HVAC Selection

For Envelope-Dominated Buildings

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Envelope-dominated buildings are those that do not have core zones. As such, envelope-dominated buildings are weather-sensitive, and heating plays a critical role, even in most cooling climates, for typical internal and solar gains and ventilation loads.

While we often think of many buildings as having a perimeter and a core, most buildings are envelope-dominated such as most hotels, apartment buildings and single-family homes, small offices and medical clinics, and houses of worship. Also included are retail storefronts such as strip malls, bank branches, single-story department stores and supermarkets, warehouses, and the list goes on. As daylighting and views become emphasized in high-performance buildings, the trend toward envelope-dominated buildings may only increase.

Regardless of the building type, HVAC system selection never seems easy. Although we are fortunate to have a huge choice of many available HVAC system types, the selection can quickly become dizzying, as each system has many pros and cons, from energy use, to installation costs, and to non-cost tradeoffs such as comfort, noise, energy metering, and aesthetics. Can these many choices be simplified, to give ourselves a head start when we start to design envelope-dominated buildings? Which systems have an edge over the others for carbon emissions? Is there a best initial choice to bring to the table for energy efficiency, specifically are geothermal systems the current Cadillac of the industry? If so, are there solid second or third choices that provide excellent energy efficiency without the higher installation costs, if geothermal cannot be afforded?

Building Characteristics

Envelope-dominated buildings require less cooling than buildings with a core. Beyond not having a core, many envelope-dominated building types have lower internal gains (occupancy, lights and plug loads such as computers), further reducing the need for cooling: for example, hotels, apartments, single-family homes, houses of worship, and warehouses. Not only are internal gain power densities lower, but daytime use, at times of peak solar gain, is lower, and duration of use is lower all-round. (This is not true for all of these buildings, for example offices, retail stores,

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and schools do tend to have higher daytime internal gains.) Envelope-dominated buildings are subject to intermittent solar gain, by time of day and building exposure, and so have a need for distributed temperature control to deal with the vagaries of the sun coming and going.

With lower core gains and less heat available from the core, and often lower internal gains, envelope-dominated buildings have higher no-load temperatures, the outdoor temperature below which heating is required and cooling is not required. This reduces the need and energy-savings potential for economizers within the HVAC system.

Another characteristic of many envelope-dominated buildings is repeating room types, where the same type and size of room is repeated throughout the building. This is certainly true of hotels and apartment buildings, and to a lesser extent applies to homes, small office buildings, and retail storefronts such as strip malls. And if room types do not repeat, then room types are often fairly simple, as is the case with small bank branches, single-story department stores and supermarkets, and warehouses. For either case (repeating room types or simple rooms types), envelope-dominated buildings are more typical for the application of fan coils or other simple single-zone terminal units, rather than central-station air-handling units.

As with all buildings, ventilation presents challenges for envelope-dominated buildings. There is frequent reliance on natural ventilation (typically, windows), with associated control problems. Alternatively, constant-volume ventilation is not infrequent (exhaust fans and/or constant-volume makeup air). Modulating ventilation, timer-controlled ventilation, or demand control ventilation is sometimes provided, but these are exceptions rather than the rule. Ventilation options are many, including no ventilation, intermittent ventilation, continuous-low-level exhaust, continuous-low-level-balanced ventilation, and energy recovery ventilation.

Envelope-dominated buildings tend to be smaller than buildings with a core, with some exceptions (for example, large apartment buildings, or large hotels). By extension, envelope-dominated buildings tend to not have full-time maintenance staff, and so can be more appropriately served with simpler HVAC systems.

First Principles

How can we translate these general characteristics of envelope-dominated buildings into concrete guidance for HVAC system selection? Simplified analysis using the first law of thermodynamics (conservation of energy) can help. We focus on four general types of HVAC systems: geothermal heat pumps, air source heat pumps, fossil heating and chilled water cooling systems, and finally water loop heat pumps ("boiler/tower" systems). We initially focus on heating, because envelope-dominated buildings typically need more heating. We also ignore internal gains, because these are low. We also ignore solar gains and distribution system energy, for simplicity. For most systems, the relationships then become simple, for a specific building with a specific annual heat loss Q, the required energy is related to the heat loss by the system efficiency (E_g for geothermal heat pumps, E_a for air source heat pumps, E_f for fossil heating systems):

Geothermal heat pumps: $Q = W_g \times E_g$
Air source heat pumps: $Q = W_a \times E_a$
Fossil heating systems: $Q = Q_a \times E_f$

Geothermal heat pump efficiency is given in COP and is typically approximately 3.1 (ASHRAE/IESNA Standard 90.1-2007, ASHRAE/USGBC/IESNA Standard 189.1-2009).[1,2] Air source heat pump efficiency ratings are given in heating seasonal performance factor (HSPF) and are typically in the range of 7.7 (Standard 90.1) to 8.5 (Standard 189.1). HSPF converts to COP by dividing by 3.412, so the equivalent or year-round COPs for air source heat pumps are 2.3 (Standard 90.1) to 2.5 (Standard 189.1).

In this simple comparison, out of the starting gate, geothermal heat pumps are already ahead of air source heat pumps. Air source heat pumps traditionally have suffered because their capacity drops with reduced outdoor air temperature, just as the load increases. However, the advent of variable speed systems is allowing improved performance at lower outdoor temperatures.

Now, how do fossil fuel heating systems stack up against these two heat pump systems? The comparison is a little harder, because we are comparing different fuels. Let us focus on natural gas, the most widely used fossil heating fuel. One basis for comparison is carbon emissions: a kWh of electricity is considered, on average, to generate 1.3 lbs (0.6 kg) CO_2,[3] while a therm of gas is considered to generate 11.5 lbs (5.2 kg) CO_2. On this basis, per MMBtu of building load (Q), a 3.1 COP geothermal heat pump generates 123 lbs (55.8 kg) of CO_2, a 7.7 HSPF air source heat pump generates 168 lbs (76.2 kg) of CO_2, and an 80% efficiency fossil fuel heating system generates 144 lbs (65.3 kg) of CO_2. In our horse race, geothermal is out front, fossil heating is in second, and air source heat pumps are in third place, using this simplified heating analysis.

Now let us examine a fourth class of popular heating systems, frequently referred to as water loop heat pumps, or "boiler/tower" systems. Here the relationship is slightly more complex. The water loop heat pump delivers heat to the space to replace the same lost heat (Q) as in the examples above, using electrical power W_l, at efficiency E_l:

$$Q = W_l \times E_l$$

But energy is also used by the boiler to supplement the electrical energy supplied by the heat pump. The supplemental input energy delivered to the heat pump is Q_i, and an energy balance on a heat pump says that the delivered heat is equal to the sum of the heat from the loop Q_i and the electrical energy used by the heat pump:

$$Q_i + W_l = Q$$

So the energy from the loop can be related to the electrical energy used by the heat pump:

$$Q_i + W_l = W_l \times E_l$$

Rearranging:

$$Q_i = W_l \times (E_l - 1)$$

Neglecting losses, the energy delivered to the loop from the boiler is related to the energy taken out of the loop by the boiler efficiency:

$$Q_i = Q_b \times E_b$$

So the boiler energy can be related to the electricity used by the heat pump:

$$Q_b = W_l \times (E_l - 1) / E_b$$

So we see that a boiler/tower water loop heat pump system uses electricity for the heat pumps, and also uses fossil fuel for the boiler. A first law analysis applied to the entire building tells us a little more:

$$Q = Q_b + W_l$$

What is fascinating is that for a specific building with an annual heat load of Q, as long as electricity costs more per unit of heat than does natural gas (which it typically does and historically has), and as long as electricity is associated with higher carbon emissions than is natural gas, the boiler/tower heat pump system will cost more to operate, and will generate higher carbon emissions than a simple fossil system. The building, as a whole, is blind to the internal workings of the heat pump, and so the net effect is that the building is essentially the rough equivalent of a building partially heated with fossil fuel, and partially heated with *electric resistance heat*. The heat pumps actually operate at a relatively high efficiency, higher than geothermal heat pumps, because of the milder temperature of the water loop. But the system essentially uses two fuels for heating, especially in envelope-dominated buildings.

So the boiler/tower water loop heat pump is significantly worse than a simple fossil-heated building. How does it stack up to air source heat pumps? On a carbon emissions basis, for

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Energy Model for Generic Multifamily Building

Parameters	Inputs/Assumptions			Source
Software	eQuest (v3.64)			DOE2.2 Comply with Standard 90.1-2007's Appendix G2.2
Weather Data	New York, Atlanta, Las Vegas, Chicago			Typical Meteorological Year Version 3, Derived from USDOE's NREL Datasets.
Climate Zone	New York – 4A, Mixed Humid Atlanta – 3A, Warm Humid Las Vegas – 3B, Warm Dry Chicago – 5A, Cool Humid			Standard 90.1-2007 Table B-1
Conditioned Gross Floor Area	102,800 ft^2			
Outdoor Design Conditions	New York	CD 88°F Dry Bulb and 72°F Wet Bulb	HD 11°F db	Standard 90.1-2007 Table D-1
	Atlanta	CD 91°F Dry Bulb and 74°F Wet Bulb	HD 18°F db	
	Las Vegas	CD 106°F Dry Bulb and 66°F Wet Bulb	HD 27°F db	
	Chicago	CD 88°F Dry Bulb and 73°F Wet Bulb	HD –6°F db	
Indoor Design Conditions	Summer 76°F Dry-Bulb Setpoint, 78°F Dry-Bulb Setback Winter 72°F Dry-Bulb Setpoint, 70°F Dry-Bulb Setback			

Table 1: Computer simulation parameters used to develop energy models.

a 4.2 COP water loop heat pump using an 80% fossil boiler, we find 200 lbs (90.7 kg) CO_2 per MMBtu of heating load, compared to 168 lbs (76.2 kg) CO_2 for a 7.7 HSPF air source heat pump. At this juncture, in a simplified analysis for heating only, geothermal is first (lowest carbon emissions), fossil is second, air source heat pump third, and dead last is the water loop heat pump (boiler/tower system).

There is an additional significance to this very rough rank ordering of systems. Anecdotal evidence suggests that many high-performance buildings are being designed with geothermal heat pumps. However, after the design is complete and is bid out, the high costs of geothermal wells result in a last-minute change to water loop heat pumps (boiler/tower system). The water loop heat pumps appear to be regarded as "second best" to geothermal heat pumps, and as a convenient last-minute substitution when high construction costs eliminate a geothermal system. However, this analysis suggests that water loop systems are not a good second choice; they are a poor fourth choice, with carbon emissions for heating that are almost twice as high as geothermal systems, and also higher carbon emissions than either fossil systems or air source heat pumps.

Now, equipment efficiency is available at different levels. How does this ranking change if we consider premium-efficiency equipment? Using values from Standard 189.1, with a geothermal heat pump COP of 3.1 (unchanged from Standard 90.1), an air source heat pump HSPF of 8.5, a boiler efficiency of 89%, and a water loop heat pump COP of 4.2 (also unchanged from Standard 90.1) with an associated 89% boiler, the ranking remains the same: geothermal first, fossil second, air source third, and water loop last.

Does the ranking change if we consider "best-available" efficiency? Using best-available published values from manufacturer's data,[4,5] with a geothermal heat pump COP of 4.5, an air source heat pump HSPF of 10.15, a boiler efficiency of 98%, and a water loop heat pump at a whopping 6.2 COP with an associated 98% efficiency boiler, the ranking *still* remains unchanged: geothermal best of the four systems, fossil second best, air source third, and water loop worst of the four systems.

We acknowledge that this rough heating-only analysis does not account for distribution system energy use, cooling use, internal gains, geographic location, solar gains, and interactive effects with the building envelope. To raise our confidence in these first-principle findings, we turn to the granddaddy of energy analysis, DOE2, to account for these important other effects.

Energy Model

The model was developed for a generic multifamily building with nine floors and 108 apartment units, hypothetically located in various climatic regions in the United States, including New York, Atlanta, Las Vegas and Chicago. It was built using eQuest (v3.64), a DOE2.2 based building energy simulation program.

Table 1 contains computer simulation parameters used to develop the energy models.

Energy System Strategies		
	Standard 90.1-2007 (See Tables 6.8.1B,C,F)	**High-Performance**
Air Source Heat Pump	EER = 10.8 at 95°F Dry Bulb COP = 3.3 at 47°F Dry Bulb	VRF System EER = 10.70 at 95°F Dry Bulb COP = 3.45 at 47°F Dry Bulb 10% Reduced Supply Fan Power
Ground Source Heat Pump	EER = 13.4 at 77°F Entering Water COP = 3.1 at 32°F Entering Water	EER = 17.9 at 77°F Entering Water COP = 4.5 at 32°F Entering Water 10% Reduced Supply Fan Power 5% Reduced Pump Power VFD Controls on WLHP Pumps
Boiler + Chiller	Natural Draft Non-Condensing Boiler, 80% E_t* Water-Cooled Screw Chiller, COP = 4.90 Cooling Tower, Two-Speed Fan, 38.2 gpm/hp	Condensing Boiler, 98% E_t at 80°F Return Water Frictionless Chiller, COP = 5.60 Full Load, VFD on Compressor, Two Compressors Per Circuit Cooling Tower, Variable Speed Fan, 10% Reduced Fan Power 10% Reduced Supply Fan Power 5% Reduced Pump Power VFD Controls on HW, CHW and CW Pumps
Heat Pump With Boiler + Tower	Water-Source HP EER = 12.0 at 86°F Entering Water COP = 4.2 at 68°F Entering Water Natural Draft Non-Condensing Boiler, 80% E_t Cooling Tower, Two-Speed Fan, 38.2 gpm/hp	Water-Source HP EER = 15.7 at 86°F Entering Water COP = 6.2 at 68°F Entering Water Condensing Boiler, 98% E_t at 80°F Return Water Cooling Tower, Variable Speed Fan, 10% Reduced Fan Power 10% Reduced Supply Fan Power 5% Reduced Pump Power VFD Controls on WLHP Pumps

*E_t = Thermal Efficiency

Table 2: Two energy system strategies based on ASHRAE/IESNA Standard 90.1-2007 and high performance systems are used.

The building shell is based on Standard 90.1-2007, Appendix G. A steel-framed wall is insulated to R-13 in the wall cavity, plus R-3.75 continuous insulation. The roof assembly has R-20 continuous insulation. Below grade insulation for New York and Chicago is R-7.5, and is not used for Atlanta and Las Vegas locations. A below-slab U-factor of 0.01 Btu/h·ft^2·°F (0.06 W/m^2·K) is used. Fenestration is vertical glazing only (no skylights). The window-to-wall ratio is 30%, distributed equally by exposure. The window assembly U-factor is 0.65 Btu/h·ft^2·°F (3.69 W/m^2·K) for Atlanta and Las Vegas, and 0.55 Btu/h·ft^2·°F (3.12 W/m^2·K) for New York and Chicago. The solar heat gain coefficient is 0.25 for Atlanta and Las Vegas, and 0.40 for New York and Chicago. No shading devices are used.

Interior lighting power densities are assumed to be 2 W/ft^2 (21.5 W/m^2) for the residences, 0.6 (6.5) for stairs, 0.5 (5.4) for hallways, 1.3 (13.9) for lobby areas, 0.8 (8.6) for storage rooms, and 1.5 (16.1) for electrical/mechanical rooms. Plug load power densities are 0.47 W/ft^2 (5.06 W/m^2) for tenant spaces, 0.2 (2.15) for supporting spaces, 0.8 (8.6) for storage rooms, and 1.0 (10.8) for lobby areas. Elevator power use is accounted for using a default DOE2.2 schedule. Cooking is done with natural gas.

Infiltration is assumed to be 0.35 air changes per hour.

We seek to evaluate comparable HVAC systems by placing either a heat pump or a fan coil in each apartment. Fan power is assumed to be 0.3 W/cfm (1.76 W/L·s), for fan coils (heat pump ratings already account for fan power). The fan schedule is "always on." Outdoor air is 55 cfm (26 L/s) per apartment, based on Standard 62.1-2007 (5 cfm [2.4 L/s] per person plus 0.06 cfm/ft^2 [0.03 L/s·m^2]) and is provided by a continuous central makeup air system. There is no economizer, no demand control, and no energy recovery for the ventilation. Exhaust is continuous at 45 cfm (21 L/s) for each apartment (20 cfm [9 L/s] for each bathroom, 25 cfm [12 L/s] for each kitchen).

For the chilled water system, the chilled water pump uses 22 W/gpm (0.10 W·L/s), the condensing water pump use 19 W/gpm (0.08 W·L/s). For the hot water system, the pump uses 19 W/gpm (0.08 W·L/s). We recognize that performance can change with the use of various pumping strategies. For the geothermal heat pumps, typical local soil characteristics were chosen.[6] For the air source heat pumps, electric resistance backup is allowed below 5°F (–15°C) if necessary.

Two energy system strategies are used, the first based on Standard 90.1-2007, and the second based on high-performance systems, as shown in *Table 2*. We note that the high-

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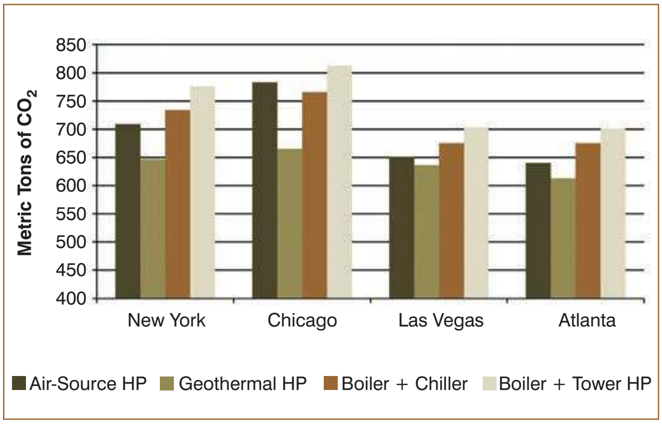

Figure 1: Carbon emissions, HVAC systems with efficiencies that meet Standard 90.1-2007.

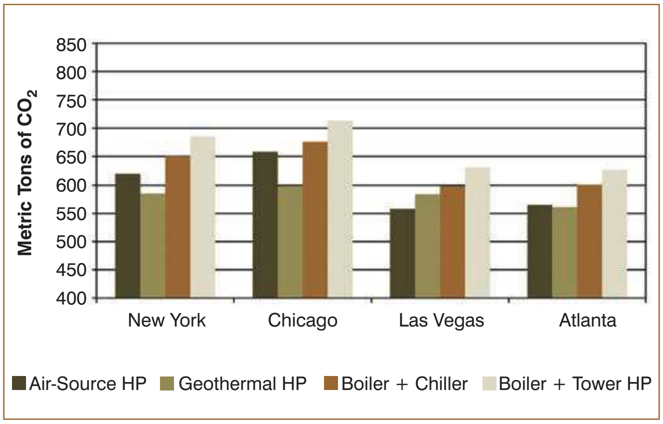

Figure 2: Carbon emissions, HVAC systems with higher rated efficiencies.

performance air source heat pump is a variable refrigerant flow system, the most widely applied system worldwide for envelope-dominated buildings, and increasingly popular in the United States.

Other assumptions include:

- Typical multifamily high-rise configuration, with repeating space/space types projected on a rectangular building footprint.
- It is assumed that each apartment is a one-bedroom unit, with 750 ft^2 (70 m^2) of floor area, and is occupied by two people.
- All the lighting power densities (LPDs) are based on Standard 90.1 -2007, Table 9.1 values except for the in-unit apartment spaces. Apartment spaces are assumed to have 2 W/ft^2 (21.5 W/m^2), according to a LEED-CIR.
- Equipment loads for the building are based on the NYSERDA Multifamily Performance Program Simulation Guidelines, and the California Non-Residential Alternative Calculation Manual (ACM) Approval Method.[7,8] Residential units are assumed to be constantly occupied throughout the year. Supporting spaces (such as mechanical/electrical rooms, storage rooms and offices) are assumed to be occupied between 8 a.m. and 6 p.m.
- Lighting schedules of corridors, hallways, and stairs are modeled as "on" all of the time. Lighting in supporting spaces (mechanical/electrical rooms, storage rooms and offices) is "on" between 8 a.m. and 6 p.m. Residential units lighting schedules are assumed to have a daily operating time of 2.34 hours, based on NYSERDA Multifamily Performance Program Simulation Guidelines.
- For domestic hot water (DHW) in the building, a natural gas heater with 80% efficiency is used. The DHW loads are based on the NYSERDA Multifamily Performance Program Simulation Guidelines.

Model Results

Carbon emissions results, in metric tons of CO_2, are shown in *Figure 1* for the systems using efficiencies from Standard 90.1-2007.

The model shows that geothermal has the lowest carbon emissions for all cities, and boiler/tower heat pumps have the highest emissions for all cities, of the four systems studied. These results are consistent with our rough heating-only first-principles analysis, mentioned previously. However, in warmer climates (Las Vegas and Atlanta), air source heat pumps have lower emissions than the boiler/chiller system. Maybe not a surprise after all, air source heat pumps have long been recognized as being efficient in warm climates.

Now, let's look at the high-performance systems, in *Figure 2*.

Interestingly, high-efficiency air source heat pumps now outperform high-efficiency boiler/chiller systems in all climates, and even outperform high-efficiency geothermal systems in the hottest climate (Las Vegas). The performance difference for high-performance air source heat pumps is the most pronounced, relative to Standard 90.1 systems, with carbon emissions reduced by 14% on average, whereas the other three systems have carbon emissions reduced by 9% to 11%.

Other metrics were examined, including source energy use intensity (EUI), and energy costs, using local rates for electricity and natural gas. Results similar to those of carbon emissions were found: For EUI and energy costs, geothermal heat pumps have the lowest use and costs, except for Las Vegas where high efficiency air source heat pumps perform better; and boiler/tower heat pumps are the worst performers in all geographic regions.

Limitations

The limitations of the study are important to acknowledge. The findings are based on computer models, and not based on real-life behavior of HVAC systems in buildings. For example, distribution systems can vary greatly in design, and can vary greatly in construction and operation. The models contain assumptions about system effects and specific hardware configurations, as well as control schemes.

The models are not validated with data from buildings. Also, only four systems were evaluated, where the real world

of HVAC allows for many more types of systems, such as packaged rooftop systems, absorption systems, packaged terminal systems, a variety of advanced heat recovery systems, and many more.

Despite the limitations, much information can still be gleaned from the findings, as the computer model is intended to provide useful energy performance predictions.

Conclusions

Among the HVAC system types chosen for modeling in this effort, geothermal heat pumps appear to have a significant advantage for envelope-dominated buildings, although this position is being challenged by the advent of high-efficiency variable speed air source heat pumps, especially in warmer climates. Boiler/chiller systems generally hold the third place position, with the exception of the coldest climate in the study (Chicago), but even here, air source heat pumps are challenging high-performance boiler/chiller systems. Water loop (boiler/tower) heat pumps are the worst choice for envelope-dominated buildings, across the board, among the four systems studied, regardless of geography or system efficiency. Therefore, they should likely not be considered as a second-best backup when geothermal system construction costs come in high on a project.

Acknowledgments

The work was supported by the Taitem Engineering C-NEW initiative for building energy conservation.

References

1. ASHRAE/IESNA Standard 90.1 -2007, *Energy Standard for Buildings Except Low-Rise Residential Buildings*.

2. ASHRAE/USGBC/IESNA Standard 189.1-2009, *Standard for the Design of High-Performance, Green Buildings, Except Low-Rise Residential Buildings.*

3. Carbonfund.org. 2011. "How We Calculate." www.carbonfund.org/site/pages/carbon_calculators/category/Assumptions.

4. American Council for an Energy Efficient Economy. 2011. "Heating." www.aceee.org/consumer/heating#new.

5. Air Conditioning, Heating and Refrigeration Institute. 2011. "Directory of Certified Product Performance." www.ahridirectory.org.

6. International Ground Source Heat Pump Association. 2011. *Residential and Light Commercial Design and Installation Manual.*

7. New York State Energy and Research Authority. 2009. Multi-family Performance Program, New Construction Simulation Guidelines. Version 3.0.

8. Nonresidential Alternative Calculation Manual (ACM) Approval Method for the 2008 Building Energy Efficiency Standards. 2004. Publication Number: 400-2008-003-CMF. California Energy Commission.●