ENERGY MODELING REPORT

Energy Performance Comparison
of
Warehouse Heating Systems

Prepared for Cambridge Engineering, Inc.

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February *2009*

Contents

Consulting Firm

GARD Analytics is an experienced consulting and testing service. They do evaluations of technologies for providing energy efficient heating services to buildings. GARD was on the team that helped the U.S. Dept. of Energy (DOE) develop and test the internationally recognized EnergyPlus energy simulation software used for this project.

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Energy Modeling Software

EnergyPlus energy modeling software meets the requirements of the U.S Green Building Council (USGBC) for determining LEED energy credit points. It conforms to the modeling requirements of ASHRAE Standard 90.1 and is an IRS approved energy modeling software for obtaining Energy Policy Act (EPAct) federal tax deductions.

Objective

Use energy modeling to determine what type of warehouse heating system is the most energy efficient for both LEED and Non-LEED warehouse facilities. Provide an energy modeling basis for obtaining energy points on LEED projects and EPAct federal tax deductions for warehouse heating equipment.

Problem Statement

Heating and ventilating large warehouses and other large industrial-type spaces require heating systems which are quite distinct from those used in typical commercial or institutional buildings. There was no known published energy modeling information that compares all six commonly used warehouse heating systems to the system prescribed by Appendix G of ASHRAE 90.1 which is the baseline used to obtain LEED energy points and tax deductions for warehouse buildings.

Solution

Use EnergyPlus energy modeling software to analyze the energy performance of each different heating system in a generic warehouse, modeled to comply with the requirements of ASHRAE 90.1-2004 and ASHRAE 62.1-2007.

Summary

Energy modeling results from this analysis found the high temperature rise, direct gas-fired “blow-thru” type space heating system used the least amount of total energy for all cases. Results for a typical LEED warehouse were 23.9% to 59.0% annual gas savings versus all other warehouse heating systems. This is attributed to its high combustion efficiency and dual 160°F maximum temperature rise/discharge temperature capability.

February 2009

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Energy, Economic and Environmental Research

Energy Performance of Warehouse Heating Systems

Simulation Analysis Using EnergyPlus

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February 2009

Energy Performance of Warehouse Heating Systems
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Introduction

The heating/ventilating of warehouses and other large industrial-type spaces usually requires systems which are quite distinct from the equipment used in typical commercial or institutional buildings. Commonly, these spaces use dedicated heating equipment, of which there are several competing types. This report describes an analysis of the energy performance of six different heating system types used in a generic warehouse. The warehouse and the heating systems were modeled to comply with the requirements of ASHRAE Standard 90.1-2004 and ASHRAE Standard 62.1-2007 as required by LEED-NC 2.2 and LEED-CS 2.0. In addition, a seventh heating system, that prescribed by Appendix G of ASHRAE Standard 90.1-2004 is analyzed, as this is the baseline heating system used for obtaining LEED energy credits for a warehouse facility. This system is a VAV system with hot water reheat coils served by natural gas boilers.

The goal of this analysis is to determine which heating system is the most energy efficient for both LEED and non-LEED warehouse facilities. Energy modeling results from this study found the direct gas fired blow-thru type heating system used the least amount of total energy in all the cases included in the analysis.

Approach

The energy performance of various heating systems was modeled using the EnergyPlus energy modeling software (version 3.0.0.013). This software has been developed by the Department of Energy (DOE), and offers simultaneous calculation of envelope and space loads and simulation of the HVAC equipment. EnergyPlus meets the requirements of the U.S. Green Building Council (USGBC) as energy modeling software that is appropriate for determining LEED energy credit points.

A 200,000 ft^2 generic warehouse located in Columbus, Ohio was developed for this study. Additional details of the modeled warehouse are provided below. The six heating systems to be modeled were selected as being representative of the systems typically used in warehouse applications. Cambridge Engineering, a leading manufacturer of warehouse heating equipment, was used as a resource for this project.

For these building types, cooling is normally not provided, at least in the northern tier of the United States. Additionally, this study was focused on heating systems. For these reasons, therefore, cooling was not included in the energy analysis.

A complicating issue for this analysis is that obtaining a LEED certification of any level requires that the provisions of ASHRAE Standard 62.1 be met. The primary difficulty here is that the standard requires a continuous supply of ventilation air (at 0.06 cfm/ft²) during periods of occupancy. An additional LEED credit (point) can also be obtained by increasing ventilation air another 30% (to 0.78 cfm/ft²). This differs from common practice in warehouses, where ventilation air is provided through infiltration, open overhead doors, and as an adjunct to the operation of some heating system types. This study therefore includes modeling for the following three ventilation requirements:

1. 100% minimum ventilation of 0.06 cfm/ft² per ASHRAE Standard 62.1;
2. 130% (0.78 cfm/ft²) for additional LEED credit;
3. Zero minimum mechanical ventilation with outdoor air provided to simulate common practice for non-LEED certified buildings.

Warehouse Description

Geometry

The warehouse is rectangular, 1000' by 200' (200,000 ft² total). There are 34 dock doors with seals, 9' by 10', and four 12' by 14' drive through doors without seals. The doors are grouped in six locations, three on each of the long sides of the building. At one end of the building, 50' and 70' from the end, two of the drive through doors are located on each side, for a total of four. Centered on each long side of the building is a group of nine dock doors. On each of the long sides of the building, at the end opposite from the location of the drive through doors, is a group of eight dock doors. Figures 1 and 2 show the modeled building.

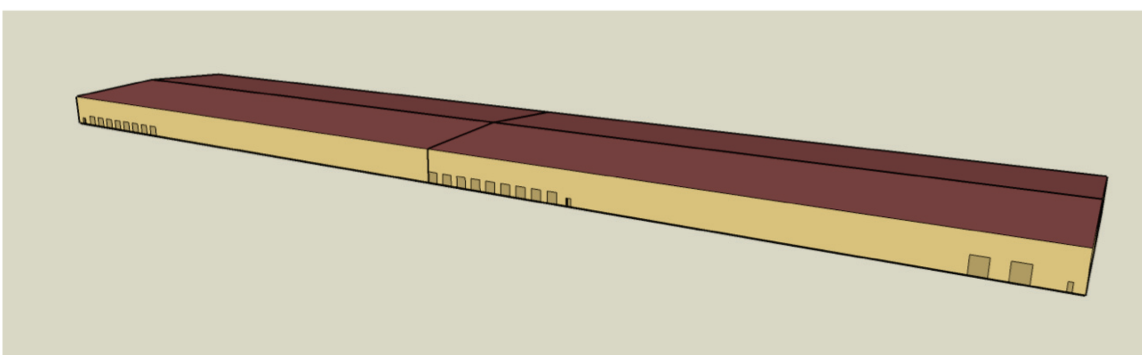

Figure 1 View of the Modeled Warehouse Showing Door Configuration on Long Side

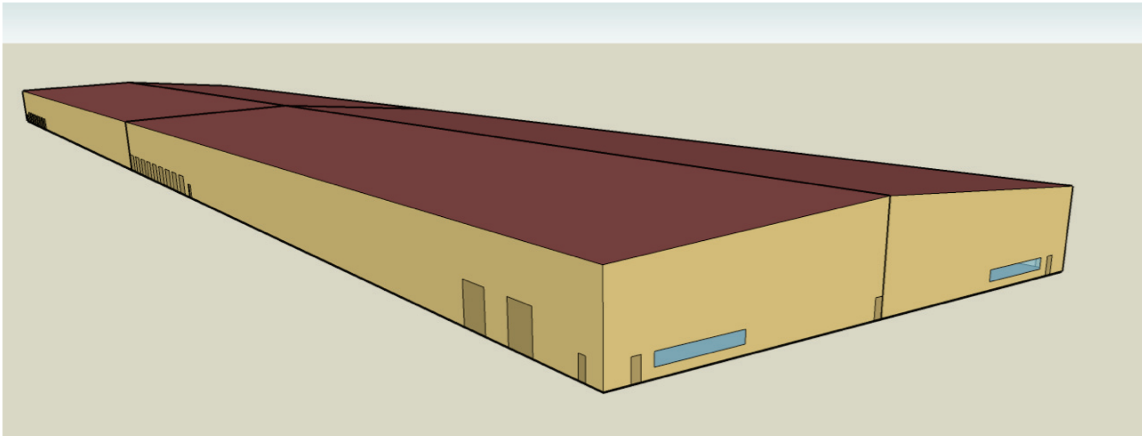

Figure 2 View of the Modeled Warehouse Showing Doors and Windows on Short Side

Adjacent to each of the six sets of overhead doors is a standard swinging door for personnel access, with an adjacent 1' wide by 6' tall view window, located with the bottom 1' above the floor and 6" from the knob side of the door. The long sides of the building have no other glazing. On each of the short sides of the building there are three swinging doors for personnel access, with two fixed ribbon windows between the center door and the two corner doors. The windows are each 30' long and 4' high, with the bottom of the glass located 3' above the floor.

The long sides of the building are 30' high. The roof a peak, running the long direction of the building, which is 36' high. The interior of the building is open. Any supporting columns that might exist in an actual building are not modeled, as they are not thermally significant.

The building is modeled as four thermal zones, one in each quadrant. Zone boundaries are visible in Figures 1 and 2.

Construction

The building is a metal construction, with 28 gauge steel backed by insulation. ASHRAE Std. 90.1-2004 places Columbus, OH in climate zone 5A, with the prescriptive insulation requirements for metal buildings of R19 in the roof and R13 in above grade walls. There is no insulation required with slab on grade floors. The swinging doors are insulated metal sandwich construction, and Std. 90.1 specifies that they must have U values of no more than 0.7. The overhead doors are also a metal sandwich construction, and Std. 90.1 specifies that the U value be no more than 1.45. The glazing is specified by Std. 90.1 to have U values no more than 0.57, and SHGC of no more than 0.49.

Internal Loads

The building is staffed throughout the operating period by 50 workers, with modification by the operating schedule below. Lighting power is 0.9 W/ft^2, based on Std. 90.1, or 180,000 Watts total. Equipment energy is based on the use of 10 electrically powered forklifts. Energy consumption is based on an NPGA case study which says that a 33 lb propane tank (for propane powered forklifts) lasts up to 8 hours, therefore an average of about 6 hours, or approximately 5 lbs/hr is assumed. Propane has a heat value of approximately 20,000 Btuh/lb, so each propane unit consumes 100,000 Btuh. For electric units, the efficiency is assumed to be 85%, compared to about 40% for the propane units. Therefore the electric units consume about 47,058 Btuh (100,000 x 40%/85%), which is rounded to 50,000 Btuh per unit, or 500,000 Btuh total. This translates to 2.5 Btuh/ft². Equipment energy consumption is adjusted by the schedule below.

Schedules

The building is operated from 5:00 a.m. to 9:00 p.m., Monday through Saturday, except national holidays. This is modeled as two shifts, each with a lunch hour. The lunch hour is modeled with a drop in occupant activity of 10% during the hours before and after the lunch hour, and of 50% during the lunch hour. The lunch hours are at 9:a.m. and 5 p.m. Staffing is consistent between the two shifts. The daily schedules for people, lights, equipment and thermostat setpoint, each with three separate schedules for Monday – Friday, Saturday, and Sunday/Holiday, are shown in Figures 3 through 7.

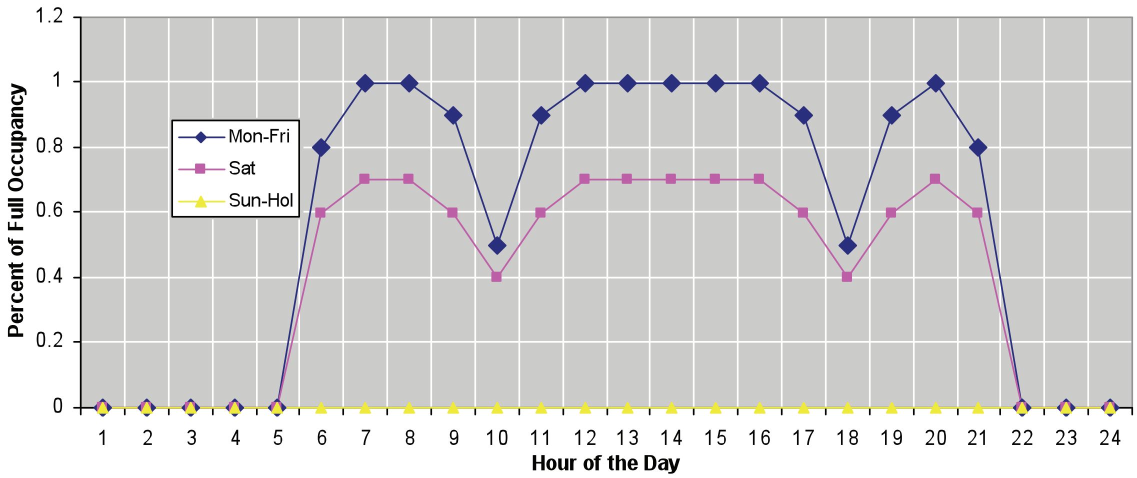

Figure 3 Occupancy Schedules

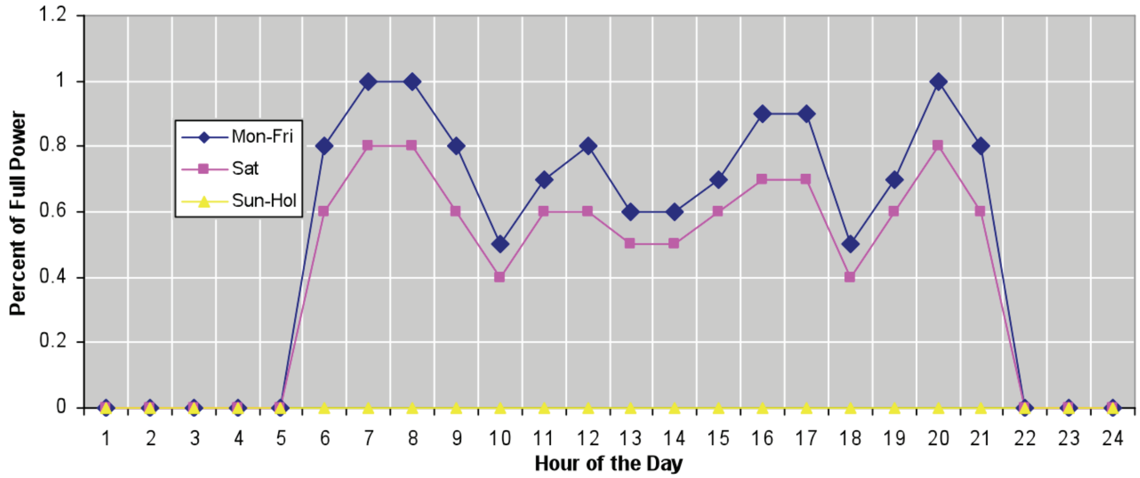

Figure 4 Equipment Operating Schedules

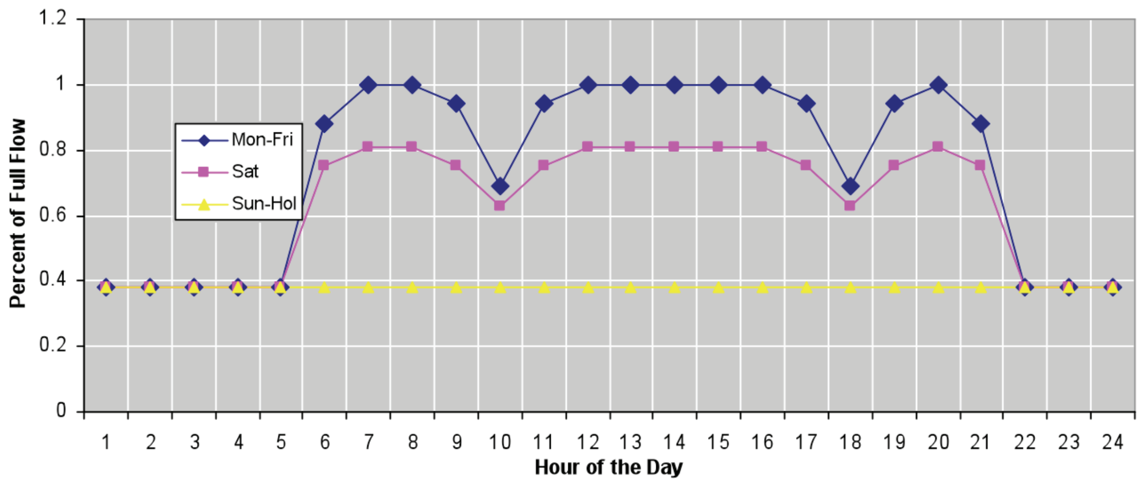

Figure 5 Infiltration Schedules

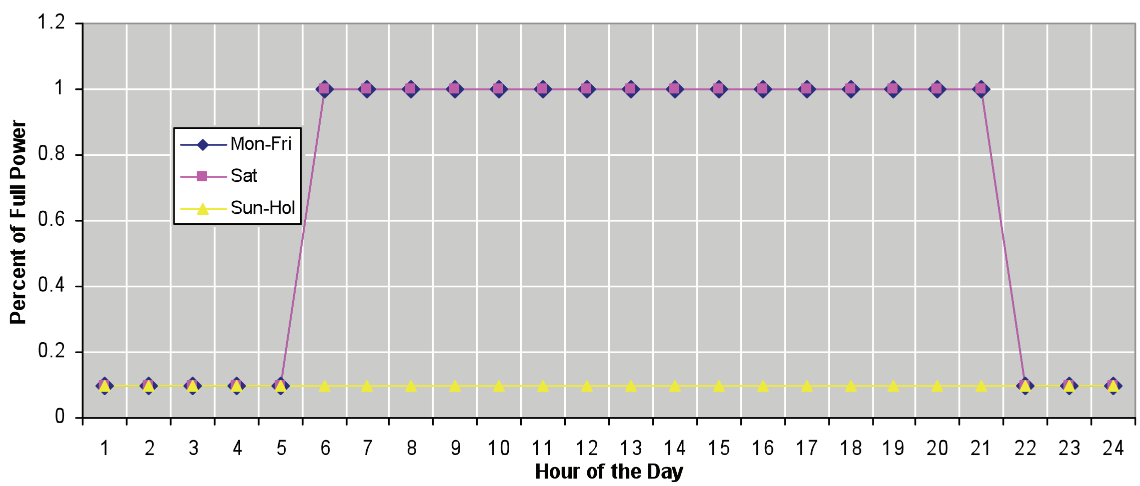

Figure 6 Lighting Schedules

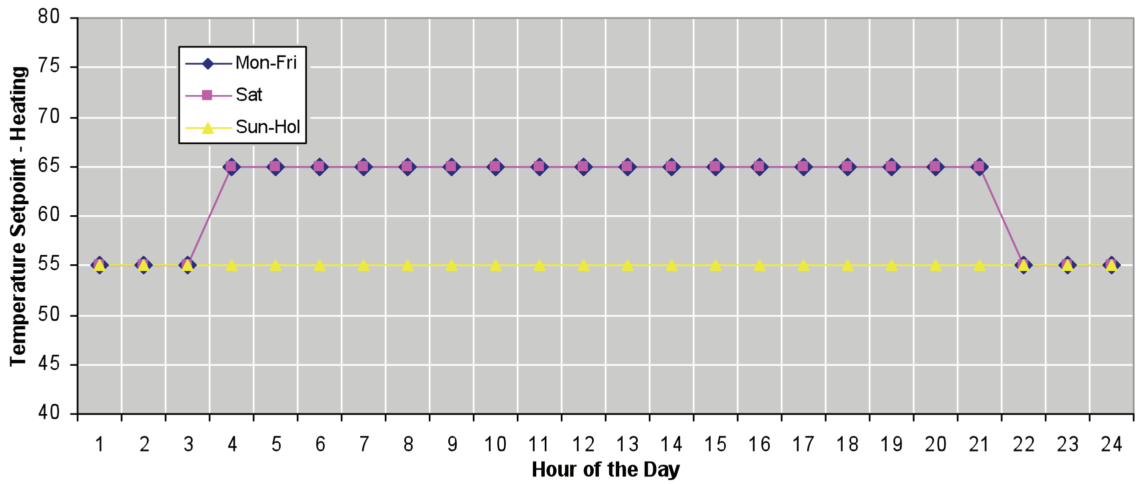

Figure 7 Heating Setpoint Temperature Schedules

Internal building mass (mass of stored material)

A value of 25 pounds per square foot, or 5,000,000 pounds total is assumed. The material is modeled as steel, with a thermal conductivity of 0.108 Btu/lb.

Door schedule and infiltration rates

Infiltration in EnergyPlus is modeled based on a design flow rate, the indoor-outdoor temperature difference, windspeed, and a schedule value. The design flow rate and the coefficients in the equation are input values, while the indoor-outdoor temperature difference is calculated by the program and the windspeed is taken from the weather file. The design infiltration flow rate is 9,492 cfm (4.48 m^3/s) for zones 1 and 3, and 6,525 cfm (3.08 m^3/s) for zones 2 and 4. (All EnergyPlus input is in SI units.) The overall peak infiltration rate was equal to 0.32 air changes per hour, although zones 1 and 3 had a higher rate due to more overhead doors, with zones 2 and 4 having lower peak rates.

The infiltration rate at each time step is calculated as:

$$Infiltration = Design\ Flow \times (0.8333 + 0.04 \times \Delta T + 0.0044 \times WS) \times Schedule$$

where: *Infiltration* is the infiltration flow rate for the simulation time step in m^3/s,
Design Flow is in m^3/s,
ΔT is the indoor-outdoor temperature difference in °C,
WS is windspeed in m/s, and
Schedule is the schedule value, which is the fraction of full flow.

Note that EnergyPlus also includes a term for the square of the windspeed. The coefficient on this term was set to zero.

The schedules for infiltration are shown above in Figure 5, with one exception. Based on actual field building study data provided by Cambridge Engineering, infiltration during occupied hours is dominated by operation of the overhead doors. The number of open doors roughly follows the occupancy schedule. During unoccupied periods, the infiltration value is 38% of the full flow for heating systems which do not bring in outdoor air. For all the direct fired heating systems which supply 100% outdoor air, heating operation serves to offset the building infiltration, reducing it from 38% of maximum to 10% during those hours.

HVAC system configuration details

Seven different heating/ventilating systems were modeled for this analysis. Six of these are systems which are commonly used in warehouse applications, and the seventh is the LEED baseline system specified by ASHRAE Standard 90.1. The heating systems are listed below, all of which are assumed to be natural gas-fired:

1. VAV with hot water reheat from gas fired boiler
2. Direct fired, high temperature rise blow-thru- space heater
3. Direct fired draw-thru low temperature rise make-up air heater
4. Indirect fired power vented (higher efficiency) unit heater
5. Indirect fired air turnover (air rotation) heating system
6. Direct fired recirculation type heating system
7. Condensing type (higher efficiency) indirect fired tubular infrared heater

The LEED baseline **VAV** system with reheat complies with the specifications in Appendix G of ASHRAE Standard 90.1-2004. This means there is a single central system serving the four zones of the building. The system has hot water heating coils. Hot water is supplied by a natural draft gas boiler. The air system operates continuously during occupied periods, and cycles to meet heating loads during unoccupied periods. Each zone is served by a VAV box with hot water reheat coils. The supply air fan has power consumption as specified in section G3.1.2.9, based on the design cfm, and uses a variable speed drive. Hot water is supplied from the boiler at 180°F with the return temperature specified as 130°F. The baseline hot water pump's energy consumption is 19W/gpm, modeled as primary-only with continuous variable flow using variable speed drives. The unit has outdoor air intakes for ventilation air. Standard 90.1-2004 specifies that the baseline equipment be oversized by 25% in heating (G3.1.2.2). Piping losses are not to be considered (G3.1.3.6).

Direct gas-fired, high temperature rise **BLOW-THRU** space heaters provide heating and ventilation air in the heating season. During normal operation, the blow-thru heaters are cycled to meet the heating load. Normally, this results in adequate ventilation airflow. As the outdoor temperature increases, however, the heating load and operating time of the heater decreases, and eventually the ventilation airflow falls below that required by Standard 62.1. When this happens, the unit is cycled on as needed to provide the needed ventilation airflow, with the burner operating at a reduced input rate to avoid overheating the space.

Direct gas-fired **DRAW-THRU** make-up air units provide heating and ventilation in the heating season. The units are operated to provide ventilation air in the same manner as the blow-thru units, i.e., when normal operation does not satisfy ventilation requirements, the units are cycled as necessary to provide the required ventilation air, with the burner cycling as needed to meet the heating load without overheating the space.

Indirect gas-fired **UNIT HEATERS** cycle to meet the heating load during the heating season, with indirect fired make-up air heaters operating continuously during occupied periods to meet the required ventilation airflow. The make-up air heaters are sized to provide the required ventilation air flow, with the burner sized at the same Btuh/cfm as the unit heaters. The efficiency of the two units is identical. At low heating loads, the make-up air heaters' burners are cycled to just meet the load.

Indirect gas-fired **AIR TURNOVER** (air rotation) system cycles to meet the heating load during the heating season. As with the unit heater system, indirect fired make-up air heaters operate continuously during occupied periods to meet the required ventilation airflow. Again, the efficiency of the air turnover and make-up air units are identical.

Direct gas-fired **RECIRCULATION** system provides heating and ventilation in the heating season. The fan operates continuously during occupied periods, with the gas input to the burner modulated as appropriate to the heating load. The system in this study supplies 20% outdoor air and 80% re-circulated air. The continuous fan operation of the units provides ventilation air in excess of the Standard 62.1 minimum requirement.

Indirect gas-fired, condensing tube **INFRARED** heaters cycle to meet the heating load during the heating season, with direct fired make-up air heaters operating continuously during occupied periods to meet the required ventilation airflow, with the burner cycling as needed. The heating capacity of the make-up air units is based on bringing the outdoor air to room neutral temperature at design outdoor temperature.

Warehouses have a minimum ventilation requirement of 0.06 cfm/ft^2, as set by ASHRAE Standard 62.1-2007. This translates to a total ventilation requirement of 12,000 cfm during periods the building is occupied, i.e., 5:00 a.m. to 9:00 p.m., Monday through Saturday.

Sizing

Equipment sizing is done by the EnergyPlus program based on the specified design days for the VAV, blow-thru space heater and infrared systems. For heating, the design day is based on the 99.6% design condition from the 2005 ASHRAE Handbook – Fundamentals, i.e., 1.4°F. For the remaining systems, sizing is calculated to match the heating capacity of the blow-thru system, taking into account the changes in outdoor airflow rates. The supply airflow, outdoor airflow and heating capacity of the outdoor air unit and main heating unit for the blow-thru, draw thru, unit heater, air turnover and recirculation systems are shown below in Tables 1 through 3. The three tables vary by the minimum outdoor airflow rate: 100% of the 62.1 minimum (0.06 cfm/ft^2), 130% of the minimum (0.078 cfm/ft^2), or zero minimum outdoor air. Note that the sizes shown are for one of the four zones, with the sizing of the units for the other three zones being identical.

Table 1 Equipment Sizing, 62.1 Minimum Outdoor Airflow (OA)

	Blow-Thru	Draw-Thru	Unit Heater	Air Turnover	Recirculation
Minimum OA Units					
Supply CFM	3,000	3,000	3,000	3,000	15,000
OA CFM	3,000	3,000	3,000	3,000	3,000
Heating Capacity (Btuh)	518,400	307,800	210,600	210,600	777,600
Main Heating Units					
Supply CFM	13,000	47,667	30,400	43,429	28,429
OA CFM	13,000	47,667	0	0	5,686
Heating Capacity (Btuh)	2,246,400	4,890,600	1,641,600	1,641,600	1,473,737

Table 2 Equipment Sizing, 130% of 62.1 Minimum Outdoor Airflow (OA)

	Blow-Thru	Draw-Thru	Unit Heater	Air Turnover	Recirculation
Minimum OA Units					
Supply CFM	3,900	3,900	3,900	3,900	19,500
OA CFM	3,900	3,900	3,900	3,900	3,900
Heating Capacity (Btuh)	673,920	400,140	273,780	273,780	1,010,880
Main Heating Units					
Supply CFM	12,100	46,767	30,400	43,429	23,929
OA CFM	12,100	46,767	0	0	4,786
Heating Capacity (Btuh)	2,090,880	4,798,260	1,641,600	1,641,600	1,240,457

Table 3 Equipment Sizing, Zero Minimum Outdoor Airflow (OA)

	Blow-Thru	Draw-Thru	Unit Heater	Air Turnover	Recirculation
Minimum OA Units					
Supply CFM	0	0	0	0	0
OA CFM	0	0	0	0	0
Heating Capacity (Btuh)	0	0	0	0	0
Main Heating Units					
Supply CFM	16,000	50,667	30,400	43,429	43,429
OA CFM	16,000	50,667	0	0	8,686
Heating Capacity (Btuh)	2,764,800	5,198,400	1,641,600	1,641,600	2,251,337

For certain systems, ventilation airflow is based on the heating load. EnergyPlus does not contain a specific object for direct fired make-up air heaters. However, they can be simulated by modifying the Packaged Terminal Heat Pump and Packaged Terminal Air Conditioner objects.

Equipment efficiency and operating characteristics

VAV System:

- Output – max discharge temperature 120°F
- Boiler – efficiency 80%

- Blower – Variable speed, modulating control, fan efficiency 52%, motor efficiency 95%

Direct fired, high temperature rise blow-thru space heaters:

- Output – max discharge temperature 160°F
  max temperature rise 160°F
- Burner – variable capacity, modulating control, efficiency 92%
- Blower – single speed, on/off control, fan efficiency 55%, motor efficiency 95%

Direct fired, draw-thru makeup air heaters (lower temperature rise):

- Output – max discharge temperature 95°F
  max temperature rise 120°F
- Burner – variable capacity, modulating control, efficiency 92%
- Blower – single speed, on/off control, fan efficiency 55%, motor efficiency 95%

Indirect fired power vented unit heaters:

- Output – max discharge temperature 115°F
  max temperature rise 50°F
- Burner – single capacity, on/off control, efficiency 80%
- Blower – single speed, on/off control, fan efficiency 45%, motor efficiency 80%

Indirect fired make-up heater providing ventilation air:

- Output – max temperature rise 65°F
- Burner – single capacity, on/off control, efficiency 80%
- Blower – single speed, on/off control, fan efficiency 45%, motor efficiency 80%

Indirect fired air turnover system:

- Output – max discharge temperature 100°F
  max temperature rise 35°F
- Burner – single capacity, on/off control, efficiency 80%
- Blower – single speed, on/off control, fan efficiency 55%, motor efficiency 95%

Indirect fired make-up heater providing ventilation air:

- Output – max temperature rise 65°F
- Burner – single capacity, on/off control, efficiency 80%
- Blower – single speed, on/off control, fan efficiency 45%, motor efficiency 80%

Direct fired recirculation system:

- Output – max discharge temperature 100°F
  max equivalent temperature rise 49°F (required by ANSI Safety Standard Z83.18)
- Burner – variable capacity, modulating control, efficiency 92%
- Blower – single speed, on/off control, fan efficiency 55%, motor efficiency 95%

Indirect fired, condensing infrared tube heaters:

- Output – autosized by EnergyPlus program to meet heating load
- Burner – single capacity, on/off control, efficiency 92% (higher efficiency is due to condensing design)
- Blower – none

Direct fired make-up air heater providing ventilation air:

- Output – max temperature rise 65°F
- Burner – single capacity, on/off control, efficiency 92%
- Blower – single speed, on/off control, fan efficiency 55%, motor efficiency 95%

Thermostat schedule

Heating temperature setpoint is 65°F with setback to 55°F. See Figure 7 for the setback schedule.

HVAC operating schedules

Any system which is serving to meet the minimum ventilation rate as specified by Standard 62.1-2007 operates continuously during the occupied periods. In the case of a system which provides ventilation airflow which exceeds the minimum requirement, the system is allowed to cycle such that the average airflow rate meets the minimum.

Heating equipment is available to meet thermal loads 24 hours a day, 7 days a week during the heating season. Outside the appropriate season, the heating function is disabled, and the system is operated only if needed for ventilation. The heating season used for this analysis is October 1 through April 30.

EnergyPlus Modeling

EnergyPlus uses a variety of modeling objects which are assembled by the user so as to simulate the building as needed. The envelope and internal loads portion of modeling is straightforward, with EnergyPlus objects that match well with the modeling intent.

EnergyPlus, however, like other energy modeling software programs used for LEED projects, does not currently include specific modeling objects for several of the heating systems included in this analysis. One goal of this project is to develop an effective solution to this problem. This was accomplished by using a combination of the EnergyPlus objects as described below for each of the seven system configurations.

1. **Rooftop VAV**: The system being modeled has multiple components, which correspond to several EnergyPlus modeling objects. The central air handling unit is modeled using *Compact HVAC:System:VAV*. The zone units are modeled with *Single Duct:VAV:Reheat*. The central boilers were modeled with *Boiler:Simple*. The piping systems with pumps and controls are modeled using *Compact HVAC:Plant:Hot Water Loop*.

2. **Direct Fired Blow-Thru Space Heaters**: Two different objects are used, one for a unit which operates continuously to provide the minimum ventilation air, and the other representing a typical draw-thru unit. The difference between these units is that the fan operates continuously for the minimum OA unit, with the burner cycling to meet load. For the typical blow-thru unit, both the fan and burner cycle together. Both objects have identical heating and fan efficiencies, such that the

energy consumption of the units will be identical to the actual units being represented. The *Packaged Terminal Heat Pump (PTHP)* object will be used to represent the MinOA unit with the airflow sized to the required minimum ventilation. The *PTHP* provides for DX cooling and heating coils, and a supplemental heating coil. In this application, the DX coils are turned off and the supplemental heating coil is a gas coil with efficiency as specified for the blow-thru units. The *PTHP* operates continuously during occupied periods, with the supplemental heating coil cycling to meet the heating load, up to the limit of its capacity. The second object is a *Packaged Terminal Air Conditioner (PTAC)*, which cycles with 100% outdoor air. This object also must have a DX cooling coil, but again it is turned off. The *PTAC* is sized to meet the entire heating load, so it can handle the load during unoccupied periods when the PTHP is turned off. The *PTHP* and *PTAC* objects have 100% outdoor airflow. The heating capacity is set at the capacity of a blow-thru unit with this airflow. For the *PTHP*, heating is modulated by cycling the heating coil to meet heating loads up to the capacity of the unit. When the load is greater than that capacity, the *PTAC* then also operates, cycling both the fan and heating coil as needed.

3. **Direct Fired Draw-Thru Make-up Air Units**: Same as blow-thru heaters, with adjusted airflow and heating capacity.

4. **Indirect Fired Unit Heaters with Indirect Fired Make-up Air Units**: Same as blow-thru heaters, with adjusted capacity, efficiency and airflow. The *PTAC* unit has no outdoor airflow, while the *PTHP* is 100% outdoor air. The *PTHP* units have a maximum temperature rise of 65°F.

5. **Indirect Fired Air Turnover System with Indirect Fired Make-up Air Units**: Same as Unit Heaters, with adjusted capacity and airflow. The *PTAC* unit has no outdoor airflow, while the *PTHP* is 100% outdoor air.

6. **Direct Fired Recirculation System:** *PTAC* units with the fan scheduled to operate continuously during occupied periods and cycle during unoccupied periods were used for this system. The airflow for these units is sufficient to provide more than the minimum required outdoor air, so no separate MinOA unit is modeled.

7. **Tube Infrared Heaters with Direct Fired Make-Up Air Units:** This system is modeled using the *High Temp Radiant System* to model the infrared heaters. These systems are specified with 87% of the radiant heat going to the floor, 10% to the walls, 2% to the ceiling and 1% to people. Ventilation during heating will be done the same as for the blow-thru heaters, with the heating capacity limited to provide a 65°F temperature rise.

NOTE: The object names listed above are for EnergyPlus version 3.0.0.013. The final version 3 release (version 3.0.0.028) renamed most objects.

Stratification

A potentially significant issue in warehouse heating is that of temperature stratification. With a ceiling height of 30' to 36', significant differences in air temperature can occur between floor level and near the ceiling. High levels of stratification can waste energy because warm temperatures near the ceiling increase the temperature difference across the roof, resulting in increased heat loss.

Reduced temperature stratification is a claimed benefit of de-stratifying fans and several of the systems modeled in this analysis (blow-thru, air turnover, infrared). EnergyPlus includes the capability to model the energy impacts of temperature stratification, although EnergyPlus cannot predict the degree of stratification which will occur for these types of heating systems. Using the *RoomAir Models* objects in EnergyPlus, each model was simulated with two different amounts of stratification occurring. For each case, the stratification was specified as varying between a maximum and zero, as the indoor-outdoor temperature difference varied between 65°F and 0°F. In each case, the stratification was linear from floor to ceiling. The maximum stratification was specified as either 4°F or 10°F, with the 10°F case identified in the results as the "HiStrat" cases.

The author has no building simulation modeling basis for determining which, if any, of the systems actually do provide superior stratification characteristics. However Cambridge Engineering has published building studies with measured stratification data that shows the blow-thru design can achieve 4°F or less stratification for a warehouse similar to the one modeled in this analysis. The energy modeling summarized in this report will allow the reader to compare any two systems with differences in stratification performance. Comparing the 10°F "HiStrat" case of one system to the 4°F "Normal" case of the other provides an indication of the significance of this performance difference on energy usage.

Ventilation Rate

In common practice for warehouses, explicit mechanical ventilation, independent of heating system operation, is not normally provided. Ventilation is provided by air movement through open overhead doors, infiltration through envelope leakage, and through the outdoor air associated with direct fired blow-thru, draw-thru or recirculation heating systems, if used.

Such an approach, however, does not meet the requirements of ASHRAE Standard 62.1-2007, and therefore does not meet the LEED rating EQ Prerequisite 1, Minimum IAQ Performance. In order to obtain a LEED rating of any level, the minimum ventilation rate set by the standard must be supplied during all occupied hours.

LEED NC 2.2 and CS 2.0 offers one point (EQ credit 2, Increased Ventilation) for mechanically ventilated spaces where the outdoor air ventilation is increased by 30% over the Standard 62.1 minimum rate.

Potentially, warehouses may be built under any of these scenarios. Accordingly, each of the heating systems described have been simulated with three ventilation rate scenarios: 0% of the minimum ventilation rate, 100%, and 130%. The exceptions are for the VAV system and the recirculation system. The VAV system is included in this analysis because it forms the baseline for energy comparison for meeting EA Prerequisite 2, Minimum Energy Performance, and obtaining any of the points available under EA Credit 1, Optimize Energy Performance. Accordingly, it would be nonsensical to apply a VAV system without meeting the Standard 62.1 ventilation requirements. The recirculation system, on the other hand, operates the fan continuously during occupied periods, and provides ventilation which exceeds all three minimum levels.

Results

The tables below present predicted energy consumption of the seven different systems, with nominally six variants for each: 0%, 100% and 130% outdoor air, at either 4°F or 10°F maximum stratification. The total natural gas consumption, total electricity consumption and the annual fan electricity consumption are presented. The bulk of the electricity consumption is due to electric lighting, which is constant across all the cases, so the variation in electricity consumption is primarily due to the variations in fan electricity between the systems. The VAV system also includes some additional pump electricity.

Tables 4 through 9 present the three energy consumption values for each system for each of the six combinations of stratification and minimum ventilation rate. For the cases with 0% of the Standard 62.1 ventilation rate, the VAV system is not included. For all three ventilation rate scenarios, the recirculation system energy consumption does not change, since the delivered ventilation rate exceeds all three minimum values.

Table 4 Energy Comparison, 4°F Maximum Stratification, 0% of 62.1 Ventilation

Energy Consumption	Gas (Therms)	Total Electric (MWh)	Fan Electric (kWh)
Blow-Thru	15,504	1,548	1,347
Draw-Thru	20,411	1,550	2,983
Unit Heater	19,623	1,555	7,925
Air Turnover	17,244	1,556	9,250
Recirculation	25,910**	1,599**	52,644**
Infrared	23,383	1,547	0
% Increase vs. Blow-Thru			
Draw-Thru	31.7%	0.1%	121.4%
Unit Heater	26.6%	0.4%	488.2%
Air Turnover	11.2%	0.5%	586.6%
Recirculation	67.1%	3.3%	3807.6%
Infrared	50.8%	-0.1%	-100.0%

** Unit fans operate continuously during occupied periods.

Table 5 Energy Comparison, 10°F Maximum Stratification, 0% of 62.1 Ventilation

Energy Consumption	Gas (Therms)	Total Electric (MWh)	Fan Electric (kWh)
Blow-Thru	17,181	1,548	1,492
Draw-Thru	22,663	1,550	3,314
Unit Heater	21,507	1,555	8,686
Air Turnover	18,898	1,557	10,136
Recirculation	27,805**	1,599**	52,644**
Infrared	24,054	1,547	0
% Increase vs. Blow Thru			
Draw Thru	31.9%	0.1%	122.2%
Unit Heater	25.2%	0.5%	482.3%
Air Turnover	10.0%	0.6%	579.5%
Recirculation	61.8%	3.3%	3429.2%
Infrared	40.0%	-0.1%	-100.0%

**** Unit fans operate continuously during occupied periods.**

Table 6 – Typical LEED Warehouse Case - Energy Comparison 4°F Maximum Stratification, 100% of 62.1 Ventilation

Energy Consumption	Gas (Therms)	Total Electric (MWh)	Fan Electric (kWh)
VAV (90.1 baseline)	30,907	1,645	76,733
Blow-Thru	20,220	1,552	5,758
Draw-Thru	25,052	1,554	7,317
Unit Heater	30,481	1,563	16,289
Air Turnover	26,822	1,564	17,153
Recirculation	25,910**	1,599**	52,644**
Infrared	32,156	1,558	11,164
% Savings vs. VAV			
Blow-Thru	34.6%	5.6%	92.5%
Draw-Thru	18.9%	5.5%	90.5%
Unit Heater	1.4%	5.0%	78.8%
Air Turnover	13.2%	4.9%	77.6%
Recirculation	16.2%	2.8%	31.4%
Infrared	-4.0%	5.3%	85.5%
% Increase vs. Blow-Thru			
Draw-Thru	23.9%	0.1%	27.1%
Unit Heater	50.7%	0.7%	182.9%
Air Turnover	32.6%	0.7%	197.9%
Recirculation	28.1%	3.0%	814.2%
Infrared	59.0%	0.3%	93.9%

** Unit fans operate continuously during occupied periods.

Table 7 Energy Comparison, 10°F Maximum Stratification, 100% of 62.1 Ventilation

Energy Consumption	Gas (Therms)	Total Electric (MWh)	Fan Electric (kWh)
VAV (90.1 baseline)	32,563	1,647	78,594
Blow-Thru	21,974	1,553	5,806
Draw-Thru	27,506	1,554	7,589
Unit Heater	32,833	1,564	16,875
Air Turnover	28,886	1,565	17,833
Recirculation	27,805**	1,599**	52,644**
Infrared	33,375	1,558	11,164
% Savings vs. VAV			
Blow-Thru	32.5%	5.8%	92.6%
Draw-Thru	15.5%	5.7%	90.3%
Unit Heater	-0.8%	5.1%	78.5%
Air Turnover	11.3%	5.0%	77.3%
Recirculation	14.6%	2.9%	33.0%
Infrared	-2.5%	5.4%	85.8%
% Increase vs. Blow-Thru			
Draw-Thru	25.2%	0.1%	30.7%
Unit Heater	49.4%	0.7%	190.7%
Air Turnover	31.5%	0.8%	207.2%
Recirculation	26.5%	3.0%	806.8%
Infrared	51.9%	0.3%	92.3%

** Unit fans operate continuously during occupied periods.

Table 8 Energy Comparison, 4°F Maximum Stratification, 130% of 62.1 Ventilation

Energy Consumption	Gas (Therms)	Total Electric (MWh)	Fan Electric (kWh)
VAV (90.1 baseline)	33,883	1,646	76,653
Blow-Thru	22,435	1,554	7,350
Draw-Thru	26,720	1,555	8,697
Unit Heater	33,858	1,566	19,103
Air Turnover	29,802	1,595	32,256
Recirculation	25,910**	1,599**	52,644**
Infrared	34,978	1,561	14,514
% Savings vs. VAV			
Blow-Thru	33.8%	5.6%	90.4%
Draw-Thru	21.1%	5.5%	88.7%
Unit Heater	0.1%	4.9%	75.1%
Air Turnover	12.0%	3.1%	57.9%
Recirculation	23.5%	2.8%	31.3%
Infrared	-3.2%	5.1%	81.1%
% Increase vs. Blow-Thru			
Draw-Thru	19.1%	0.1%	18.3%
Unit Heater	50.9%	0.8%	159.9%
Air Turnover	32.8%	2.6%	338.9%
Recirculation	15.5%	2.9%	616.3%
Infrared	55.9%	0.5%	97.5%

** Unit fans operate continuously during occupied periods.

Table 9 Energy Comparison, 10°F Maximum Stratification, 130% of 62.1 Ventilation

Energy Consumption	Gas (Therms)	Total Electric (MWh)	Fan Electric (kWh)
VAV (90.1 baseline)	35,608	1,648	78,483
Blow-Thru	24,238	1,554	7,383
Draw-Thru	29,214	1,556	8,950
Unit Heater	36,344	1,566	19,636
Air Turnover	31,983	1,595	32,828
Recirculation	27,805**	1,599**	52,644**
Infrared	36,295	1,561	14,514
% Savings vs. VAV			
Blow-Thru	31.9%	5.7%	90.6%
Draw-Thru	18.0%	5.6%	88.6%
Unit Heater	-2.1%	5.0%	75.0%
Air Turnover	10.2%	3.2%	58.2%
Recirculation	21.9%	2.9%	32.9%
Infrared	-1.9%	5.3%	81.5%
% Increase vs. Blow-Thru			
Draw-Thru	20.5%	0.1%	21.2%
Unit Heater	49.9%	0.8%	166.0%
Air Turnover	32.0%	2.6%	344.6%
Recirculation	14.7%	2.9%	613.0%
Infrared	49.7%	0.5%	96.6%

** Unit fans operate continuously during occupied periods.

Figure 8 presents the annual gas consumption of the seven systems, for the typical LEED warehouse case with 100% of the ASHRAE Standard 62.1 minimum ventilation rate and with a 4°F maximum stratification.

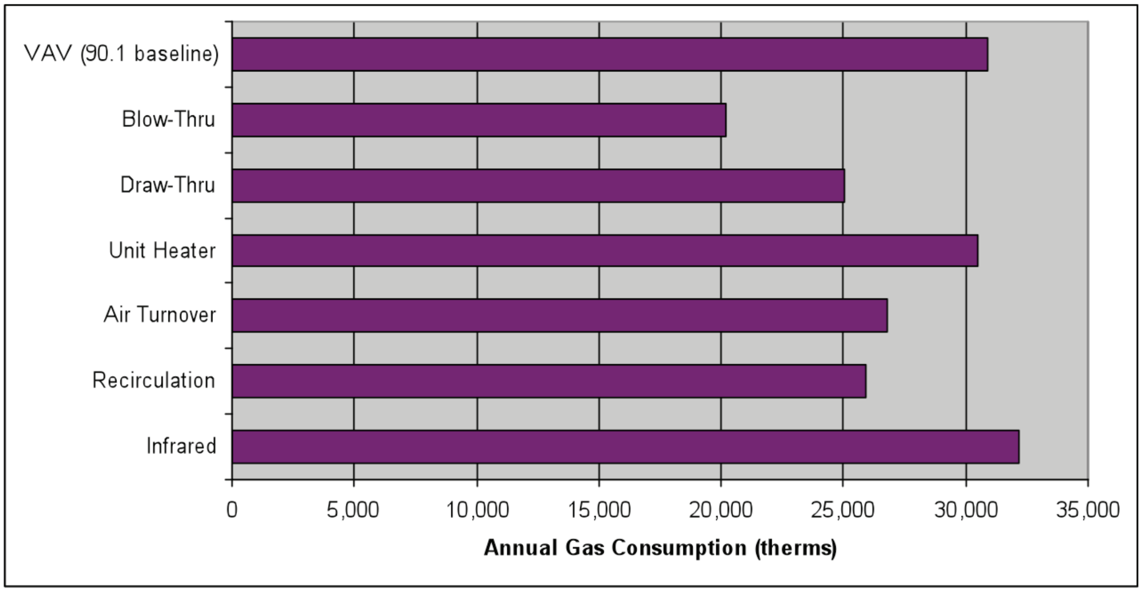

Figure 8 Annual Gas Consumption of the Systems with 4°F Maximum Stratification and 100% of the Standard 62.1 Ventilation Rate

Conclusions

In all cases the direct fired, high temperature rise blow-thru space heater used the least amount of natural gas, and the least amount of fan electricity except for the infrared heater in the case with zero ventilation air (where the infrared system used no electricity). This result fits with what might be expected. The three direct fired heating systems have significantly higher efficiency than the other systems, and the higher temperature rise/discharge temperature capability provided by the blow-thru system means that a given amount of heating can be provided with a smaller amount of outdoor air, reducing the load relative to the direct fired draw thru and direct fired recirculation systems. For the indirect fired unit heater and air turnover (air rotation) systems, it might be expected that the tradeoff of lower (or no) outdoor air could offset the reduced efficiency of these systems, but that is not seen to be the case. The very different heating mechanism of the infrared system makes it difficult to anticipate the relative performance, but these simulation results indicate it to be a poor performer for this application that requires both space heating and ventilation with outside air. Finally, the baseline LEED/ASHRAE 90.1 VAV system is seen to be a poor choice for this application, particularly in its much higher fan energy, due to much higher system static pressure, as well as high gas consumption. For the typical LEED warehouse case (Table 6 and Figure 8), this energy modeling simulation resulted in a 23.9% to 59.0% annual gas energy savings for the direct fired blow-thru space heater system versus the other six heating systems.