HOW THE LEED VENTILATION CREDIT IMPACTS ENERGY CONSUMPTION OF GSHP SYSTEMS — A CASE STUDY FOR PRIMARY SCHOOLS[1]

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Abstract: This paper presents a study on the impacts of increased outdoor air (OA) ventilation on the performance of ground-source heat pump (GSHP) systems that heat and cool typical primary schools. Four locations — Phoenix, Miami, Seattle, and Chicago — are selected in this study to represent different climate zones in the United States. eQUEST, an integrated building and HVAC system energy analysis program, is used to simulate a typical primary school and the GSHP system at the four locations with minimum and 30% more than minimum OA ventilation. The simulation results show that, without an energy recovery ventilator, the 30% more OA ventilation results in an 8.0–13.3% increase in total GSHP system energy consumption at the four locations. The peak heating and cooling loads increase by 20.2–30% and 14.9–18.4%, respectively, at the four locations. The load imbalance of the ground heat exchanger is increased in hot climates but reduced in mild and cold climates.

Key Words: LEED, GSHP, DOAS, increased ventilation, and energy consumption

1 INTRODUCTION

Indoor air quality is very important to the health and productivity of building occupants. Increasing outdoor air (OA) ventilation can reduce sick-building syndrome and improve building occupants' well-being and productivity. Schools usually require large amounts of outdoor air for ventilation because of their high occupant density. LEED 2009 (Leadership in Energy and Environmental Design), a rating system for promoting green and sustainable buildings (USGBC 2009a and 2009b), recognizes the importance of OA ventilation and gives 1 point (40 points are required to earn LEED 2009 certification for new construction and major renovations) if OA ventilation rates in the breathing zones of all occupied spaces are increased by at least 30% above the rate required by ASHRAE Standard 62.1-2007.

However, increasing OA ventilation will impact the design and energy consumption of the HVAC system serving the building. It is of our particular interest to evaluate how the increased OA ventilation affects the design and energy consumption of ground-source heat pump (GSHP) systems, which have a high first cost compared to conventional HVAC systems but operate at very high energy efficiency. In this study, through computer simulation, we examine impacts of a 30% increase in OA ventilation on the energy consumption and design of GSHP systems that provide space heating and cooling for a typical primary school in four climates. We simulate the school and GSHP system with

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eQUEST, an integrated building and HVAC system energy analysis program. eQUEST was upgraded a few years ago to be able to accurately simulate a wide range of closed-loop ground-heat exchangers and various GSHP units (Liu and Hellstrom 2006, Liu 2008).

Based on simulation results, we analyze the impacts of the 30% greater OA on annual energy consumption and peak heating and cooling loads of the simulated GSHP systems, as well as the balance of accumulated heat rejection and extraction loads of the ground heat exchanger on an annual basis.

2 DESCRIPTION OF SIMULATED BUILDING AND GSHP SYSTEM

The DOE commercial building benchmark study (DOE 2008) described in detail a primary school with all the information required for performing energy simulations. The school has an “E-shape” footprint and total conditioned space of 74,000 ft^2 (6875 m^2). For this study, we simplify the geometry of the school to a one-story rectangular building with 75,000 ft^2 (6968 m^2) total conditioned space, which has classrooms on the perimeter and one corridor in the interior, as illustrated in Figure 1. The classrooms are grouped into four corner zones and two perimeter zones, and the entire corridor is considered as one interior thermal zone, as shown in Figure 2.

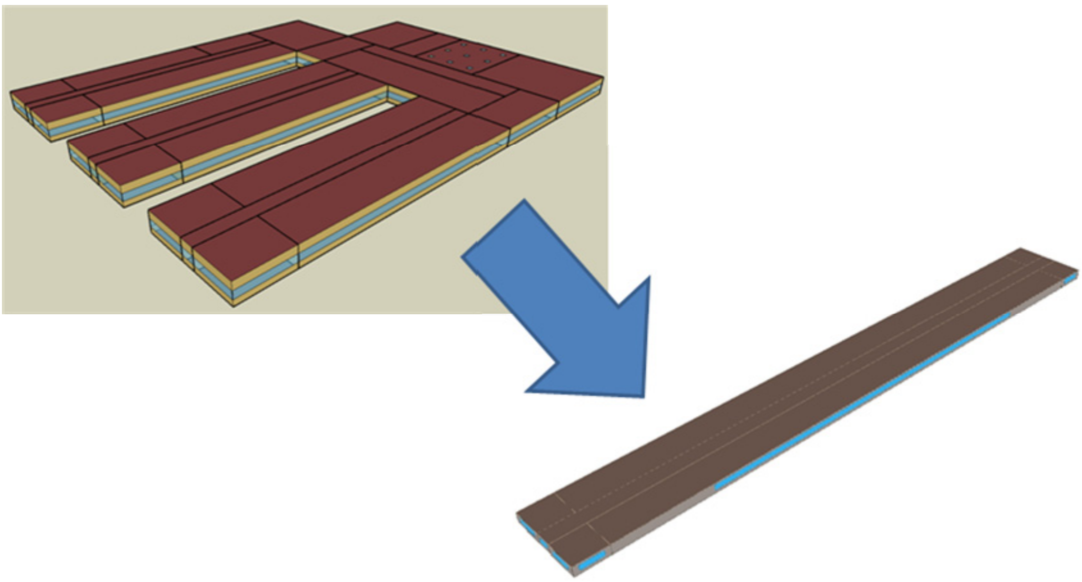

Figure 1: 3D view of the simulated primary school

We assume that the same school is located in four different U.S. climate zones as described in ASHRAE Standard 90.1-2007. The four climate zones include 2B (hot and dry), 1A (hot and humid), 4C (mild), and 5A (cold). We selected Phoenix, Miami, Seattle, and Chicago to represent these climate zones, respectively.

The simulated building has an envelope (including roof, exterior walls, slab-on-grade foundation, and window glazing) that meets the minimum requirements specified in ASHRAE 90.1-2007 for all four climate zones. Specifications of the simulated building are listed in Table 1 along with the corresponding requirements specified in ASHRAE 90.1-2007 for the four climate zones.

The lighting power density (LPD) and equipment load of the simulated school are adopted from ASHRAE Standard 90.1-2007 and EnergyPlus benchmark study and summarized in Table 2.

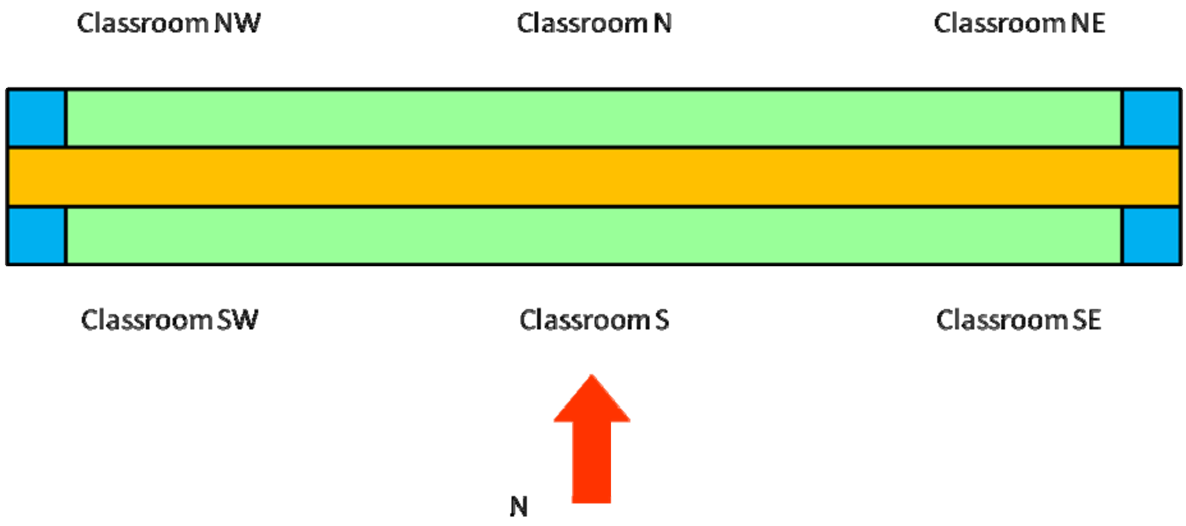

Figure 2: Floor plan and thermal zones of the simulated primary school

Table 1: Comparison between the simulated building envelop and the minimum requirements specified in ASHRAE 90.1-2007

Building Envelope	ASHRAE 90.1-2007				eQUEST Model
	Phoenix 2B	Miami 1A	Seattle 4C	Chicago 5A	
Roof (insulation entirely above deck)	U-0.358	U-0.358	U-0.358	U-0.358	U-0.233
Wall (steel-framed)	U-0.704	U-0.704	U-0.704	U-0.477	U-0.46
Slab-on-grade (Foundation)	F-1.263	F-1.263	F-1.263	F-1.263	F-1.263
Window	Ufixed-.6.927	Ufixed-.6.927	Ufixed-.3.237	Ufixed-3.237	Ufixed-2.442
Window SHGC	SHGCall-0.25	SHGCall-0.25	SHGCall-0.39	SHGCall-0.39	SHGCall-0.39

U: U-factor, thermal transmittance in W/M^2-K.
F: F-factor, the perimeter heat loss factor for slab-on-grade floors, in W/M-K.
Ufixed: U-factor for fixed window
SHGCall: Solar heat gain coefficient for all the orientations of a building

Table 2: Internal loads of the simulated primary school

Thermal Zone	Area (M^2)	LPD (W/M^2)	Equipment Load (W/M^2)
Classroom SW	84	15.1	10.8
Classroom S	1505	15.1	10.8
Classroom SE	84	15.1	10.8
Corridor	836	6.5	0.0

Classroom NW	84	15.1	10.8
Classroom N	1505	15.1	10.8
Classroom NE	84	15.1	10.8

The minimum OA ventilation rates for each of the thermal zones of the simulated primary school are determined using the data and algorithms provided in ASHRAE Standard 62.1-2007. The calculated minimum OA ventilation rates are shown in Table 3.

Table 3: Calculated minimum OA ventilation rate for each thermal zone of the simulated primary school per ASHRAE Standard 62.1-2007

Thermal Zone	Area (M^2)	People Outdoor Air Rate (M^3/HR/person)	Area Outdoor Air Rate ($M^3/HR/M^2$)	Occupant Density (#/M^2)	Outdoor Air Flow Rate (M^3/HR)
Classroom SW	84	17	2.2	0.38	719
Classroom S	1505	17	2.2	0.38	12936
Classroom SE	84	17	2.2	0.38	719
Corridor	836	0	1.1	0.00	917
Classroom NW	84	17	2.2	0.38	719
Classroom N	1505	17	2.2	0.38	12936
Classroom NE	84	17	2.2	0.38	719

Figure 3 shows a schematic of the simulated GSHP system. Each thermal zone of the school is served with one or more packaged water-to-air GSHP units and controlled independently. All the GSHP units are connected to a closed-loop vertical ground heat exchanger through a common 2-pipe loop. A dedicated outdoor air system (DOAS) tempers OA to 55°F (13°C) with a specially designed GSHP unit for conditioning 100% OA, which is connected to the common 2-pipe loop and delivers the conditioned OA to each GSHP unit in the thermal zones. The GSHP system uses a variable-speed central pump station to circulate the heat carrier fluid through all the GSHP units and the ground heat exchanger. When the school is occupied, the DOAS fan runs continuously to deliver constant OA to each zone, but the GSHP unit fan runs intermittently with the heat pump compressor, which is turned on and off by the thermostat to maintain the room temperature at the set point.

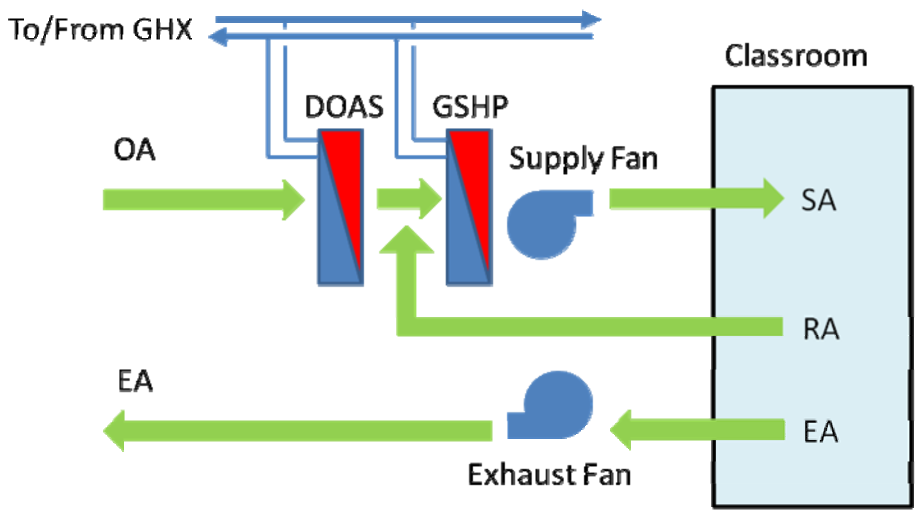

Figure 3: Schematic chart of the simulated GSHP System

The GSHP system utilizes a vertical closed-loop ground heat exchanger (VCGHX) , which is sized for each of the four locations to ensure that the entering fluid temperature to the GSHP units will remain within the range of 45 to 90°F over a 30-year period.

3 SIMULATION RESULTS AND DISCUSSION

Tables 4 and 5 summarize the annual energy consumption of the GSHP system with minimum and 30% more than minimum OA ventilation. As indicated in these tables, the GSHP system in Miami has the highest energy consumption for space cooling, while the GSHP system in Seattle consumes the least energy for space cooling. For space heating, the GSHP system in Chicago consumes the most energy and the system in Miami consumes the least.

Table 4: Annual energy consumption (by end use) of GSHP systems at four locations with minimum OA (kWh)

	Phoenix	Miami	Seattle	Chicago
Space cooling	84,448	130,108	15,431	24,251
Space heating	1,340	116	10,427	21,951
Fans	18,946	18,369	11,775	13,027
Pumps	15,399	15,518	9,009	12,609
Total	120,132	164,112	46,642	71,838

Note: The energy consumption data shown in Table 4 for space cooling and space heating are for heat pump compressor only.

Table 5: Annual energy consumption (by end use) of GSHP systems at four locations with 30% more OA than the minimum requirement (kWh)

	Phoenix	Miami	Seattle	Chicago
Space cooling	89,889	145,379	14,891	25,689
Space heating	1,616	151	12,288	25,846
Fans	20,395	19,862	13,558	14,915
Pumps	17,874	18,055	10,639	14,935
Total	129,774	183,448	51,376	81,385

Note: The energy consumption data shown in Table 5 for space cooling and space heating are for heat pump compressor only.

The percentage change in energy consumption resulting from the 30% more OA ventilation is calculated based on data shown in tables 4 and 5 and summarized in Table 6. As shown in Table 6, the (compressor) energy consumption for space heating increases by 17.8–30.2% due to the 30% greater OA ventilation. Because the GSHP system in Miami has the lowest heating energy consumption, it has the highest percentage of change compared to the other three locations. The (compressor) energy consumption for space cooling is reduced by 3.5% in Seattle because the increased OA ventilation actually provides "free cooling" to the school given Seattle's very mild weather. However, the (compressor) cooling energy consumption increases by 5.9–11.7% at other three locations with the 30% increase in OA ventilation. In addition, the energy consumed by the GSHP system fans increases by 7.7–15.1% at the four locations, and the energy consumed by the circulation pump increases 16.1–18.5%. As a result of supplying 30% more OA ventilation, the total energy consumption of the GSHP systems increases 8.0–13.3%.

Table 6: Changes of annual energy consumption (by end use) due to the 30% more OA ventilation (%)

	Phoenix	Miami	Seattle	Chicago
Space cooling	6.44	11.74	-3.50	5.93
Space heating	20.63	30.16	17.84	17.75
Fans	7.65	8.13	15.14	14.49
Pumps	16.07	16.35	18.10	18.45
Total	8.03	11.78	10.15	13.29

In addition to annual energy consumption, we also investigated how the 30% increase in OA ventilation will affect peak heating and cooling loads, which will determine the size of the GSHP units and the design of the VCGHX. As summarized in Table 7 and Table 8, increasing OA ventilation by 30% increases peak heating and cooling loads by 20.2–30% and 14.9–18.4%, respectively.

Table 7: Building peak heating and cooling loads with minimum OA (kW)

Peak Load	Phoenix	Miami	Seattle	Chicago
Heating	-157	-83	-247	-592
Cooling	549	625	362	583

Table 8: Changes of building peak heating and cooling loads due to 30% more OA (%)

Peak Load	Phoenix	Miami	Seattle	Chicago
Heating	23.66	30.00	20.20	22.23
Cooling	14.92	17.53	16.08	18.44

The design of VCGHX depends not only on building peak cooling and heating loads, but also on the annual cumulative heat rejection and extraction loads imposed on the VCGHX. Tables 9 and 10 list the cumulative heat extraction and rejection loads of the VCGHX with minimum and increased OA ventilation. Comparing data shown in tables 9 and 10, it is clear that the imbalance between the heat rejection and extraction loads of the VCGHX is increased in Phoenix and Miami. The reason is that, though increasing OA by 30% increases both heating and cooling loads, the increased cumulative cooling load is greater than the increased cumulative heating load. To compensate for this larger load imbalance, the size of VCGHX needs to be increased more than what is needed just for the increased peak cooling load. However, in the mild and cold climates of Seattle and Chicago, the 30% more OA mitigates the heat imbalance and thus could result in either reduced size of VCGHX or improved energy efficiency of the GSHP system.

Table 9: Cumulative heat extraction and rejection loads with minimum OA ventilation (MWh)

	Phoenix	Miami	Seattle	Chicago
Heat Extraction	-6	-0.1	-64	-149
Heat Rejection	653	925	155	246
Net Heat	647	925	91	97

Table 10: Heat extraction and rejection loads with 30% more OA ventilation (MWh)

	Phoenix	Miami	Seattle	Chicago
Heat Extraction	-7	-0.3	-80	-178
Heat Rejection	695	1029	149	260
Net Heat	687	1029	69	82

Integrating an energy recovery ventilator (ERV) with the DOAS system to pre-condition the OA with exhaust air has the potential to mitigate the impacts of the higher ventilation rate on GSHP peak loads and energy consumption. (Figure 4 shows a schematic of the GSHP System that has a DOAS system integrated with an ERV.) However, we are not able to evaluate the impacts of ERVs in this study because of limitations in the current version of eQUEST.

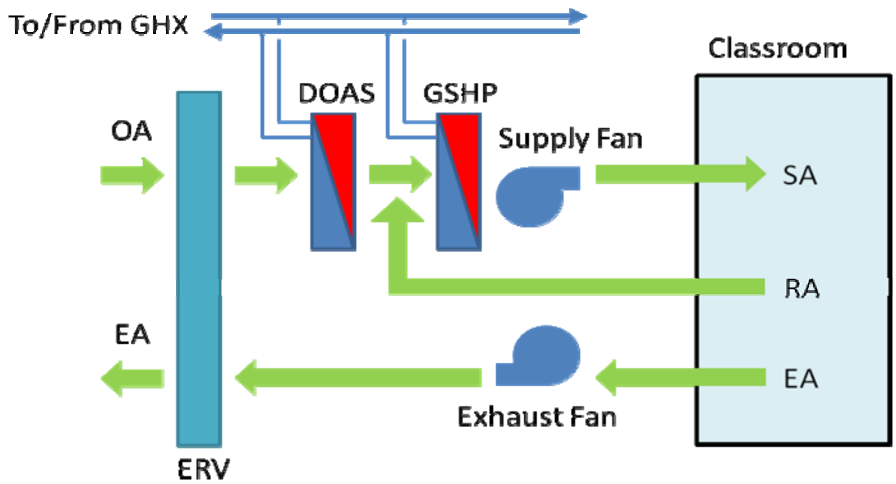

Figure 4: Schematic chart of GSHP system with DOAS integrated with ERV

4 CONCLUSION

The impacts of increased OA ventilation on the design and energy consumption of GSHP systems serving for a typical primary school are investigated through computer simulation. Due to limitations of the current simulation tool, ERVs are not accounted for in this study. The simulation results show that, as a result of increasing OA ventilation to 30% above the minimum called for by ASHRAE Standard 62.1-2007, energy consumption for space heating increases by 17.8–30.2% in the four modelled climates. The energy consumption for space cooling is reduced by 3.5% in Seattle (a mild climate) but increases by 5.9–11.7% in the other three locations (Phoenix, Miami, and Chicago) with hot or cold climates. The fan energy increases by 7.7–15.1% and pump energy increases by 16.1–18.5% in the four locations investigated in this study. Overall, the total energy consumption of the GSHP system increases by 8.0–13.3% at the four locations. The peak heating and cooling loads increase by 20.2–30% and 14.9–18.4%, respectively. The load imbalance of the ground heat exchanger is increased in hot climates but reduced in mild and cold climates.

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