Theoretical Minimum Energy Use of a Building HVAC System

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ABSTRACT.

This paper investigates the theoretical minimum energy use required by the HVAC system in a particular code compliant office building. This limit might be viewed as the “Carnot efficiency” for HVAC system. It assumes that all ventilation and air conditioning in the building are provided using the minimum energy value that does not violate physical law. Rigorous physical limits such as the Carnot efficiency are used where applicable; in other cases, a plausible approximation has been adopted. Based on the assumptions made, it is shown that heating ventilation and air conditioning for the building could theoretically be provided by approximately 0.08 kWh/(ft^2·yr) (0.86 kWh/(m^2·yr)). This limiting value is less than 1% of the simulated HVAC system energy consumption of a code compliant building in Texas.

In the U.S. air conditioning and refrigeration systems in office buildings consumed 572 trillion Btu of energy in 2003 [14]. The efficiency and efficiency limits of HVAC system components used in buildings have already been evaluated using the First and Second laws of thermodynamics [7, 11], the importance of establishing theoretical energy minimum expenditure for manufacturing a given product has also been noted [6]. However, the thermodynamic efficiency limit of the entire building has been only recently addressed [4]. This is doubtless due to the fact that different buildings have high diversity in energy-using devices and services. The energy efficiency of buildings is sometimes treated by considering buildings that are 15% or 50% “above code”. For example, ASHRAE has published a series of design guides that are intended “to provide recommendations for achieving 50% energy savings over the minimum code requirements of ANSI/ASHRAE/IESNA Standard 90.1-2004 for small to medium office buildings.”[3].

Just as it is not possible to build an air conditioner that operates at the Carnot COP, it will not be possible to build a building HVAC system that operates at the thermodynamic limit of efficiency. But the assumption of isothermal surfaces, reversible thermodynamics, and Carnot devices are idealizations that are very useful in the study thermodynamics; they are also valuable in helping determine the potential for improvements in heating and cooling devices. Likewise, a similar examination of an entire building HVAC system in the context of minimum energy uses throughout the building should be instructive in developing an understanding of the minimum energy that might be used by a building HVAC system that provides the required level of comfort and indoor air quality. Comparison of this minimum with the current performance of code compliant buildings can provide a framework for considering future targets for energy consumption of building HVAC systems.

The limit to the energy efficiency of office building HVAC systems is explored in this paper by considering a specific building. The Energy Systems Laboratory (ESL) and the Texas Center for Applied Technology recently occupied the Valley Park II Office Building (VP II) in College Station, Texas. VP II is a leased 25,774 ft^2 (2394 m^2) building located next to the Texas A&M University campus. It is a simple rectangular single-story building approximately 100 ft (30m) wide and 250 ft (76m) long as shown in Figure 1.

Figure 1. Front view and schematic floor plan of the Valley Park II office building.

The VP II office building requires most of the energy-using services found in a typical office building. The occupants typically arrive after 7:30 am and leave before 7:00 pm on weekdays. There is a small amount of weekend occupancy. This schedule can be approximated as an average occupancy time of 60 hours per week.

BASELINE VP II BUILDING MODEL

To estimate the energy consumption baseline for the Valley Park II building, a model was developed to comply with the minimum requirements of IECC 2009 [5] as the applicable energy code in the State of Texas with reference to a federal energy code ASHRAE Standard 90.1-2007.

As shown on Figure 1, the baseline building model was developed as a 25,774 ft^2 (2394 m^2) single story building. Its exterior enclosure consists of framed steel-stud walls with exterior brick veneer, slab-on-grade concrete floors, and an essentially flat roof with rigid insulation. The architectural drawings of the building were used for a DOE-2.1E building simulation. Electricity is the only available energy source at the building site. The building has windows with single pane glazing, a reflective coating and a total window-to-wall ratio of 30%. The building occupancy and people density were estimated based on ESL office and construction project design assumptions. The maximum building office area occupancy is estimated at 150 ft^2/person (14 m^2/person).

Lighting and equipment schedules were determined from the average ESL energy consumption profile (Figure 2) based on data measured in the previous ESL offices. Consistent with Figure 2, the maximum electrical density of office equipment is assumed to be 0.8 W/ft^2 for the simulation. Lighting equipment density was assumed to be 1.2 W/ft^2 in the simulation with 20% of the energy rejected to the return air stream and occupancy sensors used to control the office lighting.

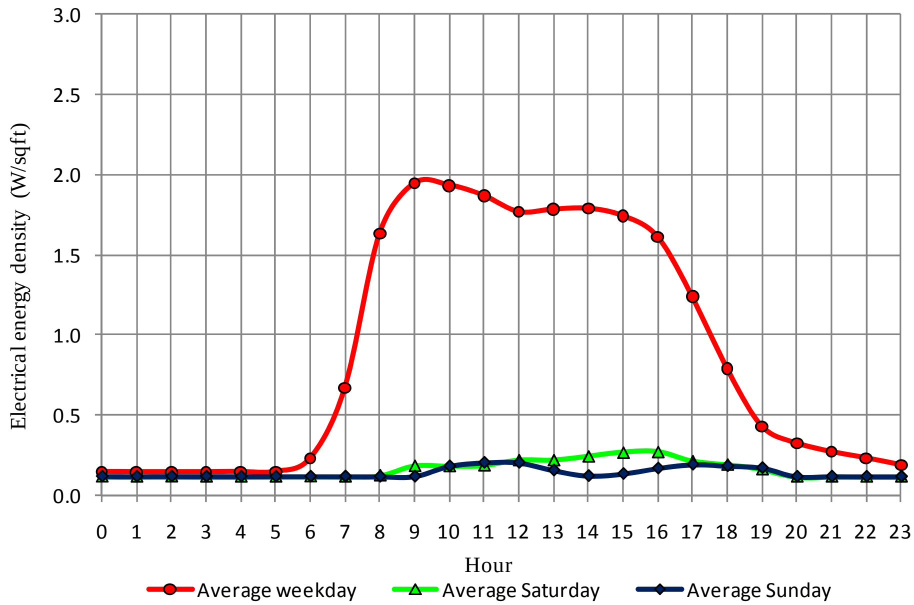

Figure 2. Average electricity consumption of lighting system and office equipment.

The building HVAC system is a packaged constant air volume system with eight roof-top units. This system cools by the direct expansion of a refrigerant and heats with electric resistance heaters (Figure 3). It is approximated as a single system with multiple zones in the simulation.

This forced-air packaged unit is a unitary system (rooftop unit) [8; 9] that has a duct to distribute cooled air. This system includes a multiple refrigeration compressors, an air cooled condenser with a fan discharging heat to the outdoors, an evaporator with a constant volume fan supplying cooled air to the indoors, a filter (not shown), and a thermostat for each zone. The building is zoned with both interior and exterior spaces in a single zone, causing significant temperature variations within a single zone. This system does not have a subzone reheating option.

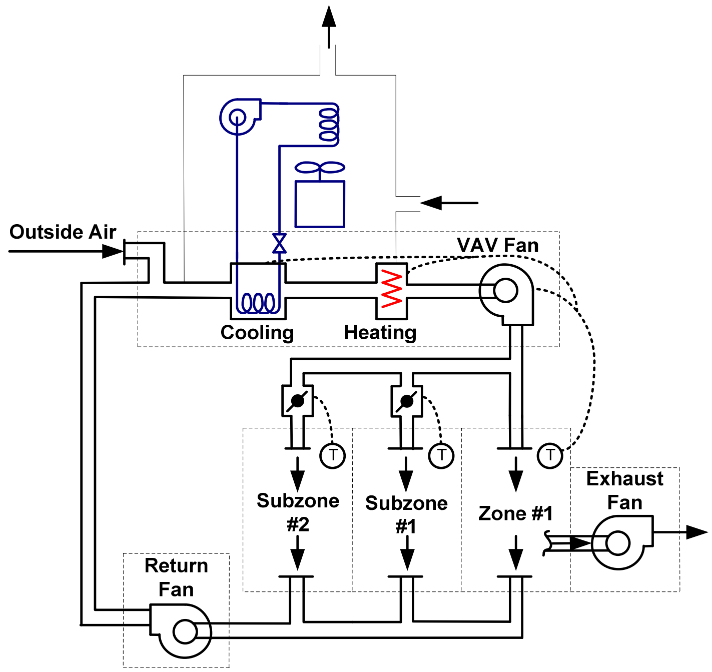

Figure 3. Simulated approximation of packaged roof-top units used in the building.

The HVAC system turns on/off the flow into a single zone to maintain the set-point temperature at each thermostat. The system is intended to be a single zone system that could serve multiple zones operating in the same mode (heating or cooling) while providing outside air ventilation. The supply fans have fan motors in the airstream. The condenser fan operates automatically on demand [9]. The thermostat is specified with night setback and night cycle control. The design thermostat setpoint is 70ºF for heating and 75ºF for cooling with a night setback temperature setpoint of 55ºF for heating and 99ºF for cooling (ASHRAE Standard 55). Night setback is used between 1:00 am and 6:00 am all year around.

Baseline cooling efficiency was selected as EER 10.0 according to the IECC 2009 requirements for electronically operated unitary air conditioning systems with air-cooled evaporator and electric resistance heating sections. According to ASHRAE 62.1-2010, the required design building outdoor airflow is 2405 cfm. The outdoor airflow is distributed equally between all conditioned zones. The total supply airflow is constant (1 cfm/ft^2). The simulated supply air fans have constant speed, with cycling control and the power consumption per unit of supply air moved 0.00082027 kW/cfm (IEEC 2009). The HVAC system will operate during the night, if the temperature in any zone of the served area falls below set-point for heating or above the set-point for cooling and the fans are cycled on for that hour. The design return air path is via a duct to the supply fan with added heat from lights vented to the return air.

The simulation of the Valley Park II was performed by using Typical Meteorological Year version 3 weather data for College Station Easterwood Airport, TX [12]. The simulated building requires cooling during occupied days at all ambient temperatures in the weather file, and heating when the daily average outside ambient temperature is below approximately 65ºF (Figure 4).

The main energy consumption categories are cooling (28%), ventilation fans (27%), lighting (21%), and office equipment (19%) (Figure 5).

The maximum simulated cooling energy consumption of 122 MMBtu/month occurs in July (Table 1) and the maximum heating energy consumption of 24.7 MMBtu/month in January.

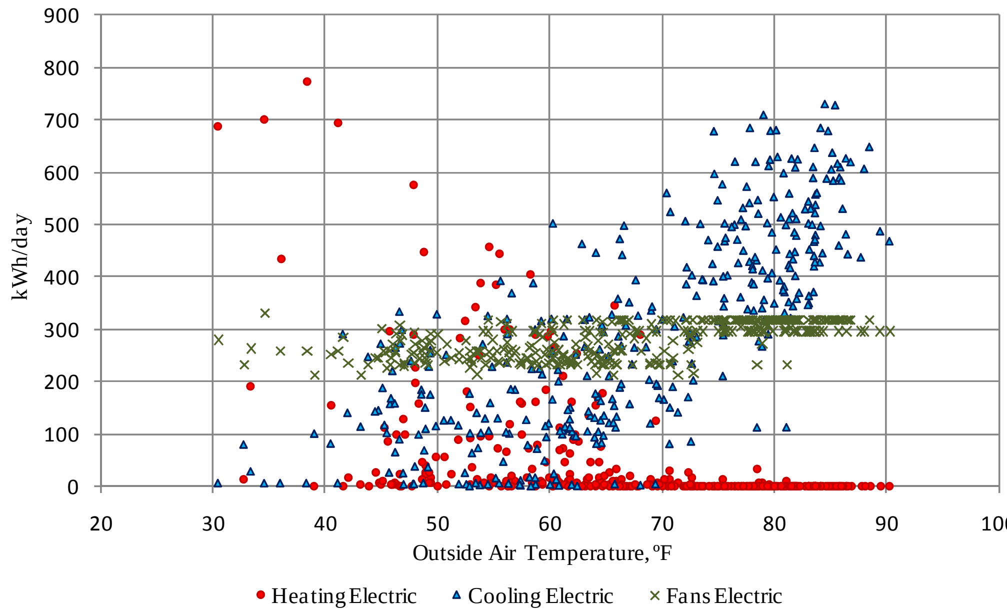

Figure 4. Valley Park office building baseline model heating and cooling system electrical energy consumption in kWh/day

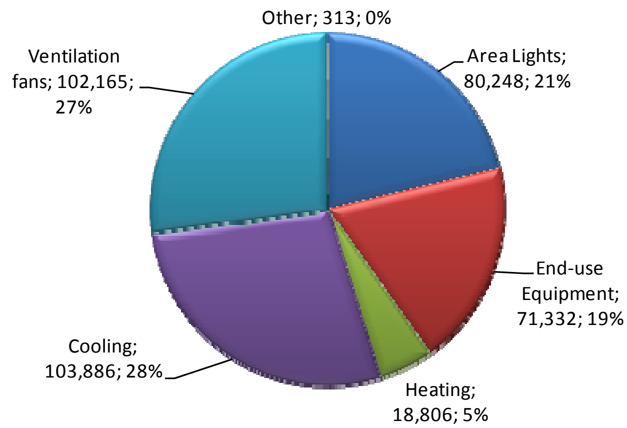

Figure 5. Annual Valley Park office building baseline model energy consumption summary in kWh/year

Table 1. Valley Park office building monthly HVAC system energy summary

Month	Dry-bulb temperature	Cooling energy	Maximum cooling load	Heating energy	Maximum heating load	Electrical Energy	Maximum Electrical Load
	°F	MMBtu	kBtu/hr	MMBtu	kBtu/hr	kWh	kW
JAN	76	21.2	138.3	24.7	126.1	12,408	43.8
FEB	81	32.9	175.8	7.2	104.3	11,538	43.8
MAR	80	41.3	186.0	5.9	69.4	13,467	43.8
APR	88	46.7	202.1	2.8	57.1	12,942	43.8
MAY	90	89.9	233.8	0.0	5.8	12,408	43.8
JUN	94	100.6	251.9	0.0	0.0	12,942	43.8

Table 1. Valley Park office building monthly HVAC system energy summary (continue)

Month	Dry-bulb temperature	Cooling energy	Maximum cooling load	Heating energy	Maximum heating load	Electrical Energy	Maximum Electrical Load
	°F	MMBtu	kBtu/hr	MMBtu	kBtu/hr	kWh	kW
JUL	99	121.9	266.5	0.0	0.0	12,759	43.8
AUG	106	120.6	285.5	0.0	0.0	13,116	43.8
SEP	85	90.6	233.7	0.0	0.0	12,590	43.8
OCT	91	60.9	233.4	0.7	32.3	12,408	43.8
NOV	80	28.9	179.4	15.0	82.3	12,238	43.8
DEC	68	25.0	131.2	18.1	84.1	12,764	43.8

Total site energy consumption is 1285.8 MMBtu or 49.9 kBtu/ft^2-yr and total source energy is 3858 MMBtu. The total annual baseline building energy consumption is 376,750 kWh.

THEORETICAL HVAC VP II BUILDING MODEL

To estimate the potential energy saving limit the actual minimum energy consumption by HVAC requirements must be known. To achieve the maximum possible energy efficiency it is not enough to simply replace HVAC system components with more efficient but require the entire building system to be redesigned based on whole building approach.

Energy in the office building is consumed by three main components: lighting system, building equipment and HVAC system (cooling and heating loads).

The HVAC system energy consumption is determined by heating and cooling loads, rates of energy input or removal required to maintain an indoor environment at a desired temperature, and humidity condition [1]. Heating and cooling loads depend on external (outside air) and internal conditions (number of people, lighting and equipment energy consumption). Amount of variables that influence building energy consumption are numerous, interrelated and often hard to estimate precisely.

The Valley Park office building energy consumption minimum limit estimation includes certain assumptions that make the results approximate:

- air in the thermal zone can be modeled as well mixed (constant properties throughout the zone);
- thermal energy storage of the building is negligible;
- the building has neither moisture migration nor infiltration (exfiltration) through the building envelope;
- cooling and heating equipment operates at the maximum possible efficiency of the Carnot cycle;
- hydronic system pumps energy consumptions is neglected;
- calculations are provided on a daily basis with the assumption of steady state process and constant properties of air and water vapor.

Building Thermal Loads

The energy efficiency limit for this building is explored by assuming that relevant comfort, lighting, and air quality codes are met and that other services are provided at the required level. To determine the requirements for cooling and heating of the building, the following sources of heat gains and losses must be considered:

- Internal equipment gains
- Occupants
- Ventilation
- Solar
- Envelope

The internal equipment gains are assumed at the same level as in baseline model.

The occupants are assumed to be moderately active office workers. According to the American Society of Heating Refrigeration and Air Conditioning Engineers, the typical heat gain for these workers is 250 Btu/h (~73 W) per person of sensible gain and 200 Btu/h (~59 W) per person of latent gain [1]. Numerous staff members working time in the building that exceed 40 hours per week is compensated by travel schedule of