An energy and economic modeling study of exhaust ventilation systems compared to balanced ventilation systems with energy recovery.

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Abstract - In order to meet the current PHIUS+ certification metrics for annual heat demand, ventilation systems with energy recovery and/or heat recovery (ERV/HRV) are a necessity in most North American climates. ERV/HRV systems can significantly reduce heating demand and cooling demand, but these systems are relatively costly to install compared to other ventilation options, are somewhat complex for owners to operate and maintain, and require a significant amount of fan energy for operation (200-400kWh/year, about 4-8% of total site energy for a modest-sized, all electric Passive House). By contrast, well-designed exhaust ventilation systems are less expensive to install, are easier to maintain and require significantly less fan energy for operation. Typical exhaust ventilation systems, however, offer no heat transfer. This paper examines energy savings and cost effectiveness for both system types in six (6) climate locations. The paper includes a brief summary of common issues with exhaust ventilation systems and also describes a measurement and testing protocol for an upcoming case study using an exhaust ventilation system. The results of the energy modeling show both the ERV and HRV modeled save energy compared to an exhaust ventilation system in every case in the study. However, the amount of site energy saved by the ERV/HRV systems is much lower in the milder climates (330-600kWh/year) than the colder climates (800-1,100kWh/year). The lower energy savings in the milder climates leads to poor cost-effectiveness when compared to other energy saving or energy producing options such as extra insulation or a photovoltaic system. Based on these results, it is recommended that other metrics for the PHIUS+ annual heating and cooling demand should be explored that focus solely on the passive elements of the building enclosure.

Introduction - In the development of Passive Houses in Germany, high efficiency heat-recovery ventilation systems were essential in order to help reduce peak heating loads to a level that would allow <u>all</u> of the heating energy needed during peak heating days to be delivered through the ventilation system, thereby eliminating the need for an additional distribution system for heat and saving significant upfront cost (Feist 2006). However, in most North American climates, this same technique is not feasible due to a combination of factors (mainly lower peak outdoor temperatures and the requirement for cooling in many climates). Therefore, in North American Passive Houses, ventilation and space conditioning are often de-coupled, requiring separate distribution systems and typically higher upfront cost. It is common for a stand-alone Passive House ventilation system to have an installed cost of \$4,000-\$7,000[1], or more. Given this expense, it is worth taking a close look at the energy savings from these systems in relation to their upfront cost, and compare them to other ventilation system options, such as exhaust-only ventilation.

Energy modeling - Three ventilation systems for a theoretical, 1,800ft^2, single-family, detached, 3-bedroom house were modeled in the Passive House Planning Package (PHPP) in six climate locations:

Atlanta, GA - 3,200 Heating Degree Days – "HDD" (^{O}F.day/year)
San Francisco, CA - 2,600 HDD
Charlottesville, VA - 4,000 HDD
Portland, OR – 4,600 HDD
Chicago, IL 6,700 HDD
Burlington, VT 7,300 HDD

[1] Based on actual installed costs in houses I have consulted on.

Energy modeling assumptions for each house, except where noted:

- Heat pump heating/cooling system with heating-season COP ranging from 2.75 to 3.50 depending on climate (warmer climate = higher COP) and cooling season COP of 5.0.
- The modeled comfort "setpoints" for the houses were 70F for winter and 75F / 50% relative humidity (0.0094 humidity ratio) for summer. These setpoints are less conservative than the typical Passive House setpoints of 68F for winter and 77F / 60%RH (0.012 humidity ratio) for summer. The setpoints used in the study tend to favor the ERV/HRV systems, compared to standard PHPP setpoints.
- Two of the ventilation systems are commonly found in North American Passive Houses: the 200DX ERV from Ultimate Air and the Comfo 350 HRV from Zehnder America. The third ventilation system modeled was a Panasonic FV-08VKS3 exhaust fan with variable airflow settings and passive air inlets.
- Blower door test result of 0.60 ACH_{50} (with ventilation systems sealed). Exhaust ventilation houses were assumed to have a blower door test result of 2.00 ACH_{50} with the passive air inlets uncovered and were modeled with 2.00 ACH_{50} in the study.
- The ventilation rate was set at 56cfm (continuous), approximately 0.30 ACH.
- The ventilation rate input for the PHPP for the exhaust ventilation system was increased slightly to 64cfm to account for occupant on-demand use of other exhaust appliances: other bath fans (50cfm x 2 hours/day), range hood (100cfm x 1 hour/day) and clothes dryer (125cfm x 1 hour/day)
- Each of the three systems was modeled based on an "ideal" fan energy situation according to manufacturer's specifications and/or in-field testing (0.58 W/cfm for the 200DX, 0.30 W/cfm for the Comfo 350, 0.10 W/cfm for the Panasonic bath fan). However, the fan efficiency of the Panasonic exhaust system was adjusted slightly higher (to 0.12 W/cfm) to account for the other exhaust systems in the house with less efficient fans, such as the kitchen range hood.
- The houses in Chicago and Burlington were assumed to have electric defrost systems for the ERV and HRV.
- The energy analysis included annual heating demand and latent cooling demand for ventilation and infiltration[2], ventilation fan energy use, defrost energy use and space conditioning energy use for ventilation and infiltration.

Energy analysis summary (see Table 1 for full results):

1) The ERV/HRV systems have lower heating demand and higher fan energy use than the exhaust ventilation system in all six climates (Figure 1).
2) The differences between the heating demand for the ERV/HRV systems and the exhaust system in the colder climates is significantly greater than in the milder climates (Figure 1).
3) The differences in latent cooling demand between the ERV system and the HRV/exhaust systems are relatively small, even in the most humid climate (Atlanta). (Figure 2).
4) The differences in total site energy use (heating, defrost, latent cooling and fan energy use) between the three systems range from 400kWh/year to 1,140kWh/year depending on climate. Total site energy savings for the ERV/HRV systems in the milder climates are significantly lower than the colder climates (Figure 3).

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[2] The PHPP is not able to accurately model the summer "bypass" features of the ERV and HRV. For this report, differences in sensible cooling demand between the system types are assumed to be negligible and are not included in the results. It would be useful to follow up on this topic using an hourly simulation model.

Economic analysis summary - The approach to economic analysis is a simplified one. Using rough estimates for total installed costs of each system type, I used the Panasonic exhaust ventilation system as a baseline cost and calculated the ratio of the incremental up-front cost for the ERV and HRV systems, divided by their respective total lifetime site energy savings over the baseline exhaust system. Lifetime was set at 20 years for this analysis, though this may be too generous given the manufacturers' equipment warranties[3]. A shorter assumed lifespan would tend to favor the lower cost equipment in this analysis.

Total installed cost estimates (see Table 2)-

1) 200DX - $4,125[4] (ERV, ductwork, fittings, registers, labor, markup)
2) Comfo 350 - $5,375 (HRV, ductwork[5], fittings, registers, labor, markup)
3) Panasonic exhaust - $2,102 (3 bath fans, 1 kitchen range hood, ductwork, fittings, labor, markup)

Cost effectiveness - The cost/kWh saved for the 200DX ranged from as low as $0.12/kWh in Burlington to as high as $0.31/kWh in San Francisco. The cost/kWh saved for the Comfo 350 ranged from as low as $0.17/kWh in Burlington to as high as $0.41/kWh in Atlanta (Figure 4). For reference, Figure 4 also includes lifespan cost-effectiveness ratios for a typical photovoltaic system ($0.13/kWh) and an attic super-insulation upgrade in Charlottesville, VA ($0.17/kWh). Based on this analysis, the ERV and HRV systems are not cost-effective (compared to the reference points) in terms of energy savings in the milder climates, and are only moderately cost effective as the house "migrates" to a cold climate (Burlington).

Known issues with exhaust ventilation systems -

1) *Random distribution* - Ventilation distribution is a concern with exhaust ventilation systems. Tracer gas studies of houses with exhaust ventilation systems (without passive air inlets) show relatively poor ventilation distribution in bedrooms with closed doors (Rudd and Lstiburek 2000, Rudd et al. 2007, and Aldrich 2010). Though detailed data was lacking, one tracer gas study (Strunk et al. 1999) of a house with passive air inlets showed satisfactory air exchange for the master bedroom (other bedrooms were not reported). In an 18-house Swedish study of houses with exhaust ventilation and passive inlets, air exchange for the closed bedrooms was satisfactory (Blomsterberg 1986).

2) *Problems with passive air inlets* - It has been demonstrated that in relatively leaky houses, the depressurization caused by exhaust ventilation fans is typically not enough to induce more than 2-4cfm of airflow through passive air inlets (Shapiro et al 1999). In these leaky houses, the free opening area of the inlets was only a small portion of the total leakage area of the house. However, in tighter houses, it has been shown that the majority of ventilation air <u>can</u> be induced to flow through passive vents. For example, according to designer/builder Michael Chandler, flow-hood testing on passive air inlets in his homes (with blower door tests $<2.0ACH_{50}$) shows the passive intake vents typically provide about 50 cfm for every 80 cfm removed from the house by the exhaust fan. (Chandler 2010). In order for passive air inlets to be effective, unintentional leaks in the building envelope must be minimized, the exhaust fan must cause enough house depressurization to overcome wind and stack effects, <u>and</u> the total free area of the inlets must make up a significant portion of the total leakage area of the house.

3) *House depressurization (safety and health)* - Negative pressure systems can pose safety and long-term health risks to occupants in certain situations. In general, these situations can be removed by

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[3] Manufacturer Warranties - Panasonic: 6yrs. on fan motor, 3yrs. on parts. 200DX: 5yrs. Comfo 350: 2 yrs.

[4] $500 was added to both the ERV and HRV system's costs for Chicago and Burlington to account for installing an electric defrost system.

[5] Not included in the cost estimate, Zehnder America sells optional, proprietary ductwork and fittings that would add to duct/fitting cost, but have the potential to save in labor costs

design and quality construction - no attached garage, no combustion appliances or sealed combustion appliances, install radon-mitigation systems in high-radon areas, build sealed crawlspaces.

4) *House depressurization (building assembly durability)* - In humid climate zones, there are concerns that negative pressure systems will lead to condensation and moisture problems within building assemblies. In the original ASHRAE 62.2-2010 ventilation standard, exhaust ventilation systems were specifically restricted in hot, humid climates to no more than 7.5cfm per 100ft^2 over floor area. However, in a recent addendum, the 62.2 committee removed this language. From the addendum: "*The committee reviewed Section 4.6, "Restrictions on System Type" and decided the restrictions were not justified by recent field experience. There was general agreement that the problems in both hot/humid and cold climates were caused by specific and easily avoidable errors in envelope design that could not be solved by the system restrictions in Section 4.6.*"

5) *Discomfort from cold airflow* - Register location and diffuser type/flow direction are much more important for comfort than supply air temperature. Even 68F air blowing directly over an occupant's skin in January is not typically considered "comfortable". Exhaust ventilation systems with passive air inlets can deliver satisfactory comfort while delivering undiluted outside air if the inlets are designed and located to encourage maximum mixing within the room without direct airflow over an occupant. Typical practice is to install the inlets near the ceiling to encourage mixing. An inlet that directs airflow upward to encourage mixing is preferred.

Implications for PHIUS+ Metrics - Based on the poor cost-effectiveness of ERV/HRV systems in the milder climates, it seems irrational that these mechanical systems should be a "de facto" requirement for meeting the annual heat demand requirement for certification. Therefore, other metrics should be explored that focus solely on the passive aspects of the building envelope, leaving project teams and manufacturers with more options for low-energy mechanical ventilation solutions.

Implications for ERV/HRV manufacturers - ERV and HRV manufacturers should be encouraged to offer other equipment options, such as lower cost, lower airflow capacity ERV/HRV systems that retain high performance levels. These would improve cost-effectiveness in smaller residential units throughout all climate zones.

Next steps - Charlottesville, VA Case Study - A new house under construction in Charlottesville, VA will allow testing and monitoring of an exhaust-only ventilation system with passive inlets in a very tight house. The 4-bedroom speculative house (built by Latitude 38 - http://latitude38llc.com/projects/palatine-avenue-310/) will sell for approximately the average price per square foot for the area (\$175/ft^2) and has modeled primary energy use of approximately 9.0kWh/ft^2 (Treated Floor Area). One of the keys to the relatively low cost is the simplified ventilation system and heating/cooling system. The house will be tested for air-tightness prior to insulation with a goal of $<0.60ACH_{50}$ (with passive inlets sealed). At the same time period, a blower door will be used to simulate the exhaust ventilation flow with the passive inlets open, in order to allow the airflow through the inlets to be measured and adjusted. Following construction, a monitoring system will track ventilation fan energy use, and will track temperature, relative humidity and CO2 levels throughout the house.

Figure 1

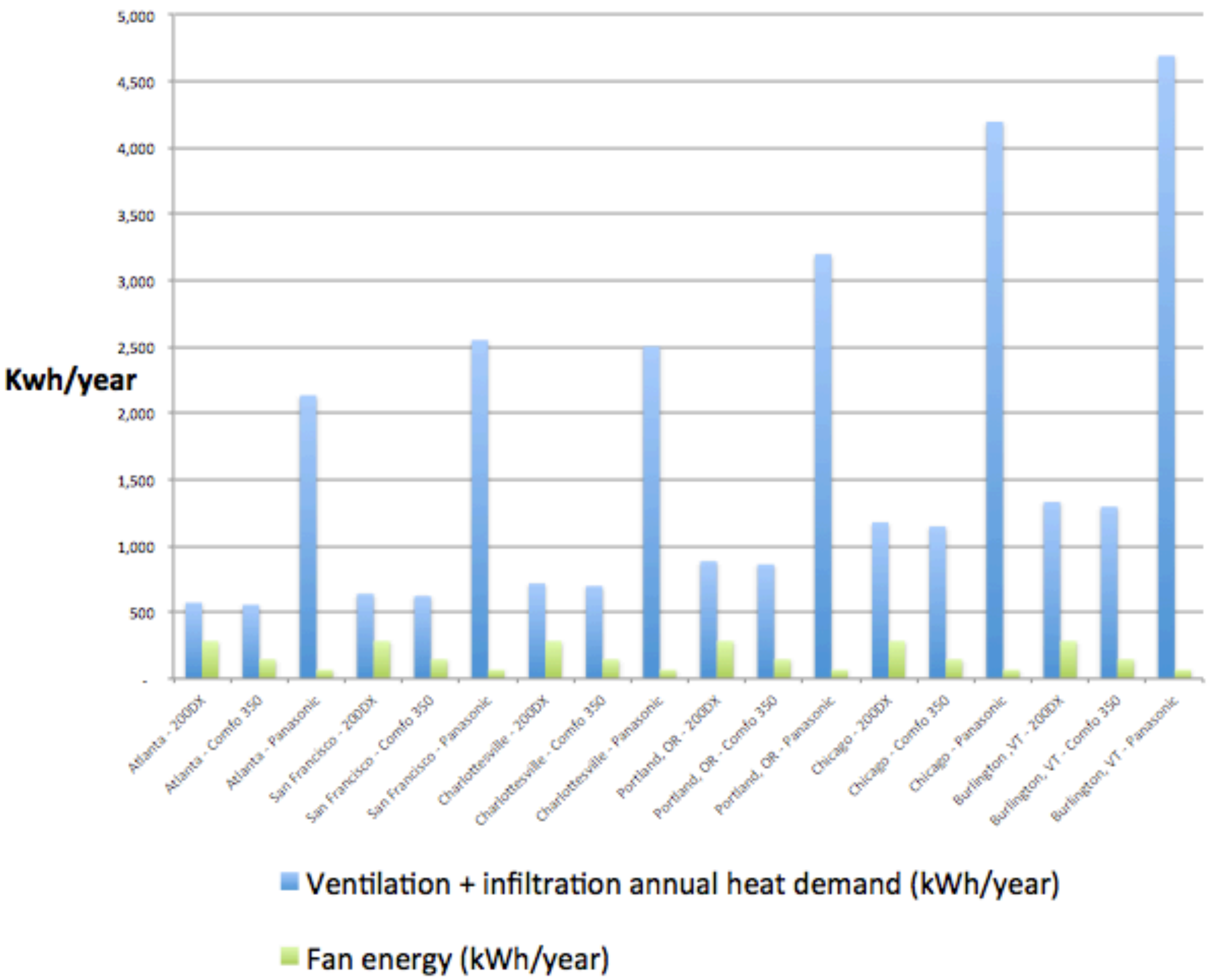
Kwh/year
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
-
Atlanta - 200DX
Atlanta - Comfo 350
Atlanta - Panasonic
San Francisco - 200DX
San Francisco - Comfo 350
San Francisco - Panasonic
Charlottesville - 200DX
Charlottesville - Comfo 350
Charlottesville - Panasonic
Portland, OR - 200DX
Portland, OR - Comfo 350
Portland, OR - Panasonic
Chicago - 200DX
Chicago - Comfo 350
Chicago - Panasonic
Burlington ,VT - 200DX
Burlington, VT - Comfo 350
Burlington, VT - Panasonic
Ventilation + infiltration annual heat demand (kWh/year)
Fan energy (kWh/year)

Figure 2
Ventilation + Infiltration Annual Latent Cooling Demand (Atlanta) - kWh/year

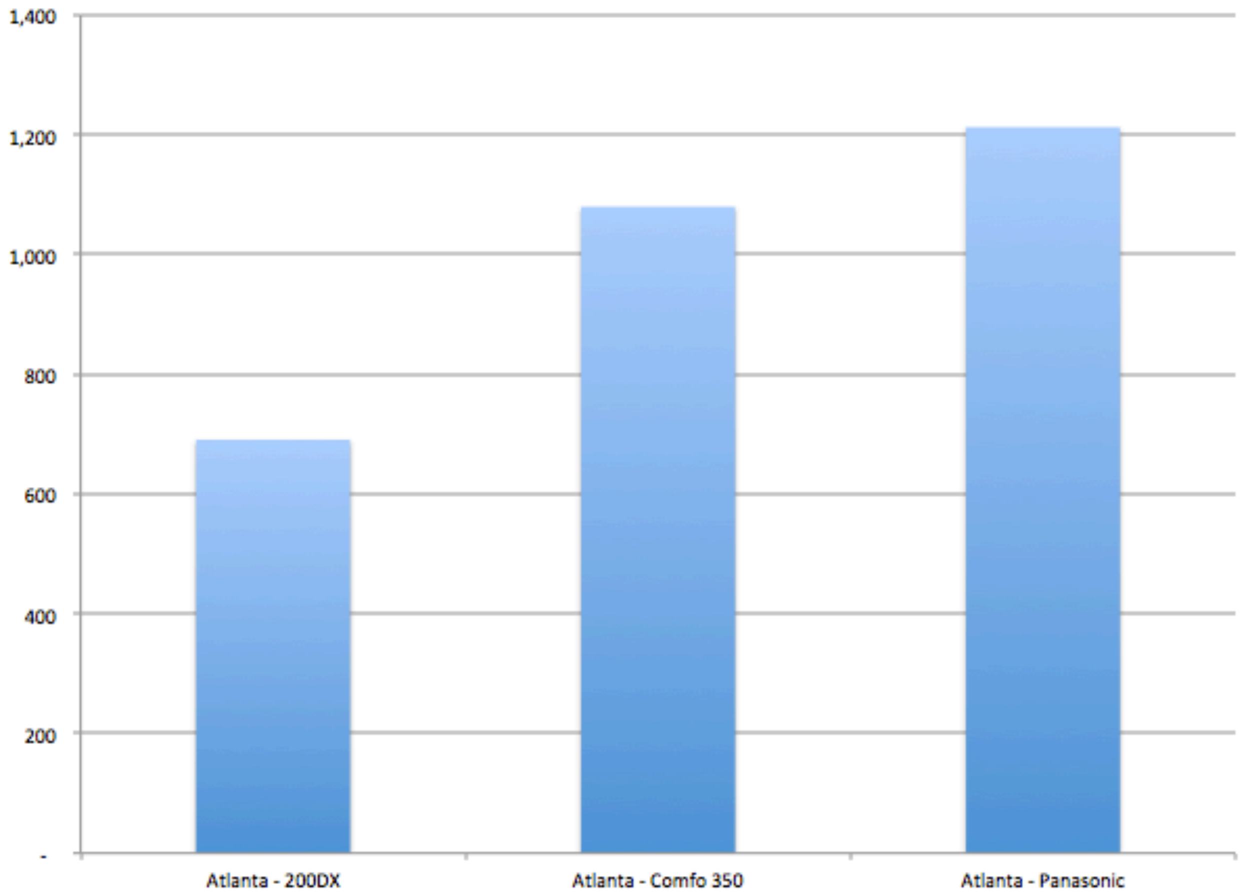

Figure 3
Total site energy use - heating, defrost, latent cooling + fan energy
(kWh/year)

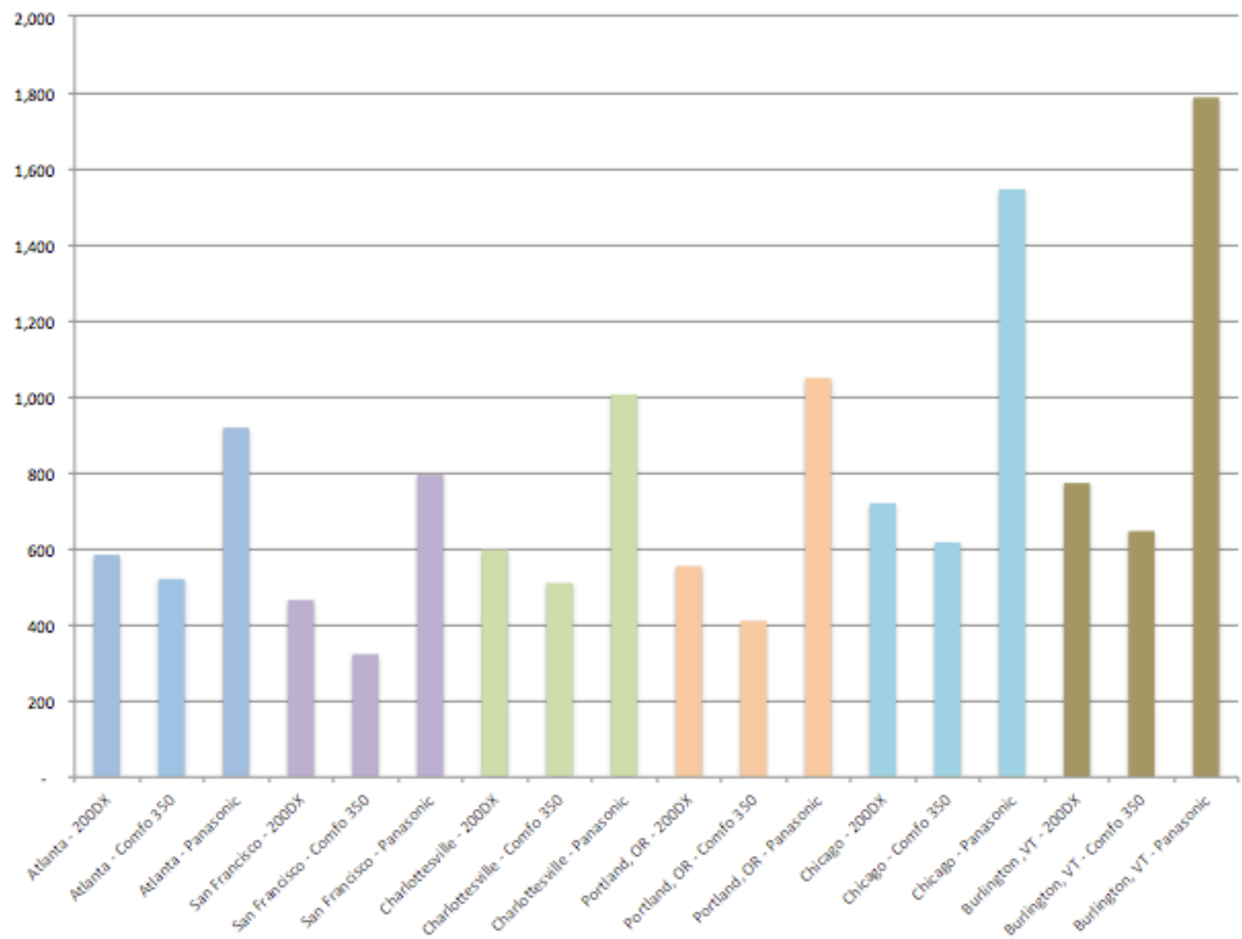

Figure 4
Cost Effectiveness: Incremental upfront cost / lifetime kWh savings
($/kWh - lower is better)

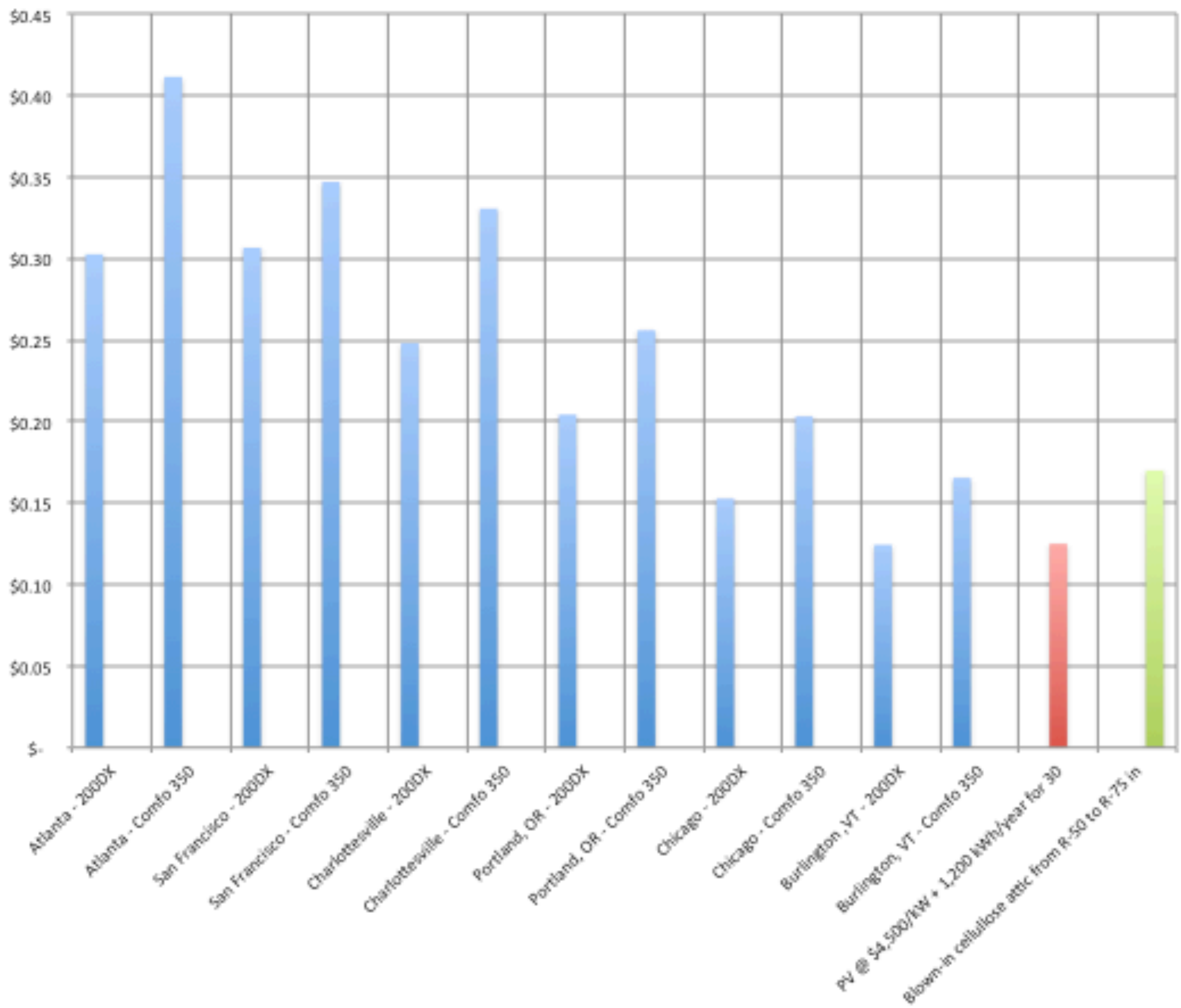

Table 1									
	Installed cost	Lifespan	Ventilation + Infiltration Annual Heat demand (kWh/year)	Ventilation + Infiltration Annual Latent Cooling demand (kWh/year)	Aux energy use - "fan energy" (kWh/year)	Defrost energy use (kWh/year)	Total site energy (kWh/year)	Lifetime site energy savings over baseline exhaust strategy (kWh)	Incremental installed cost / lifetime site energy savings ($/kWh)
Atlanta - 200DX	**$ 4,125**	**20**	572	690	283	-	584	6,683	$ 0.30
Atlanta - Comfo 350	**$ 5,375**	**20**	557	1,079	146	-	521	7,953	$ 0.41
Atlanta - Panasonic	**$ 2,102**	**20**	2,133	1,212	67	-	919	-	$ -
San Francisco - 200DX	**$ 4,125**	**20**	638	-	283	-	465	6,595	$ 0.31
San Francisco - Comfo 350	**$ 5,375**	**20**	621	-	146	-	324	9,431	$ 0.35
San Francisco - Panasonic	**$ 2,102**	**20**	2,549	-	67	-	795	-	$ -
Charlottesville - 200DX	**$ 4,125**	**20**	716	476	283	-	598	8,150	$ 0.25
Charlottesville - Comfo 350	**$ 5,375**	**20**	697	753	146	-	511	9,897	$ 0.33
Charlottesville - Panasonic	**$ 2,102**	**20**	2,502	847	67	-	1,006	-	$ -
Portland, OR - 200DX	**$ 4,125**	**20**	883	-	283	-	555	9,904	$ 0.20
Portland, OR - Comfo 350	**$ 5,375**	**20**	860	-	146	-	411	12,786	$ 0.26
Portland, OR - Panasonic	**$ 2,102**	**20**	3,196	-	67	-	1,050	-	$ -
Chicago - 200DX	**$ 4,625**	**20**	1,175	217	283	2	720	16,516	$ 0.15
Chicago - Comfo 350	**$ 5,875**	**20**	1,145	359	146	18	617	18,574	$ 0.20
Chicago - Panasonic	**$ 2,102**	**20**	4,194	407	67	-	1,546	-	$ -
Burlington ,VT - 200DX	**$ 4,625**	**20**	1,329	25	283	2	773	20,279	$ 0.12
Burlington, VT - Comfo 350	**$ 5,875**	**20**	1,294	62	146	18	647	22,806	$ 0.17
Burlington, VT - Panasonic	**$ 2,102**	**20**	4,691	74	67	-	1,787	-	$ -
PV @ $4,500/kW + 1,200 kWh/year for 30 years (does <u>not</u> include federal, state or local incentives)									$ 0.13
Blown-in cellulose attic from R-50 to R-75 in Charlottesville, VA over 50 years									$ 0.17

Tabel 2	
	Ultimate Air 200DX
ERV unit (direct from manufacturer) +	$ 1,500
Ductwork, fitting & registers	$ 500
Labor	$ 640
HVAC contractor markup (25%)	$ 660
General contractor markup (25%)	$ 825
TOTAL	**$ 4,125**
	Zehnder
HRV unit (direct from manufacturer) -	$ 2,300
Ductwork, fitting & registers	$ 500
Labor	$ 640
HVAC contractor markup (25%)	$ 860
General contractor markup (25%)	$ 1,075
TOTAL	**$ 5,375**
	Panasonic
Panasonic exhaust fans (x3)	$ 465
Kitchen exhaust fan	$ 200
Passive air inlets	$ 160
Ductwork + fittings	$ 200
Labor	$ 320
HVAC contractor markup (25%)	$ 336
General contractor markup (25%)	$ 420
TOTAL	**$ 2,102**

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