ACHIEVING ENERGY SAVINGS BY IMPROVING FAN AND DUCTWORK PERFORMANCE

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EXECUTIVE SUMMARY

The amount of energy used to move air in buildings ranges between 5% and 10% of total building energy in a typical office building and can approach 30% in a building with extensive filtration in a hot climate. This substantial contribution means air flow energy is a target for not only saving operating costs but also contributing to the achievement of mandatory energy savings targets. Improvements to various contributors to airflow energy were simulated in an energy model in order to evaluate their cost effectiveness. The results were grouped into three tiers in order of decreasing cost effectiveness.

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1. BACKGROUND

The amount of energy used to move air in buildings ranges between 5% and 10% of total building energy in a typical office building and can approach 30% in a building with extensive filtration in a hot climate. This substantial contribution means air flow energy is a target for not only saving operating costs but also contributing to the achievement of mandatory energy savings targets. Some factors that contribute to total fan energy include:

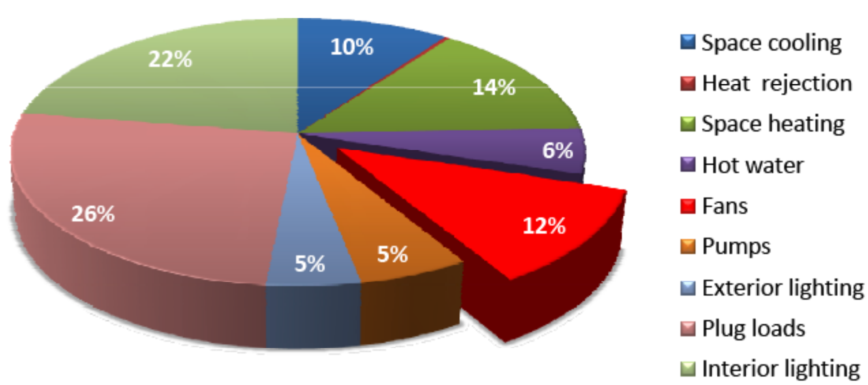
- fan efficiency
- motor efficiency
- belt losses from the fan-motor coupling
- pressure drop associated with air-handling-unit coils and filters
- pressure loss from air-handler casing leakage
- fan control
- pressure drop through ductwork

All federal projects have explicit energy savings targets, whether by requiring achievement of some level of LEED certification or by adhering to the Energy Policy Act (EPACT) of 2005. A part of achieving LEED certification is demonstrating energy cost savings of the design relative to a baseline building defined by ASHRAE 90.1-2007. The minimum building energy cost savings allowed is 10%, with a point toward certification awarded for every additional 2%, peaking at a total of 48% for new buildings. The baseline standard is revised to ASHRAE 90.1-2010 with LEED v4. Since ASHRAE 90.1-2010 is more stringent than the 2007 version, the minimum building energy cost savings allowed by LEED v4 is reduced to 5%.

EPACT resulted in the 10 CFR 433 rule, which applies to federal buildings whether LEED is invoked or not. 10 CFR 433 requires demonstrating 30% building energy savings, excluding process loads, relative to a baseline building defined by ASHRAE 90.1-

// Fan and air handling units

Images courtesy of Buffalo Air Handling



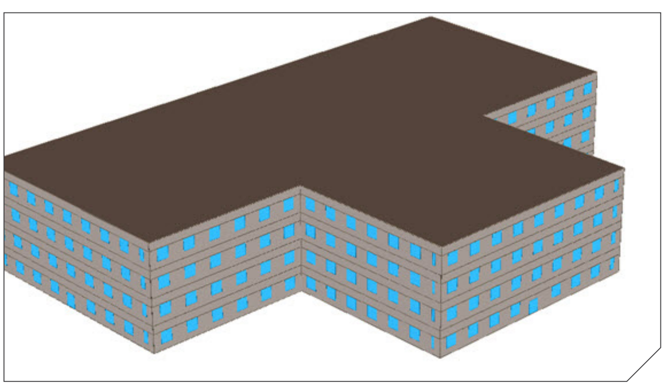
// Figure 1 - Typical proportion of building energy used by fans

2007. In mid-2014, the applicable version changed to ASHRAE 90.1-2010.

For non-federal projects, state or local requirements typically invoke the International Energy Conservation Code (IECC), which is generally similar to and allows compliance with some version of ASHRAE 90.1 as a way to meet the code.

2. PURPOSE & METHOD

In order to assess the relative effect of fan-energy improvements on energy consumption, an ASHRAE 90.1-2010-compliant baseline energy model was created. The energy model consists of a four-story, 175,000 square foot office building served by one variable-air-volume (VAV) air-handling system per floor. Each air handler contains a 40 hp motor with a presumed wheel diameter of 36.5". An external static pressure of 3" water gauge (w.g.) plus an internal air-handler static pressure loss of 3" w.g. is assumed for a total static pressure of 6" w.g. Chilled water is supplied by two water-cooled chillers and heating hot water is provided by two gas-fired boilers. Single-duct VAV boxes with hot-water reheat coils are used. Fans run during the workday and are off at night except to cycle as required to maintain setback and setup temperature set points. Alternate energy models were copied from this baseline so that one fan-energy-influencing factor could be changed at a time. Additional models were created where groups of factors were combined. Richmond, Virginia's climate was selected for the simulation because of its balance between hot, humid weather and cold weather. Richmond, Virginia is in ASHRAE climate zone 4A.



// Figure 2 - Isometric View of Modeled Building

3. ENERGY CONSERVATION MEASURES

In each of the following sections, background information about the various contributors to total fan energy is presented along with a discussion of how each contributor is modeled. Interspersed among the discussions are tables showing the results of how improvements to each contributor were modeled and an assessment of how long those improvements may take to return the required investment.

3.1 Fans

Until recently, codes such as ASHRAE 90.1 have not contained requirements that directly incentivized the selection or manufacture of more aerodynamically efficient fans[1]. ASHRAE fan power rules tend to be directed at improvements in air distribution systems. In 2010, the Air Movement and Control Association (AMCA) published standard 205, which defines a metric called Fan Efficiency Grade (FEG). This metric assigns a grade to a fan's aerodynamic efficiency based on fan size. FEG takes into consideration the fact that smaller fans are not as capable as larger fans of reaching high efficiency levels. As shown in Figure 3 below, a small fan with an efficiency of 55% can achieve the same FEG 75 rating as a larger fan that would require an efficiency of 72% to achieve FEG 75.

ASHRAE 90.1-2013 contains new requirements for fan efficiency that were first implemented in Addendum U to ASHRAE 90.1-2010: fans greater than 5 hp must achieve an FEG of 67 and be selected within 15% of the peak total efficiency shown on the fan's selection curve. The International Green Conservation Code (IGCC) has adopted AMCA 205 for fans greater than 1hp in buildings less than 25,000 square feet, requiring an FEG of 71 and selection of fans within 10% of the peak total efficiency. These criteria suggest that fans with an FEG of less than 67 are more or less average with respect to current energy standards, and that fans with an FEG above 71 are exceptional. An FEG of 67 was chosen for this simulation's baseline model.

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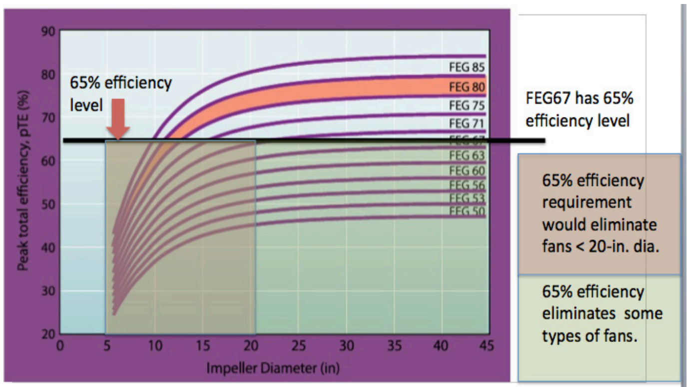
[1] ASHRAE Journal, "Fan Efficiency Requirements for Standard 90.1-2013", Cermak & Ivanovich, April 2013



// Figure 3 - Fan Efficiency Grade [2]

3.2 Motors

Electric motor efficiency requirements are contained in ASHRAE 90.1-2010, section 10. This section requires new, general purpose motors to meet efficiencies equivalent to the National Electrical Manufacturer's Association (NEMA) "Premium" rating [3]. This is an increase relative to ASHRAE 90.1-2007, which required general purpose motors to meet efficiencies equivalent to the NEMA "Efficient" rating. As an example, a 40 hp air-handling-unit motor that would have needed to be 93% efficient under ASHRAE 90.1-2007 will now need to be 94.1% efficient in most cases.

The baseline model's fan power was calculated in accordance with ASHRAE 90.1-2010. The resulting power is presented in terms of kW/cfm. Assuming 6" w.g. of total fan static pressure, total fan and motor efficiency were incorporated into the energy model so that the model's fan power was equal to the ASHRAE calculation. With a 94.1% efficient motor and a 3% belt-drive loss incorporated, an FEG 71 fan with an efficiency of 69% was required to make the baseline energy model's fan power equal to the ASHRAE 90.1-2010 calculated fan power.

3.3 Drives

As indicated above, the baseline model assumes the fan and motor are linked by belts. Also assumed is the presence of a variable frequency drive (VFD) to modulate air handler flow. A literature review reveals that belt losses for fans vary widely based on belt type, tension, and alignment, with the average hovering around 5% [4,5]. Losses for VFDs are typically between 3% and 5%[Ibid]. For the purposes of this study, VFD losses are ignored since the direct-drive alternative would also include a VFD.

For belt losses, the baseline model includes a 3% loss applied to the combined motor and fan efficiency. While this is less than the average, it is conservative. Furthermore, since there is no cost premium to implement direct drive, and fewer maintenance costs over the life of the fan, presuming a low 3% loss is of no consequence - the payback is immediate.

3.4 Simulation Results for Fan, Motor, and Drive Modifications

Table 1 illustrates the effects of various fan and motor improvements on energy and the expected simple payback period for each.

The best option from this group is to eliminate belt drive losses because it provides an immediate payback. Improving fan efficiency is also quite attractive. The payback period for improving motor efficiency may exceed the payback threshold for many.

3.5 Air Handling Unit Casing Size

Air handling units can be specified with larger casing sizes, permitting the use of larger areas and lower face velocities for coil and filter sections, reducing pressure drop. Individual improvements to coil and filter pressure drops resulting from casing-size increases are typically small, but the sum of the improvements can be significant. The baseline model assumes a total fan static pressure of 6" w.g. Increases to casing size resulting in lower pressure drops were simply modeled by reducing the total fan static pressure in the energy model. In this case, the criterion was a 0.5" w.g. total reduction in pressure drop for the entire unit which was achieved by increasing casing size by one.

While casing size affects filter size, there is one possible qualitative change to filtration that bears further investigation. For a given filtration efficacy, dynamic filters can not only reduce pressure drop but also greatly increase

[2] Air Movement and Control Association International, Inc., *Learn about Fan Efficiency Grades in AMCA Standard 205, http://www.amca.org/feg/amca205.aspx*

[3] ANSI/NEMA MG-1-2003, Revision 1-2004, *Motors and Generators*, December 17, 2003

[4] Greenheck, *AMCA's Fan Efficiency Grades: Answers to Frequently Asked Questions*, Mathson & Ivanovich, Fall 2011

[5] Carlisle Power Transmission Products, Inc., *Energy Loss and Efficiency of Power Transmission Belts*, Belt Technical Center, Springfield, Missouri

Fan & Motor Improvements					
	Baseline	Improve Fan Efficiency Grade	Eliminate Drive Loss	Incorporate More Efficient Motor	Combine all three improvements
Fan efficiency grade (FEG):	71	80	71	71	80
Fan efficiency based on wheel size and FEG:	**69%**	77%	**69%**	**69%**	77%
Relative drive loss:	3%	3%	0%	3%	0%
Motor efficiency:	**94.1%**	**94.1%**	**94.1%**	94.5%	94.5%
Fan & motor total efficiency:	63.0%	70.3%	64.9%	63.2%	72.8%
Supply-fan total static pressure (inches):	6	6	6	6	6
Case leakage:	**1.5%**	**1.5%**	**1.5%**	**1.5%**	**1.5%**
Fan VFD Curve - static pressure reset	No reset	No reset	No reset	No reset	No reset
Building energy use (elec MWh):	2016	1984	1999	2006	1975
Building energy use (gas MBtu):	**1761**	**1764**	**1762**	**1762**	**1765**
Building EUI (kBtu/sf-yr):	49.4	48.8	49.0	49.2	48.6
Building energy cost:	**$180,691**	**$178,177**	**$179,315**	**$179,912**	**$177,432**
Building electricity cost	$157,976	$155,420	$156,581	$157,185	$154,666
Blended electric rate per kWh:	**$0.078**	**$0.078**	**$0.078**	**$0.078**	**$0.078**
Fan energy use (elec MWh):	**259.1**	**231.3**	**243.4**	**249.8**	**223.4**
Fan energy cost:	$20,225	$18,119	$19,085	$19,574	$17,495
Building energy savings:		**1.2%**	**0.7%**	**0.4%**	**1.8%**
Building energy cost savings:		$2,514	$1,376	$779	$3,259
Building energy cost savings:		**1.4%**	**0.8%**	**0.4%**	**1.8%**
Fan energy cost savings:		$2,106	$1,160	$651	$2,730
Fan energy cost savings:		**10.4%**	**5.7%**	**3.2%**	**13.5%**
Cost to implement:		$20,000	$0	$16,000	$36,000*
Simple payback (years):		**8**	**0**	**21**	**9***

*see LCC analysis

// Table 1 - Results for Fan, Motor, and Drive Modifications

the amount of time between required replacement. In addition, because of their effectiveness dynamic filters may offer the opportunity to reduce outside-air requirements in accordance with the Indoor Air Quality criteria of ASHRAE 62.1. These were not evaluated for this white paper, but do warrant further study.

3.6 Air Handling Unit Casing Construction

Air handling units specified with standard casings may guarantee less than 5% leakage at design conditions. In practice, the actual leakage from a standard casing is substantially less than this, perhaps as low as 2%. Specifying a premium casing may improve the guarantee to a leakage rate of less than 0.5%. To assess the effect of switching from standard to premium casing, a duct loss of 1.5% incorporated into the baseline energy model was removed in a subsequent model.

3.7 Duct Static Pressure Reset

Wherever VAV boxes can be polled and their damper positions or flows reported to the building's control system, there is a potential for saving energy by reducing the fan's static pressure set point when none of a given system's VAV dampers are in the fully open position. Sample VAV fan part-load curves which simulate varying levels of static-pressure reset were generated by Pacific Gas & Electric Company in a study [6]. These were used in the models to simulate this feature. The baseline model assumes no reset.

3.8 Simulation Results for Coil, Casing, and Control Modifications

Table 2 illustrates the effects of these AHU and control improvements on energy and the expected simple payback for each.

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[6] Pacific Gas & Electric, Energy Design Resources, *Advanced Variable Air Volume VAV System Design Guide*, December 2009

With its low relative cost and large reduction in energy cost, implementation of duct static pressure reset is the best choice in this group. Specifying a premium casing in order to reduce casing leakage does not appear to be worthwhile, in large part because of the typically better-than-specified performance of standard casings. This analysis does not address the improved thermal performance of premium casings, however. Increasing casing size to reduce pressure drop may be attractive depending on the payback threshold. The 23 years shown in Table 2 is longer than most are willing to accept. Nonetheless, there are often many different coil and filter selections possible for a given casing size, so it is probably worthwhile to assess this on a case-by-case basis.

3.9 Ductwork

A typical standard for sizing ductwork is to design to a pressure drop of 0.3” w.g. per 100 linear feet. Improving upon this requires a combination of larger ductwork and smoother fittings, which should in turn result in fan energy savings. In order to assess the effect of improving upon this standard, a primary duct system sized using 0.3” w.g. per 100 linear feet was laid out over the baseline model’s footprint as shown in Figure 4. A second layout was generated using 0.2” w.g. per 100 linear feet.

For each layout, pressure drop calculations were performed to determine the change in static pressure. In this case, the static pressure of the duct sized to 0.2” w.g. per 100 linear feet was 0.26” w.g. lower than for the baseline case. This change was applied to the energy model as a 0.26” w.g. reduction in fan static pressure. The increase in total cost (material and labor) for the revised, larger primary ductwork was 16%.

Pressure Drop Improvements					
	Baseline	Increase casing size to reduce coil and filter pressure drop	Reduce casing leakage	Employ duct static pressure reset down to 0.7" w.g.	Combine first two improvements with reset down to 0.7" w.g.
Fan efficiency grade (FEG):	**71**	**71**	**71**	**71**	**71**
Fan efficiency based on wheel size and FEG:	69%	69%	69%	69%	69%
Relative drive loss:	3%	3%	3%	3%	3%
Motor efficiency:	**94.1%**	**94.1%**	**94.1%**	**94.1%**	**94.1%**
Fan & motor total efficiency:	63.0%	63.0%	63.0%	63.0%	63.0%
Supply-fan total static pressure (inches):	6	5.5	6	6	5.5
Case leakage:	**1.0%**	**1.0%**	**0.0%**	**1.0%**	**0.0%**
Fan VFD Curve - static pressure reset	No reset	No reset	No reset	Reset to 0.7"	Reset to 0.7"
Building energy use (elec MWh):	2016	1994	2012	1968	1946
Building energy use (gas MBtu):	**1781**	**1763**	**1725**	**1707**	**1732**
Building EUI (kBtu/sf-yr):	49.4	49.0	49.1	48.5	47.8
Building energy cost:	**$180,691**	**$178,943**	**$179,873**	**$177,461**	**$175,187**
Building electricity cost:	$157,976	$156,203	$157,624	$154,669	$152,843
Blended electric rate per kWh:	**$0.078**	**$0.078**	**$0.078**	**$0.079**	**$0.079**
Fan energy use (elec MWh):	**259.1**	**239.8**	**255.7**	**217.1**	**198.6**
Fan energy cost:	$20,225	$18,769	$20,032	$17,062	$15,693
Building energy savings:		**0.9%**	**0.5%**	**1.6%**	**3.1%**
Building energy cost savings:		$1,748	$818	$3,230	$5,504
Building energy cost savings:		**1.0%**	**0.5%**	**1.8%**	**3.0%**
Fan energy cost savings:		$1,456	$193	$3,163	$4,532
Fan energy cost savings:		**7.2%**	**1.0%**	**15.6%**	**22.4%**
Cost to implement:		$40,000	$52,000	$8,000	$100,000
Single payback (years):		**23**	**64**	**2**	**18**

// Table 2 - Results for Pressure Drop Improvements

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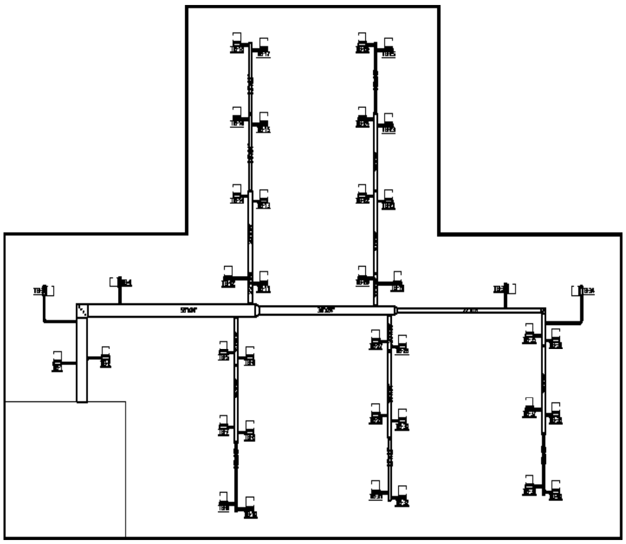
3.10 Simulation Result for Ductwork Improvement

Table 3 illustrates the effect of the ductwork improvement on energy and the expected simple payback.

The 33% improvement in sizing criteria for ductwork does not result in substantial savings relative to the cost. Furthermore, the payback analysis in Table 3 does not take into consideration the increase in building cost as a result of having to provide more space for the larger ductwork.



// Figure 4 - Test Duct Layout

Duct Improvement		
	Baseline - Duct @ 0.3"w.g. per 100 lf	Duct @ 0.2"w.g. per 100 lf
Fan efficiency grade (FEG):	**71**	**71**
Fan efficiency based on wheel size and FEG:	69%	69%
Relative drive loss:	3%	3%
Motor efficiency:	**94.1%**	**94.1%**
Fan & motor total efficiency:	63.0%	63.0%
Supply-fan total static pressure (inches):	6	5.74
Case leakage:	**1.5%**	**1.5%**
Fan VFD Curve - static pressure reset	No reset	No reset
Building energy use (elec MWh):	2016	2005
Building energy use (gas MBtu):	**1761**	**1762**
Building EUI (kBtu/sf-yr):	49.4	49.2
Building energy cost:	**$180,691**	**$179,782**
Building electricity cost:	$157,976	$157,053
Blended electric rate per kWh:	**$0.078**	**$0.078**
Fan energy use (elec MWh):	**258.1**	**248.5**
Fan energy cost:	$20,225	$19,465
Building energy savings:		**0.4%**
Building energy cost savings:		$909
Building energy cost savings:		**0.5%**
Fan energy cost savings:		$760
Fan energy cost savings:		**3.7%**
Cost to implement:		$32,000
Simple payback (years):		**35**

// Table 3 - Result for Ductwork Improvement

4. PUTTING IMPROVEMENTS TOGETHER: DOES IT PAY OFF?

Two different groups of improvements were assembled to assess payback period.

The first group consisted of those items that by themselves would pay back in less than 20 years. There were three such measures: improving fan efficiency, replacing belt drive with direct drive, and incorporating duct static pressure reset. These measures result in a whole-building energy cost savings of over 3% and a fan-energy cost savings of over 26% with a simple payback period of 4 years.

The second group consisted of the three preceding improvements, and added improving motor efficiency, reducing coil pressure drop, reducing casing leakage, and improving the duct-sizing criterion. These measures result in a whole-building energy cost savings of nearly 5% and a fan-energy cost savings of over 35% with a simple payback period of 18 years. Actual payback period presuming 3% inflation and an energy cost escalation of 5% per year is closer to 15 years.

Both groupings are shown in Table 4.

5. CONCLUSION: PICK WISELY

Features and improvements can rapidly increase the cost of an air-handling unit. Improvements aimed at reducing air flow energy have been grouped into three tiers of decreasing cost-effectiveness:

<u>Tier 1</u> changes are those which are likely to be cost effective in any situation. These include improving fan efficiency and eliminating belt drive, along with incorporating static pressure reset controls. Based on this exercise it is easy to see why the Fan Efficiency Grade (FEG) metric was created and why it is now being included in various standards. Improvements in this area are high-value, high-return items.

Tier 2 includes changes that are effective but which may have longer payback periods than many would deem acceptable. Improving motor efficiency by 0.4% and enlarging the air-handling-unit casing to reduce the unit's pressure drop by 8%, while providing decent fan energy savings, have payback periods which exceed 20 years. More aggressive improvements in these areas, or situations in which utility rates are higher, may provide better payback periods. Furthermore, when increasing casing size there are often many different coil and filter possibilities, so it would be beneficial to assess this on a case-by-case basis.

Tier 3 changes are those improvements that are least cost-effective and which might be pursued only in the most aggressive pursuit of energy savings. Spending extra money for a premium air-handler casing to achieve fan energy savings does not seem to be worthwhile based on the results of this analysis, although there are thermal benefits to this improvement that may warrant further study. Using a 33% more generous duct sizing criteria also appears not to be worthwhile in our model; the 0.26" w.g. reduction in pressure drop does not sufficiently influence the assumed 6" static pressure of the supply fan. In cases where total fan static pressure is less than the 6" w.g. assumed for this analysis, the result may be more favorable.

Strategy Combinations

	Baseline	All improvements with < 20 year payback	All improvements
Fan efficiency grade (FEG):	71	80	80
Fan efficiency based on wheel size and FEG:	69%	77%	77%
Relative drive loss:	3%	0%	0%
Motor efficiency:	94.1%	94.1%	94.5%
Fan & motor total efficiency:	63.0%	72.5%	72.8%
Supply-fan total static pressure (inches):	6	6	5.24
Case leakage:	1.5%	1.5%	0.0%
Fan VFD Curve - static pressure reset	No reset	Reset to 0.7"	Reset to 0.7"
Building energy use (elec MWh):	2016	1934	1905
Building energy use (gas MBtu):	1761	1770	1737
Building EUI (kBtu/sf-yr):	49.4	47.8	47.1
Building energy cost:	$180,691	$174,727	$171,918
Building electricity cost:	$157,976	$151,893	$149,516
Blended electric rate per kWh:	$0.078	$0.079	$0.078
Fan energy use (elec MWh):	258.1	188.6	166
Fan energy cost:	$20,225	$14,812	$13,029
Building energy savings:		3.1%	4.7%
Building energy cost savings:		$5,964	$8,773
Building energy cost savings:		3.3%	4.9%
Fan energy cost savings:		$5,413	$7,196
Fan energy cost savings:		26.9%	35.7%
Cost to implement:		$28,000*	$168,000*
Simple payback (years):		4*	18*

*see LCC analysis

// Table 4 - Results of Combinations

Tier 1 Improvements:

Improve fan efficiency
Eliminate belt drive
Incorporate static pressure reset

Tier 2 Improvements:

Improve motor efficiency
Increase air-handler casing size

Tier 3 Improvements:

Upgrade to premium air-handler casing
Oversize ductwork

ABOUT THE AUTHOR

Evan Riley, P.E. is a senior energy engineer for the Building Sciences Studio at Mason & Hanger in Glen Allen, Virginia. He has 13 years of experience in the design and analysis of heating, ventilating, and air conditioning systems, including performing comprehensive energy analyses for a diverse array of building types and commissioning of power production and space conditioning systems in large data centers. He has an additional six years of experience in the design and analysis of naval nuclear propulsion plants.