code at the time of construction, ASHRAE 90.1-1989. This established a baseline annual energy use to compare energy savings and payback periods of alternative energy efficiency measures. This base simulation had an energy use of 65,000 BTU/ft^2-yr (Klaassen, et al. 2006).

A report by the Weidt Group tells how over 80 energy efficiency upgrades were added individually to the base model to determine their effects on building energy usage and their payback periods (1998). These energy efficiency upgrades were divided into nine main categories: window glazing alternatives, daylighting continuous dimming controls, daylighting stepped controls, envelope insulation levels, lighting controls, lighting design alternatives, mechanical efficiency levels, and outdoor air conditioning alternatives. Appendix A contains a list of all 84 energy efficiency upgrades modeled using DOE-2.1E. After these efficiency upgrades were individually modeled, three alternative groups of efficiency measures that could be added to the building were chosen for modeling. The first alternative included all of the upgrades most likely to be included in the final building design. The second alternative included all of the features of the first bundle, plus several other features that could be included if the payback was acceptable. The third alternative was a variant of the first and second. These three alternatives were then simulated in DOE 2.1E to determine their combined impact on the energy usage of the building (Weidt Group 1998). The final design had a simulated energy use of 34,000 $BTU/ft^{2} \cdot yr$, which was 48% lower than the simulation of the building built to code (Klaassen et al. 2006).

3.3. Building Systems

The integrated design process and use of building energy simulation software led to the IAMU building using an average of 29,300 $BTU/ft^{2} \cdot yr$ from 2002 to 2007. The systems that led to this low energy use are described below:

3.3.1. Envelope

The building envelope was designed to minimize the load on the heating and cooling equipment. The south walls are metal stud framed walls with R-22 $h \cdot ft^{2} \cdot {}^{o}F/Btu$ spray foam insulation between the studs and concrete board exterior cladding. The north, east, and west walls are also metal stud walls with R-22 $h \cdot ft^{2} \cdot {}^{o}F/Btu$ spray foam insulation between the studs, but the exterior is 4” concrete masonry bricks The interior walls are finished with drywall. While the R-value of the insulation between the studs is R-22 $h \cdot ft^{2} \cdot {}^{o}F/Btu$, the overall thermal resistance of the walls is greatly reduced by thermal bridging across the metal studs. Calculating the R-value of the walls according ANSI/ASHRAE/IESNA Standard 90.1-2004 section A9.2b.3, the south walls have an overall thermal resistance of 13 $h \cdot ft^{2} \cdot {}^{o}F/Btu$ and the north, east, and west walls have overall thermal resistances of 11 $h \cdot ft \cdot {}^{o}F^{2}/Btu$. During the original energy analysis by the

Weidt Group an average thermal resistance of R-20 was sought by specifying continuous rigid foam insulation on the exterior of the walls to stop thermal bridging. This design detail was not included in the construction documents, and hence was not included in the construction. The Roof consists of 4 inches of foam insulation sandwiched between a metal ceiling and a standing seam metal roof for an overall thermal resistance of 29 BTU/h·ft·°F.

While windows provide daylight to a space and provide views to the outside, they can also produce unwanted glare, uncomfortable solar heat gain, or excessive heat loss in the winter. The visual transmittance, solar heat gain, and wall to window ratio is varied by orientation to maximize daylighting and minimize the negative impacts of windows. Table 3.1 summarizes the glazing properties.

Table 3.1. Glazing properties. (Klaassen, et al. 2006)

Orientation	VT	SHGC	U-Value (BTU/hr-ft^2-°F)	Window to Wall %	Window to Floor Area %
North	0.67	0.44	0.35	13%	2.4%
South	0.67	0.44	0.35	25%	7.5%
East	0.60	0.35	0.25	25%	2.9%
West	0.60	0.35	0.25	6%	0.7%
Building	-	-	-	19%	13.6%

The lower area of windows on the east and west sides reduces glare and solar heat gain associated with the low sun angles that occur near sunrise and sunset. These windows have reduced visual transmittance (VT) values to further reduce glare, and lower solar heat gain coefficients (SHGC) to help reduce heat gain from low sun angles. Greater areas of windows on the south and north sides of the building allow daylight to enter the building. The windows themselves have low-e triple panes with wood frames, and are operable to provide natural ventilation.

3.3.2. Daylighting and Lighting Controls

Incorporating daylight into the building so that it is the main source of light was a major factor driving the design of the building. The southern façade has two rows of windows: one at desk height, and one located 15 ft above the ground. The lower operable windows provide daylighting and ventilation to the southern offices. The upper inoperable windows allow daylight to penetrate into the central office area and the northern offices. Daylighting is provided to the offices on the north side of the building by windows in the northern exterior wall and windows in the southern interior wall that allows entrance of daylight from the southern office. Figure 3.4 shows the daylit interior of the north wing of the IAMU building. Beyond the left side of the picture are the southern offices, with the low and high rows of windows providing daylight to the area. The middle of the picture shows the central office area, which is largely lit by the southern and western windows. The right side of the picture shows the large interior windows that allow daylight from the southern widows to penetrate into the northern offices.

Figure 3.4. IAMU north wing, daylight office space. Southern windows to left of picture. (John Burnet, IAMU)

The previous section discussed how the glazing was chosen to maximize daylighting and minimize the negative thermal impacts of windows. Not only were the windows chosen deliberately, but the architecture of the building was designed to maximize the benefit from daylighting. Because it is important to minimize the number of windows placed on the east and west sides, the building was elongated along its east-west axis, and the majority of the windows were placed on the south and north sides of the building. Overhangs and fins on the southern façade prevent direct sunlight from shining into the building in the summer, thus reducing the cooling load and preventing glare. Figure 3.5 shows the many exterior shading devices on the southern façade of the building. The roof overhang shades the upper daylighting windows from direct sun during the summer, but allows direct sun to enter in the winter. The lower windows are shaded by a metal overhang mounted just above the windows and metal fins mounted to the left of the windows. The large concrete block wall that juts out from the southwest corner of the building shades the lower windows from direct sun in the evening. The structural wooden columns also provide shading to the windows. In the winter, seasonal banners are hung inside the building 16 ft behind the upper windows to prevent the penetration of glare from the low sun into the central and northern offices.

Figure 3.5. Southwest corner of the IAMU's north wing. Notice the many exterior shading devices. (John Burnet, IAUM)

Because a high level of daylighting was integrated into every occupied area of the IAMU building, the electric lighting is used as a supplemental rather than primary light source. Indirect eight foot T8 florescent fixtures shine the light towards the highly reflective ceiling which then diffusely reflects the light down towards the work surface. Combining daylighting and indirect florescent lighting provides high quality illumination with nearly nonexistent shadows or glare. Dimming controls are used to maintain the illumination at the work surfaces in the building between 30 and 35 footcandles. The calibrated photocells located at the same height as the light fixtures detect the amount of light reflected from the work surface and adjust the output of the fluorescent lights between 100% and 20% full output to supplement the daylight. Each desk has task lighting for further illumination of the work surface. The total connected lighting power density, including parking and driveway lighting, is 1.1 W/ft^2, which is 35% below the energy code maximum level (ASHRAE 90.1-1989) (Klaassen, et al. 2006). In addition to the dimming controls, occupancy sensors are used in most spaces to turn off the lights when no one is present.

3.3.3. Ground Source Heat Pumps

Heating and cooling of the building is accomplished with eight four ton ground source heat pumps, which supply conditioned air to the eight thermal zones shown in Figure 3.6. The heat pumps are coupled to a closed loop ground heat exchanger consisting of thirty-three (33) 175 ft deep vertical bores. The bore field is divided into three parallel loops containing eleven bores each. A constant speed three horsepower pump circulates 90 gpm of water-glycol working fluid between the heat pumps and ground heat exchanger. When all heat pumps are operating, the pump provides 1.9 gpm of working fluid per ton of nominal output. During the winter, the heat pumps extract heat from the ground heat exchanger, and in the summer the heat pumps reject heat to the ground heat exchanger. The heat pumps are water to air units, and each unit provides 1600 cfm of conditioned air to the eight thermal zones in the building. The heat pumps' coefficient of performance (COP) ranges from 3.9 to 4.3 during normal operating conditions, and the energy efficiency ratio (EER) ranges from 16 to 19. Each zone contains a programmable thermostat that allows the user to program up to four different temperatures for each day of the week. The thermostats have been programmed for temperature setbacks at night and on the weekends.

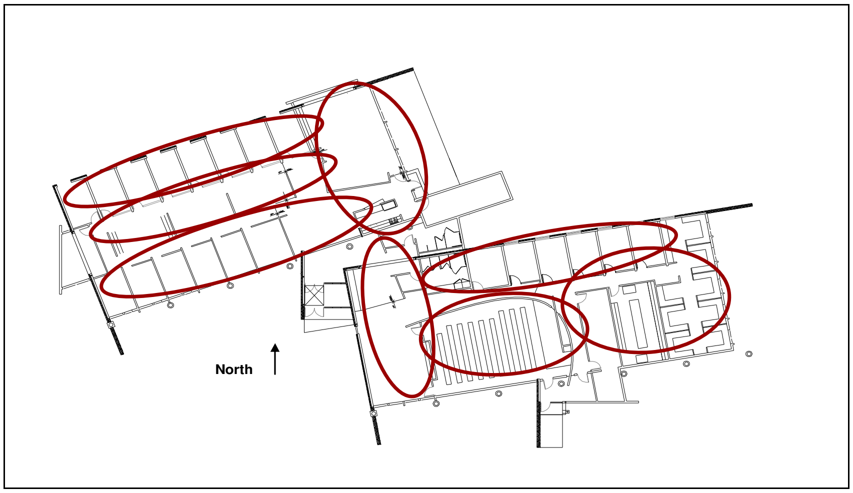


Figure 3.6. IAMU's eight thermal zones served by eight ground source heat pumps.

During the design phase, six alternative HVAC systems were considered; Table 3.2 shows the six alternatives. The base system to which the alternatives were compared contained eight natural gas fired direct expansion rooftop units with a SEER of 10. The first alternative was a similar system of eight rooftop units, but with a SEER of 12. The second and third alternatives were the same as the base system and the first alternative respectively, but both had heat recovery. The fourth alternative consisted of two natural gas fired direct expansion rooftop units that served 20 variable air volume zones. Finally, the fifth alternative was made up of eight ground source heat pumps connected to a ground heat exchanger with of 33 bores 175 feet deep. To determine which system would be the least expensive option to install and run, a life cycle analysis was performed. As the name implies, the life cycle cost analysis predicts the cost of installing and running each system over a life of 25 years, and then expresses the sum of all the costs as the net present worth of each system. The analysis was carried out using the standard methodology developed by the national Institute of Standards and Technology (NIST) as specified in Handbook 135 Life Cycle Cost.

Table 3.2. HVAC system alternatives life cycle cost analysis (Klaassen).

	Base	**Alternate 1**	**Alternate 2**	**Alternate 3**	**Alternate 4**	**Alternate 5**
Life Cycle Costs 25 Year Analysis Life	8DX RTUs SEER = 10	8 DX RTUs SEER = 12	8 DX RTUs SEER = 10 w/Heat Rec	8 DX RTUs SEER = 12 w/Heat Rec	2 DX RTUs SEER=10 Bypass VAV 20 Zones	8 GSHP Units EER = 16 33 bores @ 175 ft
Nat Gas Energy Cost	$ 23,653	$ 23,653	$ 20,130	$ 20,130	$ 21,640	$ -
Electrical Energy Cost	$ 168,222	$ 161,313	$ 166,098	$ 159,542	$ 153,392	$ 132,173
O & M Costs	$ 44,834	$ 44,834	$ 52,564	$ 52,564	$ 40,196	$ 32,466
Net First Costs	$ 134,840	$ 136,360	$ 180,800	$ 182,589	$ 173,095	$ 173,900
Total Life Cycle Costs	**$ 371,549**	**$ 366,160**	**$ 419,592**	**$ 414,825**	**$ 388,323**	**$ 338,539**
Life Cycle Ranking	3	2	6	5	4	**1**

Table 3.2 shows the present value of the natural gas used by the HVAC systems, the present value of the electricity used by the entire IAMU office building over the life of the systems, the present value of the operating and maintenance costs of the systems, and the net first cost of the systems. The value of the entire building's electrical use was used in the analysis because a lower all electric rate was available if the IAMU building used only electricity and did not use natural gas. Therefore, the use of electric ground source heat pumps, rather than natural gas fired rooftop units, decreased the cost of electricity for the lighting and general equipment as well as the HVAC system. The table shows that the first cost of the heat pump system was the fourth lowest behind the base system and alternatives one and four. In contrast the heat pump system has no natural gas cost, has the lowest electrical energy cost, and has the lowest operating and maintenance cost of all the systems. This results in the heat pump system having the lowest life cycle cost, and was thus the most economical choice for the building owner.

3.3.4. Energy Recovery Ventilator

An enthalpy wheel energy recovery ventilator (ERV) is used to precondition the building's ventilation air before it enters the building. A schematic of the ERV is shown in Figure 3.7. The unit contains two counter flowing air streams—one is the bathroom exhaust air and the other is the incoming ventilation air. Both airstreams pass through a slowly rotating wheel made of a lightweight polymer sheets coated in a silica gel desiccant. The lightweight polymer sheets are wrapped loosely around the axis of the wheel to form many small air passages between concentric layers. As air passes through the wheel, heat and water mass transfer occur between the air and the material. During hot humid weather the ERV removes heat and humidity from the ventilation air and transfers it to the exhaust air. During cold low humidity weather the ERV transfers heat and humidity from the exhaust air to the ventilation air. In both cases the ERV reduces the amount of energy required by the ground coupled heat pumps to condition the ventilation air.

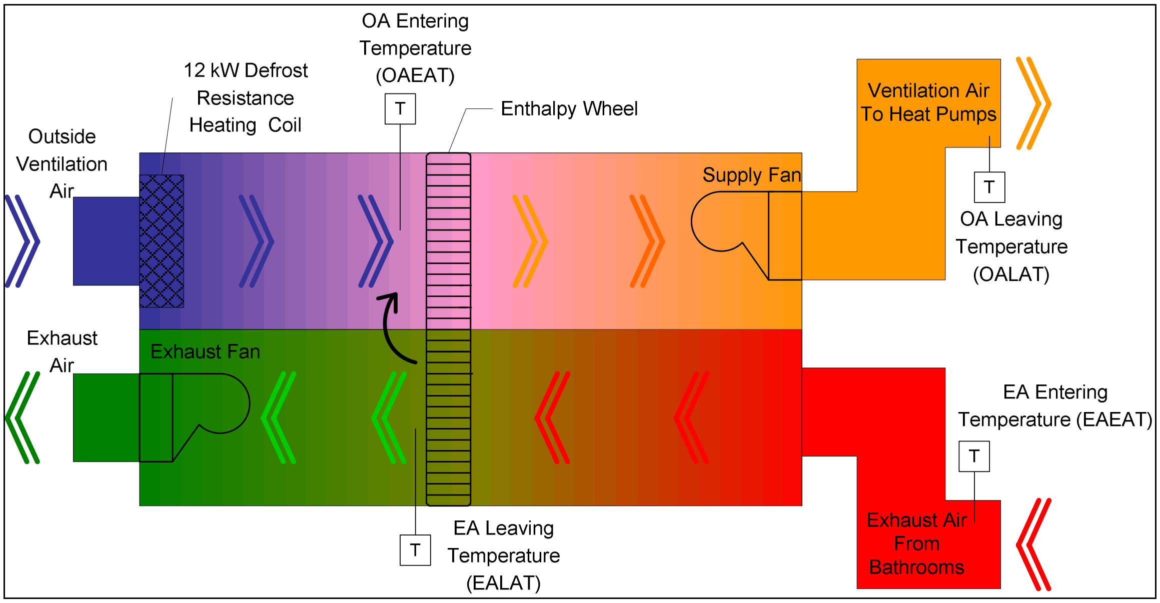


Figure 3.7. Schematic of the energy recovery ventilator (ERV).

The ERV is scheduled to run on low fan and wheel speed between 8:00 a.m. and 5:30 p.m. Monday through Friday. At low speed the ERV supplies 750 CFM of ventilation air to the HVAC system. The hours of ERV operation are the business hours of the building, and the hours when ventilation is most needed in the building. While a few employees may occupy the building outside of these hours, the ventilation load is not high enough to require the ERV to operate. Because training sessions in the auditorium greatly increase the occupancy of the building and the ventilation requirement, an occupancy sensor in the auditorium increases the ERV fan and wheel speed from low to high. At high speed the ERV supplies 1100 CFM of ventilation air. The occupancy sensor in the auditorium used to increase the speed of the ERV is also the occupancy sensor that controls the lighting in the auditorium. To activate the sensor, a switch in the auditorium must first be switched on to energize the lights and the sensor. Once energized, the sensor will turn the lights on and off and the ERV from low to high speed depending on the occupancy of the auditorium. In situations where the auditorium is occupied but the lights are turned off (such as during an overhead projection presentation), the occupancy sensor will not be energized, and the ERV will remain on low speed.

3.4. Energy Efficiency Enhancement Cost Premiums

A common concern among building owners, designers, and construction professionals is the additional cost of energy efficiency design features for buildings. A study performed by Russ Walters for the Iowa Energy Center determined that the IAMU building’s energy efficiency features added $26,183, or 1.8%, to the total construction cost of the building compared to a “typical” office building. Table 3.3 shows the nine building features that improve the energy efficiency of the IAMU building. Efficiency items two, seven, and eight, have negative costs associated with them. This means it cost less to construct the building with these efficiency items rather than without them.

Table 3.3. IAMU energy enhancement construction cost premiums (Walters).

Item	Description	Additional $\$/\text{ft}^2$	ft^2	Cost	% of Typical
1	Building Envelope: Spray foam insulation instead of fiberglass batts	0.31	10,317	$ 3,198	0.22%
2	Building Envelope: change sloped roof to flat roof with parapet and 16 ft. high perimeter wall	16.04	-688	$ (11,032)	-0.77%
3	Shading Devices: Concrete Masonry Unit Wing Walls	5.33	791	$ 4,216	0.30%
4	Shading Devices: Exterior shading around windows	36.4	75	$ 2,730	0.19%
5	Shading Devices: 4' roof overhang	6.6	931	$ 6,143	0.43%
6	Daylighting Building Section: High daylighting windows	39.2	783	$ 30,696	2.16%
7	Daylighting Building Section: change from 20% glazing to 18% glazing	39.2	-850	$ (33,330)	-2.34%
8	Daylighting Building Section: Change from suspended ceiling and recessed lights, to open ceiling with reflective paint and indirect lights			$ (15,499)	-1.09%
9	HVAC System: Change from natural gas fired, direct expansion single zone rooftop units to geothermal heat pums with bore field			$ 39,060	2.74%
Total Cost Added by the Energy Efficiency Features				**$ 26,183**	**1.8%**

Item one, the spray foam insulation, added $3,198, or 0.22% to the building cost compared to the typical fiberglass batts used in commercial office buildings. Item two, the construction of the building with a high, 18’ 8”, south wall and a low, 11’ 4”, north wall to maximize the distribution of daylighting in the building, actually reduced the total wall area compared to a typical office building construction. If the IAMU building had been built with customary 16” parapet walls with a flat roof, 688 ft^2 more wall would be needed. The sloped roof of the IAMU saved $11,032 in wall costs. The shading devices all added additional costs to the construction. The concrete block wing walls added $4,216 or 0.30%, the shading devices around the windows added $2,730 or 0.19%, and the roof overhang added $6,143 or 0.43% to the construction costs.

A typical office building would not have the high daylighting windows the IAMU building has (item 6), so they are also considered an additional cost. The daylighting windows added $30,696, or 2.16% to the building’s construction costs. Although, the

IAMU has very good daylighting, and the high daylighting windows are considered extra, the IAMU building actually has less window area than a typical office building. The IAMU has a window area to wall area ratio of 15%, while a typical office building has a ratio of 20%. Therefore, the optimized daylighting system saved $33,330 in window costs. The net affect of having daylighting windows, but have a reduced window to wall area ratio is a savings of $2,634. As part of the daylighting scheme, the IAMU has indirect lights that shine on the underside of the metal roofing deck painted with a highly reflective paint. This system avoided the cost of a suspended ceiling and more expensive recessed lights and thus saved $15,499 or 1.09% of construction costs. Finally, the heat pumps added an additional cost of $39,060 or 2.74% to the construction cost compared to a typical office building using natural gas fired direct expansion rooftop units.

Chapter 4. IAMU Building Monitoring

4.1. Introduction

This chapter discusses the long term monitoring of the IAMU building. The architecture of the data acquisition system and the types of sensors used are discussed in section 4.2. Then in section 4.3, the building monitoring strategy is given including the method used to monitor the energy use of the building and the placement of sensors throughout the building. Finally in section 4.4 the energy performance of the building over six years of complete monitoring is presented.

4.2. Data Acquisition System

As part of the strategy to demonstrate that the IAMU building is a low energy high performance building, the Iowa Energy Center's Energy Resource Station was contracted to monitor the energy use and indoor environmental quality of the building. Monitoring the building has verified that the building is operating as it was designed and that it is a high performance building (McDougall et al 2006),(Klaassen et al 2006). Monitoring has also shown that there is room for improvement in the building's energy performance (Ardehali et al. 2003). Initial monitoring began in July 2001 using a CSI data acquisition system that took readings every 15 minutes. This system proved unreliable, and in July 2004 it was replaced with an Invensys® data acquisition system. This system records data from 66 points every minute; 51 of the points are measured points and the other 15 are calculated from the measured data. The measured points include power, amperage, temperature, light levels, relative humidity, CO_2 levels, CO levels, VOC (volatile organic compounds) levels, and the occupancy status of the auditorium. The calculated points include energy use, power, and the flowrate and heat transfer rate of the working fluid in the ground source heat pump system. All the points along with their descriptions and the formulas for the calculated values are listed in Table B.1 through Table B.4 in Appendix B.

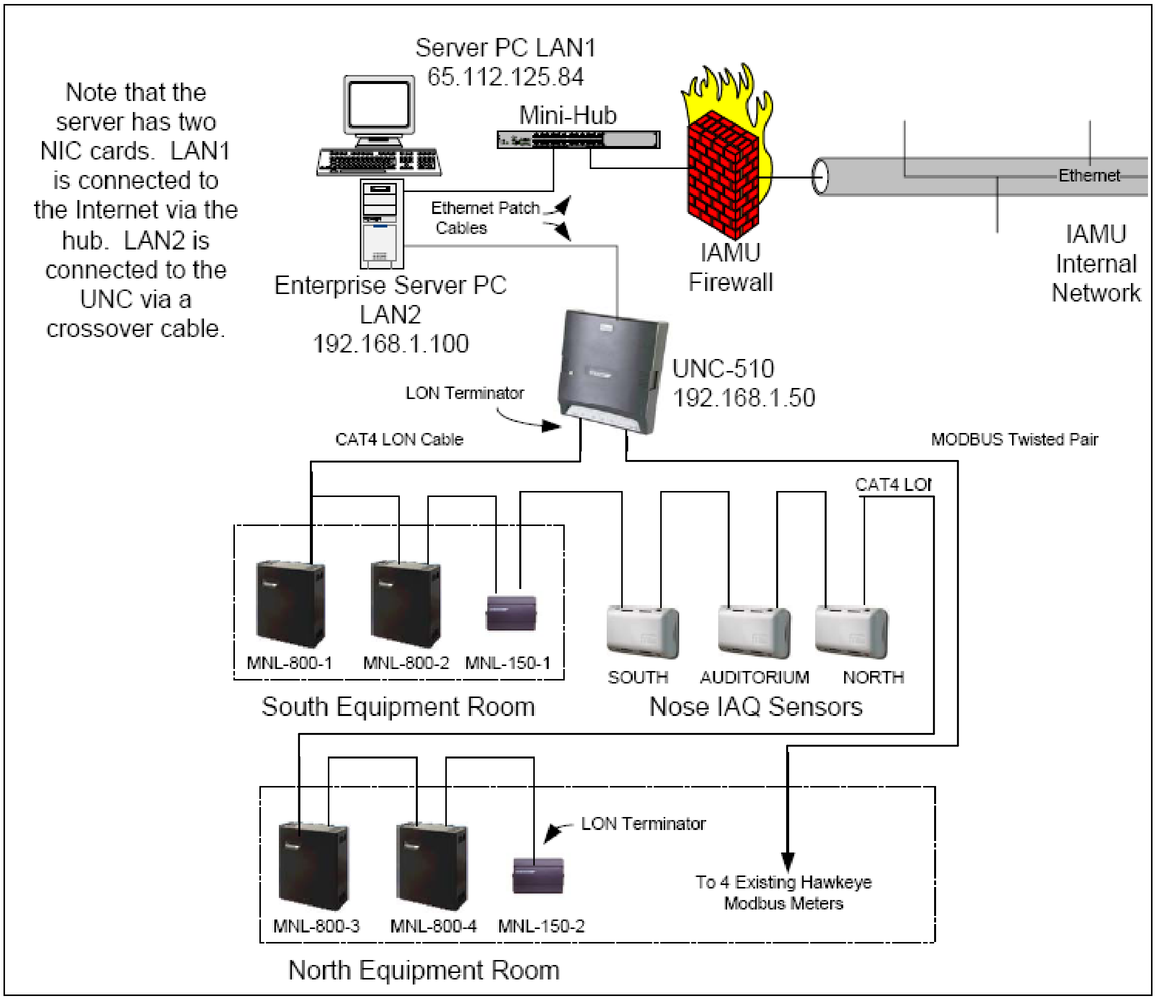


Figure 4.1. Data acquisition system architecture.

The system architecture of the Invensys® data acquisition system is shown in Figure 4.1. The Invensys® system is typically used as part of building automation system, and thus has the capability of receiving sensor inputs and then controlling devices through outputs. For the monitoring of the IAMU building, only the data collection capability is being used. The data acquisition systems has four levels: the server PC, the primary controller, the application controllers and network capable sensors, and finally the analog output sensors. The system can most easily be explained by starting at the analog sensor level and working up the hierarchy of the system. Table 4.1 lists the different types of sensors used in the IAMU building along with their outputs, types of readings, ranges, and accuracies. Three different types of analog output sensors are used in the IAMU building: a current transducer with a 4 to 20 mA output, a light meter with a 0 to 10 VDC output, and an RTD with a resistance output. Although three different models of current transducers are listed in the table, they all are essentially the same sensor. Throughout the building there are six current transducers, seven light sensors, and 14 RTD's. See Table B.1 through Table B.4 in Appendix B for a complete listing of where the sensors are located throughout the building, and the point name associated with each sensor.

Table 4.1. Instrumentation used in IAMU building monitoring.

Instruments	Output	Reading	Range	Accuracy
Veris Industries H8036/100 Hawkeye	Modbus	kW and kWh	0 to 100 amps	+/- 1% of reading, from 10% to 100% of rated current
Veris Industries H8036/300 Hawkeye	Modbus	kW and kWh	0 to 200 amps	+/- 1% of reading, from 10% to 100% of rated current
Veris Industries Current Transducer H720	4 to 20 mA	Amps	0 to adjustable 20 to 200 amps	0.5% full-scale
Veris Industries Currnet Trasducer H921	4 to 20 mA	Amps	0 to 30 amps	+/- 2% full scale
Veris Industries Current Transducer H931	4 to 20 mA	Amps	0 to 30 amps	+/- 2% full scale
Celestial MK7-B Light Sensor	0-10 VDC	FC	adjustable 0 to 10,000 ft-cd	+/- 1% of reading
Weed 1000 ohm RTD	Resistance	deg F	-160 to 1220 deg F	
NOSE-5 N5000-100	LonWorks	deg F	32 to 100 deg F	+/- 0.8 degF
		Humidity	5 to 95% rh, non-condensing	+/- 10% of reading or 5%, whichever is greater
		CO2	0 to 5000 ppm	+/- 5% of readint or 100 ppm, whichever is greater
		CO	0-200 ppm	+/- 10% of reading or 10 ppm, whichever is greater
		VOC	0 to 100%	+/- 10% of reading or 5%, whichever is greater

The outputs of the analog sensors are connected to the six application controllers: four MNL-800 controllers and two MNL-150 controllers. Both controllers serve the same purpose of interfacing with sensors and only differ in the number of inputs and outputs they can handle. The MNL-800 controllers have eight universal inputs, four analog outputs, and eight digital outputs. The MNL-150 controllers have three universal inputs, two analog outputs, and two digital outputs. Because the system is merely being used for data acquisition, only the universal inputs are used. The application controllers receive the analog inputs from the light meters, current transducers, and RTD's. They then convert these inputs into LON communications protocol signals which are transmitted to the primary controller. In addition to sensors with conventional analog output, two types of network enabled sensors are used in the building—Hawkeye power meters, and NOSE® indoor air quality meters. Both of these sensors are capable of talking directly on the network, and they are not connected to an application controller. They are connected directly to the primary controller. There are four Hawkeye power meters used to monitor the power and total energy use of the HVAC system, the lighting system, the general equipment, and the maintenance shed adjacent to the IAMU building. These meters output their readings directly to the primary controller using the Modbus communication protocol. The three indoor air quality meters monitor temperature, relative humidity, CO_2 levels, CO levels, and VOC (volatile organic compound) levels. These meters output their readings to the primary controller using the LON communication protocol.

After receiving the data signals from the six application controllers, four Hawkeye meters, and three indoor air quality sensors, the UNC-510 primary controller passes the data to the server desktop computer. The server computer records the 66 points into five daily tab delimitated text files, organized to contain related information. The files are: ElecSum.imu, HVAC.imu, Northwing.imu, SiteLite.imu, and Southwing.imu. Table B.5 in Appendix B contains a list of the points in each file. All together nearly six and a half years of energy and indoor environment data has been collected from the IAMU building.

4.3. Building Monitoring Strategy

Figure 4.2 shows the energy monitoring strategy for the IAMU building. On the left side of the figure it can be seen that the total power arriving on the site is monitored by the electric company's meter. There are then four submeters that monitor the power and energy use of the lighting system, the HVAC system, the general equipment, and the maintenance shed adjacent to the office building. The sum of the energy monitored by the four sub meters should equal the amount of energy monitored by the electric company meter. The annual sum of the four sub meters has been compared to the annual electric utility bills, and has been within 1.1% to 1.7% of the electric utility bills from 2002 through 2007. The lighting meter measures the power demand and total energy use of all the lights in the IAMU building including general interior lighting, task lighting and site lighting. The HVAC meter monitors the power and energy use of the eight heat pumps, the geothermal loop circulating pump, and the energy recovery unit. The general equipment meter monitors all appliances plugged into outlets, the water heaters, the fire alarm system, drinking fountains, and seven unit electric heaters. The fourth sub meter monitors the power and energy use of the separate maintenance shed. The energy use of the maintenance shed in not included as part of the office building energy use. To determine the total energy demand of the IAMU building, the demands from the lighting, HVAC, and general load meters are summed together. The data acquisition system maintains a running total of the energy used by each of the subsystems and the entire building.

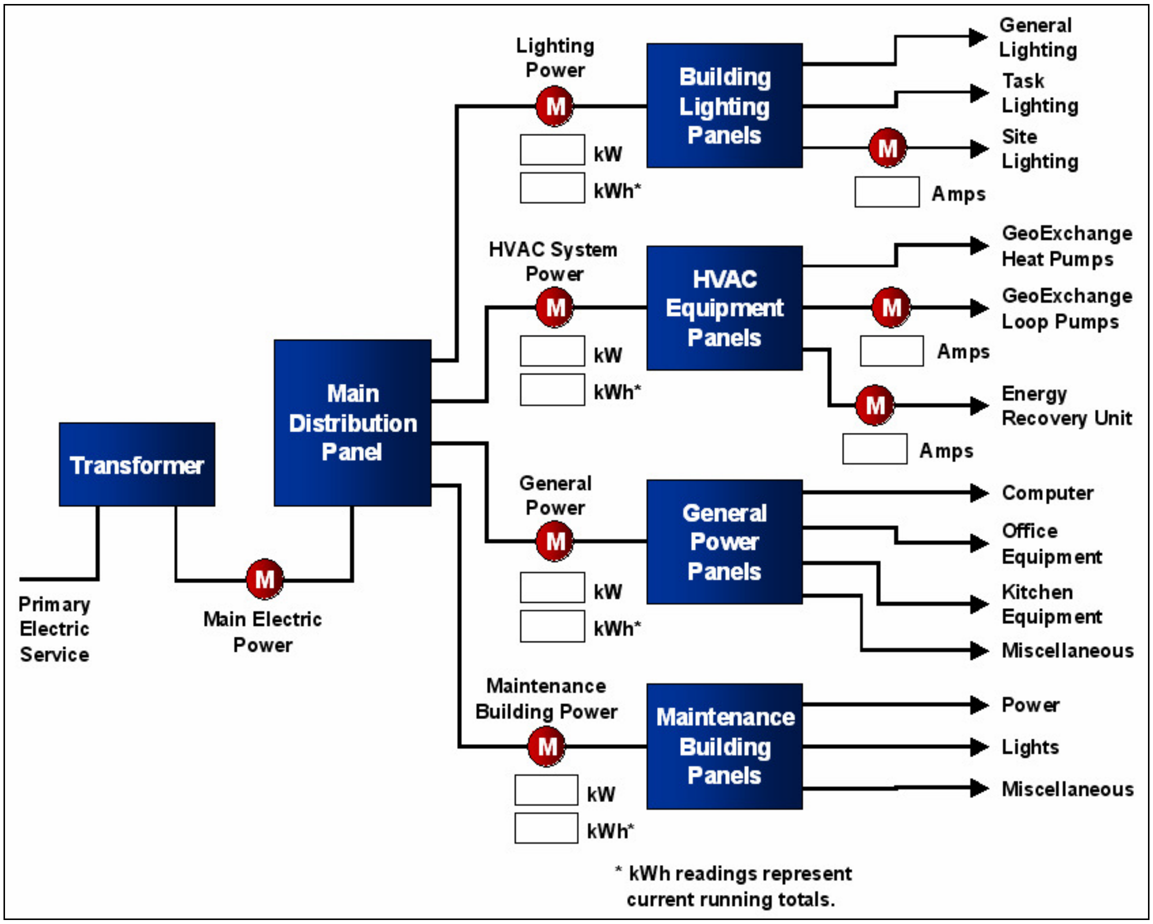


Figure 4.2. Organization of IAMU energy monitoring meters.

The energy use of several specific applications is monitored using current transducers, as shown in Figure 4.2. Current transducers are used to monitor the site lighting, the circulating pump of the HVAC system, and the energy recovery unit. The power use of each piece of equipment can be calculated from the current measurement if the voltage supplied to the equipment and the power factor of the equipment are known. These quantities were measured for each piece of equipment, and are used by the data acquisition system to calculate the power use of the equipment. Although only one ammeter is shown monitoring the site lighting, three ammeters are actually used to separately monitor the driveway lighting, parking lot lighting, and façade lighting.

The temperature of each of the eight thermal zones conditioned by the heat pumps are monitored using RTD's. The thermal zones and the locations of the RTD's behind the zones' thermostats are shown in Figure 4.3. The location of the NOSE sensors used to monitor indoor air quality are also shown in Figure 4.3. The light level is monitored in seven different locations, as shown in Figure 4.4, that represent zones that use daylighting as their primary lighting source. RTD's are used to monitor the temperature of the working fluid returning to the ground heat exchanger of the ground source heat pump system, and the temperature of the working fluid as it is supplied back to the heat pumps. Four RTD's are used to monitor the airstreams of the energy recovery ventilator. One RTD monitors the temperature of the outside entering air, a second monitors the outside air leaving temperature, a third monitors the exhaust air entering temperature, and the fourth monitors the exhaust air leaving temperature. The calculated points provide additional information about the building; these points can be viewed in Table B.4 in Appendix B.

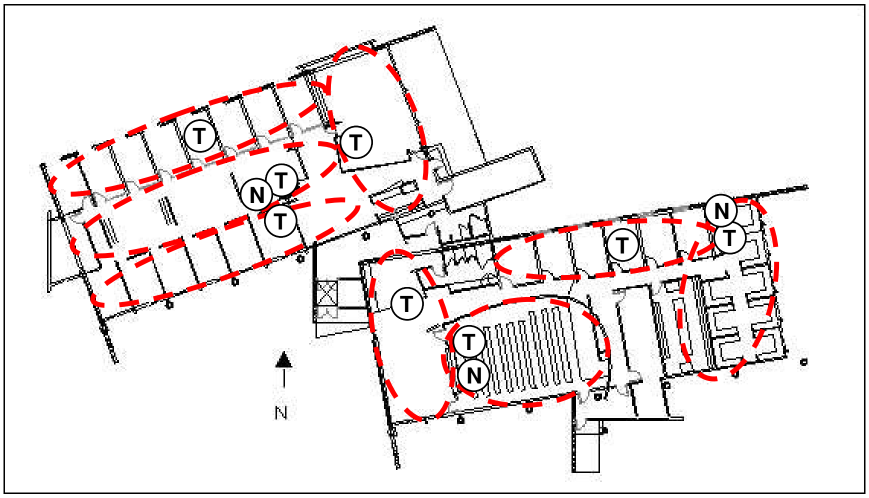


Figure 4.3. Location of temperature sensors (T) and NOSE indoor air quality sensors (N).

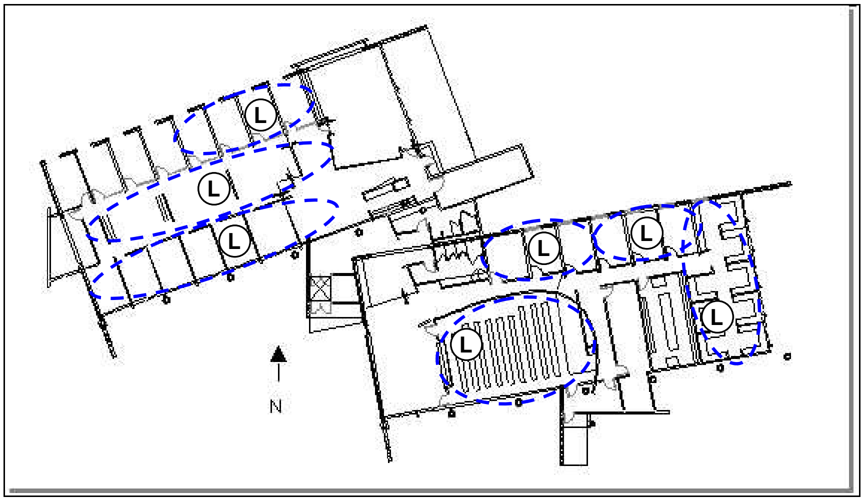


Figure 4.4. Location of light sensors (L).

4.4. Whole Building Energy Performance

The annual energy performance of the IAMU building over the six years of continuous monitoring is summarized in Table 4.2. The table contains the total annual energy use, the energy utilization index (EUI), the weather adjusted energy utilization index, and the energy cost index of the building. While the total annual energy can be used to evaluate the energy performance of the building, the EUI is a more useful method of determining the performance. Because the EUI normalizes the energy use based on the gross area of the building, it allows the energy use of different sized buildings to be compared. The average annual energy use from 2002 through 2007 was 366,000 kBtu, or, and the average annual EUI was 29.3 kBtu/ft^2. Both the total annual energy use and EUI reveal that during 2006 and 2007 the building used the second greatest and greatest amounts of energy respectively. The annual energy use of the building shown in the table is determined by summing the energy outputs of the HVAC, lighting, and general equipment power meters. Each of these meters has an accuracy of ±1% of the reading. A fourth power meter monitors the power demand and energy consumption of the maintenance shed on site. The sum of the four meters gives the total power demand and energy use of the site, and should give the same values as the electric company's electric meter. From 2002 to 2007 the sum of the annual energy metered by the four sub meters has been within 1.1% to 1.7% of the energy metered by the electric company's meter.

Table 4.2. IAMU annual energy use indices.

Year	Annual Energy Use (kBtu)	EUI (kBtu/ft2year	Weather Adjusted Index (Btu/ft2-DD-yr)	Energy Cost Index (¢/ft2-yr)
2002	365,000	29.2	3.9	53.2
2003	363,000	29.0	3.8	52.3
2004	347,000	27.8	3.9	51.5
2005	352,000	28.2	3.8	52.3
2006	371,000	29.7	4.3	55.1
2007	398,000	31.8	4.2	57.9
Average	**366,000**	**29.3**	**4.0**	**53.7**

The weather adjusted EUI is determined by dividing the EUI by the number of heating and cooling degree days in the year. A degree day is defined as a one degree difference in the mean daily temperature from a given temperature, which in this case is 65 ^{o}F. Sixty-five degrees is the outdoor temperature considered the thermal balance point of many buildings—the outdoor temperature at which no heating or cooling is needed and below which heating is required and above which cooling is required. At mean daily temperatures below 65 ^{o}F, the degree days are called heating degree days, and for mean daily temperatures above 65 ^{o}F, the degree days are called cooling degree days. While the balance point temperature of buildings vary, the number of degree days gives a rough indication of the amount of heating or cooling required for a day. The weather adjusted index allows the energy use of a building to be compared between years with different weather, or the energy use of buildings in different climates to be compared.

Table 4.2 shows that 2006 and 2007 had the first and second greatest weather adjusted EUI's respectively. This reveals that the increase in energy use during those years was not due merely to differences in outdoor air temperature. Over the six years the average weather adjusted EUI was 4.0 But/ft^{2}·DD·yr. Finally, the energy cost index is found by dividing the annual electric utility bill, including all fees and taxes, by the gross area of the building. This gives the cost of energy per square foot of building, and allows comparison of energy costs between buildings of different sizes and billing methods. The average annual energy cost index over the six years was 53.7 ¢/ft$^2\cdot$yr. The years 2006 and 2007 had the second and first greatest values, this is to be expected as these years had the second and first greatest total energy use.

Figure 4.5 shows the annual energy use of the IAMU building for the years from 2002 through 2007 divided into the three main end uses in the building: lighting, general equipment, and HVAC. The average lighting energy use makes up 20% of the annual energy use, general equipment energy makes up 32%, and HVAC energy makes up 48%. It can be seen that the lighting energy use has stayed relatively constant over the six years, with an average annual value of 72,300 kBtu. This is consistent with the use of the building—all of the lighting control schemes and lighting level set points in the building and on the site have remained the same. Although several new employees have been added to the IAMU staff since 2006, any increase in lighting energy caused by these new employees cannot be discerned in the graph. Because of the IAMU building's high utilization of daylighting, it is likely that only a small amount of energy is required to light additional occupied offices.

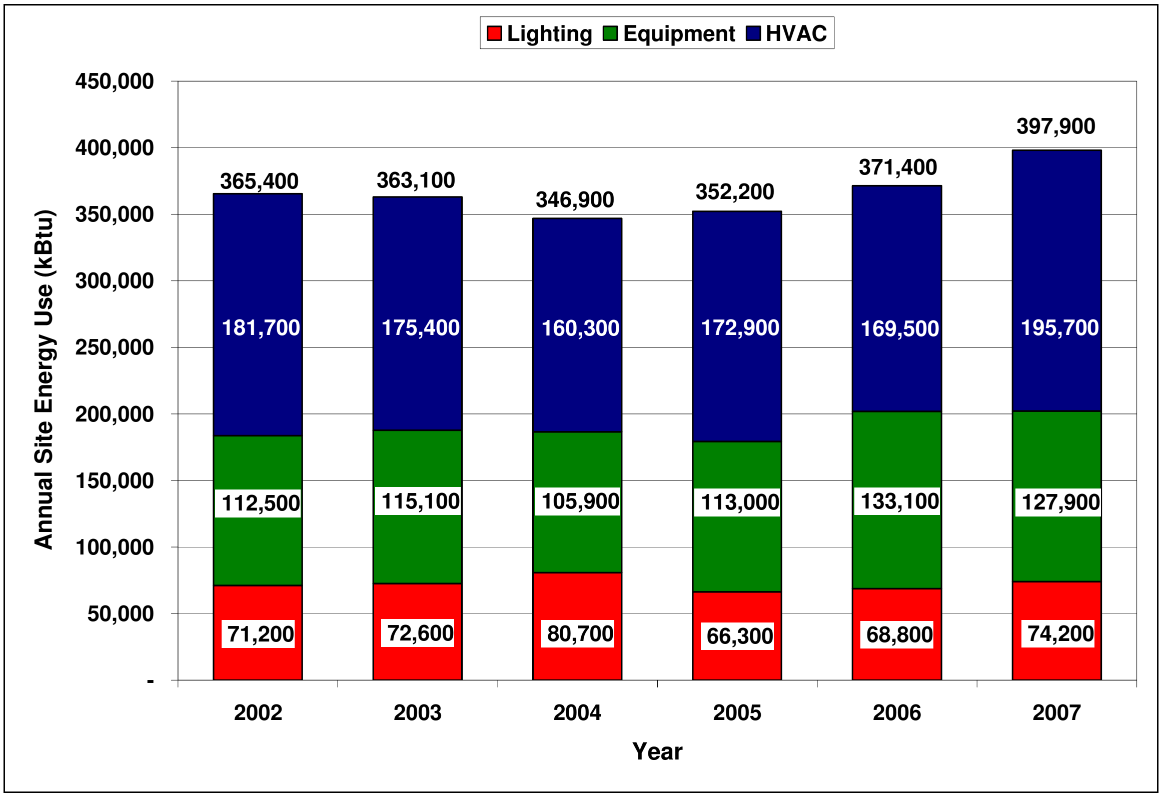


Figure 4.5. IAMU annual site energy use for the years 2002 through 2007.

Figure 4.5 shows that, unlike the lighting energy, there is a marked increase in the annual energy use of the general equipment in 2006, as compared to 2002 through 2005. The average general equipment energy use over all six year is 117,900 kBtu, but the average for the first four years is 111,600 kBtu and the average of the last two years is 130,500 kBtu. For the general loads, the increase in employees over the past two years may have caused the increase in general equipment energy in 2006 and 2007. A survey of all of the office equipment at the IAMU building, conducted in the spring of 2005 and again in the spring of 2007, found a significant increase in the amount of office equipment between surveys. Some of the equipment additions included a refrigerator, eight personal space heaters, a copy machine, and sundry small pieces of office equipment. Because of the great variability in the type of office equipment and usage patterns, it is difficult to know the exact cause of the increase in general equipment energy usage.

Finally, the annual HVAC energy use shown in Figure 4.5 has an average of 175,900 kBtu over the six years. The HVAC energy use in 2007, 195,700 kWh, was much higher than in any other year. The energy use of the HVAC system is highly dependent on outdoor air temperature, and will be greater for years with a greater number of cooling degree and heating degree days. Figure 4.6 shows the number of cooling degree days, the number of heating degree days, and the annual HVAC energy normalized by the annual number of total degree days Two-thousand seven had the most cooling degree days and the third most heating degree days of the six years. Combining cooling and heating degree days, 2007 had the most total degree days of the six years. Therefore it is expected that 2007 would have the highest HVAC energy use. The annual HVAC energy use was normalized by dividing it by the annual total number of degree days. The normalized HVAC energy use is the average amount of energy required to heat or cool the building per degree day. It can be seen that the total number of annual degree days has varied around the average of 7370 degree days over the six years. The normalized annual HVAC energy use increased from a minimum of 22.8 kBtu/DD in 2004 to a maximum of 25.6 kBtu/DD in 2007, or an increase of 12% over three years. Therefore, 2007 had the highest HVAC energy use for two reasons: it had the highest number of degree days and it used the largest amount of energy per degree day to condition the building. Currently it is unknown why the HVAC energy used per degree day has gone up, but two possible causes are:

1. Increased internal heat gain, and thus increased cooling load, due to more employees, equipment, and lighting.
2. Greater cooling or heating loads caused by different thermostat set points—lower cooling set points or higher heating set points.

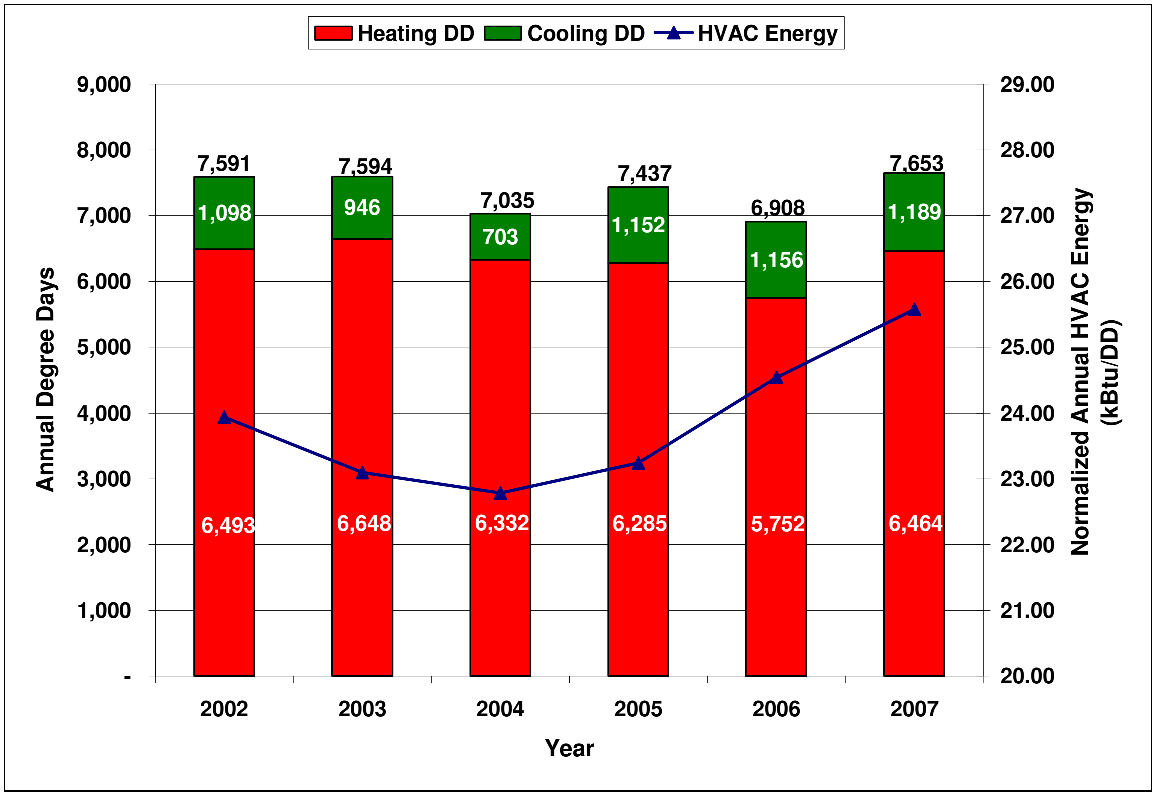


Figure 4.6. Annual number of degree days, and normalized annual HVAC energy based on annual degree days.

Figure 4.7 shows the average monthly energy use of the IAMU building. The red, green, and blue points show the average monthly energy use of the lighting, general equipment, and the HVAC system, respectively. The black points show the total average monthly energy use of the building. It can be seen that the energy use has a strong seasonal dependence. The total energy use varies from a high of 45,200 kBtu in January to a low of 22,700 kBtu in May. The HVAC energy contributes largely to the seasonal dependence. The HVAC energy use is greatest during winter months when the building requires heating; the maximum of 24,100 kBtu occurs in January. The HVAC energy use then decreases as the months become warmer, until it reaches a minimum of 8,900 kBtu in May. Then in June, when significant cooling begins, the HVAC energy increases and remains nearly constant through August. Then in September, HVAC energy use decreases to a second local minimum as the weather becomes cooler. From October through December, as the weather grows colder and greater amounts of heating is required, the HVAC energy use grows steadily.

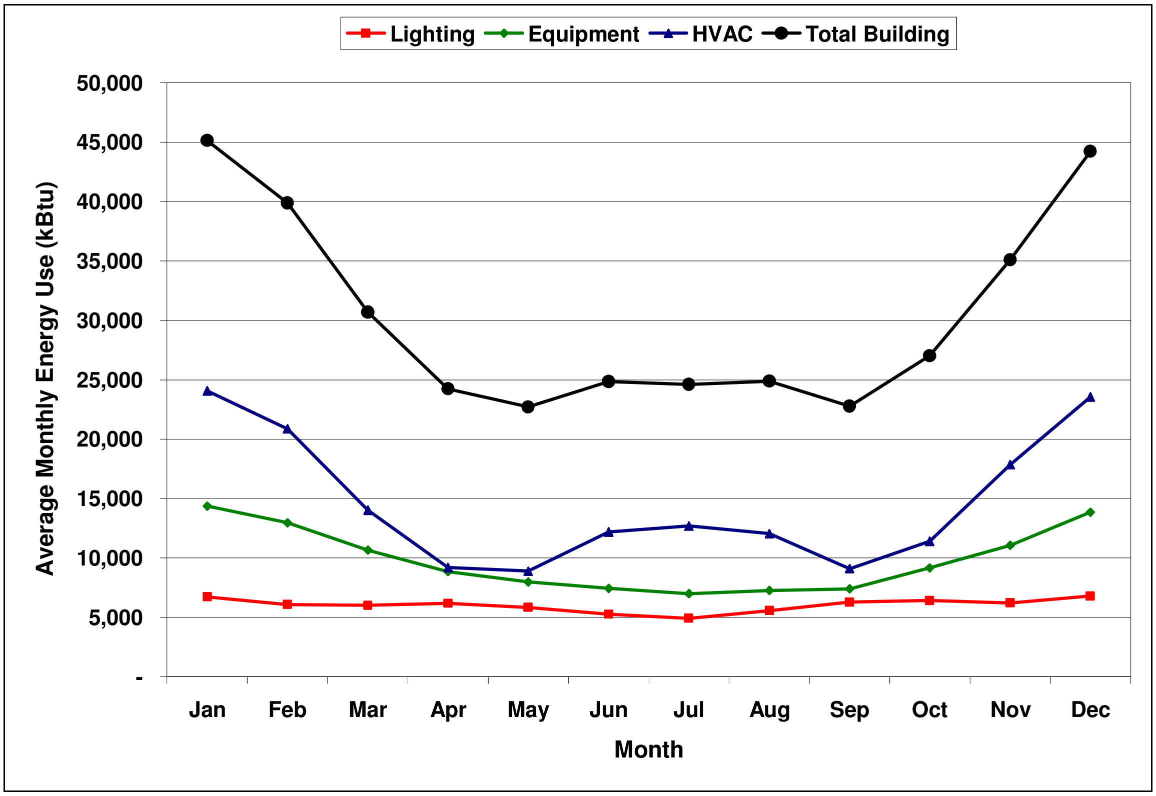


Figure 4.7. IAMU six year average, from 2002 to 2007, monthly energy use.

The general equipment energy use is also seasonally dependant, with its maximum of 14,400 kWh in January and its minimum of 7,000 kBtu in July. This seasonal dependence is mainly caused by the presence of the six unit heaters in vestibules and perimeter locations wired to the electrical panel monitored by the general equipment power meter. Although the unit heaters are part of the HVAC load, and should be monitored by the HVAC power meter, they were incorrectly wired to the general equipment meter. If the unit heaters were not on the general equipment meter there would likely be very little seasonal dependence of the general equipment energy use.

Finally, the lighting energy use has only a slight seasonal energy dependence. The lighting energy use reaches its maximum, 6,800 kBtu, in December, and its minimum of 4,900 kWh in July. Klaassen et al reported that the daylighting system reduced the energy use of the lighting system 68% below a code compliant building (2006). The small seasonal dependence of the lighting energy, and the overall low lighting energy use indicate that even in the winter, much of the building's lighting requirement is met by daylighting.

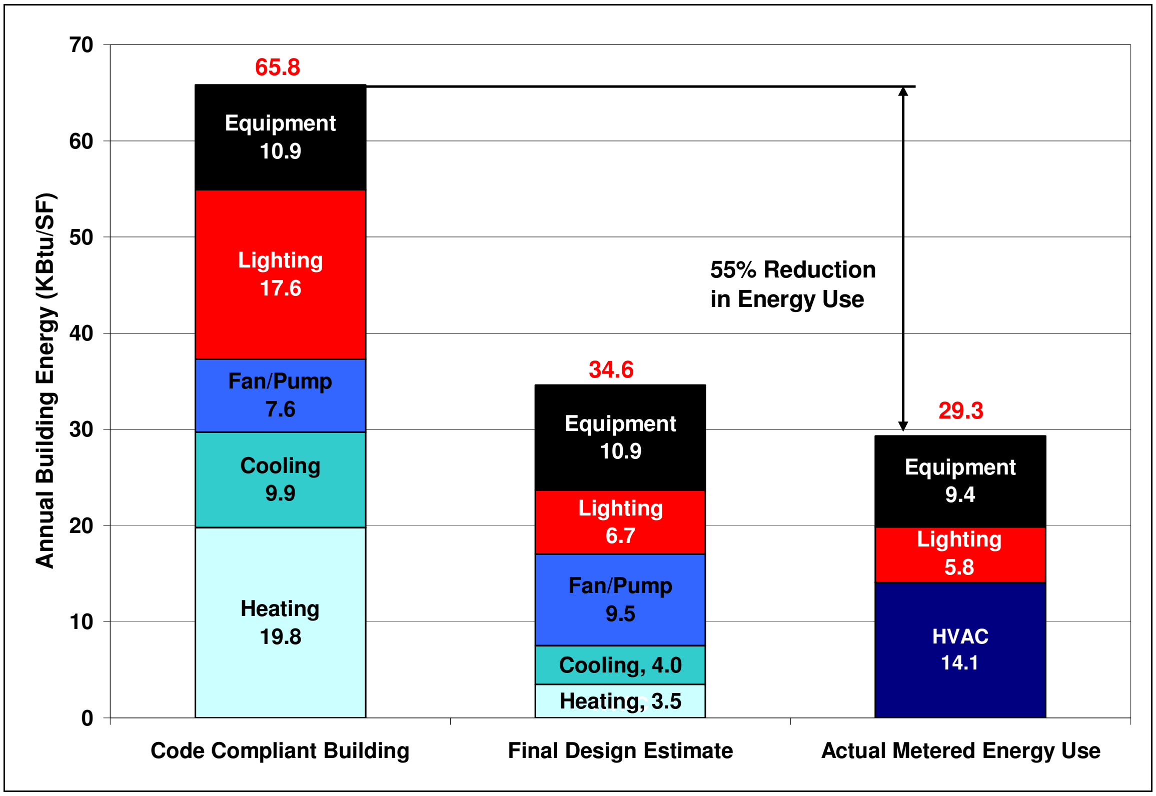


Figure 4.8. Comparison of IAMU energy use to code compliant building, and design estimate energy use.

Figure 4.8 contains a comparison of the average EUI of the IAMU building to an equivalent code compliant building and the predicted EUI of the building from the final design. The energy use of the equivalent code compliant building was determined by modeling the IAMU building, using the building energy simulation software DOE-2, as it would be if it had minimally met contemporary energy codes (Winkelmann et al. 1993).

The predicted energy use of the building from the final design was also determined using DOE-2. The IAMU building's actual EUI is 29,300 Btu/ft^2, while the modeled EUI of an equivalent minimally code compliant building is 65,800 Btu/ft^2, and the design estimate of the EUI was 34,600 Btu/ft^2. The building uses 55% less energy than an equivalent code compliant building. The building shows a similar reduction in energy cost; the building has an average annual energy cost of $6,700, while the annual energy cost of the modeled code compliant building was $14,000. Therefore the building has a 52% reduction in energy cost from the code compliant building.

According to the 2003 Commercial Buildings Energy Consumption Survey (CBECS), office buildings in the U.S. have an average EUI of 92,900 Btu/ft^2, and office buildings in climate zone 2 (the zone containing Ankeny, IA) have an average EUI of 114,900 Btu/ft^2 (EIA, 2006). The IAMU building, thus uses 68% less energy than the average U.S. office building, and 74% less energy than the average office building in climate zone 2.

Chapter 5. Experimental

5.1. Introduction

While monitoring the energy performance and the indoor environmental quality of the IAMU building confirmed that it operates as a low-energy high performance building, it also revealed several areas where improvements could be made to further reduce the energy use of the building. Informal commissioning had been performed to ensure the major building systems worked properly and continual maintenance has been performed to keep the systems operating properly, but these were not performed with the goal of optimizing the energy usage of the systems. With six years of energy data, indoor environmental quality data, and weather data, detailed analysis of the energy performance of the major building systems and equipment—envelope, lighting, HVAC (heating, ventilation, and air conditioning), and general equipment could be performed. Many areas where energy performance and environmental quality could be improved were identified, but only three specific problems were chosen as a focus for this report.

There are three main phases of a building's life that affect its energy use—the design of the building, the implementation of the design (construction and commissioning), and the occupying of the building. Decisions that greatly affect the energy use of a building, such as orientation, amount and type of fenestrations, and type of mechanical equipment, are made during the design phase. Once the design is finished a good prediction of the building's future energy use can be made. In a perfect world the specifications of the design would be followed exactly during construction and commissioning, and the implementation phase would have no impact on the energy use of a building. In reality, changes are made during construction for economic, time, or other practical reasons, which affect the energy use of a building. Even if there are no deviations from the design, the quality of construction and commissioning can greatly affect a building's energy performance. Poorly installed insulation or incorrectly calibrated daylighting controls will greatly reduce the intended energy savings of the systems. Finally the level of occupancy, the behavior of the occupants, and the use of a building all affect its energy performance.

Each of the three areas chosen to improve the energy performance of the IAMU building correspond to one of the above three building phases (design, implementation, and occupancy) that impact a building's energy use. The first area identified for improvement is the pumping system for the ground source heat pump system. During the design of the system, a constant speed continuous pumping arrangement with a wet standby pump was specified to circulate working fluid between the ground heat exchanger and the eight heat pumps in the building. This system was specified because of its simple design, reliability, and no need for a pump control system. While the pumping system has operated reliably for over seven years, the pump has used significantly more energy than needed. It is rare for all of the heat pumps to be on at once, and during times when only a few heat pumps are on, the flow of working fluid could be reduced to match the load. It is also common, over half of the time, that all of the heat pumps are not operating. During these times the circulating pump could be shut down, but the current configuration prevents this. Because a constant speed continuously operating pump was specified, it is not possible to save pumping energy by matching the supplied flow to the load of the heat pumps. An original design with staged pumping or variable speed pumping would have saved significant energy. Section 5.2 gives a full description of the pumping system, a detailed account of its energy use, and the steps taken to reduce its energy use.

The second area selected to improve the energy performance of the IAMU building is the operation of the defrost heater of the ERV. This energy use was determined during the implementation phase of the building when the thermostat controlling the heater was set. The ERV contains electric heating elements in the inlet of the outside air stream before the enthalpy wheel. The heater is used to prevent the formation of frost in the enthalpy wheel during cold weather. The heater turns on when the temperature of the incoming outside air falls below the thermostat set point. For the typical winter indoor temperature and humidity conditions at the IAMU building, the manufacturer states that frost will not start to form on the enthalpy wheel until the outdoor air temperature drops below 0 ^{o}F. Despite this recommendation, when the ERV was installed, the defrost heater was set to turn on when the outdoor temperature fell below 46 ^{o}F. Failure to properly set the defrost heater set point during the implementation stage resulted in unnecessary energy use by the heater. Section 5.3 describes the defrost heater system in detail, discusses its energy use, and gives the steps taken to reduce the energy use of the heater.

The third area chosen for energy performance improvements is the general equipment energy use. General equipment includes any equipment the occupants plug into electrical outlets—computers, clocks, refrigerators, coffee makers, etc—plus other equipment such as drinking fountains and automatic door openers. General equipment does not include indoor lighting, outdoor lighting, or HVAC equipment. The energy use of equipment is determined in the occupancy phase of a building when the number of occupants, the type and amount of equipment, and occupant behavior is determined. The equipment energy use, including the energy use when the building is unoccupied, makes up a significant portion of the IAMU's total energy use. Section 5.4 describes the equipment energy use during unoccupied hours and methods by which it can be reduced.

5.2. Ground Source Heat Pump Circulating Pump

This section discusses the energy performance of the ground source heat pump (GSHP) system's circulating pump. The pumping scheme was designed to be simple and reliable, but attention was not paid to energy use of the pump. The pump was designed to supply 11.25 gpm to all eight heat pumps all the time, whether or not all the heat pumps are running. It is, in fact, quite rare that all eight heat pumps operate at the same time, and it was found that over half of the time no heat pumps operate. Because flow rate is directly proportional to pump speed, and pump power is proportional to the cube of pump speed, matching the flow rate of the pump to the flow rate required by the running heat pumps would save significant pumping energy. Section 5.2.1 gives an overview of the entire GSHP system, and section 5.2.2 describes the energy performance and energy savings potential of the circulating pump. The addition of a variable frequency drive on the pump motor and shutoff valves on the heat pumps in an effort to reduce the energy use of the system are described in section 5.2.3. Finally, section 5.2.4 discusses the observed energy savings since the installation of the VFD and the predicted annual energy savings.

5.2.1. GSHP System Overview

The GSHP system used to provide heating and cooling at the IAMU building consists of eight four ton heat pump units connected to a ground heat exchanger. A pump circulates a glycol-water heat transfer fluid between the heat pumps and the ground heat exchanger. A schematic of the system is shown in Figure 5.1. According to a chemical analysis of the heat transfer fluid, it consists of 8.6% propylene glycol, 2.8% ethylene glycol, and 88.6% water. The glycols contain inhibitors to prevent corrosion of pipes and system components. It is not typical for a GSHP system to have two types of antifreeze in it, but in this case ethylene glycol was used as the antifreeze in the indoor piping, and propylene glycol was used as the antifreeze in the ground heat exchanger. When the indoor piping and ground heat exchanger were connected, the two heat transfer fluids mixed. The freezing point of the heat transfer fluid is 28 ^{o}F. It is recommended that enough antifreeze be added to the water to depress the freezing point 10 ^{o}F below the lowest temperature experienced in the working fluid (IGSHPA, 1988). Although the heat transfer fluid has reached temperatures as low as 34 °F, there has never been a problem with the heat transfer fluid freezing during the seven and a half years of heat pump operation.

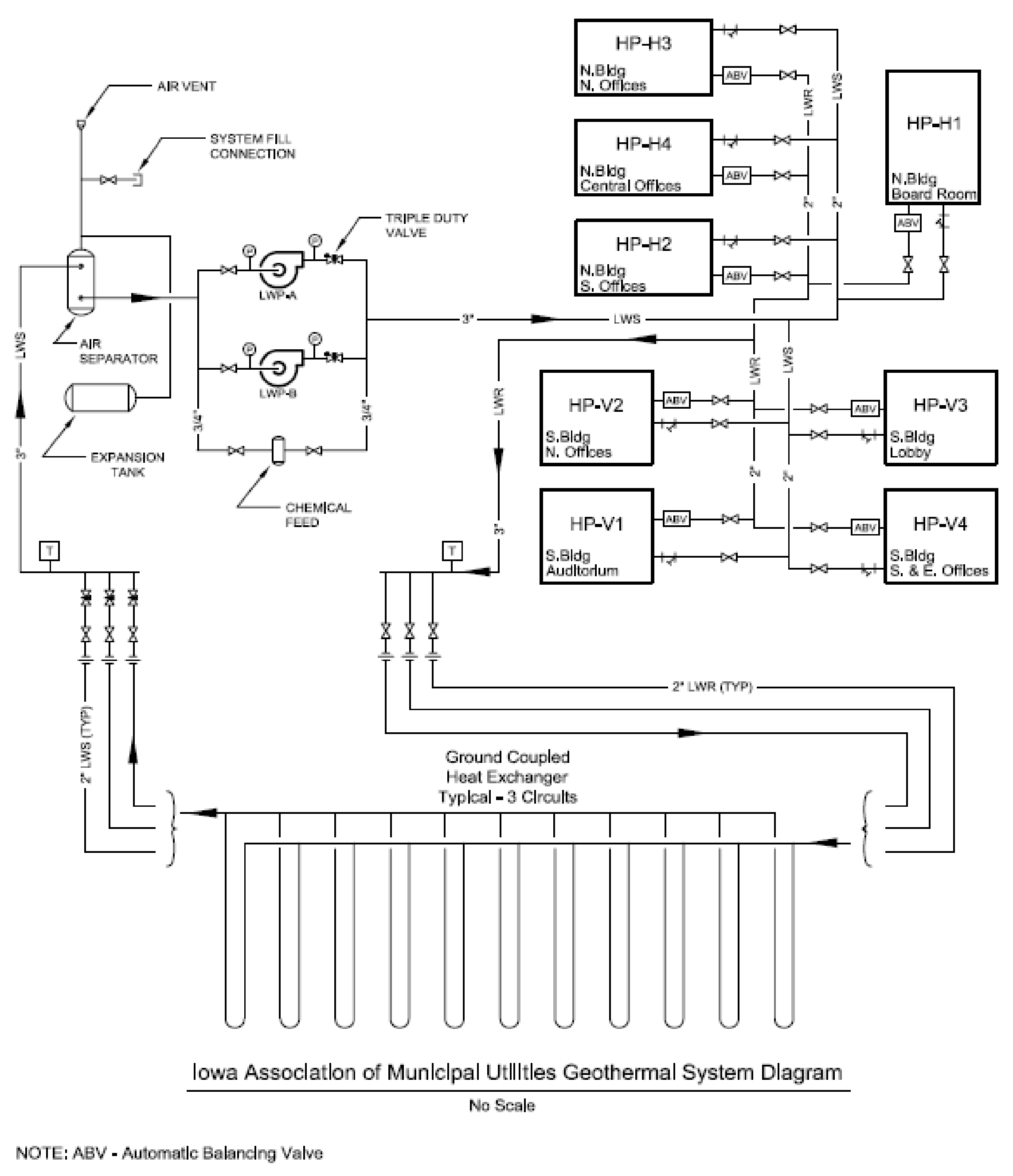


Figure 5.1. Schematic of the ground source heat pump system.

From an energy perspective, it is advantageous to have as little antifreeze in the heat transfer fluid (water) as possible for two reasons. First, the propylene and ethylene glycols decrease the heat capacity of the fluid, and therefore require the circulation of more fluid for a given amount of heat transfer. Second, the glycols increase the viscosity of the water, and thus increase the pumping energy. In addition to saving energy, limiting the amount of antifreeze added to the heat transfer fluid will also save money. For a large commercial GSHP system the antifreeze can add tens of thousands of dollars to the cost.

The ground heat exchanger is a closed system vertical bore exchanger. The exchanger consists of three parallel circuits with eleven 175 ft deep bores, for a total of 33 bores. One of the three circuits can be seen in Figure 5.1. Each bore has a u-tube piping configuration which takes the heat transfer fluid to the bottom of the bore and then back to the top, resulting in 350 ft of pipe per bore. The eleven bores on each circuit are piped in reverse return as shown in the figure. This means that the first bore on the supply header is also the first bore on the return header, and the total length of supply and return piping for each bore on the circuit is the same. Because reverse return results in the piping length of all the bores on a circuit being equal, reverse return is automatically balancing and all the bores on the circuit receive the same flow. Each circuit of the ground heat exchanger has a 2” supply and return header traveling from the building to the bore field. Because each of the three circuits is a different distance from the building, and the pressure drop in each of the circuits’ headers if different, balancing valves are required to provide equal flow to each circuit. Table 5.1 gives the percentage each valve is closed, the measured differential pressure across each valve, and the corresponding flow rate obtained from the performance characteristic curves supplied by the manufacturer. The table shows that the circuits are fairly well balanced—two circuits have flow rates of 28 GPM and the other has a flow rate of 25 GPM. The GSHP system has a total flow rate of 81 GPM. Inside the building, the circuits' individual supply and return headers are combined into single 3" supply and return headers.

Table 5.1. Pressure drop and flow rate through circuit balancing valves.

Valve	% Closed	Delta P (ft water)	Flowrate (GPM)
1	0%	1.2	28
2	18%	3.8	25
3	10%	2.4	28
Total			**81**

The system contains two identical circulation pumps piped in parallel, as can be seen in Figure 5.1. One pump is used as the main pump and the second as a standby pump in case the first pump fails or needs to be serviced. There are no automatic controls for switching between pumps; switching is accomplished by turning on the standby pump and then turning off the main pump. LWP-A has been used as the main pump with LWP-B as the standby pump. There has been no schedule in place to periodically switch operation from one pump to another to provide even wear on each pump. Table 5.2 shows the nameplate information from the two identical motors and pumps. The motors require three phase 200V power, and supply 3 HP at 1760 RPM with a full load efficiency of 89.5%. The original testing and balancing report stated that the pump provided 90 GPM at a total dynamic head of 60.9 ft of water. As was shown in Table 5.1 above, recent differential pressure measurements across the balancing valves on the three ground heat exchanger circuits indicate that only 81 GPM is being circulated through the system. The differential pressure across the pump, measured at the same time, was only 53 ft of water.

Table 5.2. GSHP system circulating pump information.

Motor	Pump
Maraton Electric	Bell & Gossett
Model # : 6VL182TTDR6027DPL	Model # : 2X9.5B 8000 BF
3-Phase, 60 Hz, 200V	90 GPM
3 HP, 1760 RPM	90 ft Head
FLA: 9 A	3 HP
Service Factor: 1.15	1800 RPM
Full Load Efficiency: 89.5	Max W.P.: 175 psi
Full Load Power Factor: 80.0	

A triple duty valve located after each pump acts a check valve, balancing valve, and shutoff valve. In the original configuration each valve was set to 40% open to set the flow in the system. When the pressure drop across the valve was measured, it was found to be only 1.8 ft of water, which is below the minimum of 3 ft of water required to determine the flow rate from the triple duty valve performance characteristics graph. The necessity of the triple duty valve for setting the flow rate in the system is questionable. The low pressure drop across the valve indicates that the flow was too small for the valve to regulate the flow, and that system was receiving nearly the same flow rate as it would have without the balancing valve. Although the triple duty valves' function as balancing valves is questionable, they remain necessary as shutoff and check valves.

Figure 5.1 shows that the eight heat pumps are divided into two groups of four each. The four heat pumps that serve the south wing are located in the south wing's mechanical room, and the four heat pumps that serve the north zone are located above the drop ceiling between the kitchen and the board room in the north wing. All of the heat pumps are WaterFurnace Spectra SX48 4 ton units, but the four in the mechanical room are vertically oriented units and the four above the ceiling are horizontally oriented units. Based on the ARI (Air-Conditioning and Refrigeration Institute) Standard 330 for rating closed loop ground source heat pumps, the heat pumps have a cooling capacity, with 77 ^{o}F entering water temperature, of 51,500 BTU/h and an EER of 13.4. According to the same standard, the heat pumps have a heating capacity, when the entering water temperature is 32 ^{o}F, of 36,000 BTU/h and a COP of 3.1. As can be seen in Figure 5.1, the two groups of four heat pumps are piped in parallel, and within each group the heat pumps are piped in parallel with direct return. Because the heat pumps are piped with direct return, the flow to each heat pump is not automatically balanced. To provide equal flow to each heat pump, automatic balancing valves were installed on the return line of each heat pump.

Figure 5.2 shows the original connection of a heat pump to its supply and return lines. The piping on left side of the figure is the supply, and the piping on the right is the return. On the supply side the water first travels through a manual ball shutoff valve with an integral PT (pressure, temperature) tap and then through a strainer before entering a flexible hose that leads to the heat pump. On the return side, after the water travels through the flexible hose it travels through an automatic balancing valve and then through a manual ball shutoff valve. The automatic balancing valve has two PT taps, so that the pressure drop across the valve can be measured.

Figure 5.2. Heat pump hook up.

The automatic balancing valves are designed to maintain a nominal flow rate of 12 GPM through each heat pump. Because flow through the entire system was only 81 GPM, as shown in Table 5.1, it is likely that each heat pump was only receiving around 10 GPM. The automatic balancing valves have a rubber orifice which changes shape depending on the upstream pressure so that they maintain a constant nominal flow of 12 GPM within a differential pressure range of 2 to 80 psid with an accuracy of ±10%. Figure 5.3 shows the pressure drop across the each of the automatic balancing valves, as well as the pressure drop across the heat pumps and strainers and the drop in the supply and return lines connecting each heat pump to the main supply and return headers. The pressure drops across the automatic balancing valves and the heat pumps were measured, while the pressure drops in the supply and return lines were calculated. Seven of the heat pumps had pressure drops between 7.9 and 12.9 ft of water across their automatic balancing valves and the eighth, HP-H3, had a drop of 0.9 ft of water. Because a differential pressure of 0.9 ft of water is outside the control range of the automatic balancing valve, HP-H3 was likely not receiving adequate flow. The pressure drop across the automatic balancing valve of HP-H3 was very small because the pressure drop across the heat pump and strainer was very large—25 ft of water. Upon removing the strainer, it was found that it was coated in a thick layer of a greasy substance. After cleaning the strainer, the pressure drop across the strainer and heat pump HP-H3 was similar to the other seven heat pumps. As can be seen in the figure, the combination of the three pressure losses for all the heat pumps are approximately the same, as they must be for a parallel system. It can also be seen that the automatic balancing valves contribute a fairly significant pressure drop; they contribute from 24% to 40% of the total pressure drop, excluding HP-H3.

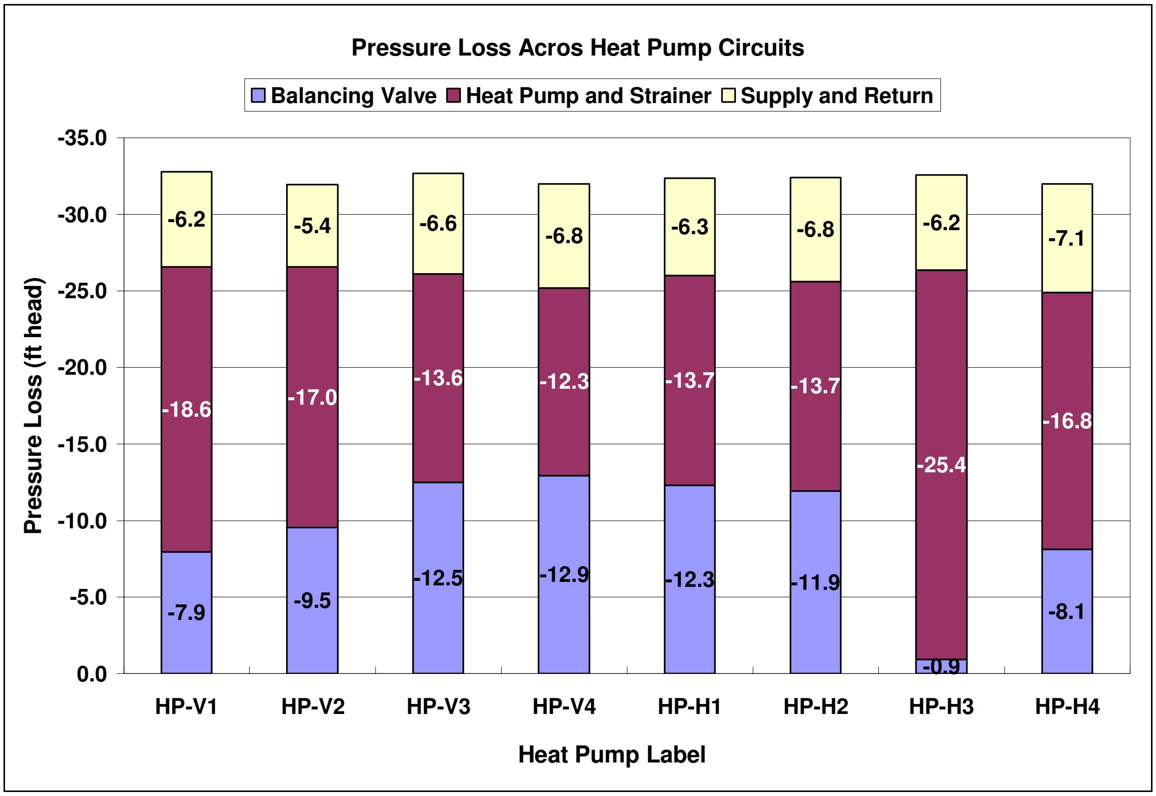


Figure 5.3. Pressure losses across heat pumps before addition of VFD.

The heat pumps are controlled by eight programmable thermostats specifically designed for heat pumps in the eight thermal zones serviced by the heat pumps. The programmable thermostats allow the user to set four different set point for each day of the week; the heating and cooling set points are set separately. Therefore the thermostats allow the user to set up to 56 individual set points (4*7*2). A inventory of the thermostat set points was conducted on June 15, 2007, and the set points are shown in the tables of Appendix C. The four daily set points occur at 6:00 am, 8:00 am, 6:00 pm, and 10:00 pm. The thermostats are programmed to go into setback from 6:00 pm to 6:00 am on weekdays and all day on weekends. At 6:00 am on weekdays the thermostats bring the building partially out of setback, and at 8:00 am bring the building to the temperature it stays at until 6:00 pm. In the heating mode the thermostats maintain the building between 69 and 75 ^{o}F depending on the thermostat and day of week. During the cooling season the building is maintained between 70 and 76 ^{o}F. The heating setback is 65 ^{o}F and the cooling setback is 78 ^{o}F for all thermostats in the building. When recovering from setback mode, the thermostats anticipate the upcoming set point change, and start the heat pumps in advance of the change so that the new set point is reached at the scheduled time. For example, if a thermostat is in heating setback at 65 ^{o}F overnight and is scheduled to increase the temperature to 70 ^{o}F at 6:00 am, it will turn on the heat pumps several hours in advance so that the room temperature is 70 ^{o}F at 6:00 am. The thermostats use a PID loop to determine how well they recovered from setback for the past several days to determine the time they should start the recovery process for the current day. The heat pumps do not have any auxiliary heating elements, and the thermostats rely solely on the heat pumps to bring the building out of setback. The thermostats must be switched manually from heating to cooling mode; this activates a valve that reverses the flow through the heat pumps and allows them to reject heat to the ground heat exchanger rather than extracting heat from it. The thermostats allow the heat pumps' fans to be set to 'auto' or 'on'. The auto setting turns the fan on only when a heat pump's compressor is running, and the on setting keeps the fan on all time even if the compressor is not running. The fans for the heat pumps serving the auditorium and conference room are set to 'on' to maintain proper ventilation, but the fans for all the other heat pumps are set to auto.

5.2.2. GSHP Circulating Pump Operation and Energy Performance

The GSHP circulating pump is only a 3 HP pump, but because it operates continuously, it contributes to a significant proportion of the total building energy use. Using a Fluke 41B power harmonics meter the power consumption of the pump was measured to be 2080 W. At this rate, for continuous operation, the pump will use 18,200 kWh of energy per year and have an annual energy cost of nearly $1200. Table 5.3 compares the monthly energy use of the circulating pump to the monthly average energy use of the entire HVAC system and the monthly average energy use of the entire building. Because the pump has a constant rate of energy use, the monthly pumping energy only varies with the number of days in the month. As was shown in section 4.4, the HVAC energy use is greatest during the winter months of January and December, and second greatest during the summer months of June, July, and August. The HVAC energy use is minimum in May and September when the outdoor air temperature is moderate and relatively little heating or cooling is needed. The monthly variation in HVAC energy use is reflected in the contribution of the circulating pump to the monthly HVAC energy use. In the table it can be seen that in January and December, when a large amount of heating is required, that the circulation pump makes up 22% of the HVAC energy use. In the temperate month of May the circulating pump makes up 59% of the HVAC energy use. These large percentages of monthly HVAV energy use are in contrast to the relatively small contribution the pump makes to the total connected power of the GSHP system. When the circulating pump and all the heat pumps are running, the total HVAC demand is 26 kW, with the circulating pump contributing 2.1 kW or 8%. Although, the circulating makes up only 8% of the peak demand from the GSHP system, it contributes 35% of the annual HVAC energy use (includes GSHP system and ERV).

Table 5.3. Comparison of circulating pump energy to HVAC energy and total office energy.

Month	Pump Energy (kWh)	HVAC Energy (kWh)	% HVAC Energy	Building Energy (kWh)	% Office Energy
Jan	1,550	7,050	22%	13,200	12%
Feb	1,400	6,120	23%	11,700	12%
Mar	1,550	4,110	38%	9,000	17%
Apr	1,500	2,690	56%	7,100	21%
May	1,550	2,610	59%	6,650	23%
Jun	1,500	3,570	42%	7,280	21%
Jul	1,550	3,720	42%	7,210	21%
Aug	1,550	3,530	44%	7,290	21%
Sep	1,500	2,660	56%	6,670	22%
Oct	1,550	3,340	46%	7,910	20%
Nov	1,500	5,230	29%	10,300	15%
Dec	1,550	6,910	22%	13,000	12%
Annual	**18,200**	**51,500**	**35%**	**107,000**	**17%**

The monthly variation in the HVAC energy use, as well as variations in general equipment and lighting energy use, which both peak in the winter and have minima in the summer, cause the total building energy use to peak in the winter, have local minima in May and September and a local maximum in the summer months. During the winter months of December, January, and February, the circulating pump contributes 12% of the building's total energy use. In May, the pump contributes 23% of the building's total energy use. For an average year, the pump uses 17% of the energy used by the entire building.

Figure 5.4 and Figure 5.5 demonstrate the relation between the GSHP system power demand and the circulating pump power demand. In both figures the blue line represents the measured demand of the GSHP system, which includes the eight heat pumps and the circulating pump. It was found by subtracting the demand of the ERV from the total HVAC demand monitored by a power meter. The red line represents the constant 2.1 kW demand of the circulating pump. Figure 5.4 shows the GSHP system and circulating pump power demands for Sunday, October 1, 2006 when the outdoor temperature varied from a low of 53 ^{o}F to a high of 86 ^{o}F. It can be seen that for most of the day there were no heat pumps running. The energy use of each heat pump is about 3 kW, and it can be seen when a heat pump turned on and off. Because the day was a weekend, all the thermostats in the building were setback to 78 ^{o}F and internal loads were negligible. Therefore there was very little cooling load during the day, and the maximum number of heat pumps on at the same time was two. For much of the day no heat pumps were on, but the circulating pump was still consuming 2.1 kW. When a heat pump is not on it is unnecessary to circulate heat transfer fluid to it. Therefore the circulating pump could have been off for most of the day, and only run at partial speed when the one or two heat pumps were on.

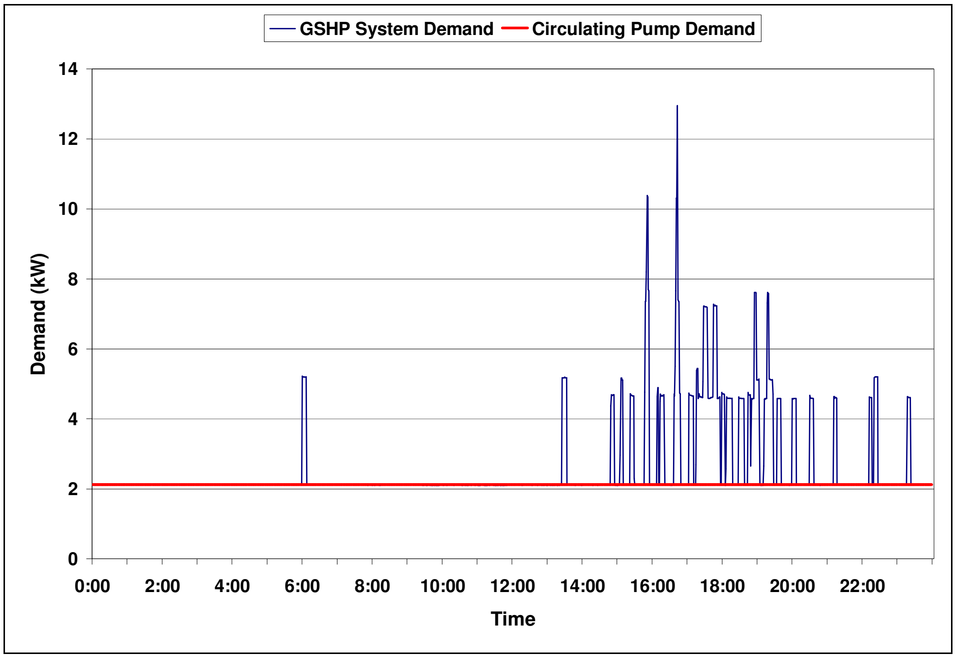


Figure 5.4 GSHP system demand and circulating pump demand for Sunday, October 1, 2006. The outside air temperature varies between 53 and 86 °F.

Figure 5.5 shows the demand of the GSHP system and circulating pump on Thursday, February 15, 2007 when the outdoor temperature varied between -8 and 7 °F. Throughout the morning, 5 to 7 heat pumps ran as the system recovered from night setback and then worked to maintain the building temperature under design outdoor air temperatures. In the afternoon, as the outdoor temperature warmed up a little, and solar and internal gains assisted in heating the building, the number of heat pumps operating decreased significantly. Then at 6:00 pm when the thermostats went into night setback, all the heat pumps turned off for 2.5 hours. During this time the circulating pump continued to operate. Even on this day when the outdoor air temperature reached design conditions, all eight heat pumps did not run continuously, and there was a 2.5 hour period when no heat pumps ran.

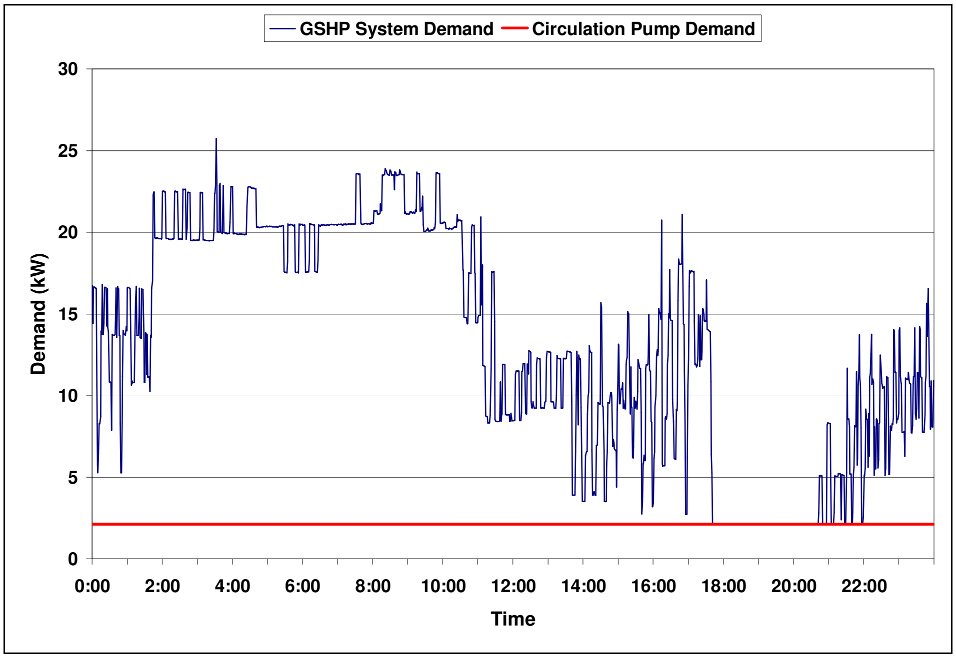


Figure 5.5 GSHP system demand and circulating pump demand for Thursday, February 15, 2007. The outside air temperature varies between -8 and 7 ^{o}F.

Table 5.3, showed that the circulating pump is using an excessive amount of energy, with it using 35% of the total annual HVAC energy and 17% of the total building's annual energy. Figure 5.4 and Figure 5.5 showed that there is a significant amount of time, even on very cold or hot days, when energy could be saved by matching the flow of heat transfer fluid provided by the circulating pump to the amount of flow required by the heat pumps. This could be accomplished by slowing the speed of the circulating pump when fewer than eight heat pumps are operating and turning the circulating pump off with no heat pumps are operating. To evaluate the potential savings from controlling the pump to supply only enough heat transfer fluid to the heat pumps running, it is necessary to determine the amount of time zero, one, two, three, four, five, six, seven, and eight heat pumps run at the same time. Heat pump operation depends largely on four different variables: outdoor temperature, thermostat set points, the time of day, and the day of the week. The outdoor temperature affects the number of heat pumps operating by directly influencing the heating or cooling load of the building. Starting from a balance point temperature, the outdoor temperature where neither heating or cooling is required, increasing outdoor temperature increases the cooling load, and decreasing the outdoor temperature increases the heating load. The thermostat set points will also influence the heating or cooling load: lower set points during the heating season will decrease the heating load and higher set points during the cooling season will decrease the cooling load. The time of day will affect the heating and cooling load in several ways. First, the thermostats can be set for four different temperatures for each day; the tables in Appendix C show the thermostat set points at the IAMU. During the day the building is typically heated to between 69 and 75 ^{o}F and is typically cooled to between 70 and 76 ^{o}F. The cooling setback temperature is 78 ^{o}F and the heating setback temperature is 65 ^{o}F. At 6:00 am the thermostats bring the building partially out of setback. Then at 8:00 am the thermostats switch to their setting for the rest of the day. At 6:00 pm the thermostats go back into setback, and at 10:00 pm they stay at the setback setting. The time of day also determines the solar and internal heat gains of the building. In the morning the majority of the solar gain is limited to the east side of the building. It then shifts to the south side of the building during mid morning, and finally to the west side of the building in the late afternoon and evening. The internal heat gains from equipment and occupancy are relatively constant through the morning and afternoon, but dip during lunchtime. The heat gain form the lights is also fairly constant throughout the day, but may be higher at the beginning and end of the day when there is less daylight available and greater output from the dimmable lights is required. The building heating and cooling loads are dependent on the day of the week because the thermostats stay in setback all day on Saturday and Sunday and there are essentially no internal heat gain on these days.

It was decided to evaluate the number of heat pumps operating as a function of outdoor air temperature and time of day separately for weekdays and the weekend. This was done by analyzing the HVAC demand data and outside air temperature to determine the average number of heat pumps running in time-temperature bins of 5 °F and one hour. While the number of heat pumps running is a function of thermostat set point, and the employees are free to change the set points, it was determined unnecessary to account for user changes in thermostat set points. It is not possible to account for changes in operation of the heat pumps due to changing set points because employees are free to adjust the set points and no record is kept of these changes. An inventory of the thermostat set points conducted on 6/15/2007 revealed that the cooling set point during weekdays varied from 70 to 76 °F and the heating set point during weekdays varied from 70 to 74 °F. The cooling setback for all the thermostats was 78 °F and the heating setback was 68 °F. It is assumed that over the previous six years of operation the thermostat set points had been within these ranges.

A MATLAB code was written to determine the average number of heat pumps running in 5 °F, one hour temperature-time bins. The code is contained in Appendix D. The program starts with the minute-by-minute data of total HVAC power demand to determine the number of heat pumps running during a specific minute. The HVAC demand contains contributions from the eight heat pumps, the circulating pump, and the ERV. The demand of the circulating pump is constant and can be directly subtracted from the HVAC demand. The demand of the ERV is variable and the program uses ERV amperage data point, and the auditorium occupancy data point (which determines if the ERV is operating at low or high speed) to determine the demand of the ERV. This is then subtracted from the HVAC demand to leave only the demand of the heat pumps. This is divided by the 3 kW nominal demand of a single heat pump to determine the number of heat pumps running during the current minute. Because data is taken every minute, it is assumed that over the minute the number of heat pumps operating remains constant. Multiplying the number of heat pumps running by one minute gives the unit “heat pump-minutes”. Using outdoor air temperature data, collected at the Iowa Energy Center’s Energy Resource Station, which is only 1.6 miles away from the IAMU office building, the program then determines what 5 °F temperature bin the current minute falls into. The heat pump-minutes are then added to the correct temperature-time bin to keep a running total of the number of heat-pump minutes in each bin over the evaluation period:

$$\text{Heat Pump-Minutes} = \sum(\text{\# of heat pumps on})(1\text{ minute}) \qquad \textbf{Equation 5.1}$$

The program also keeps track of the total number of minutes in each temperature-time bin over the analysis period. When the program reaches the end of the analysis period it divides the number of heat pump-minutes in each temperature-time bin by the total number of minutes in the bin to determine the average number of heat pumps running in the bin:

$$\text{Average \# of heat pumps running} = \frac{\text{Heat pump minutes}}{\text{Minutes in each bin}} \qquad \textbf{Equation 5.2}$$

The results of running the MATLAB code over the period from 8/1/2004 though 6/30/2007 are contained in Appendix E. The appendix contains two sets of three tables each. Table E.1 through Table E.3 are the results for the weekdays, and Table E.4 through Table E.6 are for the weekends. Each table has 24 columns for 24 hours and 22 rows for 22 5 °F temperature bins from -10 to 100 °F. The first table in each set contains the number of minutes that occurred in each bin over the analysis period, and the second table contains the total number of heat pump-minutes. The third table in each set lists the average number of heat pumps running in each temperature-time bin. In these tables a value of NaN indicates that a temperature-time bin never occurred in the analysis period. In contrast, a value of zero means no heat pumps ever operated in the bin, but the bin did occur.

The weekday binned average number of heat pumps operating is displayed as surface graphs in Figure 5.6, Figure 5.7, and Figure 5.8. These figures all display the weekday data, but show it from different angles so that the three-dimensional nature of the graph can be explored. In the graphs, the x-axis is the temperature bins, the y-axis is the hour bins, and z-axis is the average number of heat pumps operating. The data points are represented at the intersection of the gridlines; the spaces between the grid lines are colored for easier interpretation but do not represent the bins. For example, to determine the average number of heat pumps running during the hour ending in 20:00 and in the 65 to 70 ^{o}F temperature bin, follow the line from the tick mark labeled '65 to 70' until it intersects the line coming from the tick mark labeled '20:00'. The height of the grid intersection gives the average number of heat pumps running in the temperature-time bin. The color within the gridlines corresponds to the value of the adjacent data point with the earliest time and lowest temperature bin. These graphs are meant to provide insight into the operation characteristics of the GSHP system, but are not meant for reading off specific values. If specific values of the average number of heat pumps operating in a temperature-time bin are desired, please refer to Table E.3 and Table E.6 in Appendix E.

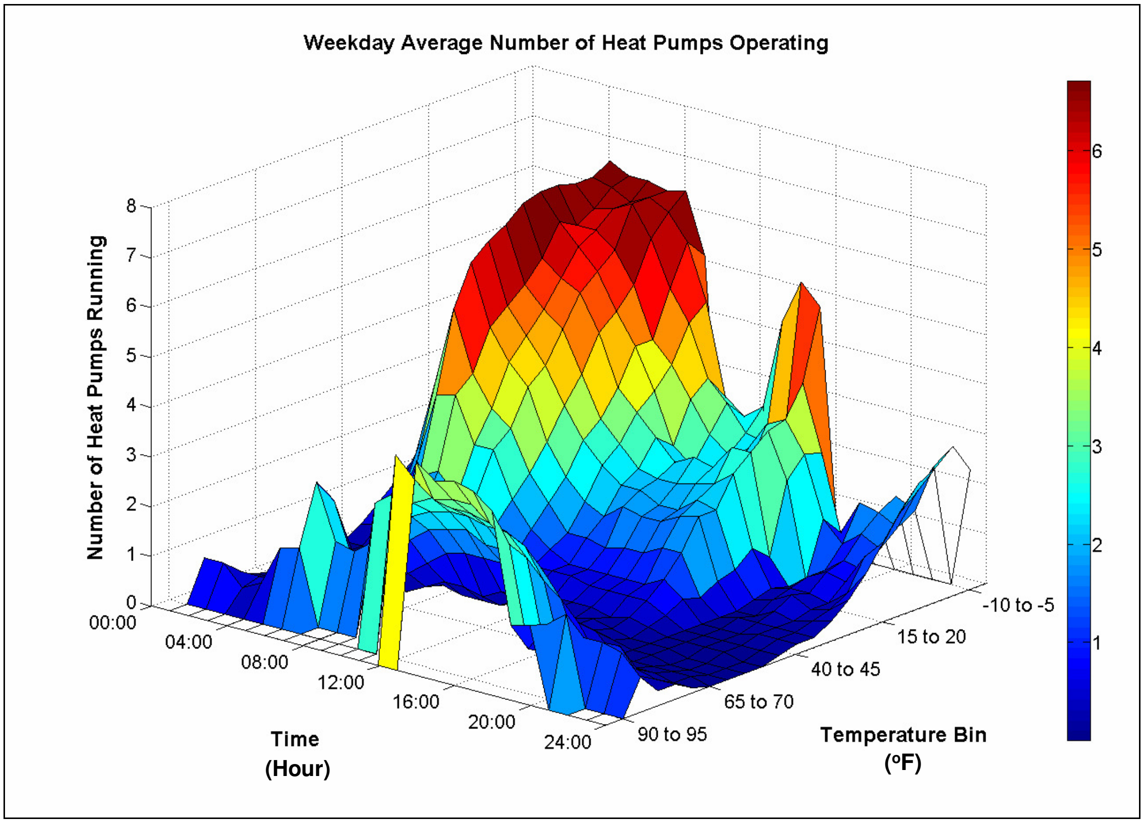


Figure 5.6. Average number of heat pumps running in 1 hour and 5 °F temperature-time bins on weekdays, view one.

Figure 5.6 gives a good general view of the average number of heat pumps running in weekday bins. The graph is shown looking from the ('95 to 100',24:00) bin toward the origin located at ('-10 to -5',00:00). One of the most prominent characteristics of the graph is that it is divided into a section where the heat pumps are heating the building and section where the heat pumps are cooling the building. This can be seen by the two mounds in the graph with a valley between them centered on the '60 to 65 °F' line. This valley will be explored further below. By the relative sizes of the heating mound and the cooling mound, it can be seen that many more heat pumps run during cold weather than in hot weather. During peak heating bins an average of between six and seven heat pumps run, whereas during peak cooling bins an average of about four heat pumps run. Maximum heating is required in the morning when the building is recovering from night setback, the outdoor temperature is the lowest, and there is little to no solar and internal heat gains. By noon in cold weather, the average number of heat pumps operating drops down as the heating load decreases. In the coldest weather, the average number of heat pumps operating spikes again in the late afternoon as the solar heat gain to the building diminishes. After 6:00 pm, when the thermostats go into night setback, the average number of heat pumps running drops drastically. In very cold weather an average of about two heat pumps run after 6:00 pm, but in milder weather the average drops below one for several hours. The cooling load occurs mostly in the afternoon when the solar heat gain to the building is large. In the hottest weather there is a small spike in the number of heat pumps running at around 6:00 am when the building recovers from night setback. As in the heating season, there is a drop-off in the average number of heat pumps running after 6:00 pm when the thermostats go into night setback.

The surface graph of the average number of heat pumps operating during the weekend is similar to the graph for weekdays but with two exceptions. First, during the weekend the thermostats stay in setback mode all day. Therefore the weekend graph does not have the rapid rise in the number of heat pumps operating when the building comes out of setback in the morning, and it does not have the drop-off in the number of heat pumps running in the evening when the building goes back into setback. Second, because the weekend setback temperatures reduce the heating and cooling loads of the building, there are generally fewer heat pumps running in the weekend bins than in the weekday bins.

Figure 5.7 gives a good view of the valley between the heating mode of the heat pumps and the cooling mode of the heat pumps. The valley is centered along the 60 to 65 ^{o}F temperature bin. Along this line the average number of heat pumps running does not exceed 0.5 in any hour, and is zero for several hours around midnight. The 60 to 65 ^{o}F temperature bin represents the thermal balance point of the building—the temperature at which the building needs neither heating nor cooling. The valley is narrowest in the hour ending in 6:00 am when the building recovers from night setback, and is widest in the hours after 6:00 pm when the building goes back into night setback. For all but the coldest and hottest temperature bins, essentially all of the heat pumps turn off for several hours after the building goes into night setback. From the size of this valley it is likely that there is a significant amount of time when only one or no heat pumps are running.

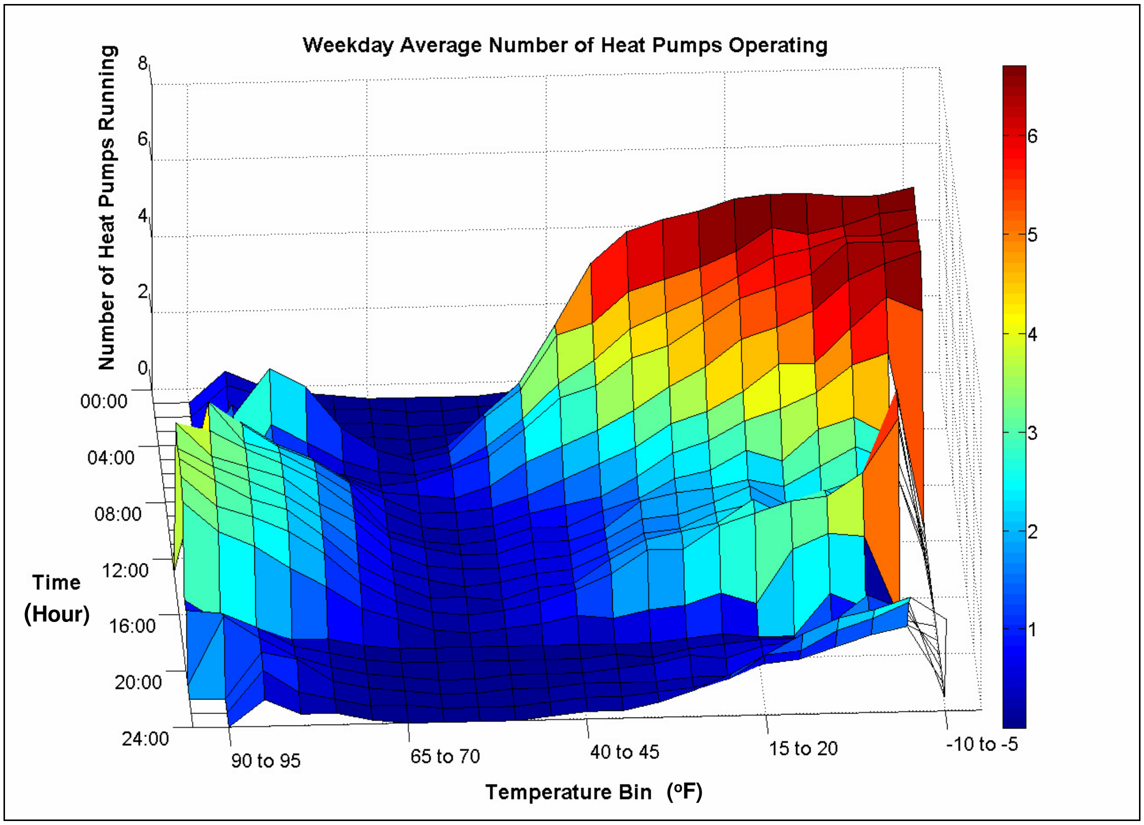


Figure 5.7. Average number of heat pumps running in 1 hour and 5 °F temperature-time bins on weekdays, view two.

Figure 5.8 gives a good portrayal of the large mound in the average number of heat pumps operating during the morning hours under heating conditions. The mound starts to grow in the hours before midnight as the building cools below the setback heating set point. The mound continues to grow until a maximum is reached in the hour ending in 5:00 am as the heat pumps bring the building out of night setback. This maximum occurs in all heating temperature bins and can be seen in the figure as the ridge that runs along the 5:00 line. The adaptive control used by the thermostats to gradually bring the building out of setback by the 6:00 am end of setback causes the heat pumps to start raising the temperature of the building as early as 1:00 am during the coldest weather. Between 5:00 and 6:00 am the heat pumps begin to reach the 6:00 am set points, and the average number of heat pumps during this hour decreases slightly from the hour ending in 5:00 am.

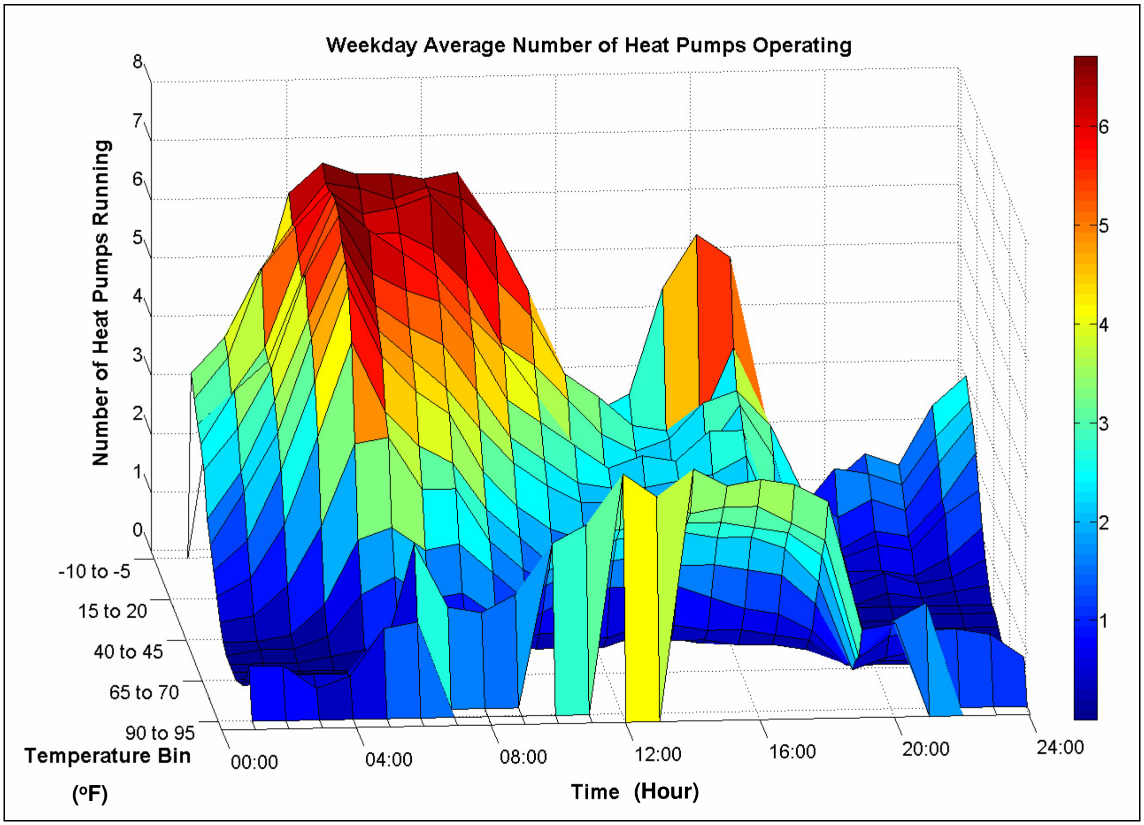


Figure 5.8. Average number of heat pumps running in 1 hour and 5 °F temperature-time bins on weekdays, view three.

Figure 5.6 shows that there are many temperature-time bins when the average number of heat pumps operating is small, but it does not tell how many hours occur in each bin annually. To evaluate the energy saving potential of a new circulating pump control scheme it is necessary to know the annual amount of time eight, seven, six, etc.

heat pumps operate. This was accomplished by modifying the MATLAB program in Appendix D to count the number of minutes that eight, seven, six, etc. heat pumps operated. The results of running the program for the three year period from 8/1/2004 to 7/31/2007 are shown in Figure 5.9. The results are divided into weekday hours and weekend hours. On the weekends there was negligible time when more than five heat pumps were running. For over half of the analysis period no heat pumps ran, and for a full 94% of the time four or fewer heat pumps ran. All eight heat pumps ran at the same time for only 36 hours or 0.2% of the analysis period. This graph gives compelling evidence that a new control strategy for the circulating pump would save significant energy. For 54% of the analysis period the circulating pump could have been turned off, and for much of the rest of the time the pump could have operated at a reduced speed.

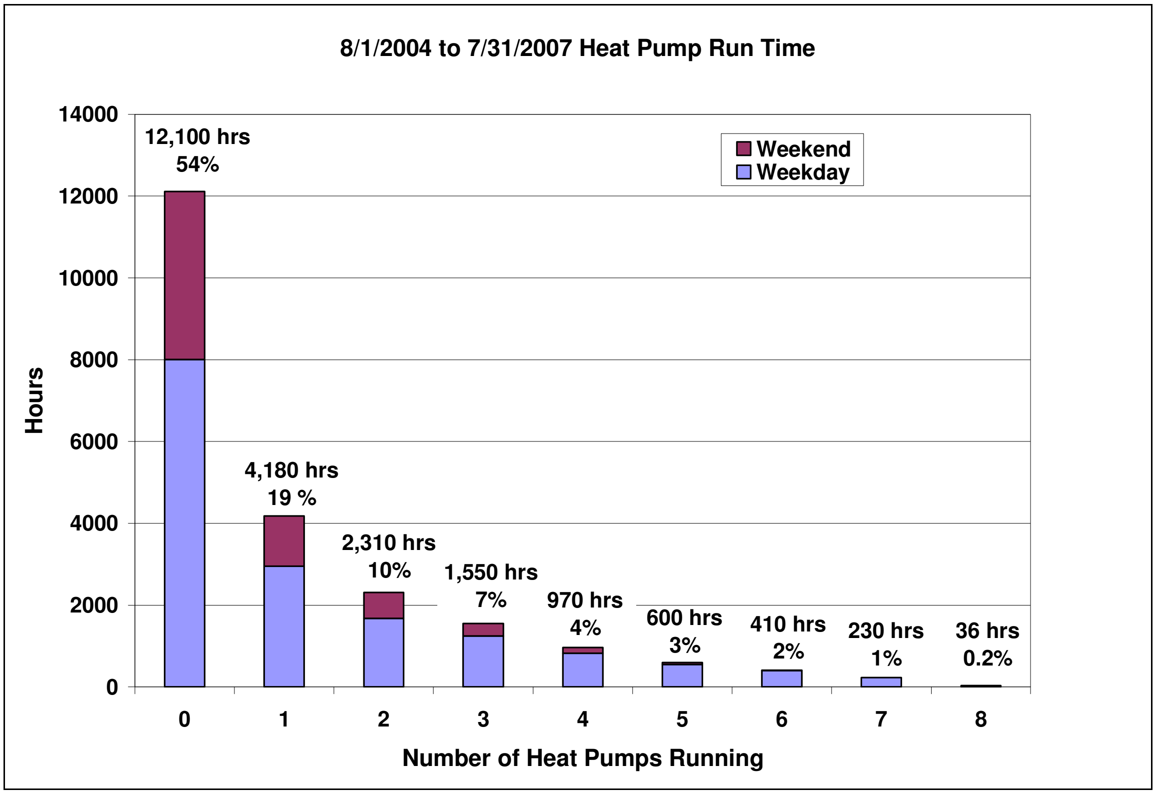


Figure 5.9. Hours of concurrent heat pump operation between 8/1/2004 and 7/31/2007.

5.2.3. GSHP Circulating Pump System Changes

To reduce the energy consumption of the circulating pump it was decided to match the flow it provided to the flow required by the operating heat pumps. This was accomplished by installing an electronic ball shutoff valve on seven of the heat pumps and connecting the pump motor to a variable frequency drive (VFD). When a heat pump turns off, its shutoff valve will close and the VFD will slow down to maintain constant flow rates through the rest of the operating heat pumps. Because flow rate is directly proportional to pump speed, and pump power is proportional to the cube of pump speed, even a small decrease in flow rate can result in significant energy savings. Because eight heat pumps operate for only 0.2% of the time, the VFD will be able to operate at less than 100% speed for nearly 8750 hours a year, and thus save pumping energy.

The installation of the VFD was a relatively straight forward process and did not require major changes to the GSHP piping configuration. Figure 5.10 contains a schematic of the updated GSHP piping configuration. Below is an outline of the changes made to the system:

1. **Installation of the VFD.** The existing motor starter and disconnect switch on the main pump were removed and replaced with an integral VFD and disconnect switch. The existing line side and load side wiring was used. The wiring of the backup pump was not altered, and it will still operate as it has in the past—the backup pump is not controlled by the VFD.
2. **Installation of a Differential Pressure Sensor.** The VFD is controlled by maintaining a constant signal from a differential pressure sensor using a PID control loop. The differential pressure sensor was installed to measure the differential pressure across the supply and return lines of HP-V1.

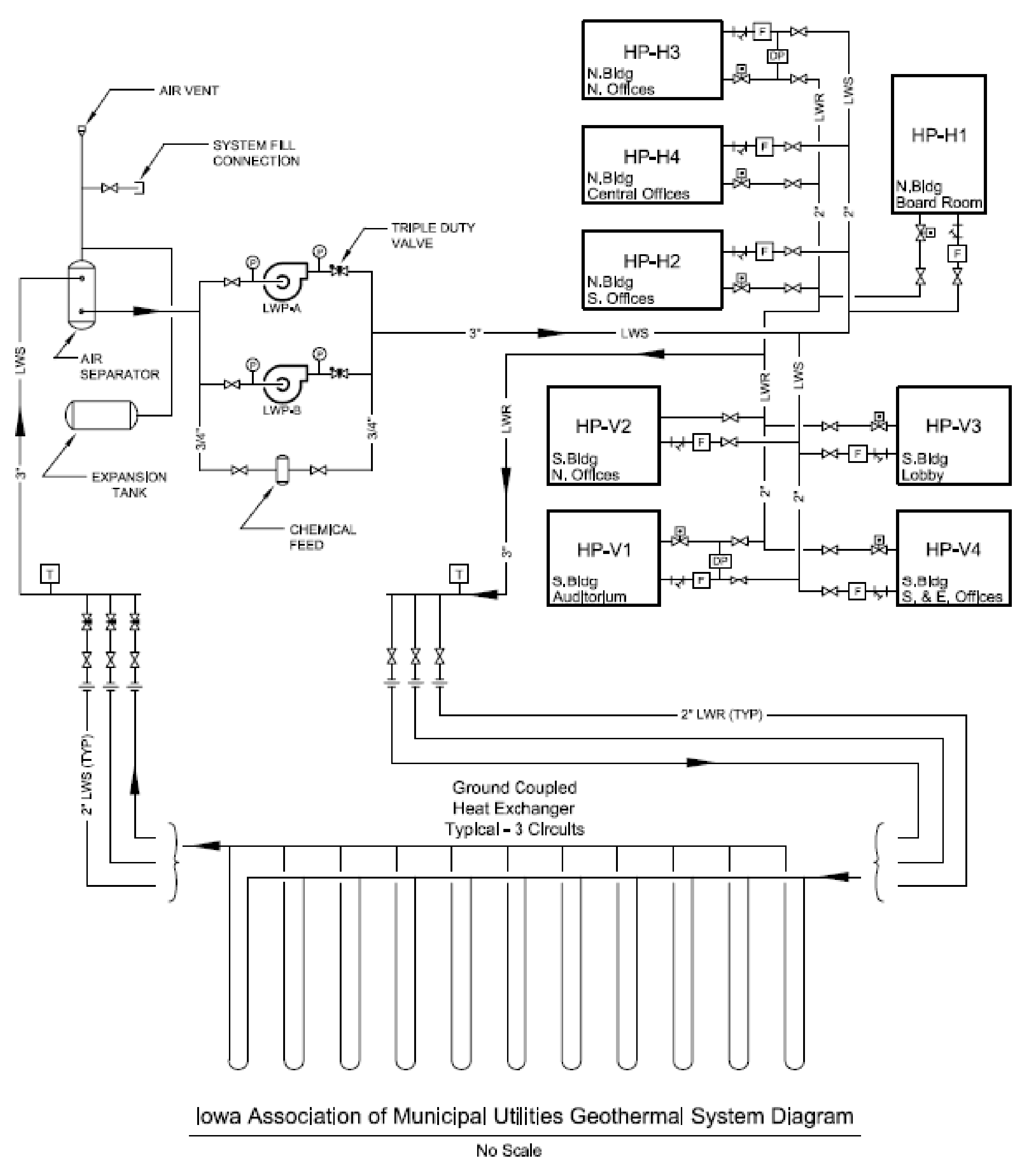


Figure 5.10. Schematic of GSHP system retrofitted for addition of VFD to control pump speed. Note addition of electronic shutoff valves, flow meters, and differential pressure sensors, as well as removal of automatic balancing valves.

3. **Installation of Electronic Ball Valves.** An electronic ball valve was installed in the return line of seven of the heat pumps to shut off flow to the heat pumps when they are not running. The eighth heat pump, HP-V2, does not have a

shutoff valve and acts as a bypass. Currently there is no way to turn the pump off, so one heat pump is required as a bypass to prevent the pump from deadheading.

4. **Installation of Ultrasonic Flow Measurement Stations.** To allow easy and accurate measurements of the flow through each heat pump, ultrasonic flow measurement stations were installed in the supply line of each heat pump.
5. **Removal of Automatic Balancing Valves.** To reduce the pressure drop in the system, the automatic balancing valves installed on each heat pump was removed.

All of the plumbing changes to the system were made below the manual shutoff valves on the supply and return lines of the heat pumps. This allowed each heat pump to be worked on one at a time, while the other seven remained operational. The new configuration of the supply and return line connections are shown in Figure 5.11. The supply line is in the left side of the figure, and the return line is in the right side of the figure. At the top of the supply line is the old shut-off ball valve with a PT tap. Below this is 6” of straight pipe required before the new ultrasonic flow meter station, the silver object with red caps. Below the flow station is the old strainer and flexible hose that connects to the inlet of the heat pump. On the return side, after leaving the heat pump, the water first passes through the old flexible hose, then through the new electronic ball valve, past a new PT tap, and finally through the old manual shutoff ball valve.

Figure 5.11. New heat pump connection piping configuration.

The flow station is used in connection with the Balance Master Hydronic Flowmeter owned by the Energy Resource Station. The flow station is merely a full ported pipe, with two sensor ports (the parts covered in red caps) that position the sensor probes of the portable ultrasonic flow meter. Air, which would interfere with flow measurements, is vented from the flow station by means of a Schrader valve located on the upper sensor port. This flow measurement system is advantageous for several reasons. First, unlike most flow measurement devices, there is no pressure drop in the flow station beyond the regular pressure drop in a piece of pipe. Second the sensor probes never enter the flow stream. The sensor ports correctly position the sensors for measurements, and thermoplastic windows at the ends of the ports transmit the ultrasonic signal from the sensors to the fluid. Finally, the system is relatively inexpensive as only one ultrasonic flow meter is required to take measurements at multiple flow stations.

When making plumbing changes to the system, attention was paid to minimizing the pressure drop in the system. One of the major pressure drops experienced in the system before the changes was the automatic balancing valves installed on each of the eight heat pumps. These valves were installed to ensure that each heat pump received the same flow rate, but accomplished this by introducing a significant pressure drop in the system. As was discussed in section 5.2.1, the pressure drop across the automatic balancing valves ranged from 50% to 100% of the pressure drop across the heat pumps. The heat pumps are piped in a parallel close-coupled system, and there is only a few feet of pipe between heat pumps. This small length of pipe only introduces a small additional pressure drop for each heat pump successively farther away from the circulating pump. The difference between the heat pump with the largest calculated supply-return line pressure drop and the heat pump with the lowest drop is only 1.7 ft of water. Therefore it was decided that the automatic balancing valves were unnecessary and were removed.

Figure 5.12 shows the flow rates in the eight heat pumps after the plumbing changes in their supply and return lines were made. The measurements were taken using the ultrasonic flow meter when full flow was being provided to all the heat pumps with the VFD running the pump at 98% of full speed. A speed of 98% was chosen to maintain a flow rate of at least 9 GPM through all heat pumps when they are all operating. The four vertical heat pumps received flows between 9.9 and 10.4 GPM, while the four horizontal heat pumps received lower flows between 9.1 and 9.4 GPM. The horizontal heat pumps receive less flow because they are farther away from the circulating pump than the vertical heat pumps and have a larger pressure drop in their supply and return lines. Among the vertical heat pumps’ flow rates there is a variation of only 0.5 GPM, and among the horizontal heat pumps there is a variation of only 0.3 GPM. The difference in flow rate between the heat pump with the highest flow and the heat pump with the lowest flow is only 1.3 GPM, so the system has remained relatively balanced without the automatic balancing valves. Heat pumps are very forgiving in the amount of flow they receive and can tolerate wide swings in flow rates. The manual for the heat pumps gives performance data for flow rates varying from 6 to 12 GPM; therefore all the heat pumps are receiving adequate flow.

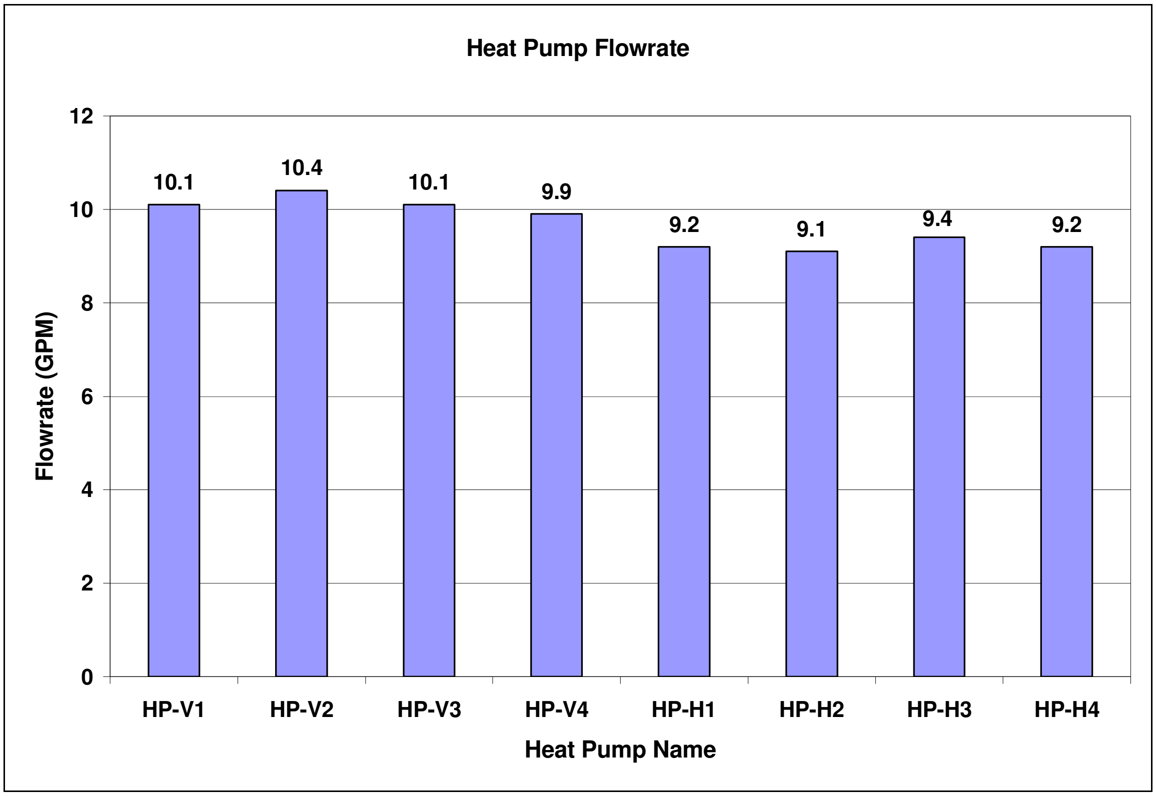


Figure 5.12. Flow rates in the heat pumps when all the heat pumps' valves are open.

The valve used to shut off flow to the heat pumps when they are not operating is a Taco E100CT2-1 electronic ball valve. The valve was chosen for its low pressure drop characteristics, fast closing and opening times, economical price, and because it has an end switch. Because minimizing the pressure drop in the system was important, it was desired to find a valve with a high C_v. C_v is the valve loss coefficient, and is the flow rate in GPM through the valve that causes a 1 psi pressure drop. The pressure loss in psi across a valve is related to flow rate (Q) in GPM and C_v by:

$$\Delta P = \left(\frac{Q}{C_v}\right)^2$$ **Equation 5.3**

Figure 5.13 shows the pressure drop through a valve versus the C_v of the valve for a flow rate of 9 GPM, the desired nominal flow rate through the heat pumps. The pressure drop decreases as a function of C_v^{-2}. The Taco valve has a C_v of 8.9, which corresponds to a pressure drop of 2.3 ft of water at a flow rate of 9 GPM. While small improvements could be made in the pressure drop performance of the valve by choosing a valve with a higher C_v, the cost of valves increases rapidly with higher C_v and it did not make sense to spend hundreds of dollars more per valve for only a small reduction in pressure drop.

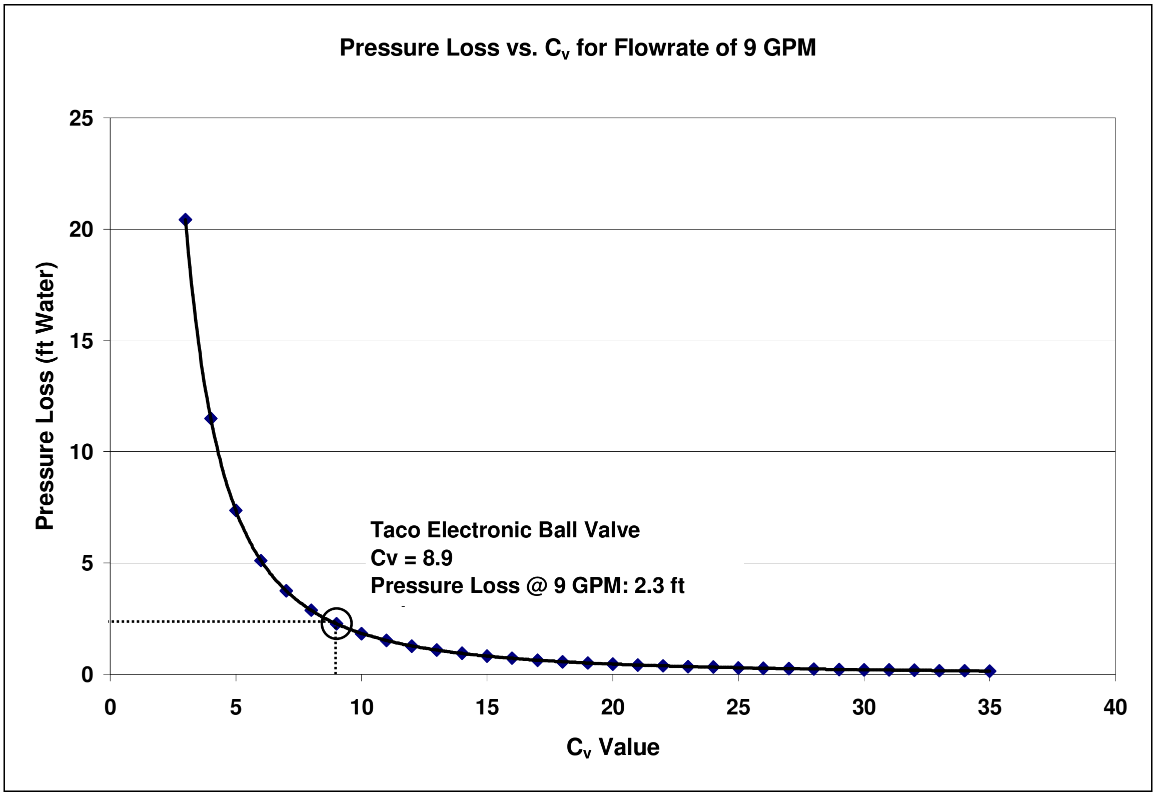


Figure 5.13. Pressure drop vs. valve C_v for a flow rate of 9 GPM.

Figure 5.14 shows the wiring diagram of the electronic ball valve actuator. The valve contains two sets of terminals—a set that powers the valve motor and a set that connects to an end switch. The valve is normally closed and the end switch is open when the thermostat is not calling for heat pump operation. When heat pump operation is required, the thermostat sends 24 VAC power to the valve actuator motor. The motor opens the valve and flow is established through the heat pump. Once the valve has opened fully, the end switch closes and provides a 24 VAC signal to the heat pump which starts the compressor. When the thermostat's set point is met, it stops sending the 24 VAC power to the valve. The end switch then opens and the compressor stops running. Finally, the valve closes and flow to the heat pump is stopped. The opening and closing of the valve takes approximately four seconds.

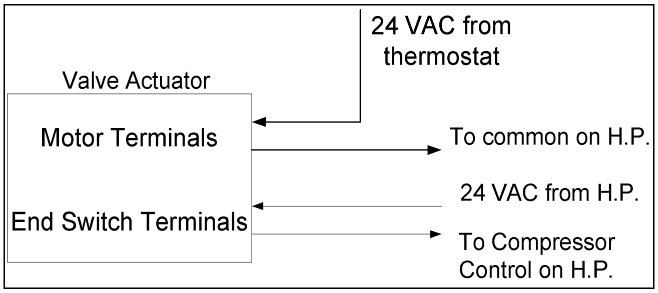


Figure 5.14. Shut off valve wiring diagram.

The installed VFD is an ABB ACH550-UH, 3 HP drive. The VFD is used in conjunction with the electronic shutoff valves on the heat pumps to match the flow provided by the pump to the flow required by the operating heat pumps. Control of the VFD is facilitated by a differential pressure sensor located across the supply and return lines of the HP-V1 heat pump as shown in Figure 5.10 on page 94. As shutoff valves in the system open and close, the differential pressure across the sensor changes and the output signal from the sensor changes. The VFD, with the assistance of an internal PID control loop, adjusts the speed of the pump to maintain a constant output signal from the differential pressure sensor. Because this control sequence merely maintains a constant differential pressure across the supply and return lines of HP-V1, it cannot recognize when all the heat pumps turn off, and hence cannot turn the pump off when all the heat pumps turn off. Therefore, to prevent the pump from deadheading and being damaged, HP-V2 does not have a shutoff valve and acts as a permanent bypass. Even if all the heat pumps are off, 9 GPM of flow will be maintained through HP-V2.

It was desired to control the speed of the VFD to maintain a nominal flow rate of 9 GPM through all the operating heat pumps. Nine GPM is in the middle of the recommended flow rates for the heat pumps, and would provide a safety buffer if a heat pump received slightly more or less flow. Therefore, it was necessary to determine the differential pressure and corresponding output from the differential pressure sensor on HP-V1 that would be used as the control point. Because it would take a prohibitively long time to test the flow rate of all the heat pumps under all flow conditions, it was determined that the flow at the critical heat pump would be monitored to determine the control point of the VFD. The critical heat pump is the heat pump with the largest piping pressure loss, and thus should be the heat pump with the lowest flow in all situations. As was shown in Figure 5.3, HP-H4 has the largest piping pressure loss. The operation of the VFD would be deemed successful if a flow rate of at least 8 GPM was maintained through HP-H4 at all times. The ultrasonic flow meter was used to measure the flow rate through HP-H4 as valves on different heat pumps were closed, and the speed of the VFD was adjusted to maintain at least 8 GPM through HP-H4. At the same time, a portable differential pressure measurement instrument was used to measure the corresponding differential pressure across HP-V1. The worst case differential pressure, or the highest differential pressure that just barely maintained 8 GPM through HP-H4 was chosen as the set point for the VFD. The highest differential pressure across HP-V1 that just maintained 8 GPM through HP-H4 was 8.0 psid. Since the differential pressure transducer has a range of 0 to 25 psid and an output range of 4 to 20 mA, 8.0 psid corresponds to a VFD control point of 9.1 mA.

After the control point of the VFD was set, two final checks were made to determine if the pump provided adequate flow to HP-H4 at all times. The checks consisted of first closing all seven shutoff valves and measuring the flow rate through the bypass heat pump—HP-V2. Then in the first check, the valve on HP-H4 was opened and the flow rate through the heat pump was measured. The flow rate through HP-H4 was then measured as the shutoff valves on the other heat pumps were opened one at a time. The valve on HP-V1, the heat pump with the control differential pressure sensor, was opened last. The position of the valve on HP-V1 affects the measured differential pressure and hence the speed of the pump. If the valve on HP-V1 is closed, the differential pressure is larger than if the valve is open, and the VFD runs the pump at a lower speed maintain the control point. This results in all of the heat pumps receiving lower flow rates when the valve on HP-V1 is closed. In the second test the flow rate through the bypass heat pump, HP-V2, was measured with all the valves closed and then with the valve on HP-V1 open. Then the valve on HP-H4 was opened and the flow rate was measured there as the rest of the shut off valves were opened.

Table 5.4 shows the results of the tests. It can be seen that in both tests, the flow rate through HP-V2 was 9.8 GPM when all the shutoff valves were closed. In the first test the flow rate through HP-H4 was maintained between 9.1 and 8.1 GPM for an average flow of 8.7 GPM over the seven test steps. In the second test, with the valve on HP-V1 open, the flow rate through HP-H4 was between 8.8 and 9.6 GPM and had an average of 9.2 GPM. In both tests, the flow through HP-H4 stayed above the minimal acceptable rate of 8 GPM. In the first test, when the valve on HP-V1 was opened last, the average flow rate through HP-H4 of 8.7 GPM was just below the desired nominal flow of 9 GPM. In the second test, when the valve on HP-V1 was opened first, the average flow rate through HP-H4 of 9.2 GPM was just above the desired nominal flow of 9 GPM. The VFD is providing adequate flow to HP-H4, and because HP-H4 is the critical heat pump all other heat pumps should be receiving adequate flow as well.

Table 5.4. Flow rates and VFD speed as heat pump valves are opened.

Flow rate Location	Flowrate (GPM)	VFD Speed (%)	Open Valves
Open valve on HP-V1 last			
HP-V2	9.8	56.7	V-2
HP-H4	9	59.7	V-2; H-4
HP-H4	9.1	63.3	V-2,3; H-4
HP-H4	8.6	67.5	V-2,3; H-1,4
HP-H4	8.9	74.2	V-2,3,4; H-1,4
HP-H4	8.6	79.8	V-2,3,4; H-1,2,4
HP-H4	8.1	85.2	V-2,3,4; H-1,2,3,4
HP-H4	8.8	98.5	V-1,2,3,4; H-1,2,3,4
Open valve on HP-V1 first			
HP-V2	9.8	56.7	V-2
HP-V2	10.3	63.2	V-1,2
HP-H4	9.6	65.8	V-1,2; H-4
HP-H4	9.2	70.7	V-1,2; H-1,4
HP-H4	9.5	77.8	V-1,2,3; H-1,4
HP-H4	8.9	84.0	V-1,2,3; H-1,2,4
HP-H4	9.2	93.0	V-1,2,3,4; H-1,2,4
HP-H4	8.8	98.5	V-1,2,3,4; H-1,2,3,4

5.2.4. GSHP Circulating Pump Energy Performance Improvements

Before the addition of the VFD, the current, voltage, power factor, and the resulting power demand of the circulating pump motor where essentially constant. The measured power demand of the pump was about 2.1 kW. The data acquisition system used a current transducer on one line of the pump's three phase power to confirm that the current draw of the pump was essentially constant. The very purpose of the VFD was to vary the power demand of the pump, and hence a new method of monitoring the VFD/pump power demand was needed. An ideal solution to this problem would be to install a power meter on the line side of the VFD to directly monitor the power demand and energy consumption of the VFD and pump motor. The meter could be integrated with the existing data acquisition system so that data could be continuously collected from the meter. Because of budget and time constraints, a power meter integrated into the data acquisition system could not be installed. Instead, it was decided to use the existing current transducer on the line side of the VFD to indicate the speed at which the VFD/pump operates. A portable power meter data logger was then used to determine the power used by the VFD/pump at different speeds. Finally the power demand of the VFD/pump was plotted versus the current recorded by the data acquisition system and a curve was fitted to the data to determine an empirical correlation between the two variables.

Figure 5.15 shows the current draw of the VFD/pump measured by the data acquisition system's current transducer, a Fluke 41B portable power harmonics meter, and a Dent Instruments ELITEpro^{TM} power logger. The data acquisition current transducer measured the current on line one of the three phase power, while the Fluke meter and Dent data power logger were used to measure the current on lines one and two. It can be seen that the current measurements by the Dent power logger and Fluke meter on lines one and two all fall close to one another, and these are taken to be the correct values. The current measurements made by the data acquisition system's current transducer fall below the measurements made by the two other instruments. It is know that the data acquisition system's current transducer gave correct readings up until the VFD was installed, and it is assumed that the VFD is altering the waveform of the current in such a way that this current transducer cannot make correct measurements. Although, the current measurements by the data acquisition system are not correct, they are still a linear function of VFD/pump speed. Therefore the readings from the data acquisition system's current transducer can still be used as an indicator of the speed of the VFD/pump.

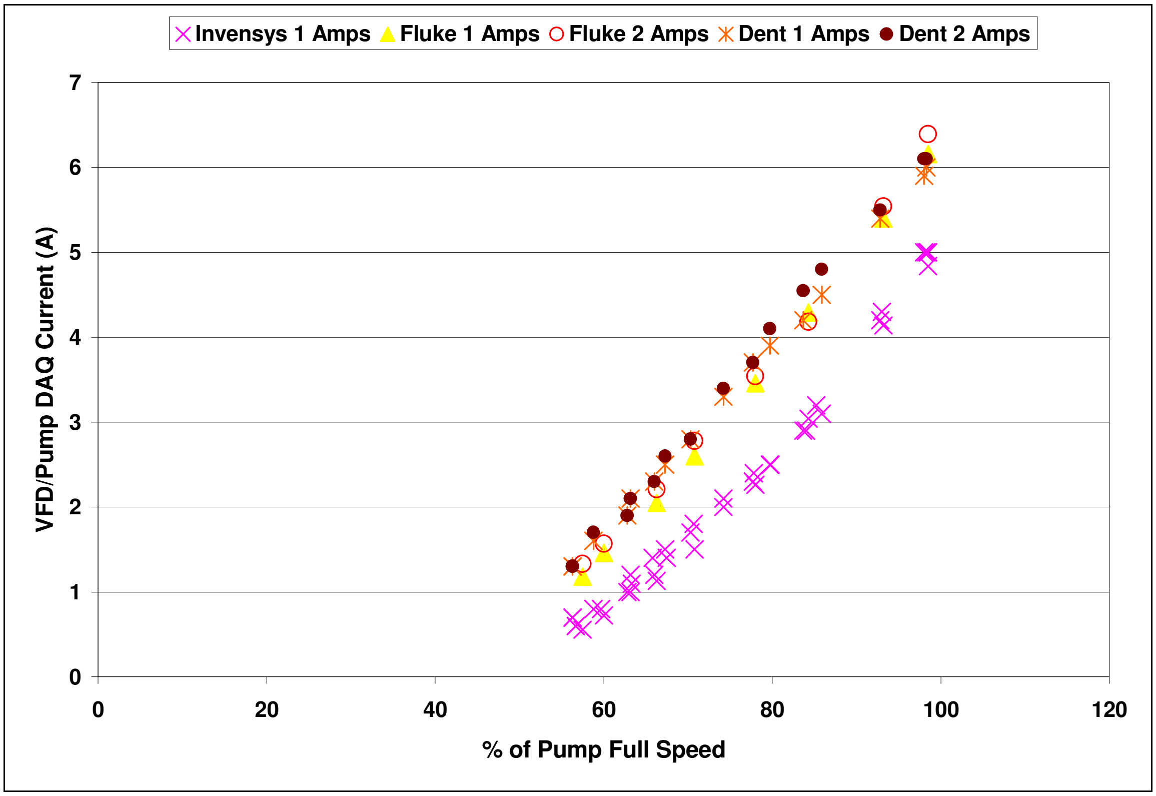


Figure 5.15. Measured VFD/Pump current on line one and line two at various pump speeds.

To determine the relation between the data acquisition current transducer's readings and the power demand of the VFD/pump, the Dent ELITEpro^{TM} power logger was used to measure the power demand at different pump speeds. The ELITEpro^{TM} power logger uses two current transducers to measure the current on two of the lines of the delta connected three phase power. The voltage from each of these lines to the third line is measured using voltage clamps. The power logger calculates the power supplied by the two line and sums them together to determine the total power supplied to the VFD/pump. The accuracy of the current transducers is ±1% of the rated 5 A current over a range of 0.5% to 140% of the rated current. The accuracy of the power measurement is within 1% of the value exclusive of the current transducer error. Figure 5.16 shows the power demand of the VFD/pump as measured by the Dent power logger and the current measured by the data acquisition system's current transducer plotted versus time as the speed of the pump changed. The measurements start at 2:14 pm with all seven heat pump shutoff valves closed. The pump is therefore only supplying flow to the bypass heat pump. The shutoff valves were then opened one at a time, with approximately five to six minutes between openings. This resulted in the step like profiles of the power and current measurements. After all eight shutoff valves were opened, all except the valve on HP-V1 were closed and the process was repeated.

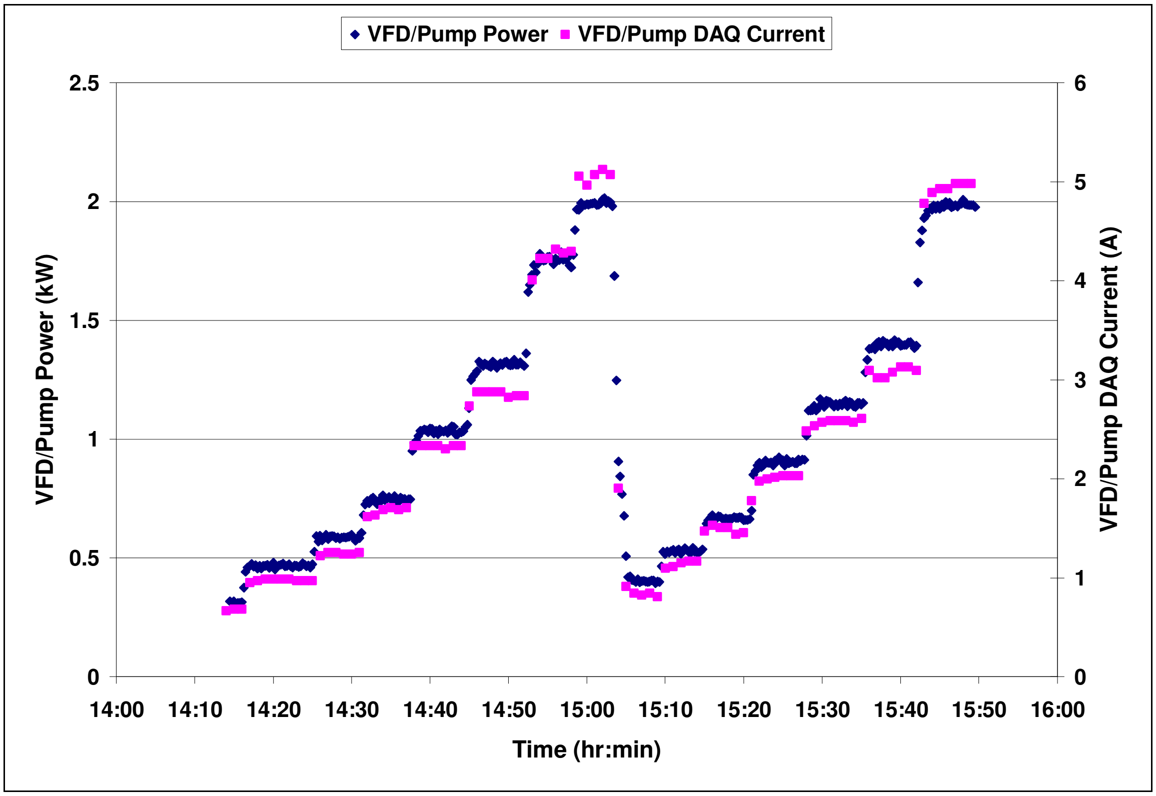


Figure 5.16. VFD/Pump power and VFD/Pump DAQ current at different pump speeds.

The Dent power logger took power measurements every 15 seconds, while the data acquisition system logged a reading from the current transducer every minute. Because the readings from the power logger and current transducer do not coincide at the same time, it is not possible to simply plot the power measurements as a function of the current measurements. Instead, the average value of power and current was found at each step once the VFD/pump had reached a steady speed, and then the average power from each step was plotted against the average current at the corresponding step. To determine the average values of current and power at each step, the transient values were removed, as shown in Figure 5.17. Because of the small amount of data involved and the fast response time of the VFD/pump, visual inspection of Figure 5.16 was sufficient for manual removal of the transient values.

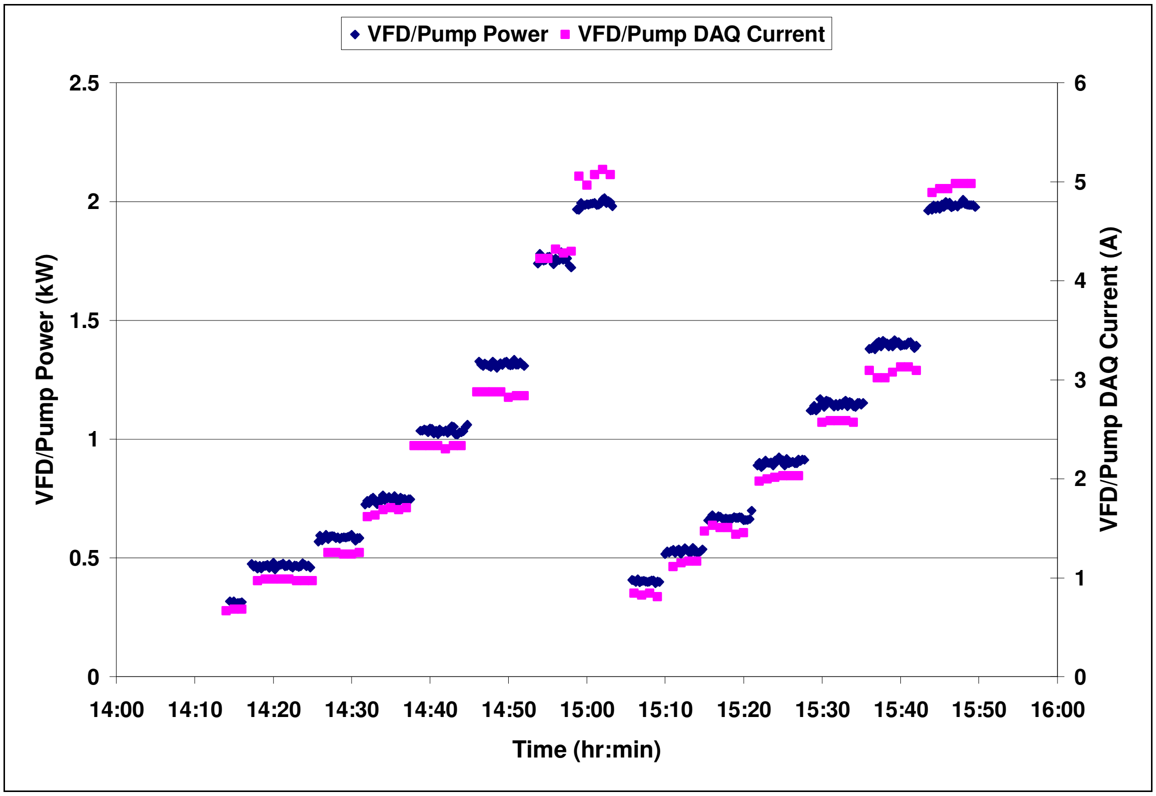


Figure 5.17. VFD/Pump power and VFD/Pump DAQ current at different pump speeds, with transient values removed.

Figure 5.18 shows the plot of the average power against the corresponding average current as read by the data acquisition system's current transducer. A quadratic curve fit of the data gives the following correlation:

$$Power = -0.0246 \cdot DAQ\_Amps^2 + 0.5283 \cdot DAQ\_Amps - 0.0398 \qquad \textbf{Equation 5.4}$$

This correlation gives the VFD/pump power demand as a function of the current read by the data acquisition system's current transducer. It should be emphasized that this empirical correlation only applies specifically to the current read by the data acquisition system's current transducer. As was shown in Figure 5.15 this current transducer gives values offset from the actual values.

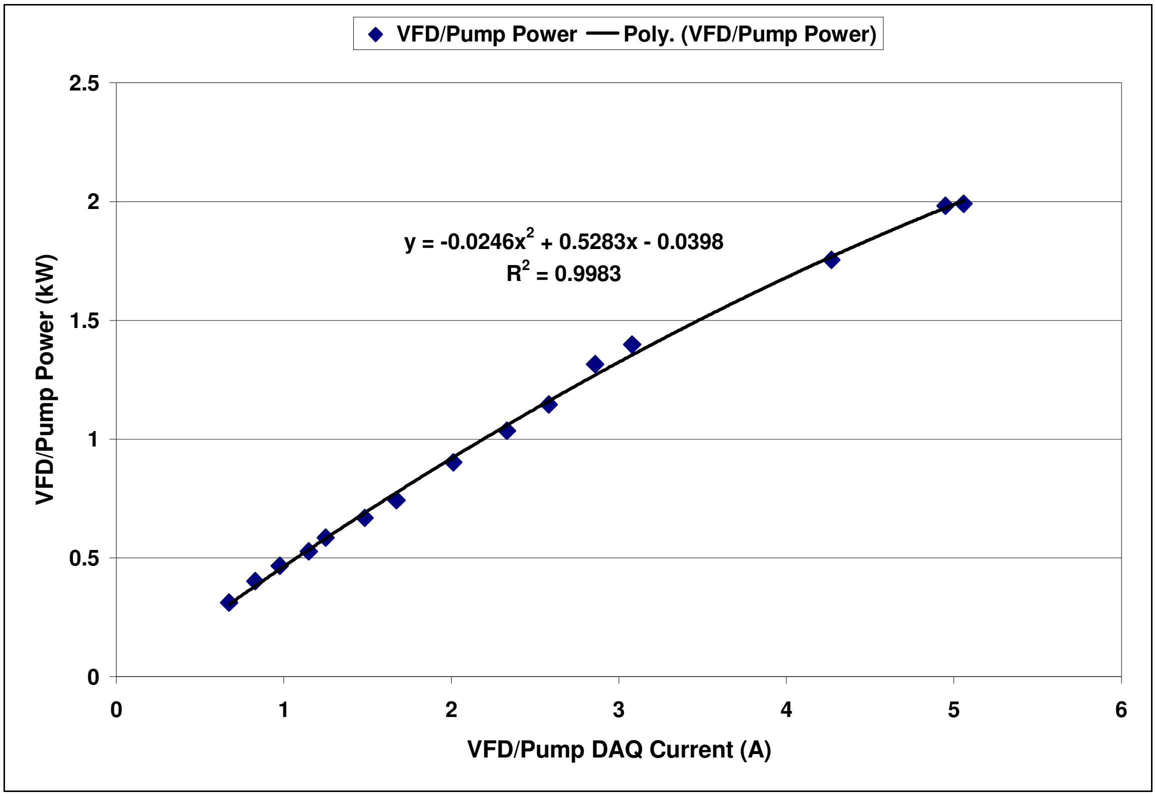


Figure 5.18. VFD/Pump power as a function of the VFD/Pump current on line 1 as measured by the data acquisition system.

Using Equation 5.4 and the current of the VFD as recorded by the data acquisition system, the power demand and the energy consumption of the VFD/pump since the installation can be determined. The VFD was commissioned on December 18, 2007, so the energy savings provided by the VFD were analyzed starting on December 19, 2007 and ending on February 26, 2008. During this time period, data is not available for December 21 and 27, January 1, February 9 after 10:00 pm, February 10 before 2:18 pm, and February 20 between 9:41 am and 3:00pm. When determining the energy savings caused by the VFD, these time periods are excluded from both the calculation of the actual energy used by the VFD/pump, and the energy that would have been used by the pump without the VFD. Because the power of the VFD/pump in kW can be calculated every minute, the energy use in kWh is determined by summing the power from every minute and dividing by 60. Over the nearly 67 days of monitoring for which data is available, the VFD/pump consumed 965 kWh. If the VFD did not control the pump, the pump would have consumed 3300 kWh; therefore the VFD saved 71% of the pumping energy compared to constant speed pumping during this time.

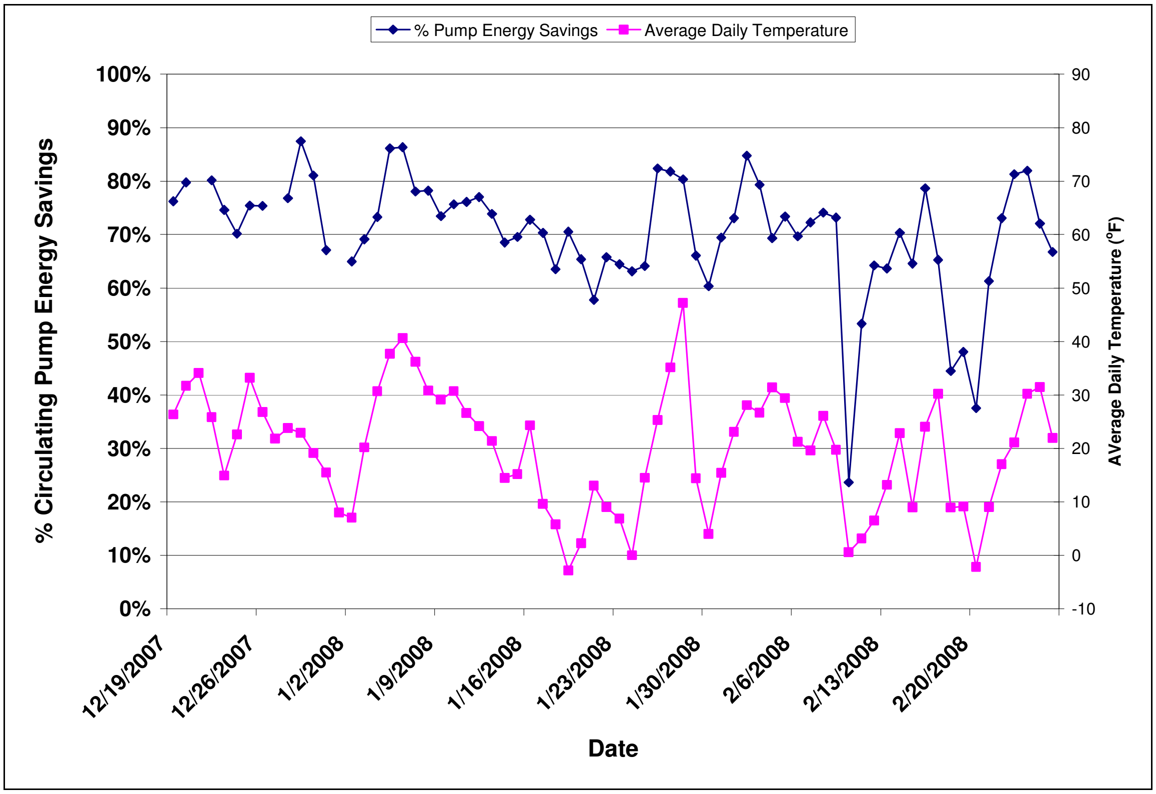


Figure 5.19. Percentage of energy saved by VFD compared to constant speed pumping over monitoring period from 12/19/2007 to 2/26/2008.

Figure 5.19 shows the daily percentage of pumping energy saved by the VFD, and the corresponding daily average temperature for the monitoring period. The gaps in the data represent the days for which no data is available. Data is available for only part of 2/10/2008, the day when the savings dip to 24%, and therefore this low percentage savings is likely not representative of the total savings for the day. Even though the monitoring period occurred during the harsh winter months of December, January, and February, and the daily average outdoor air temperature was around 0 °F on four days, significant energy savings were obtained throughout the monitoring period. During milder months, with small heating or cooling loads, it is expected that the savings will be even greater.

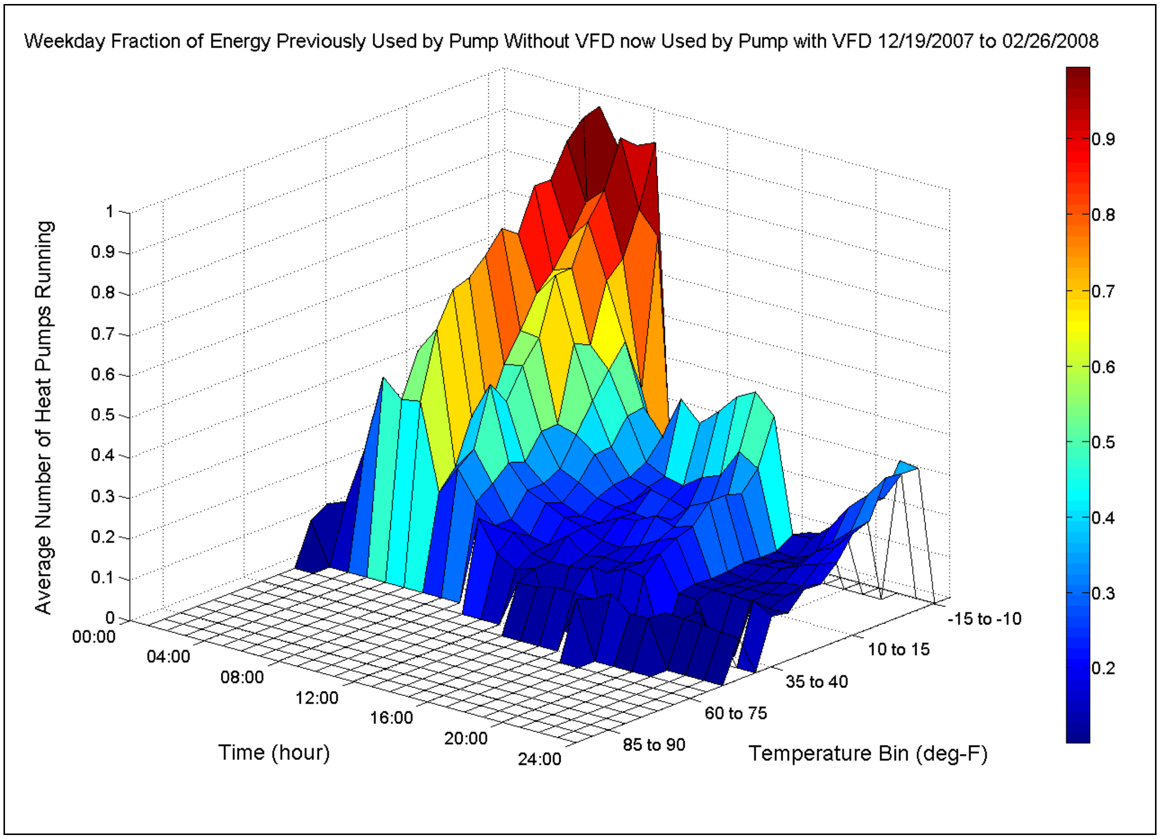


Figure 5.20. The weekday fraction of energy previously used by circulating pump without VFD now used by pump with VFD, 12/19/2007 to 2/26/2008.

Figure 5.20 shows the weekday fraction of the energy used by the pump without the VFD that is now used by the pump with the VFD in 5 °F, one hour temperature-time bins. This plot was made by slightly altering the MATLAB program used to calculate the average number of heat pumps contained in Appendix D. In bins with fractions close to one, there is little energy being saved. These bins correspond to bins where the average number of heat pumps running is high, and therefore the VFD/pump must run at high speed to provide adequate flow. The energy savings is least in the morning when many heat pumps are running to bring the building out of setback, while energy savings are greatest after 6:00 pm when the building goes into night setback and all the heat pumps turn off.

To predict the annual energy use of the circulating pump with the VFD, it is necessary to multiply the average number of hours 0, 1, 2, 3, 4, 5, 6, 7, and 8 heat pumps run by the power demand of the pump at each level. Above, Equation 5.4 established a correlation between VFD/pump power and the data acquisition system's current reading. Unfortunately a correlation for current that is solely a function of the number of heat pumps running cannot be determined. The VFD/pump current, and thus the power, is a function of the number of heat pumps running and the particular heat pumps that are running. In particular, the pump speed and current is greater when the shutoff valve on HP-V1 is open than when it is closed. The differential pressure sensor used to control the speed of the VFD is across the supply and return lines of HP-V1, and the position of its shutoff valve influences the differential pressure read by the sensor. This phenomena is demonstrated in Figure 5.21, which shows the VFD/pump current as read by the data acquisition system's current transducer versus the number of shutoff valves open. The lower curve with the diamond points represents the current when the valve on HP-V1 is closed, and the upper curve with square points represents the current when the valve on HP-V1 is open. One shutoff valve open represents the flow being provided to only the bypass heat pump. Therefore, the minimum number of valves open with the valve on HP-V1 open is two. Likewise, the maximum number of heat pumps running with HP-V1 closed is seven.

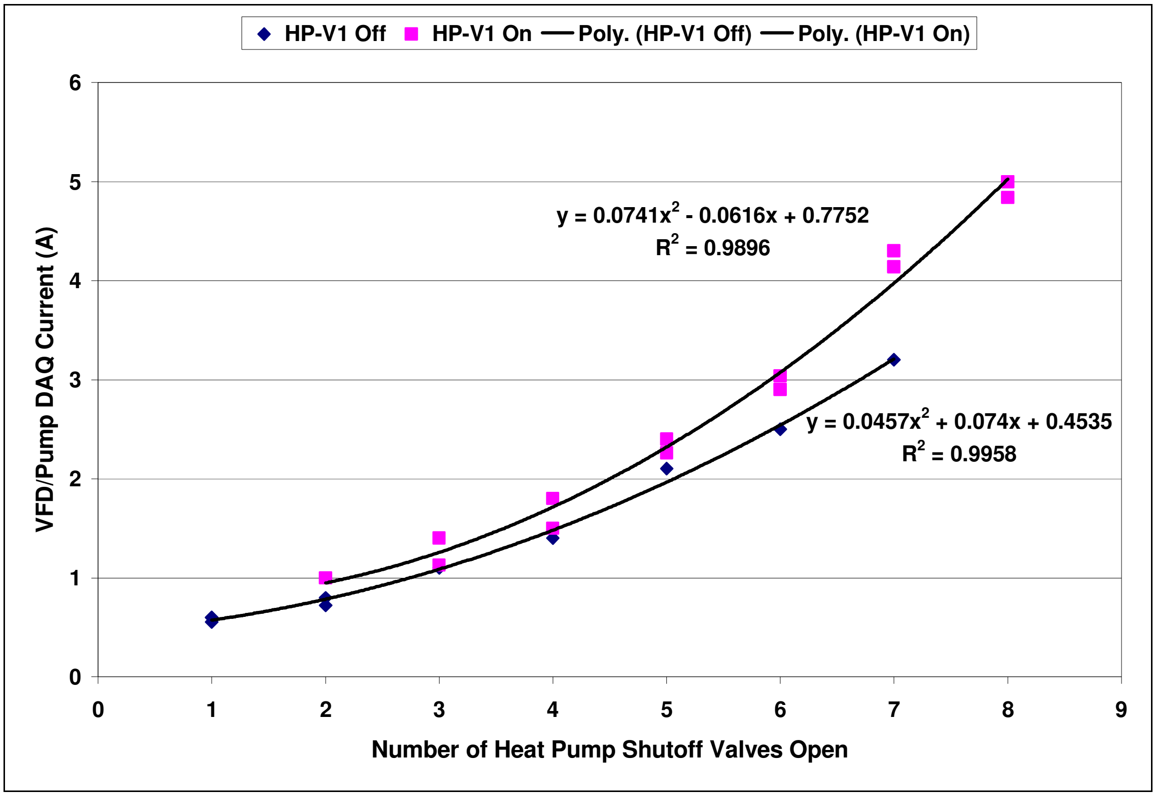


Figure 5.21. VFD/Pump current on line 1 as measured by the data acquisition system as a function of the number of shutoff valves open. The lower line represents current when the valve on HP-V1 is closed, and the upper line represents the current when the valve on HP-V1 is open.

There is no data that reveals how often the valve on HP-V1 is open. Therefore, it is not possible to predict how often the VFD/pump operates on the lower curve in Figure 5.21, and how often it operates on the upper curve. Because of this, a prediction of the maximum and minimum annual energy savings will be made. The maximum energy savings occurs if the VFD/pump always operates on the lower curve in the figure while one through seven shutoff valves are open, and then only moves to the upper curve when all eight valves are open. The minimum energy savings occurs when the VFD/pump operates on the lower curve only when flow is supplied to the bypass heat pump (one valve open) and then follows upper curve as the rest of the valves open. The annual energy use by the VFD/pump when a certain number of heat pumps is running is found by first using the appropriate curve fit from Figure 5.21 to determine the data acquisition system's current measurement. Then Equation 5.4 is used to find the corresponding power demand. Finally the power is multiplied by the annual number of hours the given number of heat pumps run from Figure 5.9. Appendix G contains a table with these calculations; Appendix F contains the electric rates used in cost savings calculations. Figure 5.22 shows the maximum an minimum predicted annual energy use of the VFD/pump compared to the annual energy use of the pump without the VFD. Without the VFD the pump would use 18,200 kWh per year, but with the VFD the maximum energy use is predicted to be 4100 kWh and the minimum is predicted to be 3100 kWh. This corresponds to a minimum annual energy savings of 77% and a maximum savings of 83%. Based on average electricity price of $0.065, the annual cost savings from the VFD should be between $920 and $990. The VFD should reduce the annual energy use of the building between 13 and 14%.

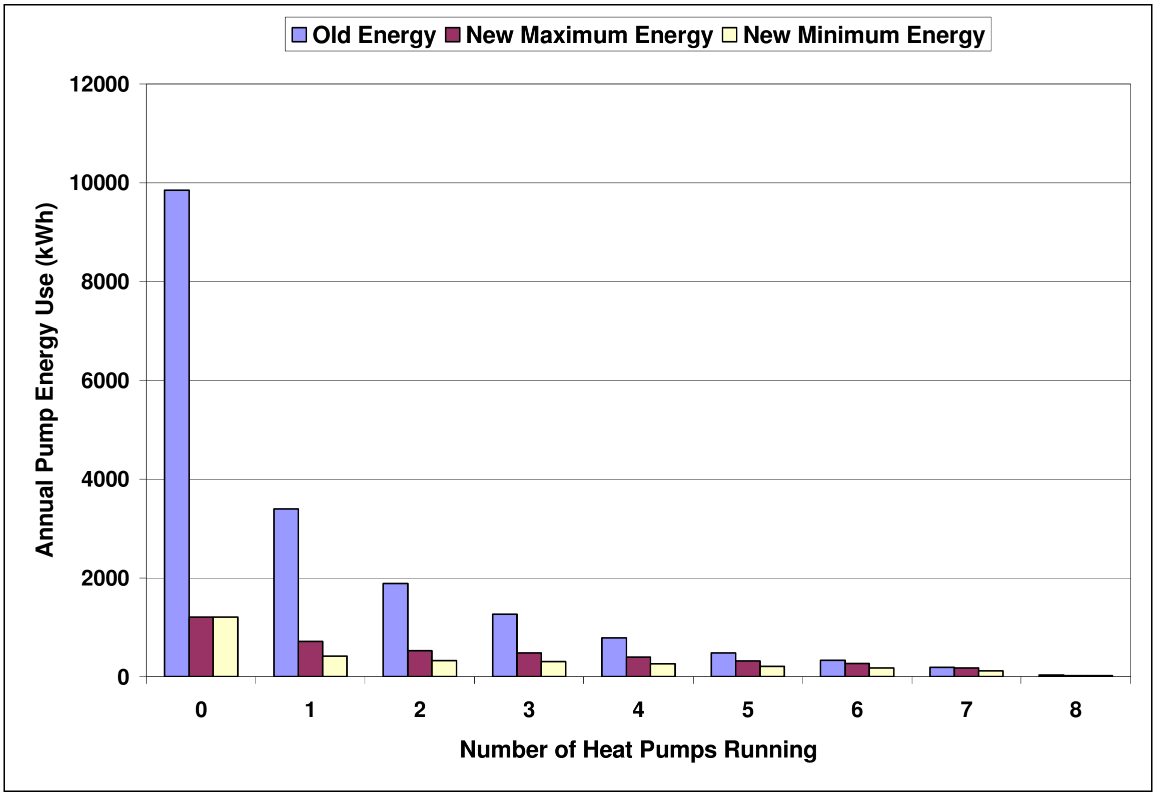


Figure 5.22. Predicted maximum and minimum annual energy use of the VFD/pump compared to energy use of the pump without the VFD.

5.3. Energy Recovery Ventilator Defrost Heater

This section covers the energy performance of the energy recovery (ERV) defrost heater, which corresponds to an energy use determined during the implementation phase of the IAMU building. Section 5.3.1 discusses the operation of the defrost heater, section 5.3.2 discusses the energy performance of the defrost heater, and section 5.3.3 details the improved energy performance of the defrost heater.

5.3.1. ERV Defrost Heater System Operation

The ERV is used to precondition outside ventilation air by transferring both sensible and latent heat between the outside air and the building exhaust air. The ERV installed at the IAMU is a Greenheck model ERV-36; a schematic of the ERV can be seen in Figure 5.23. The outside and exhaust air travel in opposite parallel flow paths through an enthalpy wheel; at all times half of the wheel is in the outside air stream and the other half is in the exhaust air stream. In Figure 5.23, the outside air is the top flow path which moves left to right, and the exhaust air is the bottom flow path which moves right to left. The enthalpy wheel consists of concentrically wrapped layers of polymer sheets with a silica desiccant bonded to them. The sheets are wrapped loosely to form thousands of small channels through which the outside and exhaust air pass. As air passes through the wheel, heat transfer and mass transfer of moisture occur between the air and wheel, either cooling and dehumidifying the air or heating and humidifying the air. In hot humid weather, heat and moisture are removed from the outside air and transferred to the exhaust air. In cold weather with low humidity, heat and humidity are transferred to the outside air from the exhaust air.

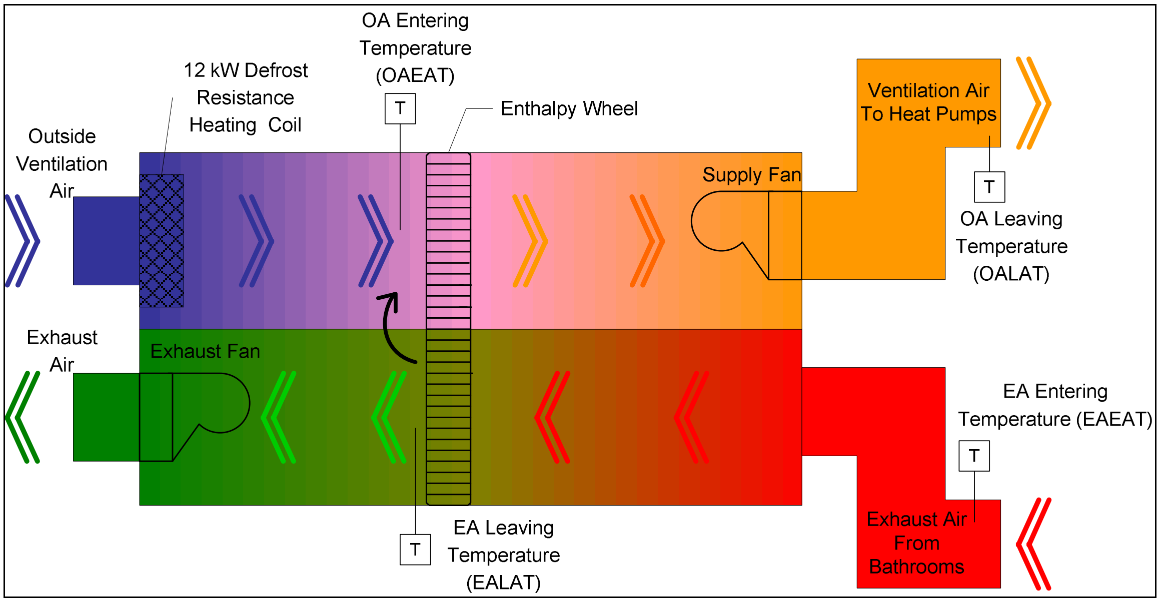


Figure 5.23. Schematic diagram of the ERV.

Heat is transferred from the warm air stream to the wheel by convection, and stored in the polymer media of the wheel. Then as the wheel turns, so that the warmed part of the wheel is in the cool air stream, the heat is transferred from the wheel to the cool air by convection. Moisture and latent heat are removed from the moist air stream by two mechanisms:

1. When the temperature of the moist air falls below its dew point water will condense onto the media of the wheel and be transferred to the dry air where the moisture will evaporate.
2. The desiccant coating the wheel media will remove moisture from the moist air and transfer it to the dry air (ASHRAE 1996).

In the winter, when the outside ventilation air is at a very low temperature, it is possible for frost to form on the enthalpy wheel. Frost can form on enthalpy wheels by two methods (ASHRAE 1996). When the temperature of the warm air falls below its dew point condensation will form on the enthalpy wheel medium. Then, if the temperature of the enthalpy wheel falls below 32 ^{o}F, the condensation will freeze.

Alternatively, if the dew point of the warm air is below 32 °F and its temperature falls below its dew point, water will sublimate out of the air and form frost on the wheel. Frost will block the airflow and damage the enthalpy wheel as it forms in the narrow airflow channels, and thus must be prevented from forming. The ERV contains an electric resistance pre-heater, shown in Figure 5.23, to preheat the incoming outside air to prevent frost buildup on the enthalpy wheel. Frost will form on the enthalpy wheel when the temperature of the wheel falls below freezing, but frost formation will not start immediately when the outside air falls below 32 °F. Because the wheel transfers heat from the warm air to the cold air, outside air at or near the freezing point will be heated up above 32 °F, and frost formation will be prevented. Table 5.5 shows the outside air temperatures where frost formation will commence for exhaust air at 70 °F and three different relative humidities. This data was provided by the manufacturer of the ERV, Greenheck, in the ERV installation, operation, and maintenance manual. During the wintertime, the IAMU's indoor air is maintained at about 72 °F and 20% humidity during occupied hours. Therefore, frost is not expected to form on the enthalpy wheel, until the outside air temperature falls below -10 °F.

Table 5.5. ERV frost thresholds (Greenheck).

Indoor RH @ 70°F	**Frost Threshold Temp**
20%	-10°F
30%	-5°F
40%	0°F

The ERV contains a two stage 12.2 kW defrost heater controlled by a two-stage T768A Honeywell thermostat. Each stage of heating is approximately 6.1 kW. As shown in Figure 5.23, the thermostat is located in the outside air stream after the defrost heater but before the enthalpy wheel. The thermostat is located so that it is not in direct line of sight of the heater, and thus does not directly receive radiant heat transfer from the heater. As the temperature of the outside ventilation air falls below the set point of the thermostat the contactor on the first stage of heating is closed. The thermostat has a 3 °F interstage differential, so if the outside air temperature falls 3 °F below the set point the contactor of the second heating stage is closed. The control wiring of the thermostat is shown in Figure 5.24.

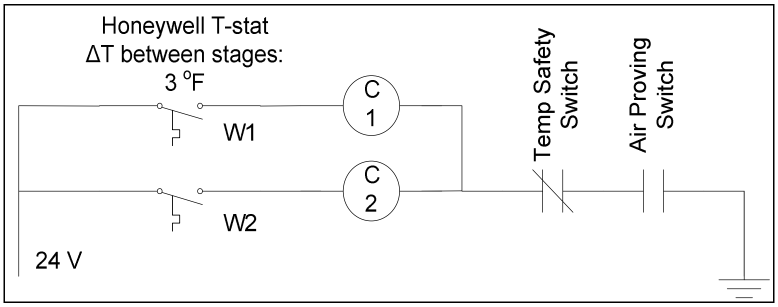


Figure 5.24. Defrost heater thermostat control wiring.

While the thermostat is set up to control two 6.1 kW heaters, the defrost heater has been wired so that it is a single stage 12.2 kW heater. The wiring diagram of the defrost heater can be seen in Figure 5.25. The defrost heater is supplied three phase power, and when the contactor (surrounded by dashed line) controlled by the first stage of the thermostat closes an electrical circuit is not formed. When the second contactor closes, an electrical circuit is formed such that all 12.2 kW of heating turns on. Because of the thermostat's interstage differential, all 12.2 kW of heating are activated when the temperature of the incoming outside air falls below 3 °F of the set point. Figure 5.26 shows the heater wiring diagram of two 6.1 kW stages. For two stage operation the first stage of the thermostat closes two contactors on the heater, forming a complete electrical circuit. Then the second stage of the thermostat closes a third contactor creating two additional electrical circuits.

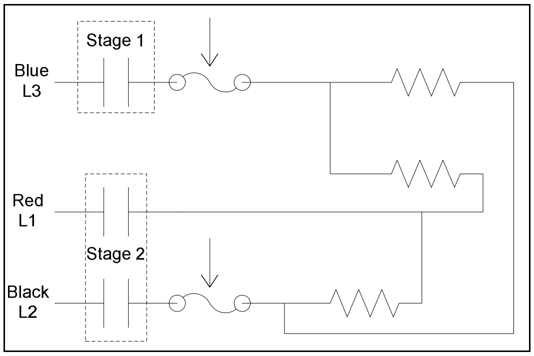


Figure 5.25. Actual defrost heater wiring diagram, single 12.2 kW stage.

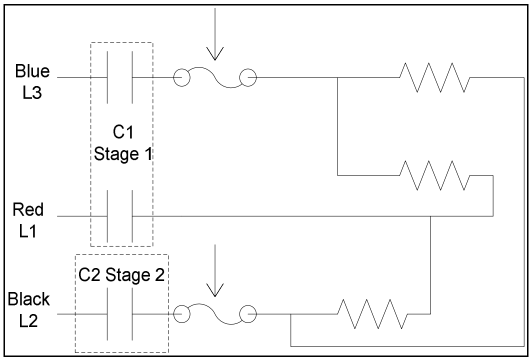


Figure 5.26. Recommended defrost heater wiring diagram, two 6.1 kW stages.

The ERV is instrumented with four thermistors and an ammeter that are connected to the data acquisition system which takes temperature and current measurements at one minute intervals. The locations of the thermistors are shown in Figure 5.23. In the outside air stream one thermistor measures the air temperature after the defrost heater but before the air passes through the enthalpy wheel; this is called the outside air entering air temperature (OAEAT). A second thermistor measures the outside air temperature after the air has passed through both the enthalpy wheel and supply fan; this is the outside air leaving air temperature (OALAT). In the exhaust air stream, a thermistor measures the air temperature before the air enters the ERV; this is the exhaust air entering air temperature (EAEAT). The second thermistor in the exhaust air measures the temperature of the air after it passes through the enthalpy wheel but before it passes through the exhaust fan; this is the exhaust air leaving air temperature (EALAT). The ammeter measures the current on L1 of the three-phase power supplied to the ERV. While the measurement of current on one line of the three phase power does not provide enough information to calculate the power use of the ERV directly, it does indicate the mode of operation of the ERV. Table 5.6 shows the five modes of operation of the ERV: off, low speed without defrost heat, low speed with defrost heat, high speed without defrost heat, and high speed with defrost heat. Field measurements of the power used by the ERV in each mode were taken using a Fluke 41 Power Harmonics Analyzer. These power measurements and the corresponding current measured on L1 are shown in Table 5.6. Because there is a one-to-one correlation between L1 current and ERV power, knowing the current of L1 indicates the power demand of the ERV.

Table 5.6. ERV modes of operation.

Wheel and Fan Speed	Heater Status	Current L1, Black (A)	Power (kW)
Off	Off	0	0
Low	Off	4	0.85
Low	On	36	13
High	Off	6	1.4
High	On	38	13.9

5.3.2. ERV Defrost Heater Operation and Energy Performance

Analysis of the current draw of the ERV showed that during cool and cold weather it frequently oscillated between 4 and 36A when the unit was operating at low speed or between 6 and 38 A when the unit was operating on high speed. This indicated that the defrost heater was frequently turning on. Figure 5.27 is a graph of the ERV's current draw, the OAEAT, the OALAT and the outdoor air temperature on February 17, 2006. This was a cold day when the outdoor temperature hovered around 0^{o}F. The current draw shows that the ERV turned on at 7:30 am and turned off at 5:30 pm according to its programmed operating schedule. Comparing the current draw in Figure 5.27 to Table 5.6 shows that the ERV was operating in low fan mode all day long and the defrost heater oscillated on and off. At this outdoor temperature the defrost heater was on for the majority of the day and off for short periods. This is indicated by the flat peaks of the current trend at 36 A when the defrost heater was on, and the narrow valleys at 4 A when the defrost heater was off. In total the defrost heater was on for 94% of the time the ERU was on.

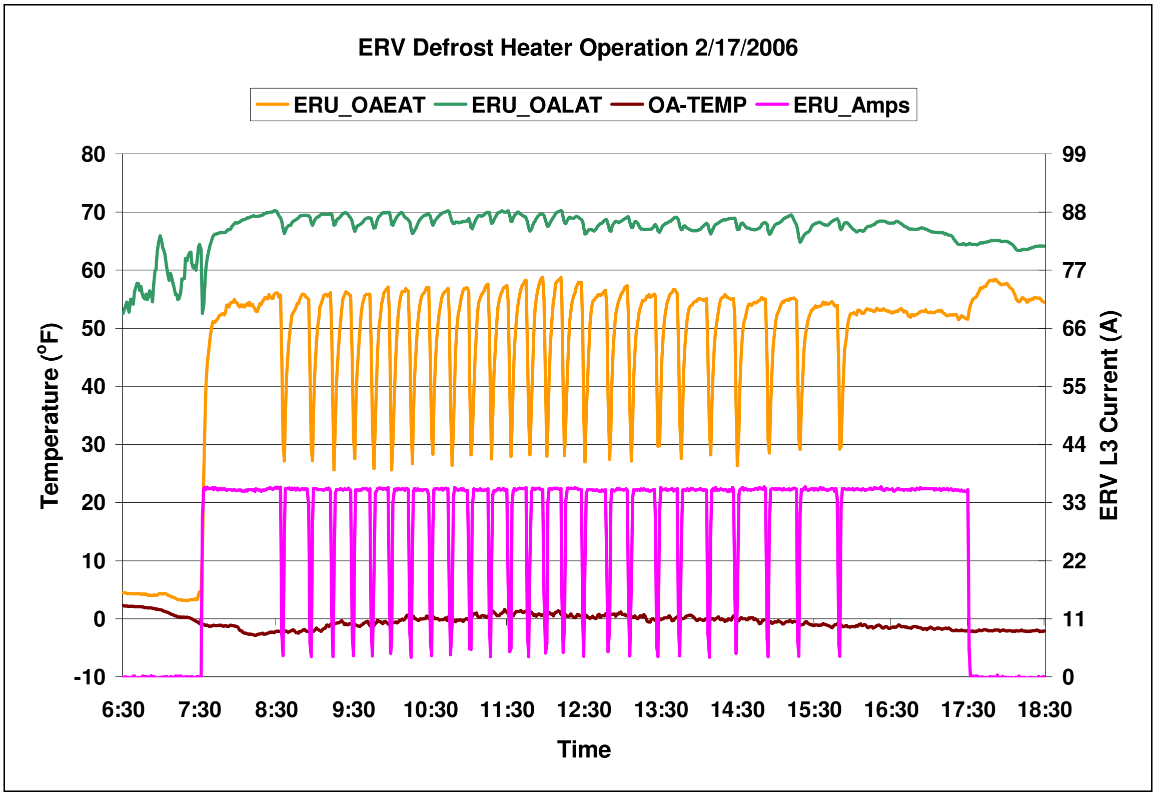


Figure 5.27. ERV defrost heater runtime with 46 °F set point.

The OAEAT oscillated corresponding to the operation of the defrost heater. During periods when the heater was on, the near 0 °F outside air was heated to between 50 and 60 °F. Then, when the heater turned off, the OAEAT quickly dipped below 30 °F before the defrost heater turned back on. The OALAT also oscillated corresponding to the operation of the defrost heater, but the amplitude of the oscillations were much smaller than those of the OAEAT. The temperature of the exhaust air entering the ERV hovered between 70 and 74 °F (not shown in graph). When the defrost heater was on, and the OAEAT was between 50 and 60 °F, the exhaust air was able to heat the outside air to an OALAT of about 70 °F. When the heater was not on, the exhaust air was able to heat the outside air to from an OAEAT of about 30 °F to an OALAT around 66 °F. Because the defrost heater is used to increase the temperature of the outside ventilation air by over 50 °F, there is a smaller temperature difference between the outside air and exhaust air and less heat can be recovered from the exhaust air. The defrost heater decreases the system efficiency of the defrost heater by incurring two energy penalties: it increases the power demand of the ERV by 12.2 kW, and it reduces the amount of energy that can be recovered from the exhaust air by decreasing the temperature difference between the outside entering air temperature and the exhaust entering air temperature.

An investigation revealed that the thermostat on the defrost heater was set to 46 ^{o}F, much higher than needed to prevent frost buildup in the enthalpy wheel. At the IAMU it is common for the indoor air to be around 70 ^{o}F and 20% relative humidity during the winter, and comparing these values to Table 5.5 on page 116, the threshold for frost formation should be around -10 ^{o}F. Because of the energy penalties incurred by the defrost heater and the unnecessarily high set point, it was decided to decrease the set point of the thermostat controlling the defrost heater to 5 ^{o}F. Five degrees was chosen to provide a safety factor above all of the frost formation thresholds in Table 5.5. The next section will detail the performance of the ERV with the decreased defrost heater set point and compare the energy usage of the defrost heater at the 46 ^{o}F set point and the 5 ^{o}F set point.

5.3.3. ERV Defrost Heater Energy Performance Improvements

Figure 5.28 shows the ERV's current draw, the OAEAT, the OALAT, and the outdoor air temperature on the February 15, 2007 after the defrost heater set point had been turned down to 5 ^{o}F. This day was very cold with outdoor temperatures ranging between -8 and 6 ^{o}F, and is comparable to the day discussed in Figure 5.27 when the heater set point was 46 ^{o}F. The values of the ERV current trend indicate that the ERV operated at low speed from 7:30 am until 12:30 pm, and then operated on high speed until 3:20 pm. At 3:20 pm the ERV went back to low speed and stayed there until it turned off at 5:30 pm. Throughout the day the defrost heater turned on, but unlike when the set point was 46 ^{o}F, the heater was on for short periods and off for long periods. This is indicated by the sharp peaks in the current trend when the heater was on and long flat valleys in the current trend when the heater was off. In all, the defrost heater was on for 19% of the time the ERV was on. The OAEAT also has corresponding oscillations from below 10 ^{o}F to above 30 ^{o}F. The OALAT entering the building stays in the mid to upper 60's ^{o}F during the day despite the low temperature of the air as it entered the enthalpy wheel. It may be noted that during times when the defrost heater is off for long periods, the OAEAT does not equal the outdoor air temperature. This is likely due to solar heating of the ERV. The ERV is on the roof of the IAMU building, and is in full view of the sun during the middle of the day.

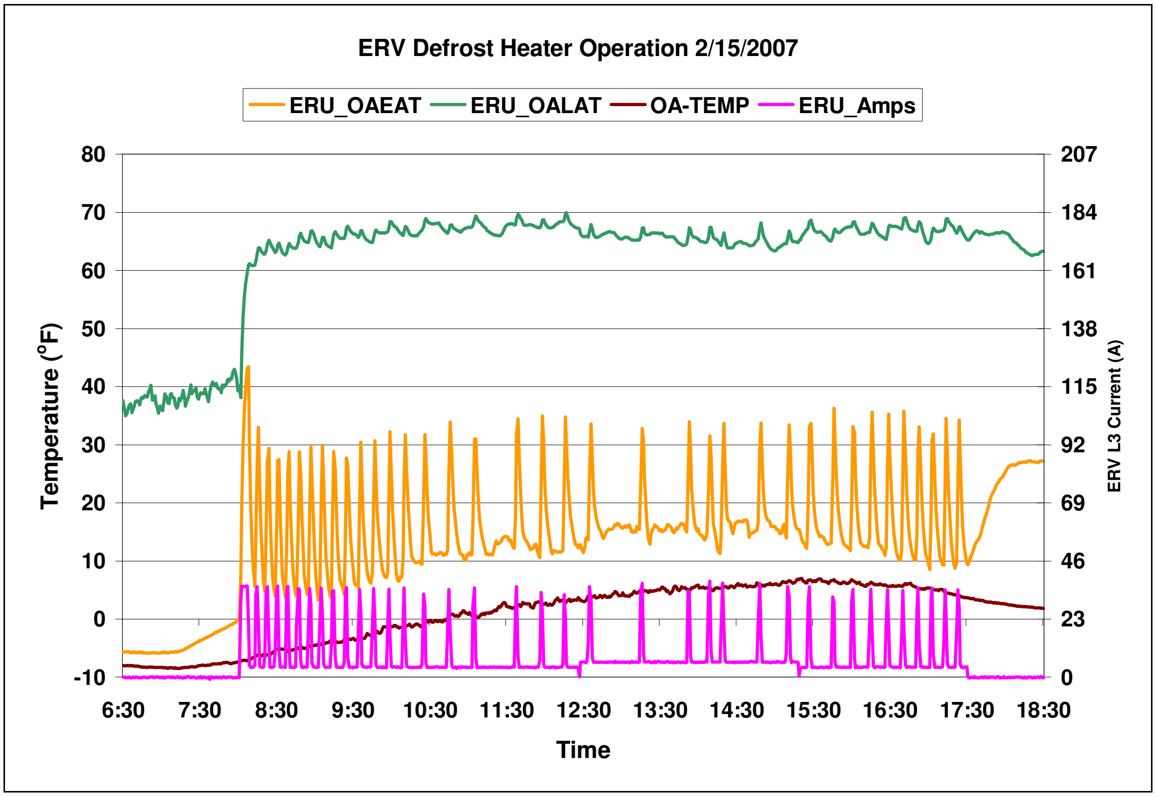


Figure 5.28. ERV defrost heater runtime with 5 ^{o}F set point.

Table 5.7 shows comparisons of several air temperatures associated with the ERV between the 46 and 5 ^{o}F set points. The average outdoor air temperature during the period of ERV operation was very similar on the two days: -0.6 ^{o}F on the day when the heater was set to 46°F and 1.7 °F when the heater was set to 5 °F. Also, the exhaust air from the building entering the ERV is at about 71 °F for both cases. When the defrost heater was set to 46 °F the average outside air temperature entering the enthalpy wheel after passing through the heater was 50 °F and the OALAT entering the building was 68 °F. In comparison, when the defrost heater was set to 5 °F, the average outside air temperature entering the enthalpy wheel was 16 °F and the OALAT was 65 °F. With the outdoor air temperature and the temperature of the exhaust air from the building at approximately the same temperatures, decreasing the defrost heater set point from 46 to 5 °F only decreased the temperature of the outside air entering the building by about 3 °F.

Table 5.7. Comparison of 46 and 5 °F defrost heater set points between 7:30 am and 5:30 pm.

	46 °F Set Point	**5 °F Set Point**
Average OA Temp (°F)	-0.6	1.7
Average EAEAT (°F)	71.1	71.2
Average OAEAT (°F)	50.0	15.5
Average OALAT (°F)	68.0	64.7

The transient nature of heat transfer in the ERV makes energy analysis of the system difficult, and it was not within the scope of this project to analyze the ERV heat transfer performance. But to illustrate the increased heat recovery by the ERV when the defrost heater was set to 5 °F, consider the following example using the temperatures shown in Table 5.7: When the defrost heater was set to 46 °F, the average increase in the outside air temperature across the heater was 51 °F (average OAEAT – average OAT), while the average increase in temperature of the this air across the enthalpy wheel was only 18 °F. In contrast, when the defrost heater was set to 5 °F, the average increase in outdside air temperature across the heater was 14 °F, and the average increase in temperature of this air across the enthalpy wheel was 49 °F. Therefore, assuming constant air properties, the ERV recovered 170% more sensible heat from the exhaust air when the defrost heater was set to 5 °F than when it was set to 46 °F.

One concern that arose when decreasing the set point of the defrost heater, was that the outside air temperature leaving the ERV (OALAT) would be lowered enough to significantly reduce the temperature of the air supplied to the heat pumps and therefore reduce the temperature of the supply air to the building. It has been shown above that under similar exhaust air and outdoor air temperatures, decreasing the defrost heater set point only reduced the outside air temperature leaving the ERV by 3 ^{o}F. After combining this outside air with the return air within the building, the heat pumps will only see a small increase in heating load. When the ERV operates at high speed it supplies 1100 CFM of air to the building, and the eight heat pumps each supply a nominal 1600 CFM. The worst case scenario would occur when the ERV was operating on high speed and only one heat pump was running. Because the heat pumps are divided into two groups of four in different locations of the building, half of the ERV outside air is ducted to each location. With the defrost heater set to 46 ^{o}F and the ERV on high speed, combining 550 CFM of 68 ^{o}F air from the ERV and 1050 CFM of 71 ^{o}F building return air would result in the heat pump receiving 70 ^{o}F return air. With the defrost heater set to 5 ^{o}F, the ERV supplying 65 ^{o}F, and all other variables remaining the same, the heat pump would see supply air of 69 ^{o}F. If more heat pumps were operating the return air from the building would increase and the mixed air temperature supplied to the heat pumps would be greater than 69 ^{o}F. Also, because the outdoor air temperatures on both these days approached the Des Moines 99% design condition of -4 ^{o}F, on milder days the return air temperature would be decreased even less by the lower defrost heater set point.

The one minute interval data collected from the ammeter on line L1 of the ERV was analyzed using MATLAB to determine the running characteristics of the defrost heater. The data was used to determine the percentage of time the defrost heater is on when the ERV is running within 5^{o}F temperature bins. The MATLAB code used is in Appendix H. The data files containing the daily ERV current data and the files containing the daily weather data collected at the Iowa Energy Center's Energy Resource station in Ankeny, IA are inputs into the MATLAB code. Because the Energy Resource Station and the IAMU building are only 1.6 miles apart, the outdoor air temperature is assumed to be the same at both locations. For each day in the analysis period, the code determines the amount of time the ERV runs, and the amount of time the defrost heater. The runtimes are sorted into 5 ^{o}F temperature bins from -10 to 100 ^{o}F corresponding to the outdoor temperature at which the operation occurred. For example, suppose the ERV operated for 60 minutes from 8:00 am to 9:00 am, and the outdoor temperature was between 30 and 35 ^{o}F from 8:00 to 8:40 am and between 35 and 40 ^{o}F between 8:40 and 9:00 am. Then 40 minutes of ERV runtime would be assigned to the 30 to 35 ^{o}F temperature bin and 20 minutes of runtime would be assigned to the 35 to 40 ^{o}F temperature bin. At the end of the day, for each temperature bin, the fraction of time the defrost heater operated while the ERV was operating was determined according to:

$$Fractional\_Heater\_Runtime = \frac{Defrost\_Heater\_Runtime}{ERV\_Runtime} \qquad \textbf{Equation 5.5}$$

This process is continued for each day in the anlaysis period. At the end of the analysis period, the average over all days of the fractional runtime in each temperature bin is found.

For the defrost heater set point of 46 ^{o}F, ERV current and outdoor air temperature data was analyzed for the period from October 1, 2005 to October 24, 2006. The defrost heater thermostat set point was adjusted to 5 ^{o}F on October 25, 2006. For the defrost heater set point of 5 ^{o}F, data was analyzed for the period beginning November 2007 through the end of July 2007. Figure 5.29 shows the defrost heater percentage runtimes when the ERV is operating in each temperature bin for both set points. The figure shows that reducing the set point of the defrost heater's thermostat from 46 ^{o}F to 5 ^{o}F significantly reduced the fraction of time the heater operates. When the outdoor air temperature was below 10 °F at the 46 °F set point the heater ran over 90% of the time. No fractional runtime for the -10 to -5 °F temperature bin is available because the data collection system malfunctioned and did not collect data for several weeks when the temperature dipped to these levels during the analysis period. According to the trend, it is likely that the defrost heater would have run nearly 100% of the time in the -10 to -5 °F temperature bin. Between the 5 to 10°F bin and 50 to 55 °F bin the fractional runtime decreases nearly linearly from around 94% to 0%.

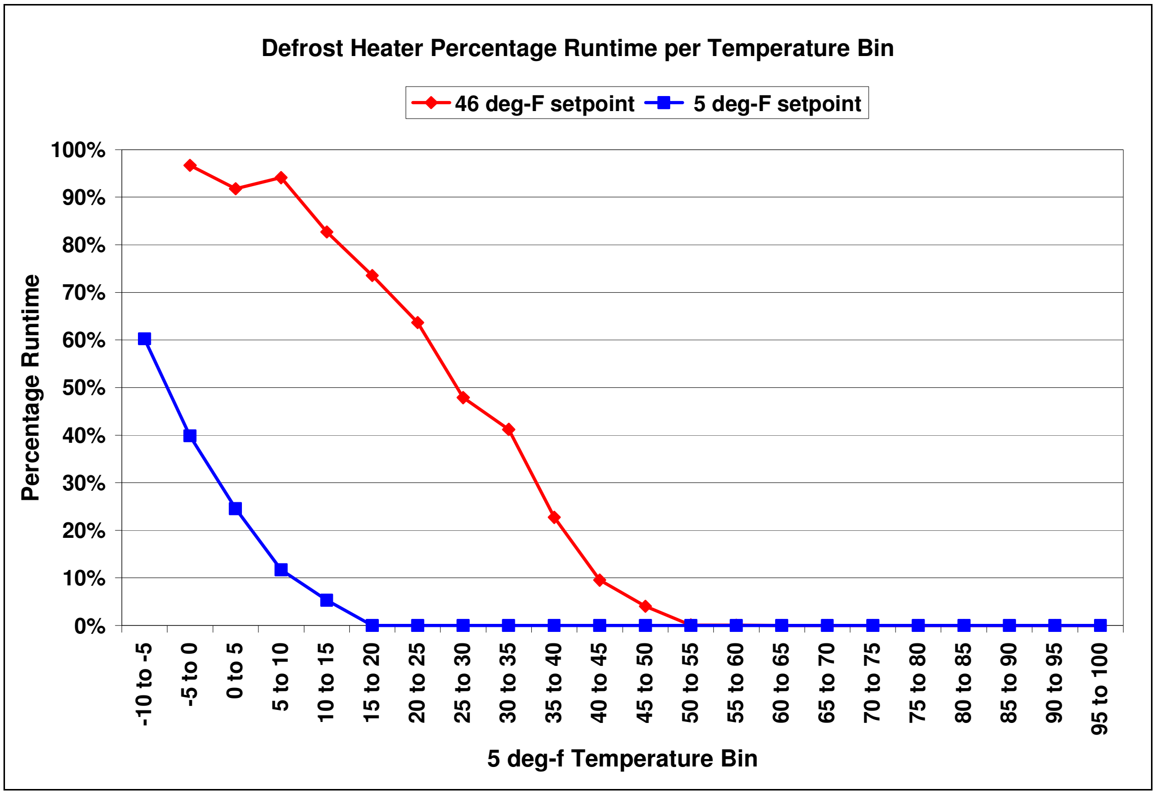


Figure 5.29. Percentage runtime of defrost heater in 5 °F temperature bins when ERV is operating.

For the 5 °F set point, the maximum fractional runtime of 60% occurs in the -10 to -5 °F bin. The heater fractional run time then decreases nearly linearly to 0% in the 15 to 20°F bin. Although the heater set point is 5°F, the heater runs 12% of the time in the 5 to 10 °F bin and 5% in the 10 to 15°F bin. This is likely do to the slow response time of the liquid filled remote bulb connected to the thermostat by a capillary tube, or inexact calibration of the thermostat. Because the fractional runtimes and total predicted annual hours of operation (see Figure 5.30 below) in these temperature bins are small, it was determined unnecessary to further adjust the thermostat to eliminate all operation of the defrost heater at outdoor air temperatures above 5 °F.

To make a fair determination of the energy savings obtained by reducing the set point of the defrost heater, a comparison of annual runtimes based on TMY-2 data was made. It is not possible to directly compare the defrost heater runtime from one year at the 46 °F set point to the runtime in a different year at the 5 °F because different temperature distributions in each year would affect heater runtime. It would not be possible to determine what energy savings are attributable to the decreased set point and what savings are attributable to variations in outdoor temperature between the two years. Table 5.8 shows the number of hours in 5 °F temperature bins during the runtime of the ERV. The ERV runs from 8:00 am to 5:30 pm on weekdays, for a total annual runtime of 2470 hours. The bin data was obtained from the computer program BinMaker™ Plus (1999) which uses TMY-2 hourly weather data developed by NREL. The software allows the user to specify the days and hours for which bin data is desired. The smallest time resolution in the software is an hour, so Table 5.8 contains bin data from 8:00 am to 6:00 pm instead of from 8:00 am to 5:30 pm. This adds 130 extra hours to the bin data. These 130 extra hours will add equally to the runtime of the defrost heater at both set points, and therefore should not affect the energy savings determined from the TMY data.

Table 5.8. Temperature bin data for ERV operation times: 8:00 am to 6:00 pm during weekdays. Total annual hours: 2600 (BinMaker^{TM} Plus 1999).

Temperature Bins (^{o}F)	Total Hrs	Jan Hrs	Feb Hrs	March Hrs	April Hrs	May Hrs	June Hrs	July Hrs	Aug Hrs	Sep Hrs	Oct Hrs	Nov Hrs	Dec Hrs
95 to 100	4							4					
90 to 95	51							32	18	1			
85 to 90	96					3	24	41	24	4			
80 to 85	196				6	19	45	44	48	29	5		
75 to 80	172					29	41	38	41	21	2		
70 to 75	209			1	9	34	51	32	34	33	15		
65 to 70	202			6	21	30	29	12	32	40	29	3	
60 to 65	263			13	36	69	22	7	23	51	30	12	
55 to 60	155		3	15	34	32	5		10	15	27	14	
50 to 55	183	3	15	28	35	11	3			14	46	22	6
45 to 50	136	6	6	20	16	1				2	36	43	6
40 to 45	125	14	7	16	18	2					22	38	8
35 to 40	202	22	30	56	10						7	22	55
30 to 35	192	17	24	48	14						1	37	51
25 to 30	112	29	18	20	1							26	18
20 to 25	77	26	27	5								3	16
15 to 20	79	23	34	2									20
10 to 15	52	27	15										10
5 to 10	34	10	14										10
0 to 5	25	13	7										5
-5 to 0	21	20											1
-10 to -5	14	10											4

Multiplying the number of hours in each temperature bin in Table 5.8 with the corresponding percentage runtime of the defrost heater in those bins from Figure 5.29, will give the average annual runtime of the defrost heater in each temperature bin. Figure 5.30 shows the average annual runtime in each temperature bin for both the 46^{o}F and 5^{o}F set points. It can be seen that decreasing the set point greatly reduced the total runtime of the defrost heater. For the 46^{o}F set point, the bin with maximum runtime is the 30 to 35^{o}F bin with 79 hours annually. For the 5^{o}F set point the -10 to -5 ^{o}F temperature bin has the maximum runtime with 8.4 hours annually. The total annual runtime of the defrost heater based on TMY data decreased from 420 hours at the 46 ^{o}F set point to 30 hours at the 5 ^{o}F set point . The decrease in defrost heater runtime was affected by two factors. First turning the set point down reduced the temperature range in which the heater could operate. Second, the bins in which the defrost heater operates at the lower set point contain relatively few hours. The five temperature bins the heater operates in at the 5 ^{o}F set point only contain 5.6% of the annual hours the ERV is in operation. In comparison, the first 12 temperature bins the heater operates in (-5 to 50 °F) at the 46 °F set point contain 41% of the annual hours of ERV operation.

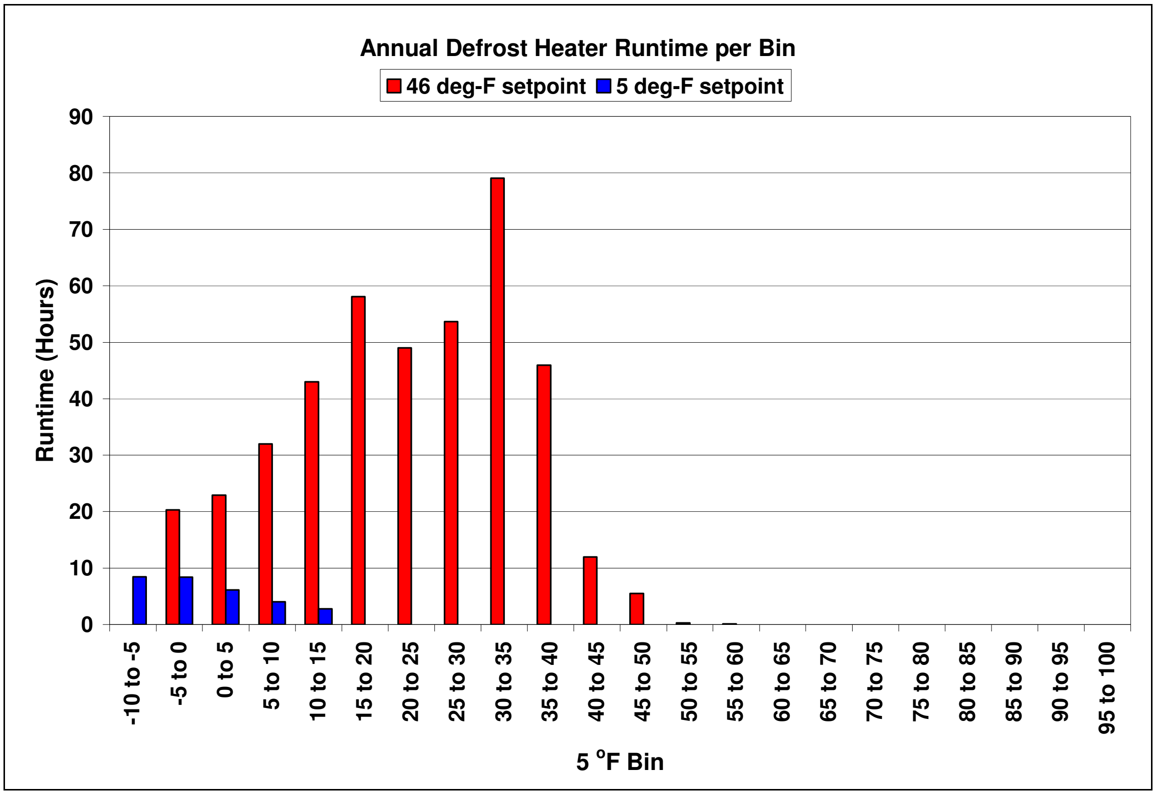


Figure 5.30. Annual runtime of ERV defrost heater in 5°F temperature bins.

Table 5.9 shows the energy and cost savings obtained by turning the set point of the thermostat down. Initially the defrost heater was using 4.8% of the building's annual energy use, but this was decreased to 0.3% by reducing the set point of the thermostat to 5 °F. The total annual runtime of the heater decreased from 420 hours to 30 hours, the annual energy use decreased from 5100 kWh to 360 kWh, and the annual cost of the electricity decreases from $278 to $20. Each of these is a 93% decrease. The cost savings is based on an average non-summer (excludes June, July, August and September) electric rate of $0.054/kWh obtained from electric billing statements from November 2004 through January 2008 (See Appendix F for over three years of monthly IAMU electric bill charges).

Table 5.9. Savings resulting from decreasing defrost heater set point from 46 °F to 5 °F.

	46 °F Heater Setpoint	5 °F Heater Setpoint	Percentage Decrease
Annual Runtime (Hr)	420	30	**93%**
Annual Energy (kWh)	5100	360	
Percentage of Building Energy	4.8%	0.3%	
Annual Cost	$278	$20	

5.4. Unoccupied General Equipment Loads

This final section of the experimental chapter discusses the energy used by the IAMU building's general equipment when the building is unoccupied. For this discussion, the building is considered unoccupied outside of normal business hours. The IAMU's regular office hours are from 8:00 am to 5:00 pm Monday through Friday. Therefore the time outside of these hours on weekdays, and all day on Saturday, Sunday, and holidays are the unoccupied periods. While employees occasionally come to work early, stay late, or come in on weekends, the building is still largely unoccupied outside of normal business hours. Section 5.4.1 gives a brief discussion of the general equipment in the IAMU building, section 5.4.2 describes the energy usage of the general equipment during unoccupied periods, and finally 5.4.3 outlines ways to reduce the general equipment's energy use during unoccupied periods.

5.4.1. General Equipment Description

The IAMU building contains a variety of general equipment ranging from electrical appliances in the kitchen, to computers and office equipment, to the building monitoring system and fire alarm system. For ease of monitoring the energy use of this equipment, breakers for general equipment, including plug outlets, were grouped together in three electrical panels. The general load meter monitors all plug loads and other electrical devices not included in the HVAC and lighting categories. Two notable exceptions should be noted. First, special plug outlets exist for task lighting that are monitored by the lighting power meter. The task lighting outlets have identifying labels, and employees are instructed to only plug task lighting into these outlets. Second, the seven electric unit heaters in perimeter locations and adjacent to entrances were mistakenly wired to electrical panels monitored by the general load meter instead of a panel monitored by the HVAC load meter. The effect of the unit heaters being on the general plug load meter will be discussed below. Appendix I contains a table with a complete listing of all the circuit breakers, including the breakers containing the unit heaters, monitored by the general load meter. The table gives a description of the type of load on the breaker. Some breakers serve multiple plug outlets, and in that case a listing of all the items plugged into the breaker is given. Other breakers serve a specific device hard wired to the breaker such as a water heater or the fire alarm system.

5.4.2. Unoccupied Hours General Equipment Energy Performance

Figure 5.31 shows a typical general load power profile taken from the week beginning on Sunday August 5, 2007. While a power measurement is taken every minute, the data for this figure as well as Figure 5.32 and Figure 5.33 were averaged over five minute intervals to smooth the data and make it more presentable. Figure 5.31 shows that a residual general equipment electrical demand between 2 kW and 3 kW remains in the building when the building is unoccupied during the night and on weekends. For the week shown in Figure 5.31, the average residual general equipment load during the weekend and unoccupied periods of week days is 2.7 kW. This residual load is nearly half the general equipment load when the building is occupied. The general power load sharply rises between 7:00 and 8:00 am as the building becomes occupied and then falls back to the residual level when the building becomes unoccupied between 5:00 and 6:00 pm. The peak five minute average load during the summer of 2007 was 8.3 kW and occurred on August 8 between 11:10 and 11:15 am. This peak load may be associated with using the stove and other kitchen appliances in preparation for lunch. Throughout the week the general load stays far below the design electric power density of 1.0 W/ft^2 which corresponds to a total building load of 12.5 kW.

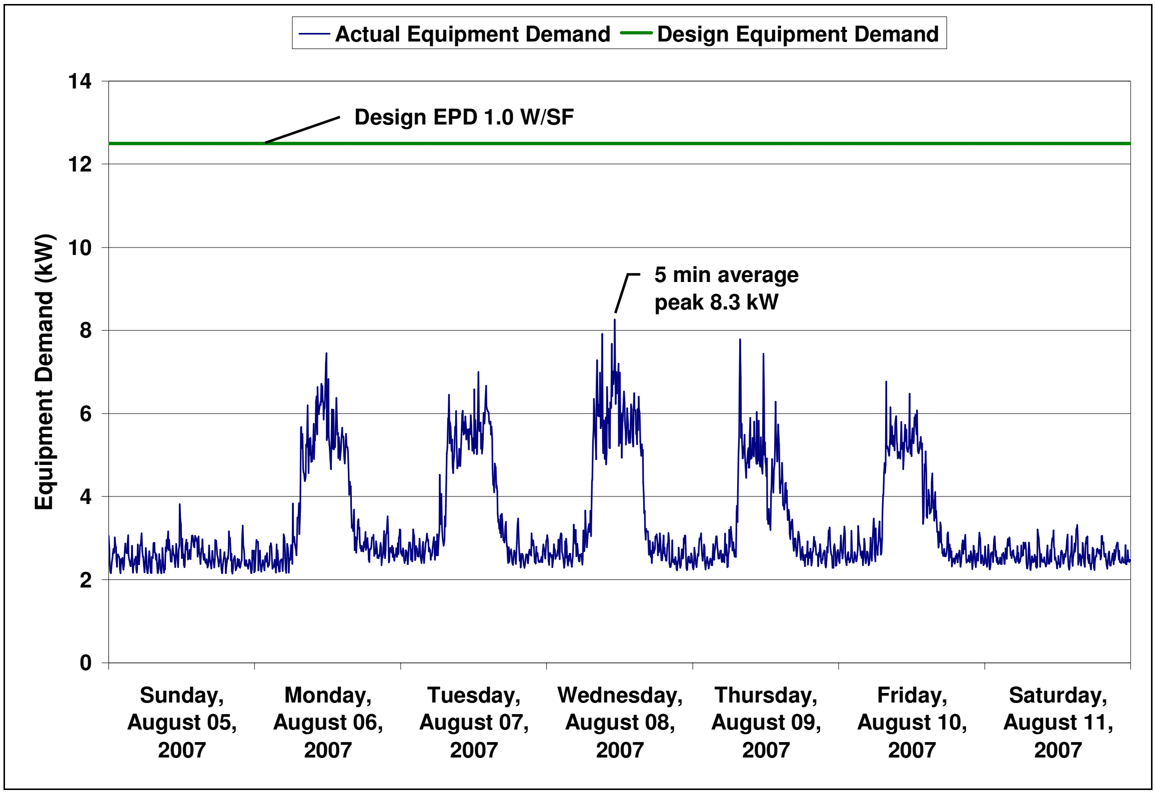


Figure 5.31. Summer general load meter power profile.

Figure 5.32 shows a typical general equipment load profile for a winter week. The winter load profile is more variable and is shifted to higher power levels compared to the summer profile; this is caused by the operation of the electric unit heaters during cold weather. The outdoor air temperature during this week ranged from a low of -9 ^{o}F on January 16 at 7:40 am and a high of 29 ^{o}F on January 19 at 2:30 pm. The winter of 2006-2007 maximum five minute average general equipment load of 21.7 kW occurred on January 16, 2007 between 7:55 and 8:00 am, and the maximum one minute load during this period was 24.6 kW. This corresponds to a time when the outdoor temperature was below -8 ^{o}F, and all unit heaters were likely running to heat up entrance areas as the employees arrived for work. The total connected power of the seven unit heaters is 13.9

kW. If this is subtracted from the maximum load of 24.6 kW, a load of 10.7 kW results, which is close to the maximum loads experienced in the summer when no unit heaters run. The variability of the plot indicates that unit heaters are frequently turning on and off. During this cold week, the unit heaters ran enough so that the residual unoccupied load of 2 to 3 kW is not apparent in the graph. The unit heaters cause the load profile to spike above the design electric power density of 1.0 W/ft^2. Note that the unit heaters are considered part of the HVAC load, but were mistakenly wired to an electrical panel monitored by the general load meter.

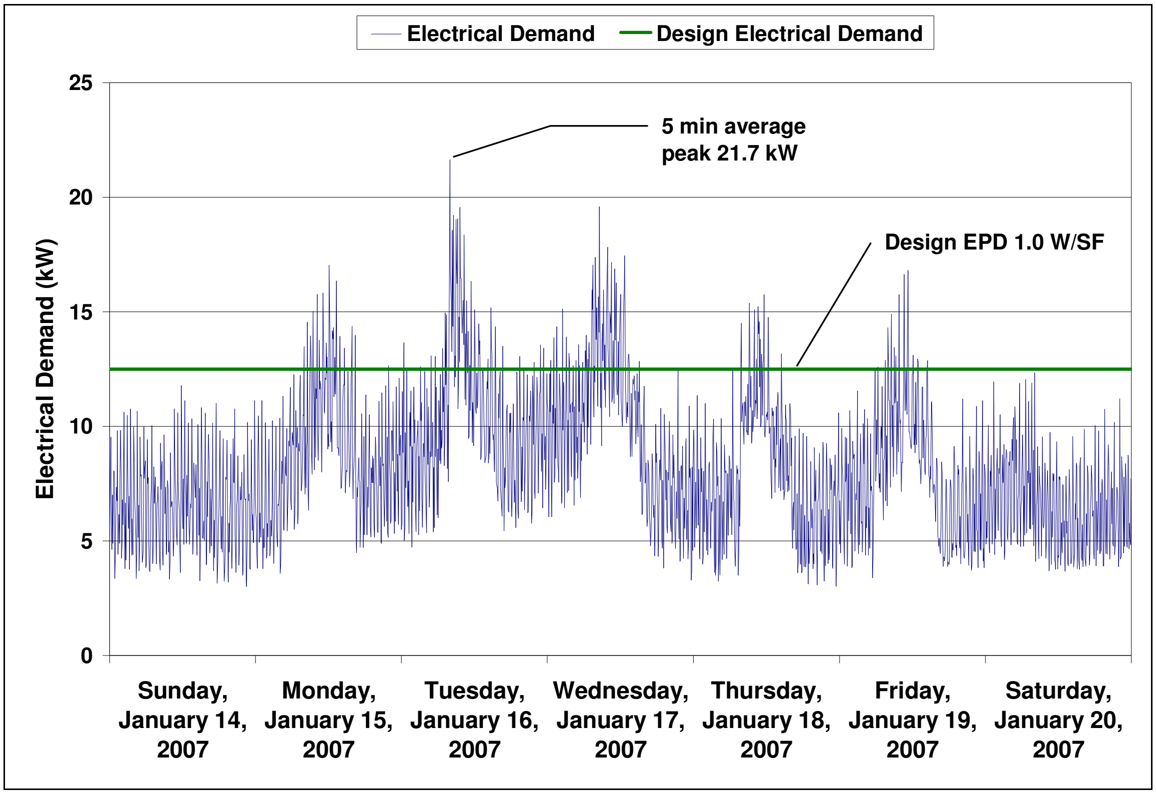


Figure 5.32. Winter general load meter power profile.

The 2 to 3 kW residual general equipment load when the office building is unoccupied represents a significant amount of the total general equipment load annual energy use. To learn what devices made up the residual load, a trip to the IAMU building was made on March 8, 2007 in the evening after all the employees had left. There, all of the devices connected to electrical breakers monitored by the general load meter were documented, and a power measurement of each of these breakers was taken.

The temperature on March 8 varied between 22 and 48 ^{o}F and therefore was cold enough for the unit heaters to operate. Because the unit heaters were mistakenly wired to electrical panels monitored by the general load meter, the heaters were turned off so that they would not interfere with the measurements. Figure 5.33 shows the period from 6:50 to 9:46 pm when the unit heaters were turned off. The large amount of variability in the power trend during the day before this period and the day after this period indicate that the unit heaters were running frequently when turned on. The average general equipment meter load during the period when the unit heaters were turned off was 2.74 kW, which corresponds well with the residual loads shown previously in Figure 5.31. Using a Fluke 41 power harmonics analyzer meter, the instantaneous power of each circuit breaker monitored by the general load meter was measured. The breaker schedules were then used to determine the equipment that was drawing power from each breaker. The table in Appendix I contains a list of all the general load breakers, the equipment supplied by each breaker, and the power measurements taken on each breaker. The total of all of the instantaneous power measurements was 2.64 kW, which is within 4% of the 2.74 kW average general equipment power usage recorded by the data acquisition system during the same time period. The 2.64 kW load also corresponds well with the average general equipment load of 2.7 kW for the unoccupied periods during the week of August 5 through the 11 as shown in Figure 5.31.

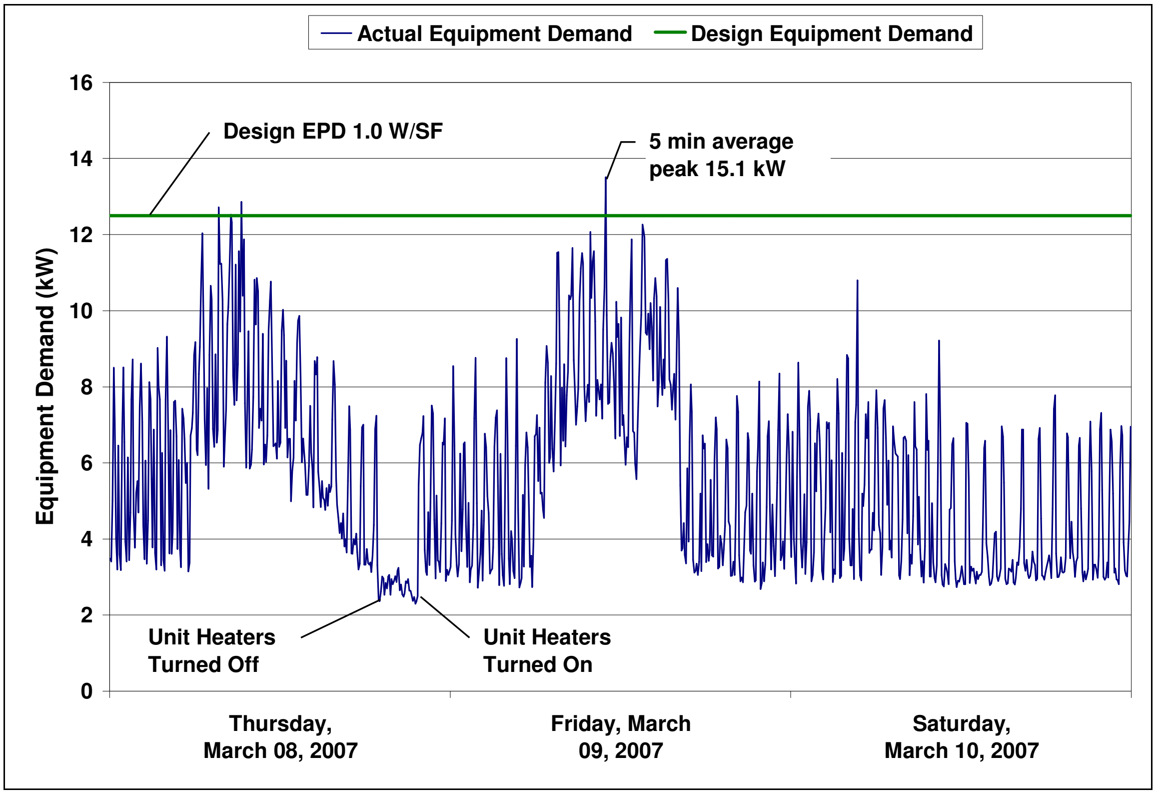


Figure 5.33. Winter general plug load profile showing unit heaters shut off from 18:50 to 21:46 on March 8, 2007.

The bottom row of Table 5.10 summarizes the energy usage and cost of the general load power usage during unoccupied periods. A 2.64 kW load during unoccupied hours will use 17,000 kWh of electricity annually. This is based on the building being unoccupied from 5:00 pm in the evening to 8:00 am on the next day during the week, all day on weekends, and all day for eight holidays. This results in 6588 hours or 75% of the time when the building is unoccupied and 2.64 kW of power is being drawn. The annual cost of the 2.64 kW residual load is $1,100 based on an average electricity cost of $0.065 per kWh. The 17,000 kWh of unoccupied hours general load makes up 53% of the total annual general load (including energy used by unit heaters), and 16% of all the energy used by the building in a year. The energy used by the general equipment when the building is unoccupied is not insignificant, and a large potential for savings exists if an attempt is made to decrease the general equipment unoccupied load.

Table 5.10. Unoccupied hours general equipment energy use.

Unoccupied General Equipment Load Type	Power (W)	Unoccupied Gen. Power (kW)	Annual Energy (kWh)	Annual Energy Cost	% Annual General Meter Energy	% Annual Building Energy
Nondiscretionary Loads:	1,200	47%	8,100	$530	25%	7.6%
Discretionary Common Loads:	710	27%	4,700	$300	14%	4.3%
Discretionary Personal Loads:	710	27%	4,700	$300	14%	4.4%
Total Off Hour Electrical Load:	**2,600**	**100%**	**17,000**	**$1,100**	**53%**	**16%**

5.4.3. General Equipment Energy Performance Improvements

To determine the potential for saving energy by turning off equipment during unoccupied times, the general equipment was classified into three different categories: nondiscretionary (N), discretionary communal (DC), and discretionary personal (DP). Nondiscretionary equipment is equipment that must remain on when the building is unoccupied. This includes a computer server that must remain remotely accessible at all times, refrigerators required to keep food fresh, the fire alarm system, and other devices. Because this equipment must remain on at all times, there is no potential for energy savings by simply turning it off. In some cases an evaluation to determine if more efficient equipment is available or if the piece of equipment is necessary may be appropriate. Discretionary communal equipment is equipment used communally by the office staff, and can be turned off when the building is unoccupied. This equipment includes copiers, printers, and the coffee pot. Because many people use a piece of communal equipment it many be difficult to determine when it should be shut off, and it has a decreased likelihood that it will be turned off. It would be difficult to designate a person and a time to shut the piece of equipment off since employees' work schedules are varied. Discretionary personal equipment is equipment used by a single person and can be turned off during unoccupied times. This equipment includes personal computers, radios, fans, and other items in personal offices. Discretionary personal equipment has the greatest potential for being turned off during unoccupied times since only one person uses it and can turn it off when they are finished with it for the day. The table in Appendix I lists whether a breaker serves a nondiscretionary, discretionary personal, or discretionary communal load.

Table 5.10 summarizes the energy use and energy cost of the three categories of general equipment loads during unoccupied periods. Nondiscretionary loads account for 47% of the unoccupied general equipment load while discretionary communal and personal discretionary loads each account for 27% of the load. Therefore there is an opportunity to save up to 9400 kWh and $600 a year by turning off discretionary equipment during unoccupied periods. This would reduce the entire building's annual energy use by 9%. Turning equipment off has no first cost and will have an immediate payback.

Table 5.11 contains a sample of general equipment whose energy use was monitored using a "Kill-a-Watt" meter. This is a meter that plugs into an outlet, and the piece of equipment to be monitored is then plugged into the meter. The "Kill-a-Watt" meter monitors voltage, current, frequency, power, total energy consumed and time since the device was plugged in, power factor, apparent power. An employee of the IAMU monitored office equipment using the "Kill-a-Watt" meter to help teach employees how much energy the equipment uses. The table lists the average power used by each piece of equipment during the monitoring period, predicted total annual energy use (average power * 8760 hr/year), the percentage of total building annual energy use based on the average energy use of the building from 2001 to 2007, and the annual cost of running the appliance, based on an average electricity rate of $0.065/kWh. The total percentage of annual building energy use of the any one appliance does not exceed 1.1%, but together the appliance make up an appreciable amount of the annual energy use.

Table 5.11 is not a comprehensive listing of all the appliances in the IAMU office building, rather it offers examples of just some of the equipment for which energy savings are possible.

Table 5.11. Sample appliance energy use.

Description	Remarks	Average Power (W)	Annual Energy (kWh)	% of Annual Building Energy	Annual Energy Cost
Copier/printer (DC)	Weekend, no energy saver Weedays	137 137	1200	1.1%	$ 78
Vending machine (N)	VendMiser off	133	1200	1.1%	$ 76
	VendMiser on	93	810	-	$ 53
Coffee Maker (DC)	Keeps water hot 24/7	125	1100	1.0%	$ 71
2 Office Printers (DP)	Weekdays, left on at night	92	570	0.5%	$ 46
	Weekend left on	53	130	0.1%	
Fridge, Back Room (N)	Secondary Fridge	85	740	0.7%	$ 48
Fridge in Kitchen (N)	Primary Fridge	85	750	0.7%	$ 48
Typewriter (DP)	On all day	23	200	0.2%	$ 13
TV/VCR Cart (DC)	Cart plugged in, TV and VCR off	16	140	0.1%	$ 9
Laser Jet Printer (DP)	Weekdays, off at night/weekends	12	110	0.1%	$ 6

Table 5.12. Sample appliance energy savings

Description	Savings Method	Savings (kWh)	Savings
Copier/printer (DC)	Cut power nights/weekends	880	$ 57
Vending machine (N)	Replace vending machine with high efficiency fidge	640	$ 42
Coffee Maker (DC)	Cut power nights/weekends	800	$ 52
2 Office Printers (DP)	Cut power nights/weekends	490	$ 32
Fridge in Back Room (N)	Replace with High efficiency fridge	570	$ 37
Fridge in Kitchen (N)	Replace with High efficiency fridge	570	$ 37
Typewriter (DP)	Cut power nights/weekends	150	$ 10
TV/VCR Cart (DC)	Cut power nights/weekends	100	$ 7
Laser Jet Printer (DP)	No savings likely		

Table 5.12 shows steps that can be taken to decrease the energy use of some of the appliances and the resulting savings.

1. A copier/printer with no energy saver mode and which is not turned off during unoccupied times uses 1.1% of the building's annual energy. Turning the copier off during periods when the building is unoccupied would save 880 kWh and $57 annually.

2. The vending machine uses a Vending Miser device that has an occupancy sensor that turns on the vending machine when the area is occupied but turns the vending machine off when the area is unoccupied. In addition, the Vending Miser monitors ambient temperature and turns on the vending machine when necessary to keep the product cool. The Vending Miser saves 350 kWh of energy a year, or 30% of the energy the vending machine would use without the device. Recently, the vending machine was replaced with a new high efficiency fridge. The fridge uses an average of 20 W compared to the vending machine with the Vending Miser's average of 93 W. The fridge saves 640 kWh and $42 per year compared to the vending machine with the Vending Miser or 990 kWh and $64 annually compared to the vending machine without the Vending Miser. It would not be practical to turn the fridge off at night.
3. The coffee maker automatically maintains a tank of hot water at all times and consumes 1091 kWh of energy a year. By putting the coffee pot on a timer to produce hot water only during occupied periods, 800 kWh and $52 could be saved.
4. Two desktop office printers in a private office are left on at all times and do not have an energy saving mode. Turning these off when the building is unoccupied could save 490 kWh and $32.
5. The fridge in the storage room and the fridge in the kitchen use between 740 and 750 kWh of energy a year respectively. While the fridges cannot be turned off at night, replacing them with new high efficiency fridges, like the one that replaced the vending machine, would annually save 570 kWh and $37 each.

6. An electric typewriter that remains on at all times could be turned off during unoccupied periods and save 150 kWh and $10.
7. A cart with a plugged in but turned off TV and VCR uses 138 kWh. Unplugging these devices when the building is unoccupied would save 100 kWh and $7. Only plugging the TV and VCR in when they are used would present even greater savings.
8. A desktop laser jet printer uses an average of 12 W during the day, but it is shut off during the night and on weekends. Therefore there are no potential savings for the printer.

If all of the energy saving steps in the list above—cutting power to unneeded equipment during unoccupied periods, replacing the vending machine with an efficient refrigerator, and replacing the two old refrigerators with new refrigerators—were undertaken, it is predicted that 4200 kWh of energy would be saved annually. This would cause a 4% reduction in annual energy consumption, and save $280 in annual energy costs. This shows that although each piece of equipment uses 1.1% or less of the building's annual energy, the cumulative savings from multiple pieces of equipment can be significant. The opportunity for energy savings is not limited to the equipment listed in Table 5.11, Table 5.12, and the list above. As mentioned above, by merely turning off all the discretionary communal and discretionary personal equipment in the building when it is unoccupied, there is a potential to save 9300 kWh of energy a year. This would result in a nearly 9% reduction in building energy use and save $620 a year. Additional savings could be achieved by replacing old equipment with new more efficient equipment.

Chapter 6. Conclusion

This study has demonstrated that the Iowa Association of Municipal Utilities' headquarters is a low energy office building, but that it also has room for significant improvements in the energy performance of the GSHP system's circulating pump, the ERV's defrost heater, and the unoccupied general equipment load. In a conventional office building constructed without the energy efficiency items of the IAMU building, these three items would only make small contributions to the total building energy use. Because the IAMU building was designed to be a low energy building, and these three energy uses did not receive energy efficiency measures, they consumed 38% of the building's average annual energy use of 107,300 kWh. Table 6.1 summarizes the energy usage of each of the three items before and after the energy efficiency enhancements were made, and the savings obtained for each item. The savings sited for general equipment during unoccupied periods are the potential savings if all discretionary equipment is turned off during unoccupied periods of the building. It is predicted that up to 29,000kWh or 72% of the energy used by the three items can be saved, for total building annual energy savings of 27%. This would result in an annual cost savings of $1850. If the energy savings from turning off discretionary equipment during unoccupied periods is not achieved, then the savings from installing the VFD on the circulating pump and turning the set point of the ERV's defrost heater down will save 18% of the building's annual energy and have an annual cost savings of $1250.

Table 6.1. Summary of IAMU building energy enhancements.

	Before Changes		**After Changes**			
Annual Building Energy: 107,300 kWh	**Annual Energy (kWh)**	**% of Total Building Energy**	**Annual Energy (kWh)**	**Cost Savings**	**% Savings**	**% Savings of Building Energy**
Circulating Pump	18200	17%	3100 to 4100	$920 to $990	77% to 83%	13% to 14%
Defrost Heater	5100	5%	360	$260	93%	4%
Unoccuped Period General Equipment	17400	16%	8100*	$600*	53%*	9%*
*Savings potential if all discretionary equipment is turned off during unoccupied periods						

The introduction of this report contained three objectives. Below is a discussion of how these objectives were met:

Objective 1: Give an overview of the work being done in low energy building through a literature review.

Outcome 1: The literature review in Chapter 2 shows that considerable work is under way to reduce the energy use of buildings. The 2007 Buildings Energy Data Book states that in 2005 U.S. buildings used 39.7 quads of primary energy, or 40% of the U.S.'s total primary energy consumption (DOE 2007). Commercial buildings used 18% of the total primary energy and residential buildings used 22% of the total primary energy. The energy use of U.S. buildings contributes to 39% of U.S annual carbon emissions and 9% of global annual carbon emissions. The growing demand for limited energy supplies, the growing cost of energy, and the pollution caused by the production and use of energy motivate research in low energy buildings.

The literature review revealed that several phrases are frequently used to refer to low energy buildings. These include 'high performance building', 'green building', and 'sustainable building'. A high performance building is simply a building that performs its tasks in an exceptional way. High performance buildings are the result of careful design that integrates the function of building systems so that they complement each other. Because low energy buildings by definition perform their functions with exceptionally low energy, they are frequently termed high performance buildings. The phrases 'green building' and 'sustainable building' are synonymous, and refer to buildings that have significantly reduced impacts on the natural environment in five categories: site development, water savings, energy efficiency, materials selection, and indoor environmental quality (USGBC 2005). Because energy efficiency is one of the qualifications of a green building, a low energy building is frequently referred to as such.

The U.S. Department of Energy is seeking to develop cost effective paths to net-zero energy building by 2025. A net-zero energy building is a building that uses renewable energy sources and grid connected energy sources to obtain its energy, but the amount of energy used from the gird must equal the amount of excess onsite produced renewable energy fed back into the grid. A study performed by Griffith et al. found that with technical improvements, 70% of all commercial buildings could be net-zero energy by 2025 (2006). Significant work has been done to determine characteristics of low energy buildings, and many guides are available to the practitioner on low energy building design, design optimization, and building energy monitoring. Ongoing case studies of low energy and zero energy buildings provide insights into what design features work and what design features don't work.

Objective 2: Document that the IAMU building is a low energy building by:

a) Presenting how a focus on energy efficiency by the design team led to a building with energy efficiency integrated into all of its systems.

b) Presenting building monitoring data that reveal that the IAMU building uses significantly less energy than typical office buildings.

Outcome 2: Chapter 3 contains information on the design of the IAMU office building and the energy efficiency systems that were incorporated into the building. The use of DOE-2 building energy simulation software facilitated an integrated design approach and allowed the most cost effective efficiency measures to be chosen. Integrated design focused on first reducing the heating, cooling, and lighting loads of the building, then picking the most efficient equipment for the building, then controlling and operating the building in a way that minimized energy use (McDougall et al. 2006). Energy efficiency measures in the building include:

- The building envelope was designed to minimize building load with spray foam insulation in the walls, a highly insulated roof, and strategically placed windows with low U-values.
- Building architecture and window placement maximizes daylighting within building. Dimming controls and occupancy sensors control lights to supplement daylighting only when needed. Shading devices are used to limit direct sunlight from passing through the windows.
- Efficient ground coupled heat pumps are used to condition the building, and an energy recovery ventilator is used to provide fresh air to the building.

Chapter 4 contains the results of monitoring the energy use of the building for six years from 2002 through 2007. The data clearly shows that the IAMU building uses significantly less energy than a typical office building. The IAMU's average EUI of 29,300 Btu/ft$^{2}\cdot$yr is 68% less than the EUI of an average U.S. office building and 74% less than the EUI of an average office building in climate zone 2. According to an energy simulation using DOE-2, the IAMU building uses an 55% less energy annually and has a 52% lower annual energy cost than an equivalent building designed to minimally meet the contemporary energy code.

Objective 3: Identify three systems within the building where energy efficiency improvements can be made. Each energy use will correspond to one of the three building phases within which building energy use is determined.

a) Provide complete description of system

b) Present monitored energy performance data for system

c) Make changes to systems to improve energy performance

d) Document changes in energy performance

Outcome 3: The energy use of the GSHP system's circulating pump, the ERV's defrost heater, and the unoccupied hours' general equipment loads were documented and steps were taken to reduce them. The energy use of the GSHP system's circulating pump corresponds to an energy use determined during the design phase of the building. The ERV's defrost heater's energy use was determined during the design implementation phase of the building when the ERV was installed. The energy use of the general equipment is being determined now during the occupancy phase of the building. A summary of the how the objectives were met for each system follows:

GSHP Circulating Pump

a) The GSHP system consists of eight four ton water to air heat pumps connected to a ground heat exchanger with 33 175 ft deep vertical bores. The ground heat exchanger provides a heat source for the heat pumps during the heating season and a heat sink for heat pumps during the cooling season. A 3 HP pump circulates a water-antifreeze mixture heat exchange fluid between the heat pumps and the ground heat exchanger. In the original configuration, the circulating pump operated at a constant speed, and provided a nominal 11.25 GPM of flow to all heat pumps at all times. Automatic balancing valves were used to ensure all heat pumps received the same flow rates.

a. The constant speed circulating pump had a constant power demand of 2.1 kW and used 18,200 kWh of energy per year with a cost of $1200. This corresponded to 35% of the annual HVAC system energy use, and 17% of the total building's annual energy use. Analyzing the operation of the heat pumps, it was found that eight heat pumps only operate for 0.2% of the time, while no heat pumps operate for 54% of the time. This showed that sizeable energy savings could be obtained if the circulating pump was controlled to provide only enough flow required by the operating heat pumps.

b) To decrease the energy use of the circulating pump, a variable frequency drive was installed to control the speed of the pump motor, and shutoff valves were installed on seven of the eight heat pumps. When a heat pump turns off, its shutoff valve closes, and the VFD decreases the speed of the pump to maintain a constant 9 GPM flow rate to the heat pumps that continue to operate. The VFD is controlled by a differential pressure sensor located across the supply and return lines of the heat pump HP-V1. The VFD has an internal PID control loop that seeks to maintain a set point signal from the differential pressure sensor. Because the control system cannot turn the VFD/pump on and off, one heat pump does not have a shutoff valve and flow is maintained to the heat pump even when it is off.

c) Over the period of nearly 67 days from the end of December 2007 to the end of February 2008, the VFD/pump consumed 965 kWh of energy compared to 3300 kWh if the pump had not been controlled by the VFD. This represents a 71% decrease in pumping energy during this time period. For an entire year, it is predicted that the VFD/pump would consume between 3100 and 4100 kWh compared to the 18,200 kWh it would consume without the VFD. The VFD would provide between a 77% and 83% annual pumping energy savings and save between $920 and $990 in electric costs per year. Because the circulating pump had been using 17% of the annual total building's energy, the VFD will decrease the building's annual energy consumption about 13%.

ERV Defrost Heater

a) The 12.2 kW defrost heater on the ERV is used to prevent the frosting of the enthalpy wheel when it is exposed to cold outdoor air. The heater is controlled by a thermostat located in the air stream between the heater and the enthalpy wheel. Based on typical wintertime exhaust air temperatures and relative humidity levels, the manufacturer states that frost will not form on the wheel until the outside air temperature drops below -10 ^oF, but the thermostat was set to 46 ^oF during installation. This resulted in unnecessary operation of the operation of the defrost heater.

b) Using the monitored ERV current as an indicator of when the defrost heater operated, the percentage of time the heater operated in 5 ^oF temperature bins was determined. Then multiplying these percentages by the number of hours in the temperature bins during ERV operating hours, the typical number of hours the heater operates in each temperature bin was found. During a typical year the defrost heater would operate for 420 hours, consume 5100 kWh of energy and cost $280. At the original set point, the defrost heater consumed nearly 5% of the building's annual energy.

c) Because the frost threshold given by the manufacturer was -10 ^oF, the defrost heater set point was turned down to 5 ^oF. This set point provides a margin of safety for the defrost heater.

d) Using the same analysis of the monitored ERV current as above, it was determined that the defrost heater would only run for 30 hours in a typical year and use only 360 kWh of energy with a cost of $20 after its set point was decreased to 5 °F. This represents a 93% decrease in the energy consumption of the heater, and it is predicted that the heater will now use less than 1% of the building's annual energy.

Unoccupied General Plug Loads

a) The general equipment in the IAMU building is typical of many small office buildings—computers, printers, copiers, a coffee pot, drinking fountains, etc. Also included in the general equipment is a kitchen with two refrigerators, a small computer server room, and a third refrigerator used to dispense soft drinks. Monitoring the general equipment load of the IAMU building revealed a base load of about 2.6 kW when the building is unoccupied. This base load is nearly a third of the typical summertime peak general equipment load during the day. (The summertime peak load is specified because unit heaters, which were mistakenly wired to be monitored by the general equipment meter instead of the HVAC meter, interfere with determining the peak general equipment load in the winter.) A general equipment base load between 2 and 3 kW has been present since building energy monitoring began.

b) The 2.6 kW general equipment demand during unoccupied periods uses 17,400 kWh of electricity a year and costs $1,100. This is 16% of the annual building energy use. The general equipment loads were divided into three categories: nondiscretionary, discretionary communal, and discretionary personal. A nondiscretionary general equipment load is a piece of equipment that must remain on during the unoccupied periods. This category includes refrigerators and the computer server equipment. Discretionary communal equipment is equipment that can be turned off during unoccupied periods and is communally shared with the entire office staff. Copy machines, some printers, and the coffee pot fall into this category. Finally, discretionary personal equipment is equipment that can be turned off during unoccupied periods and is used by only one person. Any equipment that an employee uses in their office, such as computers, falls into this category. A survey of the equipment left on during unoccupied hours revealed that nondiscretionary loads made up 47% of the unoccupied hours general equipment loads, and communal discretionary and personal discretionary loads both contributed 27%.

c) Although, direct changes were not made to the equipment that is turned off during unoccupied periods, the staff was educated on the importance of turning equipment off when the building will be unoccupied. Several pieces of equipment were monitored by the staff to learn how much energy they used. Most pieces of office equipment used between a few tenths of 1% and 1% of the building's annual energy if left on during unoccupied periods.

d) There is significant potential to reduce the energy use of the building by shutting off as much general equipment as possible when the building is unoccupied. Both the discretionary communal and discretionary personal loads contribute a little more than 4% of the buildings annual energy use. If all of these pieces of equipment were turned off during unoccupied hours, 1400 kWh of energy and about $600 a year could be saved. This would reduce the building's energy use by about 9%.

Recommendations

1. Even though the IAMU building is a low energy building, monitoring revealed areas where significant reductions in energy use could be achieved. This report documented three of these areas and the steps taken to reduce their energy use. Two of the changes made—reducing the set point of the ERV's defrost heater and turning off general equipment when the building is unoccupied—had no expense but combined could save $850 a year. The addition of the VFD to the GSHP system's circulating pump had an expense, but was still a relatively simple project. The VFD is predicted to save up to $990 a year in electricity costs. Based on these observations, it is recommended that all buildings, whether new or old, designed to be efficient or not, be monitored to reveal areas for energy efficiency enhancements. The monitoring does not need to involve a data acquisition system and take place over many years; it can be done quickly with handheld instruments. Energy efficiency enhancements can be made to all buildings if the opportunities are looked for.

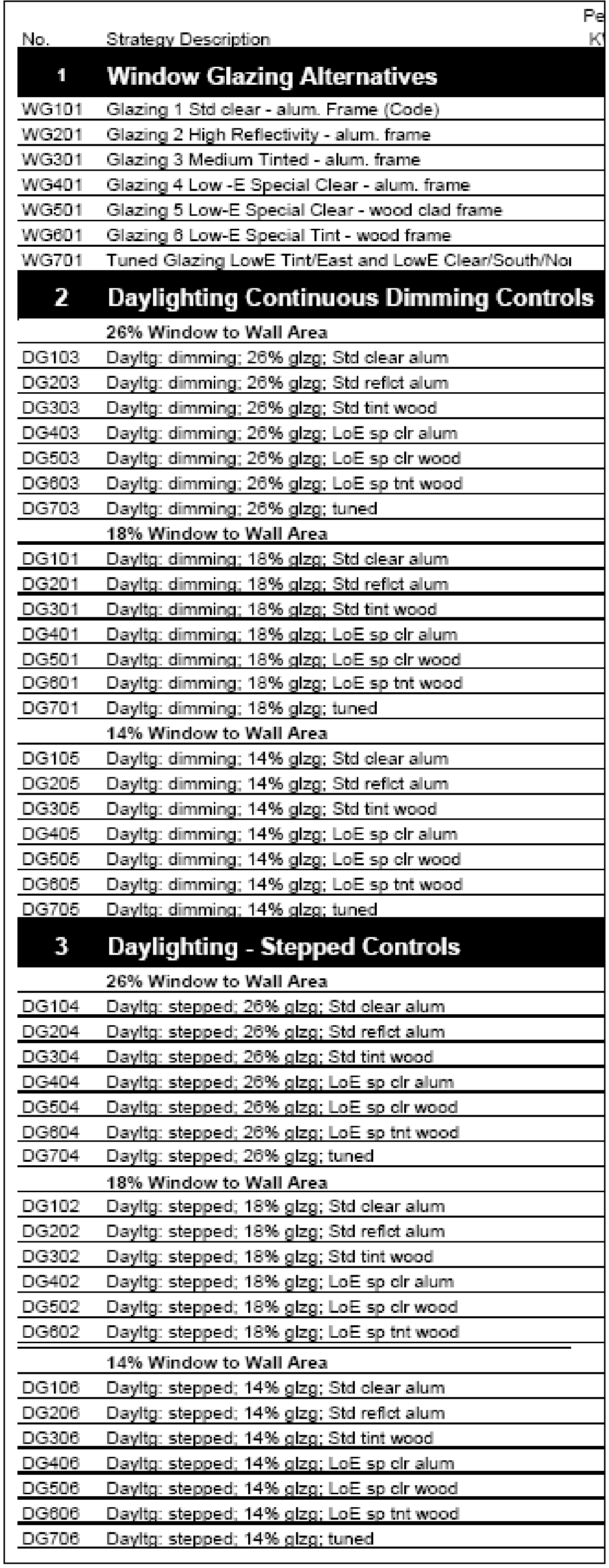
2. Although the energy use of the GSHP system's circulating pump has been significantly reduced, further energy savings could be achieved if the pump could be turned off when all the heat pumps are off. When all the heat pumps are off, the VFD/pump still supplies flow to HP-V2. During the 4700 hours per year that no heat pumps operate, the VFD/pump would consume 1200 kWh of energy at a cost of $80. This energy and cost could be saved if an

inexpensive and reliable method of turning the VFD/pump off and on can be found.

3. This report documented three areas where the energy use of the IAMU building can be reduced, but there are many other areas where energy savings could be achieved. Some areas that should be explored for further savings are:
    a. The dimming lighting controls can dim the lights to 20% full output, but cannot dim them any further or turn them off when a large amount of daylight is available. The energy savings from a control strategy that can further dim the lights and/or turn the lights off should be investigated.
    b. The ERV does not have an economizer mode, and it is known that it sometimes preheats ventilation air when the building requires cooling. The energy savings and economics of an ERV economizer mode should be investigated.
    c. The IAMU building's slab does not have insulation around its edge. This creates a thermal bridge that greatly increases the heating load of building. An investigation to quantify the increase in heating load due to the lack of insulation and determine potential solutions for installing insulation should be undertaken.
    d. It is known that the original balancing of airflow provided too little air to some locations of the building and too much air to other areas. This causes thermal discomfort in some areas; particularly several offices are especially cold in the winter. Load calculations on the building should be done, and the airflow should be rebalanced. This will provide greater comfort in the building and may reduce the HVAC energy use by allowing thermostats to be set lower in the winter or higher in the summer.

Appendix A. DOE-2 Modeled Energy Efficiency Strategies

Table A.1. Individual energy efficiency strategies modeled in DOE-2 (The Weidt Group 1998).



No.	Strategy Description	Pe K
1	**Window Glazing Alternatives**	
WG101	Glazing 1 Std clear - alum. Frame (Code)	
WG201	Glazing 2 High Reflectivity - alum. frame	
WG301	Glazing 3 Medium Tinted - alum. frame	
WG401	Glazing 4 Low -E Special Clear - alum. frame	
WG501	Glazing 5 Low-E Special Clear - wood clad frame	
WG601	Glazing 6 Low-E Special Tint - wood frame	
WG701	Tuned Glazing LowE Tint/East and LowE Clear/South/No	
2	**Daylighting Continuous Dimming Controls**	
	26% Window to Wall Area	
DG103	Dayltg: dimming; 26% glzg; Std clear alum	
DG203	Dayltg: dimming; 26% glzg; Std reflct alum	
DG303	Dayltg: dimming; 26% glzg; Std tint wood	
DG403	Dayltg: dimming; 26% glzg; LoE sp clr alum	
DG503	Dayltg: dimming; 26% glzg; LoE sp clr wood	
DG603	Dayltg: dimming; 26% glzg; LoE sp tnt wood	
DG703	Dayltg: dimming; 26% glzg; tuned	
	18% Window to Wall Area	
DG101	Dayltg: dimming; 18% glzg; Std clear alum	
DG201	Dayltg: dimming; 18% glzg; Std reflct alum	
DG301	Dayltg: dimming; 18% glzg; Std tint wood	
DG401	Dayltg: dimming; 18% glzg; LoE sp clr alum	
DG501	Dayltg: dimming; 18% glzg; LoE sp clr wood	
DG601	Dayltg: dimming; 18% glzg; LoE sp tnt wood	
DG701	Dayltg: dimming; 18% glzg; tuned	
	14% Window to Wall Area	
DG105	Dayltg: dimming; 14% glzg; Std clear alum	
DG205	Dayltg: dimming; 14% glzg; Std reflct alum	
DG305	Dayltg: dimming; 14% glzg; Std tint wood	
DG405	Dayltg: dimming; 14% glzg; LoE sp clr alum	
DG505	Dayltg: dimming; 14% glzg; LoE sp clr wood	
DG605	Dayltg: dimming; 14% glzg; LoE sp tnt wood	
DG705	Dayltg: dimming; 14% glzg; tuned	
3	**Daylighting - Stepped Controls**	
	26% Window to Wall Area	
DG104	Dayltg: stepped; 26% glzg; Std clear alum	
DG204	Dayltg: stepped; 26% glzg; Std reflct alum	
DG304	Dayltg: stepped; 26% glzg; Std tint wood	
DG404	Dayltg: stepped; 26% glzg; LoE sp clr alum	
DG504	Dayltg: stepped; 26% glzg; LoE sp clr wood	
DG604	Dayltg: stepped; 26% glzg; LoE sp tnt wood	
DG704	Dayltg: stepped; 26% glzg; tuned	
	18% Window to Wall Area	
DG102	Dayltg: stepped; 18% glzg; Std clear alum	
DG202	Dayltg: stepped; 18% glzg; Std reflct alum	
DG302	Dayltg: stepped; 18% glzg; Std tint wood	
DG402	Dayltg: stepped; 18% glzg; LoE sp clr alum	
DG502	Dayltg: stepped; 18% glzg; LoE sp clr wood	
DG602	Dayltg: stepped; 18% glzg; LoE sp tnt wood	
	14% Window to Wall Area	
DG106	Dayltg: stepped; 14% glzg; Std clear alum	
DG206	Dayltg: stepped; 14% glzg; Std reflct alum	
DG306	Dayltg: stepped; 14% glzg; Std tint wood	
DG406	Dayltg: stepped; 14% glzg; LoE sp clr alum	
DG506	Dayltg: stepped; 14% glzg; LoE sp clr wood	
DG606	Dayltg: stepped; 14% glzg; LoE sp tnt wood	
DG706	Dayltg: stepped; 14% glzg; tuned	

Table A.1 continued. Individual energy efficiency strategies modeled in DOE-2 (The Weidt Group 1998).

4	**Envelope Insulation Levels**
ER3W1	R-30 roof insulation
ER4W1	R-38 roof insulation
ER2W2	R-16 wall insulation
ER2W3	R-20 wall insulation
5	**Lighting Controls**
LCPO1	Office occup. sensor control
LCCN1	Conf/Training occup. sensor control
LCCN2	Conf/Training dual level switching
LCST1	Storage /Restroom Occupancy sensor
LCAU1	Auditorium manual dimming
LCAU2	Auditorium occupancy sensor control
LCAU3	Auditorium dual level switching
LCSH1	Shop occupancy sensor control
LCSH2	Shop dual level switching
6	**Lighting Design Alternatives**
LDPO1	Office direct system at 70 fc
LDPO2	Office direct system at 50 fc
LDPO3	Indirect system at 50 fc
LDPO4	Task/ Ambient at 25 to 30 fc ambient; 0.2 to 0.3 W/sf Tas
LDPO5	Office direct/indir, 85% reflct ceiling, 45 fc
LDCN1	Conference direct system at 70 fc
LDCN2	Conference direct system at 50 fc
LDCN3	Conference indirect system at 50 fc
LDCN5	Conference direct/indir, 85% reflct ceiling, 45 fc
LDAU1	Auditorium Direct Compact Fluorescent 60 fc
LDAU2	Auditorium Indirect system 40 fc
LDSH1	Shop - Industrial Fluorescent 50fc
LDSH2	Shop - HID 70 fc
7	**Mechanical Efficiency Levels**
MCH01	Recip chiller, 5% decr KW/ton, air cooled
MCH02	Scroll chiller, 10% decr KW/ton, air cooled
MLR02	VFD's on supply & return air fans
MLR03	VFD on htg pump
MHT01	Modular gas boiler 83% effic
MHT02	Modular gas boiler 92% effic
MCH03	Scroll chlr, VFD's on fans/pumps, 92% blr
MHP05	Water ht pmp w/ econo, VFD, 92% blr
9	**Conditioning of Outside Air**
MOA02	CO2 control of outside air
MOA03	Occup ctrl VAV/ outside air

Appendix B. IAMU Data Acquisition Points List

Table B.1. Points connected to controller in north equipment room.

Data Point	Description	Point Name	Units	Monitoring Device	Manufacturer	Model Number	Output	Remarks
1	Lighting Power to Lighting Panels	LiteMtr-kWh	KWH	Power Meter	Veris Industries	H8036/100	Modbus	MDP feeders to 1A and 1C
2	General Power to Plug Load	GenMtr-kWh	KWH	Power Meter	Veris Industries	H8036/100	Modbus	MDP feeders to 1A and 1B
3	HVAC Power to HVAC Equipment	HVACMtr-kWh	KWH	Power Meter	Veris Industries	H8036/300	Modbus	MDP feeders to 2B
4	Maint Power to Maintenance Bldg	MtncMtr-kWh	KWH	Power Meter	Veris Industries	H8036/300	Modbus	MDP feeders to SP
5	South Driveway Lighting	DriveLite	Amps	Current Transducer	Veris Industries	H931	4-20 ma	Locate in Panel
6	Building Facade & West Driveway Lighting	FacadeLite	Amps	Current Transducer	Veris Industries	H720	4-20 ma	Locate in Panel
7	Parking Lot and Sidewalk Lighting	ParkingLite	Amps	Current Transducer	Veris Industries		4-20 ma	Locate in Panel
8	N Wing NorthEast Office Lite Level	NEOff_Lite	FC	Light Sensor	Celestial	MK7-B	0-10 VDC	Mount with Lite Controller
9	N Wing Center Office Lite Level	NCOff_Lite	FC	Light Sensor	Celestial	MK7-B	0-10 VDC	Mount with Lite Controller
10	N Wing South Office Lite Level	NSOff_Lite	FC	Light Sensor	Celestial	MK7-B	0-10 VDC	Mount with Lite Controller
11	N Wing North Office Temp	NNOff_Temp	Deg F	Platinum RTD	Weed	1000 ohm	RTD	Mount Under Thermostat
12	N Wing Center Office Temp	NCOff_Temp	Deg F	Platinum RTD	Weed	1000 ohm	RTD	Mount Under Thermostat
13	N Wing South Office Temp	NSOff_Temp	Deg F	Platinum RTD	Weed	1000 ohm	RTD	Mount Under Thermostat
14	N Wing S Office Temp	Nconf_Temp	Deg F	Platinum RTD	Weed	1000 ohm	RTD	Mount Under Thermostat
15	HX OA Entering Air Temp	ERU_OAEAT	Deg F	Platinum RTD	Weed	Combo	RTD&Therm	Locate in HX Unit
16	HX OA Leaving Air Temp	ERU_OALAT	Deg F	Platinum RTD	Weed	Combo	RTD&Therm	Locate in OA Supply Duct
17	HX EA Entering Air Temp	ERU_EAEAT	Deg F	Platinum RTD	Weed	Combo	RTD&Therm	Locate in EA Duct
18	HX EA Leaving Air Temp	ERU_EALAT	Deg F	Platinum RTD	Weed	Combo	RTD&Therm	Locate in HX Unit
19	HX OAFan EAFan & ElecHeat Amps	ERU_Amps	Amps	Current Transducer	Veris Industries	H921	4-20 ma	Locate in Elec Panel
19	Total for Electrical Room Controller		15	Analog Inputs		4	Modbus Network connections	

Table B.2. Points connected to controllers in south equipment room.

Data Point	Description	Point Name	Units	Monitoring Device	Manufacturer	Model Number	Output	Remarks
1	GeoExchange Loop Water Supply Temp	GeoEx_LWST	Deg F	Platinum RTD	Weed	Combo	RTD&Therm	Direct Immersion
2	GeoExchange Loop Water Return Temp	GeoEx_LWRT	Deg F	Platinum RTD	Weed	Combo	RTD&Therm	Direct Immersion
3	GeoExchange Loop Pump Amps	LWPA_Amps	Amps	Current Transducer	Veris Industries	H720	4-20 ma	Alternate locate in HVAC Panel
4	GeoExchange Loop Pump Amps	LWPB_Amps	Amps	Current Transducer	Veris Industries	H720	4-20 ma	Alternate locate in HVAC Panel
5	S Wing West Office Lite Level	SWOff_Lite	FC	Light Sensor	Celestial	MK7-B	0-10 VDC	Mount with Lite Controller
6	S Wing North Office Lite Level	SNOff_Lite	FC	Light Sensor	Celestial	MK7-B	0-10 VDC	Mount with Lite Controller
7	S Wing East (Open) Office Lite Level	SEOff_Lite	FC	Light Sensor	Celestial	MK7-B	0-10 VDC	Mount with Lite Controller
8	S Wing Auditorium Lite Level	Aud_Lite	FC	Light Sensor	Celestial	MK7-B	0-10 VDC	Mount on ceiling box
9	S Wing Lobby Temp	Lobby_Temp	Deg F	Platinum RTD	Weed	1000 ohm	RTD	Mount Under Thermostat
10	S Wing Auditorium Temp	Aud_Temp	Deg F	Platinum RTD	Weed	1000 ohm	RTD	Mount Under Thermostat
11	S Wing North Office Temp	SNOff_Temp	Deg F	Platinum RTD	Weed	1000 ohm	RTD	Mount Under Thermostat
12	S Wing East (Open) Office Temp	SEOff_Temp	Deg F	Platinum RTD	Weed	1000 ohm	RTD	Mount Under Thermostat
13	Auditorium Occupied/Unoccupied*	Aud_Occ	Occ/Unoc	WS Slave Pack	WattStopper	S120	Contact	Slave Pack Contact Closure
13	Total for Mechanical Room Controller		12	Analog Inputs		1	Binary Inputs	

Table B.3. NOSE IAQ sensor points.

Data Point	Description	Point Name	Units	Monitoring Device	Manufacturer	Model Number	Output
1	N Wing Center Office Relative Humidity from IAQ sensor	NCOff_IAQ_Temp	Deg F	IAQ Sensor	Pure Choice	NOSE-5 (N5000-100)	LonWorks
2	N Wing Center Office Relative Humidity from IAQ sensor	NCOff_IAQ_RH	%RH				
3	N Wing Center Office CO2 from IAQ sensor	NCOff_IAQ_CO2	PPM				
4	N Wing Center Office CO from IAQ sensor	NCOff_IAQ_CO	PPM				
5	N Wing Center Office VOC from IAQ sensor	NCOff_IAQ_VOC	%				
6	S Wing East (Open) Office Temp from IAQ sensor	SEOff_IAQ_Temp	Deg F	IAQ Sensor	Pure Choice	NOSE-5 (N5000-100)	LonWorks
7	S Wing East (Open) Office Relative Humidity from IAQ sensor	SEOff_IAQ_RH	%RH				
8	S Wing East (Open) Office CO2 from IAQ sensor	SEOff_IAQ_CO2	PPM				
9	S Wing East (Open) Office CO from IAQ sensor	SEOff_IAQ_CO	PPM				
10	S Wing East (Open) Office VOC from IAQ sensor	SEOff_IAQ_VOC	%				
11	Auditorium Temp from IAQ sensor	Aud_IAQ_Temp	Deg F	IAQ Sensor	Pure Choice	NOSE-5 (N5000-100)	LonWorks
12	Aufitorium Relative Humidity from IAQ sensor	Aud_IAQ_RH	%RH				
13	Auditorium CO2 from IAQ sensor	Aud_IAQ_CO2	PPM				
14	Auditorium CO from IAQ sensor	Aud_IAQ_CO	PPM				
15	Auditorium VOC from IAQ sensor	Aud_IAQ_VOC	%				
15	Total for LonWorks compatible IAQ sensors		15	LonWorks Inputs			

Table B.4. Calculated points.

Data Point	Description, Calculated Points	Calculation Formula
1	OffBldg-kWh	OffBldg-kWh = (LiteMtr-kWh) + (HVACMtr-kWh) + (GenMtr-kWh)
2	Totl-kWh	Totl-kWh = (OffBldg-kWh) + (MtncMtr-kWh)
3	DriveLite-kW	DriveLite-kW = DriveLite x (Line Voltage) x (Line Power Factor) Notes: line voltage and line power factor are values taken during calibration on 07/22/2004.
4	FacadeLite-kW	FacadeLite-kW = FacadeLite x (Line Voltage) x (Line Power Factor)
5	ParkingLite-kW	ParkingLite-kW = ParkingLite x (Line Voltage) x (Line Power Factor)
6	SiteLiteTotal-kWh	SiteLiteTotal-kWh = (SiteLiteTotal-kWh) + (DriveLite-kW) x (1/60) + (FacadeLite-kW) x (1/60) + (ParkingLite-kW) x (1/60) Notes: Based on 1 minute sample interval.
7	BldgLiteTotal-kWh	BldgLiteTotal-kWh = (LiteMtr-kWh) - (SiteLiteTotal-kWh)
8	ERU-kW	ERU-kW = ERU_Amps x (Line Voltage) x (Line Power Factor) x 1.732
9	ERU-kWh	ERU-kWh = (ERU-kWh) + (ERU-kW) x (1/60)
10	LWPA-kw	LWPA-kW = LWPA_Amps x (Line Voltage) x (Line Power Factor) x 1.732
11	LWPB-kw	LWPB-kW = LWPB_Amps x (Line Voltage) x (Line Power Factor) x 1.732
12	LWPA-kWh	LWPA-kWh = (LWPA-kWh) + (LWPA-kW) x (1/60)
13	LWPB-kWh	LWPB-kWh = (LWPB-kWh) + (LWPB-kW) x (1/60)
14	GeoExchange_btu/h	GeoExchange_Btu_per_h = (GeoEx_LWRT - GeoEx_LWST) x GeoEx_GPM x 500.0
15	GeoEx_GPM	GeoEx_GPM = 90.0 (if one pump is running) and 0.0 (if no pump is running)
14	Total for Virtual (Calculated) Points	14 Virtual Points

Table B.5. Point names and controllers the points are connected to.

	No.	Point Name	Controller		No.	Point Name	Controller
HVAC.imu	1	ERU_OAEAT	MNL-800-2-UI-2	Northwing.imu	1	NEOff_Lite	MNL-800-1-UI-1
	2	ERU_OALAT	MNL-800-2-UI-3		2	NCOff_Lite	MNL-800-1-UI-2
	3	ERU_EAEAT	MNL-800-2-UI-4		3	NSOff_Lite	MNL-800-1-UI-3
	4	ERU_EALAT	MNL-800-2-UI-5		4	NNOff_Temp	MNL-500-1-UI-1
	5	ERU_Amps	MNL-800-1-UI-4		5	NCOff_Temp	MNL-500-1-UI-2
	6	GeoEx_LWST	MNL-800-4-UI-3		6	NSOff_Temp	MNL-500-1-UI-3
	7	GeoEx_LWRT	MNL-800-4-UI-4		7	NConf_Temp	MNL-800-2-UI-1
	8	LWPA_Amps	MNL-800-3-UI-6		8	NCOff_IAQ_Temp	NOSE North
	9	LWPB_Amps	MNL-800-3-UI-5		9	NCOff_IAQ_RH	NOSE North
	10	GeoEx_GPM	Calculated		10	NCOff_IAQ_CO2	NOSE North
	11	ERU-kW	Calculated		11	NCOff_IAQ_CO	NOSE North
	12	ERU-kWh	Calculated		12	NCOff_IAQ_VOC	NOSE North
	13	LWPA-kw	Calculated	Southwing.imu	1	SWOff_Lite	MNL-800-3-UI-1
	14	LWPB-kw	Calculated		2	SNOff_Lite	MNL-800-3-UI-2
	15	LWPA-kWh	Calculated		3	SEOff_Lite	MNL-800-3-UI-3
	16	LWPB-kWh	Calculated		4	Aud_Lite	MNL-800-3-UI-4
	17	GeoExchange_btu/h	Calculated		5	Lobby_Temp	MNL-800-4-UI-1
ElecSum.imu	1	LiteMtr-kWh	Hawkeye Light		6	Aud_Temp	MNL-800-4-UI-2
	2	HVACMtr-kWh	Hawkeye HVAC		7	SNOff_Temp	MNL-150-2-UI-2
	3	MtncMtr-kWh	Hawkeye Maintenance		8	SEOff_Temp	MNL-150-2-UI-3
	4	GenMtr-kWh	Hawkeye General		9	SEOff_IAQ_Temp	NOSE South
	5	OffBldg-kWh	Calculated		10	SEOff_IAQ_RH	NOSE South
	6	Totl-kWh	Calculated		11	SEOff_IAQ_CO2	NOSE South
	7	LiteMtr-Demand	Hawkeye Light		12	SEOff_IAQ_CO	NOSE South
	8	HVACMtr-Demand	Hawkeye HVAC		13	SEOff_IAQ_VOC	NOSE South
	9	MtncMtr-Demand	Hawkeye Maintenance		14	Aud_IAQ_Temp	NOSE Auditorium
	10	GenMtr-Demand	Hawkeye General		15	Aud_IAQ_RH	NOSE Auditorium
SiteLite.imu	1	DriveLite	MNL-800-1-UI-5		16	Aud_IAQ_CO2	NOSE Auditorium
	2	FacadeLite	MNL-800-1-UI-6		17	Aud_IAQ_CO	NOSE Auditorium
	3	ParkingLite	MNL-800-1-UI-7		18	Aud_IAQ_VOC	NOSE Auditorium
	4	DriveLite-kW	Calculated		19	Aud_Occ	MNL-150-2-UI-1
	5	FacadeLite-kW	Calculated				
	6	ParkingLite-kW	Calculated				
	7	SiteLiteTotal-kWh	Calculated				
	8	BldgLiteTotal-kWh	Calculated				

Appendix C. Thermostat Set Points

In the following tables one temperature set point for a time period indicates that the set point is the same everyday. If there are five temperatures for weekday set points or two temperatures for weekend set points, the set point varies from day to day.

Table C.1. HP-H1, north wing, conference room's thermostat settings (6-12-2007).

Weekdays				
	Time	Cooling (^oF)	Heating (^oF)	Fan
Wake	6:00 AM	76	70	Auto
Leave	8:00 AM	75, 71, 76, 73, 76	72, 72, 73, 74, 73	On
Return	6:00 PM	78	65	Auto
Sleep	10:00 PM	78	65	Auto
Weekend				
Wake	6:00 AM	78	65	Auto
Leave	8:00 AM	78	65	Auto
Return	6:00 PM	78	65	Auto
Sleep	10:00 PM	78	65	Auto

Table C.2 HP-H2, north wing, south offices' thermostat settings (6-12-2007).

Weekdays				
	Time	Cooling (^oF)	Heating (^oF)	Fan
Wake	6:30,6,6,6,6 AM	75	70, 72, 72, 72, 70	Auto
Leave	11:30,8,8,8,8 AM	75, 72, 75, 75, 75	69, 73, 74, 71, 74	Auto
Return	6:00 PM	78	65	Auto
Sleep	10:00 PM	78	65	Auto
Weekend				
Wake	6:00 AM	78	65	Auto
Leave	8:00 AM	78	65	Auto
Return	6:00 PM	78	65	Auto
Sleep	10:00 PM	78	65	Auto

Table C.3. HP-H3, north wing, north offices' thermostat settings (6-12-2007).

Weekdays				
	Time	Cooling (^oF)	Heating (^oF)	Fan
Wake	5:45,6 6,6,6 AM	76	72	Auto
Leave	8:00 AM	75, 74, 76, 76, 76	74, 73, 74, 71, 73	Auto
Return	6:00 PM	78	65	Auto
Sleep	10:00 PM	76, 78, 78, 78, 78	65	Auto
Weekend				
Wake	6:00 AM	78	65	Auto
Leave	8:00 AM	78	65	Auto
Return	6:00 PM	78	65	Auto
Sleep	10:00 PM	78	65	Auto

Table C.4. HP-H4, north wing, central offices' thermostat settings (6-12-2007).

Weekdays				
	Time	Cooling (°F)	Heating (°F)	Fan
Wake	6:00 AM	76	72	Auto
Leave	8:00 AM	73	68	Auto
Return	6:00 PM	78	65	Auto
Sleep	10:00 PM	78	65	Auto
Weekend				
Wake	6:00 AM	78	65	Auto
Leave	8:00 AM	78	65	Auto
Return	6:00 PM	78	65	Auto
Sleep	10:00 PM	78	65, 62	Auto

Table C.5. HP-V1, south wing, auditorium's thermostat settings (6-12-2007).

Weekdays				
	Time	Cooling (°F)	Heating (°F)	Fan
Wake	6:00 AM	76	70	Auto
Leave	8:00 AM	72, 70, 76, 67, 76	68	On
Return	6:00 PM	78	65	Auto
Sleep	10:00 PM	78	65	Auto
Weekend				
Wake	6:00 AM	78	65	Auto
Leave	8:00 AM	78	65	Auto
Return	6:00 PM	78	65	Auto
Sleep	10:00 PM	78	65	Auto

Table C.6. HP-V2, south wing, north offices' thermostat settings (6-12-2007).

Weekdays				
	Time	Cooling (°F)	Heating (°F)	Fan
Wake	6:00 AM	75	72	Auto
Leave	8,8,8,9:15,8 AM	70, 75, 75, 81, 75	72, 73, 74, 72, 74	Auto
Return	6:00 PM	78, 77, 78, 78, 78	74, 65, 66, 65, 65	Auto
Sleep	10:00 PM	78	65, 65, 66, 65, 65	Auto
Weekend				
Wake	6:00 AM	78	65	Auto
Leave	8:00 AM	78	65	Auto
Return	6:00 PM	78	65	Auto
Sleep	10:00 PM	78	65	Auto

Table C.7. HP-V3, south wing, lobby's thermostat settings (6-12-2007).

Weekdays				
	Time	Cooling (^{o}F)	Heating (^{o}F)	Fan
Wake	6:00 AM	76, 76, 74, 76, 76	70	Auto
Leave	8:00 AM	76, 73, 74, 76, 76	72, 71, 72, 70, 74	Auto
Return	6:00 PM	78	66, 65, 68, 65, 65	Auto
Sleep	10:00 PM	78	65, 65, 66, 65, 65	Auto
Weekend				
Wake	6:00 AM	78	65	Auto
Leave	8:00 AM	78	65	Auto
Return	6:00 PM	78	65	Auto
Sleep	10:00 PM	78	65	Auto

Table C.8. HP-V4, south wing, south and east offices' thermostat settings (6-12-2007).

Weekdays				
	Time	Cooling (^{o}F)	Heating (^{o}F)	Fan
Wake	6:00 AM	76	72	Auto
Leave	8:00 AM	72, 75, 76, 75, 76	75, 72, 74, 71, 72	Auto
Return	6:00 PM	74, 78, 78, 78,78	65	Auto
Sleep	10:00 PM	78	65	Auto
Weekend				
Wake	6:00 AM	78	65	Auto
Leave	8:00 AM	78	65	Auto
Return	6:00 PM	78	65	Auto
Sleep	10:00 PM	78	65	Auto

Appendix D. Heat Pump Runtime Analysis MATLAB Code

Main Program 'HP_NRG2'

```
% IAMU heat pump energy use analyzer.
% This m-file reads in IAMU data files and ERS weather data files and
% analyzes energy use of the heat pumps at the IAMU building based on
% the time of day and outdoor temperature.  Using the total HVAC
% demand, the current draw by the ERU, and the occupancy of the
% auditorium, the program uses logic to determine the number of heat
% pumps running during each minute of each day analyzed.  Then using
this data and the minute-by-minute outdoor air temperature obtained
% from ERS weather files, the program allocates the number of heat
% pumps running in each minute to appropriate temperature-time bins.
% The bins have a size of 1 hour by 5 degrees (Example: 01:00 to 01:59
% by 10 to 15 deg F).  Each bin will have total cumulative runtime of
% heat pumps in that bin for that day.  The program also forms another
% matrix that contains the number of minutes in each time/temperature
% bin during the day.  The program will repeat this for each day in the
% analysis period.  At the end of the analysis period, the program will
% sum all of the daily heat pump runtime minute matrices, and all of
% the occurrence matrices.  Finally the average number of heat pumps
% running each bin is found by dividing the heat pump runtime matrix
% by the occurrence matrix.

%///Clean-up the workspace/////////////////////////////////////////////
close all
clear all
clc

%///Input and output file information//////////////////////////////////
%Prefixes for input and output files
prefix = 'C:\IAMU\Daily_Data\';
prefix2 = 'C:\ERS_Weather\';
fidO = fopen('\\Ank1\public\USERBackups\Joel
      Logan\Heat_Pumps\VFD_NRG.txt','w');

%///User inputs the starting date and ending date for data analysis////
year = input('What is the starting year for data analysis? (1898,2002)
      ','s');
month = input('What is the starting month for data analysis? (01 =Jan,
      12=Dec)  ','s');
disp('Data analysis will begin on the first day of the month
      specified');

year_e = input('What is the ending year for data analysis? (1898,2002)
      ','s');
month_e = input('What is the ending month for data analysis? (01=Jan,
      12=Dec)  ','s');
day_e = input('What is the last day of the last month of data analysis?
      (28,29,30,31)  ','s');

%///Initialize Variables///////////////////////////////////////////////
Datestr_c =[month,'/01/',year]                  %String of starting date
```

```
Datestr_e = [month_e,'/',day_e,'/',year_e];       %String of ending date
Date_c = datenum(Datestr_c,23);
                            %Initialize numerical starting date variable
Date_e = datenum(Datestr_e,23);
                              %Initialize numerical ending date variable
m = str2num(month);                         %Initialize the month counter
y = str2num(year);                           %Initialize the year counter
ddd=0;                         %Counts number of days the program runs for
D_ref = 733258;
          %Numerical date of the reference Saturday (8/4/2007, Saturday)
D_count = Date_e-Date_c+1 %Total number of days the program will run for
SDay_array = zeros(24,22,D_count);
                                 %Initializes monthly sum array to zeros
MDay_array = NaN(24,22,D_count);  %Initializes monthly mean array to NaN

%///Read data from files and analyze data for each day between the
      starting and ending date
while Date_c<=Date_e
    %Logic statement determines number of days in month
    if (m==1)||(m==3)||(m==5)||(m==7)||(m==8)||(m==10)||(m==12)
        dayinmonth = 31;
    elseif (m==4)||(m==6)||(m==9)||(m==11)
        dayinmonth = 30;
    elseif (m==2)
        if y==2004
            dayinmonth = 29;
        else
            dayinmonth = 28;
        end
    else
        disp('Month out of range')
    end

    for d=1:1:dayinmonth %Loop iterates data analysis over days in month
        ddd=ddd+1;
        if ((d>=1)&&(d<10))  %If-statement creates a day string variable
            day = ['0',num2str(d)];
        elseif (d>=10)&&(d<=dayinmonth)
            day = num2str(d);
        elseif (d>dayinmonth)
            disp('Day exceeds number of days in month')
        end
        disp([month,'/',day,'/',year])
                          %Allows program user to see progress of program
        D_num = datenum([month,'/',day,'/',year],2);
                                      %Numerical date of the current date

       %///Open input data and weather files////////////////////////
       filename1 =[prefix,year,month,day,'\',month,day,'ElecSum.imu'];
       filename2 = [prefix,year,month,day,'\',month,day,'HVAC.imu'];
       filename3=[prefix,year,month,day,'\',month,day,'Southwing.imu'];
       filename4 = [prefix2,year,month,'\',month,day,'wthr.ers'];
       fid1 = fopen(filename1, 'r');
       fid2 = fopen(filename2, 'r');
       fid3 = fopen(filename3, 'r');
```

```
 fid4 = fopen(filename4, 'r');
 if (fid1==-1)||(fid2==-1)||(fid3==-1)||(fid4==-1) %If statement
    advances brogram to next day if any of the input files do not
    exist
      fid1, fid2, fid3, fid4
      D_count = D_count - 1;
      continue
  end


%////////////////////////////////////////////////////////////////
%Read the header of ElecSum.imu and write each heading into a row
%vector and prepare for writing to a output file
Header1a = fgetl(fid1);      %Reads data file header into an array
  i = 1;                    %Initializes the row vector index to 1
  while true               %Loop converts header into a row vector
      [Header1b, Remainder1] = strtok(Header1a);
      %Divides the header into the column before the first white
      space and the remainder of the columns
      HeaderCheck1(1,i) = {Header1b};
           %Writes the individual header columns into a row vector
            if isempty(Remainder1), break; end
            %Ends loop if there are no more header columns to be
            written to the row vector
      Header1a = Remainder1;
              %Reassigns the header as the remainder of the header
      i = i+1;                      %Advances the row vector index
  end

  L_1 = length(HeaderCheck1);   %Gives number of columns in header
  N_1 = strmatch('HVACMtr-Demand', HeaderCheck1);
                        %Gives column position of 'HVACMtr-Demand'

  fullformat_1 = []; %Initializes 'fullformat' to an empty martrix
  for k=1:1:L_1
     %Loop sets format that 'textscan' will use to read data files
      if k==1
      %Loop sets format of individual data columns: %s is script,
      %f is floating point decimal, %*f skips floating point decimal
          format = '%s';
      elseif k==2
          format = '%s';
      elseif k==N_1
          format = '%f';
      else
          format = '%*f';
      end
      fullformat_1 = [fullformat_1,format];
      %Concatonates format of individual column to format of
      entire row
  end


%////////////////////////////////////////////////////////////////
  %Read the header of HVAC.imu and write each heading into a row
```

```
  %vector and prepare for writing to a output file.  Code
  analogous as for ElecSum.imu section above.
  Header2a = fgetl(fid2);
  i = 1;
  while true
      [Header2b, Remainder2] = strtok(Header2a);
      HeaderCheck2(1,i) = {Header2b};
      if       isempty(Remainder2), break; end
      Header2a = Remainder2;
      i = i+1;
  end

  L_2 = length(HeaderCheck2);
  N_2 = strmatch('ERU_Amps', HeaderCheck2);
  fullformat_2 = [];
  for k=1:1:L_2
      if k==1
          format = '%s';
      elseif k==2
          format = '%s';
      elseif k==N_2
          format = '%f';
      else
          format = '%*f';
      end
      fullformat_2 = [fullformat_2,format];


%////////////////////////////////////////////////////////////////
%Read the header of Southwing.imu and write each heading into a
row vector and prepare for writing to an output file.  Code
analogous to code for ElecSum.imu section above.
  Header3a = fgetl(fid3);
  i = 1;
  while true
      [Header3b, Remainder3] = strtok(Header3a);
      HeaderCheck3(1,i) = {Header3b};
      if isempty(Remainder3), break; end
      Header3a = Remainder3;
      i = i+1;
  end

  L_3 = length(HeaderCheck3);
  N_3 = strmatch('Aud_Occ', HeaderCheck3);
  fullformat_3 = [];
  for k=1:1:L_3
      if k==1
          format = '%s';
      elseif k==2
          format = '%s';
      elseif k==N_3
          format = '%f';
      else
          format = '%*f';
      end
```

```
    fullformat_3 = [fullformat_3,format];
end



%///////////////////////////////////////////////////////////////
%Read the heater of wthr.ers and write each heading into a row
%vector and prepare for wirting to an output file.  Code
%analogous to section of ElecSum.imu above.
Header4a = fgetl(fid4);
i = 1;
while true
    [Header4b, Remainder4] = strtok(Header4a);
    HeaderCheck4(1,i) = {Header4b};
    if isempty(Remainder4), break; end
    Header4a = Remainder4;
    i = i+1;
end

L_4 = length(HeaderCheck3);
N_4 = strmatch('OA-TEMP', HeaderCheck4);

fullformat_4 = [];
for k=1:1:L_4
    if k==1
        format = '%s';
    elseif k==2
        format = '%s';
    elseif k==N_4
        format = '%f';
    else
        format = '%*f';
    end
    fullformat_4 = [fullformat_4,format];
end

%////Read Data from open input files/////////////////////////
i = 2;
%Initializes vector index to 2, starts at 2 becuase a virtual
    data point must be placed before the first Demand data
    point
Date = {};
%These 7 lines initialize the matricies into which data will be
    read to empty matricies
Time = {};
Time_num = [];
Demand = [];
ERU_Amps = [];
Aud_Occ= [];
OA_TEMP = [];

while  feof(fid1)==0
%Loop reads Date, Time, ERU_Amps, and OA_Temp from files and
    writes them to arrays and an output file
    Breaker = 0
```

```
%Initializes 'Breaker' to 0, Breaker allows the loop to
     advance to next day if data or weather file end before
     23:59 is reached
Elec = {textscan(fid1,fullformat_1, 1)};
%Reads data from ElecSum.imu data file, similar below
if isempty(Elec{1,1}{1,1}) == 1, break; end
%Terminates reading the data files if a blank line is
     encountered before the end of file signature, similar
     below
HVAC = {textscan(fid2,fullformat_2, 1)};
if isempty(HVAC{1,1}{1,1}) == 1, break; end
South = {textscan(fid3,fullformat_3, 1)};
if isempty(South{1,1}{1,1}) == 1, break; end
Weather = {textscan(fid4,fullformat_4, 1)};
if isempty(Weather{1,1}{1,1}) == 1, break; end
Date_1 = datenum([char(Elec{1,1}{1,1}), ', ',
         char(Elec{1,1}{1,2})]);
%Converts the ElecSum.imu file date and time into strings,
     concatonates the strings, and converts the strings to
     decimal dates
Date_2 = datenum([char(HVAC{1,1}{1,1}), ', ',
         char(HVAC{1,1}{1,2})]);
Date_3 = datenum([char(South{1,1}{1,1}), ', ',
         char(South{1,1}{1,2})]);
Date_4 = datenum([char(Weather{1,1}{1,1}),',
         ',char(Weather{1,1}{1,2})]);

Data_skip = 0;
Wthr_skip = 0;
%Data and Wthr skip show how many times data in a file must
     be skiped to match the date and time in the weather and
     data files
while (Date_4-Date_1)>(1/1440)
%While loop compares the data file and weather file dates
    Data_skip = Data_skip + 1;
    Elec = {textscan(fid1,fullformat_1, 1)};
    %If the weather file date is greater than the Elec.imu
        file date by 1 minute, read the next line in
        Elec.imu is read
    HVAC = {textscan(fid2,fullformat_2, 1)};
    %If the weather file date is greater than the Elec.imu
        file date by 1 minute, read the next line in
        HVAC.imu is read
    South = {textscan(fid3,fullformat_3, 1)};
    %If the weather file date is greater than the Elec.imu
        file date by 1 minute, read the next line in
        South.imu is read
    if isempty(Elec{1,1}{1,1}) == 1
        Breaker = 1
        break
    end
    Date_1 = datenum([char(Elec{1,1}{1,1}), ', ',
        char(Elec{1,1}{1,2})]);
```

```
        %Converts the ElecSum.imu file date and time into
            strings, concatonates the strings, and converts the
            strings to decimal dates
        Date_2 = datenum([char(HVAC{1,1}{1,1}), ', ',
            char(HVAC{1,1}{1,2})]);
        Date_3 = datenum([char(South{1,1}{1,1}), ', ',
            char(South{1,1}{1,2})]);
    end

    while (Date_1-Date_4)>(1/1440)
    %While loop compares the ElecSum.imu file and weather file
        dates
        Wthr_skip = Wthr_skip+1;
        Weather = {textscan(fid4,fullformat_4, 1)};
        if isempty(Weather{1,1}{1,1}) == 1
            Breaker = 1;
            break
        end
        Date_4 = datenum([char(Weather{1,1}{1,1}), ', ',
            char(Weather{1,1}{1,2
    end

    if Breaker == 1, break; end
    %Advances to next day if data or weather file end before
        23:59 is reached

    if (isempty(Weather{1,1}{1,1})) ||
        (isempty(Elec{1,1}{1,2})) || (isempty(Elec{1,1}{1,3}))
        || (isempty(HVAC{1,1}{1,3})) ||
        (isempty(South{1,1}{1,3})) ||
        (isempty(Weather{1,1}{1,3})) == 1
        continue
        %Advances to read the next line of data in each file if
            any of the necessary data points are missing from
            current line
    end

    %The next seven lines criate column vectors from data read
        from files
    Date(i) = Weather{1,1}{1,1};
    Time(i) = Elec{1,1}{1,2};
    Time_num(i) = datenum(Time(i),13)-733408;
    Demand(i) = Elec{1,1}{1,3};
    ERU_Amps(i) = HVAC{1,1}{1,3};
    Aud_Occ(i) = South{1,1}{1,3};
    OA_TEMP(i) = Weather{1,1}{1,3};
    i=i+1;                                %Advances vector index
end

if isempty(Demand)==1,
%Advances to next day if 'Demand' vector is empty (all other
    vectors will be empty as well)
    disp('Demand matrix is empty, check contents of data
        files')
    continue
```

```
    end

    [SDay_array(:,:,ddd),NDay_array(:,:,ddd)] = HP_analyze2(Date,
       Time, Demand, ERU_Amps, Aud_Occ, OA_TEMP, Time_num);
    %Passes information to function "HP_analyze2"

    %///Determine if the current day under analysis is a weekday or
        a week end
    N_ref1 = (D_num-D_ref)/7;
                         %If a Saturday, quotient will be an integer
    N_ref2 = (D_num-D_ref-1)/7;
                           %If a Sunday, quotient will be an integer
    N_comp1 = round(N_ref1);
    N_comp2 = round(N_ref2);
    if ((N_ref1-N_comp1)==0)||((N_ref2-N_comp2)==0)
    %Determines if day is Saturday or Sunday, if so, assigns data
        to weekend arrays
        NWE_array(:,:,ddd) = NDay_array(:,:,ddd);
        SWE_array(:,:,ddd) = SDay_array(:,:,ddd);
        NWD_array(:,:,ddd) = zeros(24,22);
        SWD_array(:,:,ddd) = zeros(24,22);
    elseif ((N_ref1-N_comp1)~=0)&&((N_ref2-N_comp2)~=0)
    %Determins if day is a weekday, if so, assigns data to weekday
      array
        NWD_array(:,:,ddd) = NDay_array(:,:,ddd);
        SWD_array(:,:,ddd) = SDay_array(:,:,ddd);
        NWE_array(:,:,ddd) = zeros(24,22);
        SWE_array(:,:,ddd) = zeros(24,22);
    else
        disp('Error in determining if day is weekday or weekend')
    end

    %///Close input files/////////////////////////////////////////
    fclose(fid1);
    fclose(fid2);
    fclose(fid3);
    fclose(fid4);
end

%///Advance the year, month, and date
if m==12
    y=y+1;
    year = num2str(y);
end

if m==12
    m=1;
else
    m=m+1;
end

if(m>=1)&&(m<10)
    month=['0',num2str(m)];
elseif (m>=10)&&(m<=12)
    month=num2str(m);
```

```
    else
        disp('Month out of range')
    end
    Date_c=datenum([month,'/01/',year],23);
end

%///Initialize ouput matricies/////////////////////////////////////////
%Weekend ouput arrays
NWE_tot_array = zeros(24,22);
                           %Number of minutes in each bin, similar below
SWE_tot_array = zeros(24,22);
                        %Total operation time in each bin, similar below
MWE_tot_array = NaN(24,22);
           %Average number of heat pumps operating in bin, similar below
WE_Color_array = zeros(24,22);
                           %Used in coloring output graph, similar below

%Weekday output arrays
NWD_tot_array = zeros(24,22);
SWD_tot_array = zeros(24,22);
MWD_tot_array = NaN(24,22);
WD_Color_array = zeros(24,22);

%Combined weekend and weekday output arrays
Ntot_array = zeros(24,22);
Stot_array = zeros(24,22);
Mtot_array = NaN(24,22);
Color_array = zeros(24,22);

%///Caluculate values to put in output matricies/////////////////////
%N..._array is (24,22) and containes the number of minutes within
    eachtime/temp bin.  S..._array is (24,22) and containes the total
    heatpump runtime minutes within each time/temp bin.  M..._array is
    (24,22) and is determined by dividing each (ii,jj) element  in
    S..._array by the coresponding (ii,jj) element in N..._array.  It is
    the mean number of heatpumps operating in each bin.  A value of 0
    indicates that during that bin an average of zero heat pumps run.  A
    value of NAN indicates that there is no data for that bin.
for ii=1:1:24
    for jj=1:1:22
        for dd=1:1:D_count
            NWE_tot_array(ii,jj) =
                NWE_tot_array(ii,jj)+NWE_array(ii,jj,dd);
            SWE_tot_array(ii,jj) =
                SWE_tot_array(ii,jj)+SWE_array(ii,jj,dd);
            NWD_tot_array(ii,jj) =
                NWD_tot_array(ii,jj)+NWD_array(ii,jj,dd);
            SWD_tot_array(ii,jj) =
                SWD_tot_array(ii,jj)+SWD_array(ii,jj,dd);
            Ntot_array(ii,jj) = Ntot_array(ii,jj)+NDay_array(ii,jj,dd);
            Stot_array(ii,jj) = Stot_array(ii,jj)+SDay_array(ii,jj,dd);
        end

        if NWE_tot_array(ii,jj)==0
            MWE_tot_array(ii,jj)=NaN;
```

```
            %NAN in output array indicates that there was no time in
                the time/temp bin in the analysis period
            WE_Color_array(ii,jj)=0;
        else
            MWE_tot_array(ii,jj) =
                SWE_tot_array(ii,jj)/NWE_tot_array(ii,jj);
            WE_Color_array(ii,jj)=MWE_tot_array(ii,jj);
        end

        if NWD_tot_array(ii,jj)==0
            MWD_tot_array(ii,jj)=NaN;
            WD_Color_array(ii,jj)=0;
        else
            MWD_tot_array(ii,jj) =
                SWD_tot_array(ii,jj)/NWD_tot_array(ii,jj);
            WD_Color_array(ii,jj)=MWD_tot_array(ii,jj);
        end

        if Ntot_array(ii,jj)==0
            Mtot_array(ii,jj)=NaN;
            Color_array(ii,jj)=0;
        else
            Mtot_array(ii,jj) = Stot_array(ii,jj)/Ntot_array(ii,jj);
            Color_array(ii,jj)=Mtot_array(ii,jj);
        end
    end
end

%///Make surface plots of output figure(1) if of the weekend output,
      figure(2) is of the weekday output, and figure(3) is of the
      combined weekend and weekday output.
Time_label = {'00:00','04:00','08:00','12:00','16:00','20:00','24:00'};
Bin_label ={'-10 to -5','15 to 20','40 to 45','65 to 70','90 to 95'};

figure(1)
p1 = surf(WE_Color_array,MWE_tot_array);
colormap jet
axis([0,22,0,25])
set(gca,'XTick',[1,6,11,16,21])
set(gca,'XTickLabel',Bin_label)
set(gca,'YTick',[0,4,8,12,16,20,24])
set(gca,'YTickLabel',Time_label)
title(['Weekend Average Number of Heat Pumps Operating as a Fucntion of
      Time and Temperature ',Datestr_c,' to ',Datestr_e])
xlabel('Temperature Bin')
ylabel('Time')
view([130,25])
colorbar

figure(2)
p2 = surf(WD_Color_array,MWD_tot_array);
colormap jet
axis([0,22,0,24,0,8])
set(gca,'XTick',[1,6,11,16,21])
set(gca,'XTickLabel',Bin_label)
```

```
set(gca,'YTick',[0,4,8,12,16,20,24])
set(gca,'YTickLabel',Time_label)
title(['Weekday Average Number of Heat Pumps Operating as a Fucntion of
      Time and Temperature ',Datestr_c,' to ',Datestr_e])
xlabel('Temperature Bin')
ylabel('Time')
zlabel('Average Number of Heat Pumps Running')
view([130,25])
colorbar

figure(3)
p2 = surf(Color_array,Mtot_array);
colormap jet
axis([0,22,0,24,0,8])
set(gca,'XTick',[1,6,11,16,21])
set(gca,'XTickLabel',Bin_label)
set(gca,'YTick',[0,4,8,12,16,20,24])
set(gca,'YTickLabel',Time_label)
title(['Total Average Number of Heat Pumps Operating as a Fucntion of
      Time and Temperature ',Datestr_c,' to ',Datestr_e])
xlabel('Temperature Bin')
ylabel('Time')
zlabel('Average Number of Heat Pumps Running')
view([130,25])
colorbar
```

Function 'HP_analyze2.m'

```
function [Sbin,N_count] = HP_analyze2(Date, Time, Demand, ERU_Amps,
    Aud_Occ,OA_TEMP, Time_num)
%This function analyzes the energy use of the IAUM heat pumps.  This
    function accepts the daily minute-by-minute date, time, HVAC energy
    use, ERU amps, auditorium occupancy, and outdoor air temperature.
    It calculates the minute-by-minute heat pump energy use and the
    minute-by-minute number of heat pumps running.  It then determines
    the number of data points in each temperature/time bin and the heat
    pump-minutes of runtime in each bin.  It outputs these calculation
    in the form of two 24 by 22 matricies.

n1 = length(Demand)         %Displays number of datapoints exist for day
Demand(1) = Demand(2);
%Creates 'virtual' datapoint at beginning of Demand vector for use in
    logic
Demand(n1+1) = Demand(n1);
%Creates 'virtual' datapoint at end of Demand vector for use in logic

Demand2 = [];
Demand2 = [];
Motors = [];
HP = [];

for i=2:1:n1
%Loop calculates energy used by and number of heat pumps running at
    each time step
    diff1 = Demand(i) - Demand(i-1);
```

```
    %Calculate difference between the current HVAC demand and the
        demand at the previous time step
    diff2 = Demand(i) - Demand(i+1);
    %Calculate difference between the current HVAC demand and the
        demand at the following time step

    if (diff1>8)||((abs(diff1)<2.2)&&(ERU_Amps(i)>10))||((diff2>8.5)
        &&(ERU_Amps(i)>10))
    %Logic determines if ERU defrost heater is on during current time
        step
        Demand2(i) = Demand(i)-12.2;
        %If defrost heater is on, 12.2kW is subracted from the HVAC
            demand
    else
        Demand2(i) = Demand(i);
        %If defrost heater is off, HVAC demand is not changed
    end

    if (Aud_Occ(i)==0)&&(ERU_Amps(i)>2)
    %Logic determines if ERU fans are on low speed
        Motors(i) = 0.85;    %If fans are on low, motor demand is 0.85kW
    elseif (Aud_Occ(i)==100)&&(ERU_Amps(i)>2)
    %Logic determines if ERU fans are on high speed
        Motors(i) = 1.39;   %If fans are on high, motor demand is 1.29kW
    else
        Motors(i) = 0;
    end
    Demand3(i) = Demand2(i) - Motors(i) - 2.121;
    %Calculates energy use of heat pumps in time step (subtracts ERU
        motor and pump (2.121kW) demand)
    HP(i) = round(Demand3(i)/3);
    %Caluculates number of heat pumps running in time step (Each HP
        uses ~3kW when on)
end

i = 2;                                         %'i' is index of Time_num

for m=0:(1/24):(23/24)
%Loop advances trough one-hour time bins using decimal time
    n = m+(1/24);%m            %m is beginning of hour, n is end of hour
    p = round(n*24);      %p is the index of the time bin (1,2,3,...,24)
    o=0;                   %'o' is the number of occurances in each hour
    Bin = [];                       %Initializes bin matrix to all zeros
    if i<=numel(Time_num)
    %Only performs time/temp. bin logic if i<= the number of elements
       in the Time_num vector
        while (Time_num(i)>=m)&&(Time_num(i)<n)                %Time bin
            o=o+1;                                   %Advances 'o' index
            k = -10;
               %Initializes the lower bound of the first temperature bin
            l = -5;
               %Initializes the upper bound of the first temperature bin
            for mm=1:1:22            %Temperature bins (22 5 deg-F bins)
                if(OA_TEMP(i)>=k)&&(OA_TEMP(i)<l)
```

```
                %Logic determines which temperature bin the the
                   temperature at the current time step is in
                    Bin(o,mm) = HP(i);
                    %Assigns number of heat pumps running to
                        appropriate temperature bin
                else
                    Bin(o,mm) = NaN;
                    %Assigns NaN (as opposed to 0) if the OA_TEMP is
                        not within the current temperature bin
                end
                k = k+5;           %Advances lower temperature bin limit
                l = l+5;           %Advances upper temperature bin limit
            end
            i = i+1;                                  %Advances 'i' index
            if i>numel(Time_num), break; end
            %Breaks if while loop if 'i' is greater than number of
            elements in 'Time_num'
        end
    end

    N_count(p,:) = zeros(1,22)+o;
    %N_count is the number of non_NaN occurances in each
        temperature/time bin used in finding averge # of heat pumps
        running in each bin
    Sbin(p,:) = zeros(1,22);
    %pth row of Sbin is the sum of each column of the Bin matrix
    for jj=1:1:22                   %Advances through each temperature bin
        for ii=1:1:o
        %Advances through the o minutes in the pth time bin (ususally
            60 minutes in each time bin)
            if isnan(Bin(ii,jj))==1
            %Subtracts 1 from N_count if current element of Bin is NaN
                N_count(p,jj) = N_count(p,jj)-1;
                continue
                %Continue prevents 'NaN' from being added to Sbin
            end
            Sbin(p,jj)=Sbin(p,jj)+Bin(ii,jj);
            %Adds up the number of H.P. operating in each temperature
               bin of each time bin
        end
    end
end
```

Appendix E. Heat Pump Binned Runtime

Table E.1. Number of minutes occurring in weekday bins (8/1/2004 to 6/30/2007).

	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
-10 to -5	0	46	60	166	251	281	312	297	151	29	0	0	0	0	0	0	0	0	0	0	0	0	0	5
-5 to 0	484	488	519	448	430	454	478	455	501	347	207	72	56	63	45	60	74	120	127	181	277	379	417	415
0 to 5	464	477	533	564	602	579	612	619	533	518	476	518	380	245	195	166	229	392	528	568	455	452	416	446
5 to 10	568	473	471	615	487	459	342	283	451	556	540	446	536	578	607	627	622	509	410	368	452	385	422	560
10 to 15	645	702	701	453	497	711	732	778	515	446	444	502	472	384	297	324	309	338	397	431	461	569	703	748
15 to 20	734	736	1007	1246	1223	1238	1502	1505	1303	957	775	578	563	571	584	640	781	744	782	759	929	879	702	719
20 to 25	2149	2400	2297	2340	2470	2274	2289	2059	1507	1421	1411	1261	992	832	911	931	866	974	1024	1221	1264	1507	1604	1692
25 to 30	2948	2945	2977	3004	3045	3147	3272	3375	3453	2962	1905	1839	1567	1607	1601	1472	1507	1834	2103	2133	2444	2763	3218	3377
30 to 35	3324	3216	3314	3623	3389	3551	3671	3581	3416	3559	3568	2885	2907	2589	2265	2073	2136	2521	3074	3549	3696	3798	3199	3167
35 to 40	3001	3040	3144	3069	3331	3576	3439	3080	3431	3185	3040	3168	2878	2763	2862	2989	2979	3102	3051	2779	2743	2695	2857	2974
40 to 45	2989	2835	2799	2896	2738	2598	2527	2359	2648	2962	3056	3050	2919	3025	2538	2329	2704	2401	2608	2898	2855	2803	2847	3021
45 to 50	2053	2038	2296	2564	2617	2823	2595	2561	2207	2292	2236	2232	3007	2927	3389	3597	3057	3175	2768	2332	2371	2317	2234	2132
50 to 55	3554	3400	3290	3109	2957	3132	3489	3399	2877	2521	2751	3055	2321	2069	2242	2219	2148	2155	2264	2186	2293	2531	2789	3041
55 to 60	2398	2752	2910	3305	3448	3364	3032	2661	3057	2897	2730	2704	3016	2857	2401	2460	2352	2094	2146	2119	2206	2565	2598	2732
60 to 65	2982	3032	3342	3260	3233	3449	3643	3143	2876	3371	2814	2430	2433	2633	2530	2364	2164	1994	1888	2081	2318	2507	2938	2858
65 to 70	3997	3904	3985	4243	4055	3634	3779	4171	3895	3199	3294	3374	2968	2569	2685	2422	2512	2423	2793	2884	3672	4157	4131	4339
70 to 75	4012	3527	3063	2608	2297	2231	2107	2369	3376	3938	3562	3534	3543	3056	2986	3120	2918	3171	3451	3887	3960	4140	4000	4092
75 to 80	1514	1190	973	602	360	328	377	824	1496	2252	3214	3521	3815	4087	4219	4169	3989	4044	3925	3554	3364	3328	2633	1716
80 to 85	304	342	265	328	263	205	183	179	335	888	1577	2480	2822	3185	3444	3584	3281	3371	3312	2905	2356	1096	465	409
85 to 90	212	133	97	61	37	6	0	0	0	80	279	641	1361	1891	2144	2551	2858	2582	1948	1394	551	210	166	180
90 to 95	0	0	0	0	0	0	0	0	0	0	0	76	246	265	487	733	695	553	389	148	69	3	0	0
95 to 100	0	0	0	0	0	0	0	0	0	0	0	0	1	90	115	85	107	69	61	29	0	0	0	0

Table E.2. Number of heat pump-minutes in weekday bins (8/1/2004 to 6/30/2007).

	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
-10 to -5	0	171	251	1026	1675	1815	2014	1906	988	154	0	0	0	0	0	0	0	0	0	0	0	0	0	12
-5 to 0	1595	1923	2587	2608	2801	2890	2982	2931	3095	1989	947	202	142	177	207	331	380	29	61	223	458	586	1025	1249
0 to 5	1373	1787	2770	3340	3935	3530	3818	3969	3089	2549	2066	1703	1096	592	451	393	849	923	485	919	688	598	856	1189
5 to 10	1561	1495	1893	3353	3191	2710	2002	1585	2236	2245	1940	1356	1261	1241	1397	1798	1935	1297	519	314	548	381	762	1374
10 to 15	1587	2362	2753	2407	3297	4347	4143	4156	2363	1762	1417	1124	903	707	574	714	940	695	79	206	346	420	947	1535
15 to 20	1631	2161	3930	6875	7939	6768	7816	7516	5635	3173	2216	1453	1163	1298	1257	1741	2085	499	165	404	691	561	843	1185
20 to 25	3306	5428	7968	11493	15388	11649	10829	9110	5409	4036	3349	2552	1865	1552	1780	1930	2067	1017	278	449	513	455	958	1848
25 to 30	3426	6168	9339	14071	18354	15056	14206	12743	10590	7379	3958	3224	2769	2617	2625	2737	2717	1293	370	583	1181	691	1321	2350
30 to 35	2912	4617	8723	14890	19203	16035	14229	12511	8654	6676	5435	3848	4602	3992	3490	3502	3769	1582	368	467	950	761	835	1304
35 to 40	1671	2690	5540	10019	16441	13249	10744	8684	6949	4653	3094	3080	2657	2666	2821	3486	3532	1142	453	462	542	557	543	712
40 to 45	909	1217	2500	5371	8977	8841	6278	5857	4340	3199	2381	1702	1645	1838	1568	1488	2103	1156	333	311	390	491	457	507
45 to 50	193	207	443	1800	4690	5680	4028	4472	2617	1597	1279	1411	1692	1446	1775	1810	1578	821	286	249	142	301	249	137
50 to 55	72	197	453	1021	2906	4145	3061	3334	1843	1114	828	793	705	571	665	535	540	358	261	233	136	190	90	83
55 to 60	82	108	106	332	691	1233	1092	1948	938	907	635	656	903	855	565	693	472	313	227	184	11	4	46	29
60 to 65	5	1	-4	-9	134	602	709	1271	1035	873	924	822	1096	1075	933	788	715	481	143	177	39	34	64	16
65 to 70	192	254	213	237	247	1862	1061	1454	2095	2170	2319	2104	2315	2102	1818	1655	1618	1158	331	371	282	476	340	179
70 to 75	343	518	355	271	377	2519	1241	1463	3206	4872	5228	5644	5493	4744	4224	3868	3193	2603	732	873	813	900	545	451
75 to 80	267	232	260	143	104	718	397	774	2023	4029	6737	7858	8691	8670	8773	8357	7442	5854	1460	1469	1329	1363	865	432
80 to 85	134	161	145	177	167	563	300	260	597	1918	3922	6788	7967	8995	9385	9535	8183	6297	1460	1843	1703	1051	241	122
85 to 90	175	105	42	35	50	9	0	0	0	227	865	1926	4379	5900	6692	7773	8149	6348	1394	1475	684	257	179	134
90 to 95	0	0	0	0	0	0	0	0	0	0	0	311	916	910	1688	2548	2243	1609	354	220	127	1	0	0
95 to 100	0	0	0	0	0	0	0	0	0	0	0	0	6	386	462	352	426	257	92	45	0	0	0	0

Table E.3. Average number of heat pumps running in weekday bins (8/1/2004 to 6/30/2007).

	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
-10 to -5	NaN	3.7	4.2	6.2	6.7	6.5	6.5	6.4	6.5	5.3	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	2.4
-5 to 0	3.3	3.9	5.0	5.8	6.5	6.4	6.2	6.4	6.2	5.7	4.6	2.8	2.5	2.8	4.6	5.5	5.1	0.2	0.5	1.2	1.7	1.5	2.5	3.0
0 to 5	3.0	3.7	5.2	5.9	6.5	6.1	6.2	6.4	5.8	4.9	4.3	3.3	2.9	2.4	2.3	2.4	3.7	2.4	0.9	1.6	1.5	1.3	2.1	2.7
5 to 10	2.7	3.2	4.0	5.5	6.6	5.9	5.9	5.6	5.0	4.0	3.6	3.0	2.4	2.1	2.3	2.9	3.1	2.5	1.3	0.9	1.2	1.0	1.8	2.5
10 to 15	2.5	3.4	3.9	5.3	6.6	6.1	5.7	5.3	4.6	4.0	3.2	2.2	1.9	1.8	1.9	2.2	3.0	2.1	0.2	0.5	0.8	0.7	1.3	2.1
15 to 20	2.2	2.9	3.9	5.5	6.5	5.5	5.2	5.0	4.3	3.3	2.9	2.5	2.1	2.3	2.2	2.7	2.7	0.7	0.2	0.5	0.7	0.6	1.2	1.6
20 to 25	1.5	2.3	3.5	4.9	6.2	5.1	4.7	4.4	3.6	2.8	2.4	2.0	1.9	1.9	2.0	2.1	2.4	1.0	0.3	0.4	0.4	0.3	0.6	1.1
25 to 30	1.2	2.1	3.1	4.7	6.0	4.8	4.3	3.8	3.1	2.5	2.1	1.8	1.8	1.6	1.6	1.9	1.8	0.7	0.2	0.3	0.5	0.3	0.4	0.7
30 to 35	0.9	1.4	2.6	4.1	5.7	4.5	3.9	3.5	2.5	1.9	1.5	1.3	1.6	1.5	1.5	1.7	1.8	0.6	0.1	0.1	0.3	0.2	0.3	0.4
35 to 40	0.6	0.9	1.8	3.3	4.9	3.7	3.1	2.8	2.0	1.5	1.0	1.0	0.9	1.0	1.0	1.2	1.2	0.4	0.1	0.2	0.2	0.2	0.2	0.2
40 to 45	0.3	0.4	0.9	1.9	3.3	3.4	2.5	2.5	1.6	1.1	0.8	0.6	0.6	0.6	0.6	0.6	0.8	0.5	0.1	0.1	0.1	0.2	0.2	0.2
45 to 50	0.1	0.1	0.2	0.7	1.8	2.0	1.6	1.7	1.2	0.7	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.3	0.1	0.1	0.1	0.1	0.1	0.1
50 to 55	0.0	0.1	0.1	0.3	1.0	1.3	0.9	1.0	0.6	0.4	0.3	0.3	0.3	0.3	0.3	0.2	0.3	0.2	0.1	0.1	0.1	0.1	0.0	0.0
55 to 60	0.0	0.0	0.0	0.1	0.2	0.4	0.4	0.7	0.3	0.3	0.2	0.2	0.3	0.3	0.2	0.3	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.0
60 to 65	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.4	0.4	0.3	0.3	0.3	0.5	0.4	0.4	0.3	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0
65 to 70	0.0	0.1	0.1	0.1	0.1	0.5	0.3	0.3	0.5	0.7	0.7	0.6	0.8	0.8	0.7	0.7	0.6	0.5	0.1	0.1	0.1	0.1	0.1	0.0
70 to 75	0.1	0.1	0.1	0.1	0.2	1.1	0.6	0.6	0.9	1.2	1.5	1.6	1.6	1.6	1.4	1.2	1.1	0.8	0.2	0.2	0.2	0.2	0.1	0.1
75 to 80	0.2	0.2	0.3	0.2	0.3	2.2	1.1	0.9	1.4	1.8	2.1	2.2	2.3	2.1	2.1	2.0	1.9	1.4	0.4	0.4	0.4	0.4	0.3	0.3
80 to 85	0.4	0.5	0.5	0.5	0.6	2.7	1.6	1.5	1.8	2.2	2.5	2.7	2.8	2.8	2.7	2.7	2.5	1.9	0.4	0.6	0.7	1.0	0.5	0.3
85 to 90	0.8	0.8	0.4	0.6	1.4	1.5	NaN	NaN	NaN	2.8	3.1	3.0	3.2	3.1	3.1	3.0	2.9	2.5	0.7	1.1	1.2	1.2	1.1	0.7
90 to 95	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	4.1	3.7	3.4	3.5	3.5	3.2	2.9	0.9	1.5	1.8	NaN	NaN	NaN
95 to 100	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	4.3	4.0	4.1	4.0	3.7	1.5	1.6	NaN	NaN	NaN	NaN

Table E.4. Number of minutes occurring in weekend bins (8/1/2004 to 6/30/2007).

	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
-10 to -5	37	83	131	153	124	120	121	158	57	0	0	0	0	0	0	0	0	0	0	0	0	11	33	14
-5 to 0	144	96	109	161	326	334	314	315	363	312	123	93	61	59	59	17	10	107	122	118	120	111	85	106
0 to 5	215	342	300	285	140	146	169	123	161	224	304	208	170	120	88	105	165	73	60	115	180	180	191	240
5 to 10	379	253	282	243	303	326	364	323	224	186	172	274	257	244	175	177	75	195	302	198	151	181	181	203
10 to 15	246	326	302	389	354	335	385	391	338	299	253	185	238	268	311	367	389	356	350	438	389	381	336	306
15 to 20	580	547	552	424	389	357	419	405	434	440	469	339	213	234	308	242	273	229	177	257	410	518	593	627
20 to 25	407	450	715	722	742	792	788	717	508	362	300	422	514	502	441	482	464	611	625	540	478	417	411	425
25 to 30	1134	1039	765	950	1117	1339	1375	1330	1196	1072	928	659	558	432	432	327	354	384	427	470	576	648	657	786
30 to 35	1683	1788	1818	1953	1925	1891	1886	1806	1900	1666	997	1068	1100	969	940	1052	1238	1304	1405	1303	1357	1571	1675	1734
35 to 40	1205	1169	1263	1272	1179	1297	1268	1255	1236	1133	1597	1449	1208	1152	1160	1146	977	1085	1316	1631	1791	1717	1719	1671
40 to 45	1536	1568	1553	1574	1426	1043	1071	1061	1073	1490	1384	1495	1613	1609	1339	1237	1373	1252	1181	1117	1174	1137	1083	1173
45 to 50	891	865	687	658	754	976	853	935	1057	1021	1053	998	1035	898	1039	982	974	1041	1148	1231	1252	1152	920	757
50 to 55	536	590	800	951	857	1045	1337	1059	839	871	1025	1322	1145	1333	1249	1374	1111	1029	855	687	468	677	938	901
55 to 60	1435	1436	1397	1414	1615	1503	1253	1238	1447	1243	944	434	833	773	935	1014	1088	1006	889	764	1061	1041	900	932
60 to 65	1419	1495	1650	1704	1663	1835	1910	1533	1253	1318	1178	1423	915	812	829	675	632	607	750	918	860	958	1171	1229
65 to 70	1878	1663	1633	1526	1262	1044	1083	1628	1760	1553	1339	1142	1193	1251	1014	1033	988	1046	1076	1017	1365	1614	1705	1873
70 to 75	841	836	659	720	810	811	724	553	824	1268	1662	1714	1608	1386	1569	1607	1460	1487	1494	1402	1392	1705	1543	1335
75 to 80	722	563	492	466	359	286	338	493	516	542	768	1146	1541	1634	1653	1524	1490	1410	1478	1658	1415	926	869	949
80 to 85	192	119	120	108	60	60	60	143	394	563	590	685	641	795	900	1133	1193	1119	873	743	722	605	400	216
85 to 90	0	0	0	0	0	0	0	0	20	253	470	472	663	626	643	716	681	755	791	621	445	353	235	168
90 to 95	0	0	0	0	0	0	0	0	0	0	30	192	348	396	484	497	530	508	504	417	174	12	0	0
95 to 100	0	0	0	0	0	0	0	0	0	0	0	0	0	93	122	156	180	176	92	0	0	0	0	0

Table E.5. Number of heat pump-minutes in weekend bins (8/1/2004 to 6/30/2007).

	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
-10 to -5	144	317	485	569	464	457	485	603	188	0	0	0	0	0	0	0	0	0	0	0	0	35	131	52
-5 to 0	511	337	381	568	1155	1222	1179	1169	1212	797	236	161	107	109	93	27	17	279	356	365	415	407	321	399
0 to 5	704	1132	999	972	477	551	621	473	549	519	444	171	148	130	115	152	276	139	132	307	525	556	620	804
5 to 10	1135	775	842	688	917	979	1112	924	603	420	352	344	205	225	131	178	102	287	617	538	479	542	589	628
10 to 15	586	827	801	1044	976	926	1060	1070	839	613	301	187	325	297	335	463	603	627	641	1022	965	999	920	828
15 to 20	1295	1263	1300	1002	917	845	927	953	819	592	588	393	226	177	324	320	337	287	315	524	900	1204	1420	1488
20 to 25	652	806	1260	1363	1416	1563	1548	1337	846	457	351	479	453	508	425	520	624	832	927	865	866	747	783	853
25 to 30	1253	1321	970	1373	1635	2035	2170	2040	1793	1437	985	724	611	452	459	370	408	470	562	652	882	980	1121	1374
30 to 35	1438	1798	2091	2302	2224	2157	2166	2111	1920	1332	806	875	867	657	753	1034	1286	1297	1409	1500	1788	1946	2002	2188
35 to 40	622	585	671	630	579	676	677	712	613	529	917	909	742	790	806	768	725	725	747	973	1065	1274	1424	1413
40 to 45	187	192	173	232	262	246	286	321	443	458	374	373	498	708	640	692	729	366	251	291	281	224	346	440
45 to 50	50	35	28	54	70	103	127	123	126	170	148	61	168	159	258	290	272	194	162	108	112	97	68	47
50 to 55	31	10	10	39	35	7	48	43	65	37	128	215	172	182	212	169	175	176	31	41	18	3	34	56
55 to 60	18	25	39	45	28	29	27	25	79	152	127	141	209	152	313	247	273	190	62	56	56	45	50	25
60 to 65	28	21	47	11	30	42	65	54	19	20	39	67	14	65	64	27	47	113	104	33	2	24	22	25
65 to 70	70	33	65	9	33	23	1	64	59	65	74	47	91	94	117	144	128	96	181	81	52	82	102	77
70 to 75	12	13	67	44	22	33	35	34	41	96	165	214	208	252	327	406	509	531	465	336	228	194	145	121
75 to 80	128	95	89	67	42	44	35	96	106	139	205	425	639	765	884	776	741	751	684	722	503	286	254	225
80 to 85	105	37	73	45	30	19	28	70	260	368	449	557	529	751	924	1214	1233	1008	891	730	565	359	185	134
85 to 90	0	0	0	0	0	0	0	0	14	308	730	789	1113	1079	1082	1127	1133	1316	1277	913	562	385	205	127
90 to 95	0	0	0	0	0	0	0	0	0	0	70	386	740	910	1078	1068	1209	1070	1108	868	314	11	0	0
95 to 100	0	0	0	0	0	0	0	0	0	0	0	0	0	252	344	379	509	485	236	0	0	0	0	0

Table E.6. Average number of heat pumps running in weekend bins (8/1/2004 to 6/30/2007).

	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
-10 to -5	3.9	3.8	3.7	3.7	3.7	3.8	4.0	3.8	3.3	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	3.2	4.0	3.7
-5 to 0	3.5	3.5	3.5	3.5	3.5	3.7	3.8	3.7	3.3	2.6	1.9	1.7	1.8	1.8	1.6	1.6	1.7	2.6	2.9	3.1	3.5	3.7	3.8	3.8
0 to 5	3.3	3.3	3.3	3.4	3.4	3.8	3.7	3.8	3.4	2.3	1.5	0.8	0.9	1.1	1.3	1.4	1.7	1.9	2.2	2.7	2.9	3.1	3.2	3.4
5 to 10	3.0	3.1	3.0	2.8	3.0	3.0	3.1	2.9	2.7	2.3	2.0	1.3	0.8	0.9	0.7	1.0	1.4	1.5	2.0	2.7	3.2	3.0	3.3	3.1
10 to 15	2.4	2.5	2.7	2.7	2.8	2.8	2.8	2.7	2.5	2.1	1.2	1.0	1.4	1.1	1.1	1.3	1.6	1.8	1.8	2.3	2.5	2.6	2.7	2.7
15 to 20	2.2	2.3	2.4	2.4	2.4	2.4	2.2	2.4	1.9	1.3	1.3	1.2	1.1	0.8	1.1	1.3	1.2	1.3	1.8	2.0	2.2	2.3	2.4	2.4
20 to 25	1.6	1.8	1.8	1.9	1.9	2.0	2.0	1.9	1.7	1.3	1.2	1.1	0.9	1.0	1.0	1.1	1.3	1.4	1.5	1.6	1.8	1.8	1.9	2.0
25 to 30	1.1	1.3	1.3	1.4	1.5	1.5	1.6	1.5	1.5	1.3	1.1	1.1	1.1	1.0	1.1	1.1	1.2	1.2	1.3	1.4	1.5	1.5	1.7	1.7
30 to 35	0.9	1.0	1.2	1.2	1.2	1.1	1.1	1.2	1.0	0.8	0.8	0.8	0.8	0.7	0.8	1.0	1.0	1.0	1.0	1.2	1.3	1.2	1.2	1.3
35 to 40	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.5	0.5	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.7	0.8	0.8
40 to 45	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.3	0.3	0.2	0.3	0.4	0.5	0.6	0.5	0.3	0.2	0.3	0.2	0.2	0.3	0.4
45 to 50	0.1	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.1
50 to 55	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.2	0.2	0.1	0.2	0.1	0.2	0.2	0.0	0.1	0.0	0.0	0.0	0.1
55 to 60	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.3	0.3	0.2	0.3	0.2	0.3	0.2	0.1	0.1	0.1	0.0	0.1	0.0
60 to 65	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.2	0.1	0.0	0.0	0.0	0.0	0.0
65 to 70	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.0	0.1	0.1	0.0
70 to 75	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.3	0.2	0.2	0.1	0.1	0.1
75 to 80	0.2	0.2	0.2	0.1	0.1	0.2	0.1	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.3	0.3	0.2
80 to 85	0.5	0.3	0.6	0.4	0.5	0.3	0.5	0.5	0.7	0.7	0.8	0.8	0.8	0.9	1.0	1.1	1.0	0.9	1.0	1.0	0.8	0.6	0.5	0.6
85 to 90	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	0.7	1.2	1.6	1.7	1.7	1.7	1.7	1.6	1.7	1.7	1.6	1.5	1.3	1.1	0.9	0.8
90 to 95	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	2.3	2.0	2.1	2.3	2.2	2.1	2.3	2.1	2.2	2.1	1.8	0.9	NaN	NaN
95 to 100	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	2.7	2.8	2.4	2.8	2.8	2.6	NaN	NaN	NaN	NaN	NaN

Appendix F. IAMU Electric Rates

Table F.1. Electric rates including all fees and taxes.

End of Billing Period	Billed kWh	Amount Billed	Price per kWh
1/9/2008	14040	$ 671.34	$ 0.048
12/6/2007	11040	$ 568.48	$ 0.051
11/5/2007	7800	$ 438.84	$ 0.056
10/5/2007	7740	$ 436.11	$ 0.056
9/6/2007	8820	$ 774.95	$ 0.088
8/7/2007	8460	$ 746.80	$ 0.088
7/9/2007	8760	$ 770.26	$ 0.088
6/7/2007	7020	$ 634.11	$ 0.090
5/8/2007	8340	$ 466.98	$ 0.056
4/9/2007	9840	$ 535.70	$ 0.054
3/9/2007	12840	$ 646.55	$ 0.050
2/8/2007	16440	$ 814.03	$ 0.050
1/9/2007	12000	$ 605.38	$ 0.050
12/7/2006	10920	$ 569.80	$ 0.052
11/6/2006	9060	$ 502.84	$ 0.056
10/6/2006	7380	$ 425.32	$ 0.058
9/7/2006	7620	$ 686.80	$ 0.090
8/8/2006	8280	$ 738.94	$ 0.089
7/10/2006	7860	$ 705.76	$ 0.090
6/8/2006	7800	$ 701.01	$ 0.090
5/9/2006	7140	$ 411.61	$ 0.058
4/10/2006	10380	$ 553.53	$ 0.053
3/10/2006	12540	$ 641.35	$ 0.051
2/9/2006	12480	$ 647.98	$ 0.052
1/10/2006	14760	$ 739.27	$ 0.050
12/8/2005	12000	$ 634.05	$ 0.053
11/7/2005	7320	$ 419.84	$ 0.057
10/7/2005	7080	$ 408.86	$ 0.058
9/8/2005	7140	$ 646.23	$ 0.091
8/9/2005	7620	$ 683.96	$ 0.090
7/11/2005	7320	$ 660.38	$ 0.090
6/9/2005	6240	$ 575.45	$ 0.092
5/10/2005	6960	$ 405.06	$ 0.058
4/11/2005	8520	$ 476.84	$ 0.056
3/11/2005	10500	$ 559.59	$ 0.053
2/9/2005	12300	$ 612.26	$ 0.050
1/10/2005	12420	$ 615.78	$ 0.050
12/9/2004	9480	$ 521.03	$ 0.055
11/5/2004	6720	$ 394.03	$ 0.059
Avg. over all months			$ 0.065
Avg.exclude June, July, Aug, Sep			**$ 0.054**
Avg. of June, July, Aug, Sep			**$ 0.090**

Appendix G. Energy Savings from Circulating Pump VFD

Table G.1. Calculations performed to determine maximum and minimum energy use by VFD/pump.

	# H.P. Operating	# Valves Open (N)	H.P. That Comes into Operation	Curve Fit Used to Calculate DAQ Current	DAQ Current (A)	VFD/Pump Power* (kW)	% of Annual Operation	Annual Hours of Operation	Annual Enegy (kWh)	Old Annual Energy (kWh)	% Savings
Predicted Minimum Annual Energy	0	1	-	$0.0457*N^2 + 0.074*N + 0.4535$	0.57	0.25	54.1%	4738	1208	9854	88%
	1	1	HP-V2	$0.0457*N^2 + 0.074*N + 0.4535$	0.57	0.25	18.7%	1634	417	3399	88%
	2	2	Any	$0.0457*N^2 + 0.074*N + 0.4535$	0.78	0.36	10.3%	905	325	1882	83%
	3	3	Any	$0.0457*N^2 + 0.074*N + 0.4535$	1.09	0.51	6.9%	608	307	1265	76%
	4	4	Any	$0.0457*N^2 + 0.074*N + 0.4535$	1.48	0.69	4.3%	378	261	787	67%
	5	5	Any	$0.0457*N^2 + 0.074*N + 0.4535$	1.97	0.90	2.7%	233	211	485	57%
	6	6	Any	$0.0457*N^2 + 0.074*N + 0.4535$	2.54	1.14	1.8%	160	183	333	45%
	7	7	Any	$0.0457*N^2 + 0.074*N + 0.4535$	3.21	1.40	1.0%	89	125	185	33%
	8	8	HP-V1	$0.0741*N^2 - 0.0616*N + 0.7752$	5.02	1.99	0.2%	14	28	29	4%
	Total							**8760**	**3065**	**18221**	**83%**
Predicted Maximum Annual Energy	0	1	-	$0.0457*N^2 + 0.074*N + 0.4535$	0.5732	0.25	54.1%	4738	1208	9854	88%
	1	2	HP-V1	$0.0741*N^2 - 0.0616*N + 0.7752$	0.9484	0.44	18.7%	1634	718	3399	79%
	2	3	Any	$0.0741*N^2 - 0.0616*N + 0.7752$	1.2573	0.59	10.3%	905	530	1882	72%
	3	4	Any	$0.0741*N^2 - 0.0616*N + 0.7752$	1.7144	0.79	6.9%	608	483	1265	62%
	4	5	Any	$0.0741*N^2 - 0.0616*N + 0.7752$	2.3197	1.05	4.3%	378	399	787	49%
	5	6	Any	$0.0741*N^2 - 0.0616*N + 0.7752$	3.0732	1.35	2.7%	233	315	485	35%
	6	7	Any	$0.0741*N^2 - 0.0616*N + 0.7752$	3.9749	1.67	1.8%	160	268	333	20%
	7	8	Any	$0.0741*N^2 - 0.0616*N + 0.7752$	5.0248	1.99	1.0%	89	178	185	4%
	8	8	HP-V2	$0.0741*N^2 - 0.0616*N + 0.7752$	5.0248	1.99	0.2%	14	28	29	4%
	Total							**8760**	**4125**	**18221**	**77%**

*Curve Fit for calculating VFD/Pump Power: $P = -0.0246*A^2 + 0.5283*A - 0.0398$

Appendix H. Defrost Heater Energy Analysis MATLAB Code

Main Program ‘Defrost’

```
%ERU Defrost Heater Analyzer
%Outputs fraction of time defrost heater runs in each 5-deg-F
%temperature bin when the ERU is in operation.

close all
clear all
clc

%Calls function 'yearmon' to determine input year and month, and number
%of days in month
[year,month,dayinmonth] = yearmon;

%Directory paths for data, weather and output files
Dprefix = 'C:\IAMU\Daily_Data\';
Wprefix = 'C:\ERS_Weather\';
Oprefix = '\\Ank1\public\USERBackups\Joel Logan\ERU\Defrost\';

%Opens ouput file, displays error message if file cannot be opened
fidO = fopen([Oprefix,year,month,'Defrost2.imu'],'w');
if fidO == -1
    fidO
end

%Prints column headers to output file
fprintf(fidO,
'%s\t%s\t%s\t%s\t%s\t%s\t%s\t%s\t%s\t%s\t%s\t%s\t%s\t%s\t%s\t%s\t%s\t%s\t%s
\t%s\t%s\t%s\t%s\n','DATE','Bin -10 to -5','Bin -5 to 0','Bin 0 to
5','Bin 5 to 10','Bin 10 to 15','Bin 15 to 20','Bin 20 to 25','Bin 25
to 30','Bin 30 to 35','Bin 35 to 40','Bin 40 to 45','Bin 45 to 50','Bin
50 to 55','Bin 55 to 60','Bin 60 to 65','Bin 65 to 70','Bin 70 tp
75','Bin 75 to 80','Bin 80 to 85','Bin 85 to 90','Bin 90 to 95');

%Loop iterates data analysis over days in month specified
for d=18 %1:1:dayinmonth
    %If-statement creates a day string variable
    if ((d>=1)&&(d<10))
        day = ['0',num2str(d)]
    elseif (d>=10)&&(d<=dayinmonth)
        day = num2str(d)
    elseif (d>dayinmonth)
        disp('Day exceeds number of days in month')
    end

    %Forms name of daily data and weather files, opens files, displays
    %error message if either file cannot be opened.
    filenameD = [Dprefix,year,month,day,'\',month,day,'HVAC.imu'];
    filenameW = [Wprefix,year,month,'\',month,day,'wthr.ers'];
    fidD = fopen(filenameD, 'r');
    fidW = fopen(filenameW, 'r');
```

```
    if (fidD==-1)||(fidW==-1)
        fidD
        fidW
        continue
    end

%////////////////////////////////////////////////////////////////////////
    %Read the header column of the data file and write each heading
    %into a row vector and prepare for writing to a the output file
    HeaderD1 = fgetl(fidD);      %Reads data file header into an array
    i = 1;                       %Initializes the row vector index to 1

    %Loop converts header into a row vector
    while true
         %Divides the header into the column before the first white
         %space and the remainder of the columns
        [HeaderD2, RemainderD] = strtok(HeaderD1);

        %Writes the individual header columns into a row vector
        HeaderCheckD(1,i) = {HeaderD2};

        %Ends loop if there are no more header columns to be written to
        %the row vector
        if isempty(RemainderD), break; end

        %Reassigns the header as the remainder of the header
        HeaderD1 = RemainderD;

        %Advances the row vector index
        i = i+1;
    end

    %Gives number of columns in header and colum position of 'ERU_Amps'
    L_D = length(HeaderCheckD);
    N_D = strmatch('ERU_Amps', HeaderCheckD)

    %Initializes 'fullformat' to an empty martrix
    fullformat_D = [];
    %Loop sets format that 'textscan' will use to read data files
    for k=1:1:L_D
        if k==1
            format = '%s';
        elseif k==2
            format = '%s';
        elseif k==N_D
            format = '%f';
        else
            format = '%*f';
        end

        fullformat_D = [fullformat_D,format];
    end
```

```
%//////////////////////////////////////////////////////////////////////
    %Read the header column of the weather file and write each heading
     %into a row vector and prepare for writing to the output file
    HeaderW1 = fgetl(fidW);  %Reads weather file header into and array
    i = 1;                   %Initializes the row vector index to 1

    %Loop converts header into a row vector
    while true
        %Divids the header into the column before the first white space
         %andthe remainder of the columns
        [HeaderW2, RemainderW] =strtok(HeaderW1);

        %Writes the individual header coluns into a row vector
        HeaderCheckW(1,i) = {HeaderW2};

        %Ends loop if there are no more header columns to be written to
         %the row vector
        if isempty(RemainderW), break; end

        %Reassigns the header as the remainder of the header
        HeaderW1 = RemainderW;

        %Advances the row vector index
        i = i+1;
    end

   %Gives number of columnes in header and column position of 'OA-TEMP'
    L_W = length(HeaderCheckW);
    N_D = strmatch('OA-TEMP', HeaderCheckW);

    %Initializes 'fullformat' to an empty martrix
    fullformat_W = [];
    %Loop sets format that 'textscan' will use to read data files
    for k=1:1:L_W
        if k==1
            format = '%s';
        elseif k==2
            format = '%s';
        elseif k==N_D
            format = '%f';
        else
            format = '%*f';
        end
      %Concatonates format of individual column to format of entire row
        fullformat_W = [fullformat_W,format];
    end


%//////////////////////////////////////////////////////////////////////
    i = 1;                                        %Initializes vector index to
1
     %While loops data from data and weather file and matches the data
     %minute-by-minute, writes data into arrays
```

```
while  feof(fidD)==0
 %Initializes 'Breaker' to 0, Breaker allows the loop to advance
  %to next day if data or weather file before 23:59 is reached
    Breaker = 0;

    %Read data from data  and weather files, reading terminated if
    %blank line reached in either file before end of file marker
    Data = {textscan(fidD,fullformat_D, 1)};
    if isempty(Data{1,1}{1,1}) == 1, break; end
    Weather = {textscan(fidW,fullformat_W, 1)};
    if isempty(Weather{1,1}{1,1}) == 1, break; end

    %Converts the data file date and time into strings,
     %concatonates the strings, and converts the strings to decimal
     %dates
    Date_D = datenum([char(Data{1,1}{1,1}), ', ',
              char(Data{1,1}{1,2})]);

    %Converts the weather file date and time into strings,
     %concatonates the strings, and converts the strings to decimal
     %dates
    Date_W = datenum([char(Weather{1,1}{1,1}), ', ',
              char(Weather{1,1}{1,2})]);

    %While loop compares the data file and weather file dates, if
     %the weather file date is greater than the data file date by 1
     %minute, the next line in the data file is read
    while (Date_W-Date_D)>(1/1440)
        Data = {textscan(fidD,fullformat_D,1)};
        if isempty(Data{1,1}{1,1}) == 1
            Breaker = 1
            break
        end
       %The data file date and time are converted to a decimal date
        Date_D = datenum([char(Data{1,1}{1,1}), ', ',
                 char(Data{1,1}{1,2})]);
    end

    %While loop compares the data file and weather file dates, if
     %the data file date is greater than the weather file date by
     %more than 1 minute, the next line in the weather file is read
    while (Date_D-Date_W)>(1/1440)
        Weather = {textscan(fidW,fullformat_W, 1)};
        if isempty(Weather{1,1}{1,1}) == 1
           Breaker = 1
            break
        end
    %The weather file date and time are converted to a decimal date
        Date_W = datenum([char(Weather{1,1}{1,1}), ', ',
                 char(Weather{1,1}{1,2})]);
    end

    %Advances to next day if data or weather file end before 23:59
     %is reached
```

```
        if Breaker == 1, break; end

        %Creates column vector of the date
        Date(i) = Data{1,1}{1,1};

        %Creates column vector of the ERU_Amps
        ERU_AMPS(i) = Data{1,1}{1,3};

        %Creates column vector of the OA_Temp
        OA_TEMP(i) = Weather{1,1}{1,3}
        i=i+1;   %Advances vector index
    end

    L = length(Date);%Length of Date vector

    %Calls Analyze function to analyze operation of ERU defrost heater
    [ERU_ON, Defrost_on, High, Low, sum_bin, sum_defrost_bin,
            Percent_On] = Analyze(L,ERU_AMPS, OA_TEMP);

    %Prints heater percentage of runtime in temp bins for current day
     %to output file
    fprintf(fidO,
            '%s\t%f\t%f\t%f\t%f\t%f\t%f\t%f\t%f\t%f\t%f\t%f\t%f\t%f\t%f
            \t%f\t%f\t%f\t%f\t%f\t%f\t%f\n',
            [month,'/',day,'/',year],Percent_On(1),Percent_On(2),Percen
            t_On(3),Percent_On(4),Percent_On(5),Percent_On(6),Percent_O
            n(7),Percent_On(8),Percent_On(9),Percent_On(10),Percent_On(
            11),Percent_On(12),Percent_On(13),Percent_On(14),Percent_On
            (15),Percent_On(16),Percent_On(17),Percent_On(18),Percent_O
            n(19),Percent_On(20),Percent_On(21));
    fclose(fidD);                   %Close data file
    fclose(fidW);                   %Close weather file
end
fclose(fidO);                       %Close output file
disp('End of Program')
```

Function ‘yearmon’

```
function [year,month,dayinmonth] = yearmon
% This function asks for the year and month for which the user would
% like to analyze data.  It then determines the number of days in the
% month.  It outputs the the year, month and the nuber of days in the
% month to the calling program.

%Input year in four digits (1998) and then month in two ditits (01) for
%data analysis.
year = input('For what year will ERU defrost heater be analyzed? (ex:
      1999, 2007)  ','s');
month = input('For what month will ERU defrost heater be analyzed?
      January = 01, December = 12  ','s');

%Loop allows user to input whether the year is a leap year
if month == '02'
```

```
    leap = input('Is this a leap year? (y/n)  ','s');
end

%Converts month string input to number for use in logical statements
mon = str2num(month);

%Loop determines number of days in specified month
if
      (mon==1)||(mon==3)||(mon==5)||(mon==7)||(mon==8)||(mon==10)||(mon
      ==12)
    dayinmonth = 31;
elseif (mon==4)||(mon==6)||(mon==9)||(mon==11)
    dayinmonth = 30;
%Sub-loop determines number of days in February based on leap year
      input
elseif mon==2
    if leap == 'n'
        dayinmonth = 28;
    elseif leap == 'y'
        dayinmonth = 29;
    else
        disp('Improper leap year input')
    end
else
    disp('Month out of range')
end
%Outputs number of days in month to screen
disp(['Number of days in month: ',num2str(dayinmonth)])
```

Function ‘Analyze’

```
function [ERU_ON, Defrost_on, High, Low, sum_bin, sum_defrost_bin,
Percent_On, Bin] = Analyze(L,ERU_AMPS,OA_TEMP)
%This function anlyzes the runtime and energy use of the ERU defrost
heater
%The energy consumption is determined using a bin method

%Initialize matricies to zeros
  ERU_ON = zeros(L,1);
  Defrost = zeros(L,1);
  High = zeros(L,1);
  Low = zeros(L,1);
  Bin = zeros(L,21);

for i=1:1:L
    %If statement determines if the ERV is on and whether or not the
    %defrost heater is operating.
    if (ERU_AMPS(i) > 10)
        Defrost_on(i) = 1;
        High(i) = 0;
        Low(i) = 0;
        ERU_ON(i) = 1;
    elseif (ERU_AMPS(i) <= 10) && (ERU_AMPS(i) > 5)
        Defrost_on(i) = 0;
```

```
        High(i) = 1;
        Low(i) = 0;
        ERU_ON(i) = 1;
    elseif (ERU_AMPS(i) <= 5) && (ERU_AMPS(i) > 1.5)
        Defrost_on(i) = 0;
        High(i) = 0;
        Low(i) = 1;
        ERU_ON(i) = 1;
    else
        Defrost_on(i) = 0;
        High(i) = 0;
        Low(i) = 0;
        ERU_ON(i) = 0;
    end

    k = -10;
    l = -5;

    %Determines what temperature in each minute is in, assigns each
minute
    %of ERV operation and defrost heater operation to appropriate
    %temperature bin.
    for m=1:1:21
        if (ERU_ON(i)==1)&&((OA_TEMP(i)>=k)&&(OA_TEMP(i)<l))
            Bin(i,m) = 1;
        else
            Bin(i,m) =0;
        end

        if (Defrost_on(i) == 1)&&((OA_TEMP(i)>=k)&&(OA_TEMP(i)<l))
            Defrost_Bin(i,m) = 1;
        else
            Defrost_Bin(i,m) = 0;
        end
        k=k+5;
        l=l+5;
    end
end

%For loop determines the percentage of time defrost heater is on while
ERV
%is on in each temperature bin
for n=1:1:21
    n
    sum_bin(n) = sum(Bin(:,n))
    sum_defrost_bin(n) = sum(Defrost_Bin(:,n))
    Percent_On(n) = sum_defrost_bin(n)/sum_bin(n)
end
```

Appendix I. General Equipment Load Breaker Schedule

Table I.1. General equipment loads measured on March 8, 2007.

	Breaker Description	Breaker	Time	Power (W)	Load Type	Equipment on Breaker
North Wing	Office	1A-13	19:52	6	DP	laptop, space heater, radio
	Office	1A-15	19:53	4	DP	laptop, speakers
	Office	1A-17	19:54	21	DP	laptop, speakers, power supply
	Conference	1A-19	19:54	7	DC	power supply
	Office	1A-21	19:55	4 to 9	DP	Computer, CRT screen, power supply
	Office	1A-23	19:57	20	DP	?
	Office	1A-25	19:57	5	DP	Adding machine, lamp (unplugged), space heater
	Office	1A-27	19:58	15	DP	light (unplugged), space heater (unplugged),
	Office	1A-29	19:58	34	DP	space heater (unplugged), laptop, lamp
	Open Office	1A-31	19:59	9	DC	none
	Open Office	1A-33	20:00	12	DC	none
	Open Office	1A-35	20:00	10	DC	none
	Office	1A-14	20:01	7 to 16	DP	computer, CRT screen, lamp
	Office	1A-16	20:02	16	DP	laptop computer, lamp, radio
	Office	1A-18	20:02	8	DP	computer, CRT screen
	Office	1A-20	20:02	60	DP	computer, LCD screen, adding machine, speakers
	Office	1A-22	20:03	100	DP	space heater, (2) printers, computer, LCD screen
	Office	1A-24	20:04	11	DP	computer, CRT screen, fan (unplugged), radio, speakers, power supply
	Office	1A-26	20:04	6	DP	?
	Office	1A-28	20:05	160	DC	(2) computers, CRT screen, LCD screen, radio, typewriter, copier, scanner, cd label writer, speakers, zipdrive printer, 3 modem
	Reception	1A-30	20:05	45	DC	(2) lamp, computer, CRT screen, speakers, printer
	Open Office Copier	1A-32	20:06	70	DC	none
	Open Office	1A-34	20:06	2	DP	?
	Open Office	1A-36	20:07	0	DP	none
	Electric Heater	1A-40	-	-	-	Electric baseboard heater for west
Central Area	Door Openers	1B-31	20:58	20	N	Handicapp Door Openers
	Drinking Fountains	1B-33	20:59	10	N	Drinking Fountains
	Lobby	1B-35	20:59	62	DC	Soda Machine
	Lobby	1B-37	21:00	11	DC	?
	Fire Alarm	1B-45	21:00	2	N	Fire Alarm
	Sprinkler Alarm	1B-47	21:01	16	N	Sprinkler Alarm
	Invensys System	1B-32	21:02	23	N	Invensys System
	Patio Plugs	1B-34	21:02	0	DC	none
	Conference Room	1B-40	21:03	1	DC	none
	Conference Room	1B-42	21:03	0	DC	none
	Electrical Room	1B-44	21:04	200	N	Old Refrigerator
	Conference Room	1B-46	21:05	3 to 11	DC	power supply
	Conference Room	1B-48	21:05	6	DC	?
	Hot Water Heater	1B-50	21:07	3	N	Hot water heater
	Hot Water Heater	1B-52	21:08	1	N	Hot water heater
	Electric Heater	1B-41&43	-	-	-	Electric heater in electrical panel room
	Electric Heater	1B-36&38	-	-	-	Electric heater by patio door

Load Type Key:
N: Nondiscretionary load—cannot be turned off when the building is unoccupied
DC: Discretionary Communal Load—can be turned off, not in a personal office
DP: Discretionary Personal Load—can be turned off, in a personal office

Table I.1 (Continued). General equipment loads measured on March 8, 2007.

	Breaker Description	Breaker	Time	Power (W)	Load Type	Equipment on Breaker
South Wing	TVSS	1D-1	21:28	6	N	TVSS
	TVSS	1D-3	21:28	2	N	TVSS
	TVSS	1D-5	21:29	1	N	TVSS
	Corridor	1D-7	21:30	4	DC	?
	W. 1/2 Hall Wall	1D-9	21:31	0	DC	none
	E. 1/2 Hall Wall	1D-11	21:31	0	DC	none
	Work Room	1D-13	21:31	0	DC	none
	Work Room	1D-15	21:34	17	DC	Work room
	Work Room	1D-17	21:34	10	DC	Work room
	Work Room	1D-19	21:34	50	DC	Work room
	Server Room S. & C.	1D-23	21:35	770	N	Server room
	Server Room N.	1D-25	21:36	280	N	Server room
	Server Room S. & E.	1D-27	21:36	25	N	Server room
	Kitchen, Microwave	1D-29	21:37	5	DC	Kitchen
	Kitchen S.E	1D-31	21:37	5	DC	Kitchen
	Kitchen, Refrigerator	1D-33	21:38	3	DC	Kitchen
	Kitchen N.W	1D-35	21:38	4	DC	Kitchen
	Aud. Sound System	1D-37	21:38	3	DC	Aud. Sound System
	Aud Sound System	1D-39	21:38	1	DC	Aud Sound System
	Aud. Window Blinds	1D-41	21:39	5	N	Aud. Window Blinds
	Office	1D-43	21:59	0	DC	laptop
	South Vestibule	1D-45	21:59	0	DC	none
	Server Room W.	1D-47	21:59	80 to 140	DC	Server room
	?	1D-51	22:00	1	DC	?
	?	1D-53	22:01	1	DC	?
	Office	1D-2	21:40	10	DP	space heater, lamp
	Office	1D-4	21:40	120	DP	typewriter, laminator, modem, scanner, (2)
	Office	1D-6	21:41	2	DP	?
	Office	1D-8	21:41	2	DP	computer, LCD screen, speakers, radio
	Office	1D-10	21:42	16	DP	(2) laptops, LCD screen (3) power supplies,
	Office	1D-12	21:42	5	DP	laptop, lamp, speakers
	Work Room	1D-16	21:43	10	DC	Work room
	Work Room	1D-18	21:43	7	DC	Work room
	Aud. Projector	1D-20	21:43	3	DC	Aud. Projector
	Aud. Projector Screen	1D-22	21:44	11	DC	Aud. Projector Screen
	Aud. Outlets	1D-24	21:44	6	DC	?
	Aud Floor Outlets	1D-26	21:45	3	DC	?
	Oven	1D-28	21:45	6	DC	Oven
	Oven	1D-30	21:46	7	DC	Oven
	Kitchen S.W.	1D-32	21:46	0	DC	Kitchen S.W.
	Kitchen Dishwasher	1D-34	21:46	0	DC	Kitchen Dishwasher
	Kitchen W, sink	1D-36	21:47	48	N	Kitchen W, sink
	Kitchen Disposal	1D-38	21:47	1	DC	Kitchen Disposal
	South Vestibule	1D-40	21:48	3	DC	?
	South Vestibule	1D-42	21:48	2	DC	?
	Office	1D-44	22:01	22	DP	(2) laptops, speakers, power supply, VCR,
	Office	1D-46	22:01	15	DP	laptop, speakers, lamp
	Office	1D-48	22:01	3	DP	laptop, radio, speadkers, lamp, spaceheater
	Electric Heater	1D-61,63,65	-	-	-	Main entry electric heater
	Electric heater	1D-67	-	-	-	Lobby electric heater
	Electric Heater	1D-69,71	-	-	-	South entrance electric heater
	Electric Heater	1D-73	-	-	-	Storage room electric heater

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