Saving Electricity in Commercial Buildings with Adjustable-Speed Drives

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Abstract—**Fan and chiller energy savings achievable in commercial buildings with adjustable-speed drives are described. The savings are estimated with the aid of parametric simulations from a sophisticated, hourly building energy simulation model. Two prototypes—a single-zone retail store and a multizone medium office building—are simulated for five U.S. locations. The model incorporates part-load performance curves for both inlet vane and adjustable-speed drive controls for fans and centrifugal chillers. The results identify economic conditions that justify the added expense of adjustable-speed drives.**

INTRODUCTION

VARIABLE-FLOW devices for formerly constant-flow systems are popular energy-saving measures that have both industrial and commercial building applications. Commonly, flows are modulated by inlet vanes, discharge dampers, or other throttling techniques. Less well understood in commercial building applications are the additional electricity savings available through the use of the adjustable-speed drives (ASD).

Industry has begun to employ ASDs with great success [1], [2]. Simple inspection of the idealized operating characteristics of ASD versus inlet vane control illustrates the potential for savings. Fig. 1, for example, compares the part-load performance of inlet vane and ASD fan controls. The actual savings are defined by the length of operation at each part-load condition. For many industrial processes these conditions are regularly monitored and evaluation is straightforward.

Evaluating the potential for ASD savings in commercial building applications is complicated by the diverse building and heating, ventilating, and air-conditioning (HVAC) system types in the sector as well as climatic variations. Existing work tends to take the form of case studies, from which it can be difficult to generalize [3]; or, at the other end of the spectrum, cases in which completely hypothetical load conditions are assumed [4]; and the reader is left to judge the degree to which these assumptions are realistic.

This paper evaluates the energy savings achievable with ASDs in commercial building fans and chillers versus inlet vanes. We use parametric computer simulations of energy use for two prototypical commercial buildings located in five diverse U.S. climates. Although the evaluation is generalized in nature, the modeling procedures described can be used to study specific applications.

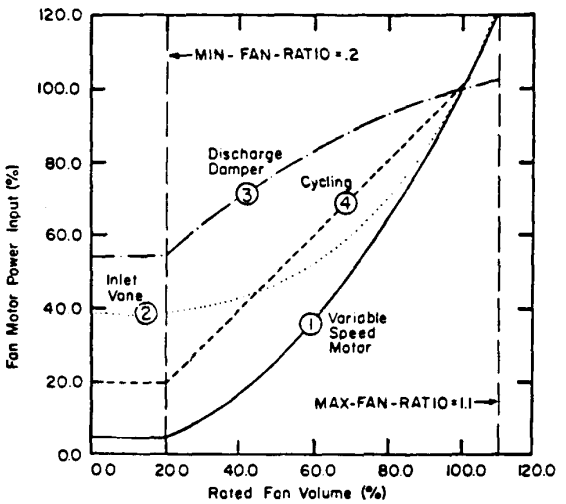

Fig. 1. Part-load performance for several variable air flow techniques. (Source: *DOE-2 Reference Manual* [12].)

In the next section we describe the commercial building prototypes used in the evaluation. This discussion is followed by brief reviews of the climates used and of the building energy simulation model. The final section describes our results. The results include comments on the energy and peak demand savings from ASDs as well as the economic value of these savings relative to increased first cost. We use several sets of economic assumptions in an effort to generalize our results.

COMMERCIAL BUILDING PROTOTYPES

We used two commercial building prototypes in our evaluation. The prototypes are designed to be broadly representative of the existing stock of commercial buildings. For a specific evaluation of a particular building, actual building specifications would, of course, be used. Nevertheless, the general method of analysis to be described would remain unchanged. Table I summarizes major features of both prototypes.

The first prototype is a set of two single-zone retail stores in a strip store complex. The stores are based on an actual structure but have been modified to comply with ASHRAE Standard 90-1975 [6]. The HVAC equipment for the stores is a

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TABLE I
SUMMARY OF COMMERCIAL BUILDING PROTOTYPES

	Strip Store	Medium Office
Size	11,760 sq.ft.	48,600 sq.ft.
Shape	Two units (edge and adjacent unit), single story (18 ft),	3 floors, rectangular in cross section, approximately 16,000 sq.ft./floor.
Construction	Wood-frame construction.	Steel frame superstructure, exterior walls of 4" pre-cast concrete panels
Glazing	35% of wall area on southern and western exposures, no glass on northern and eastern exposures.	36% of wall area, evenly distributed.
Operation	10am - 10pm six days per week, reduced schedule of 10am - 8pm on Sundays and holidays.	8am - 6pm weekdays, with some evening work, 30% occupancy on Saturday, Closed Sundays and Holidays
Thermostat Settings	78°F Cooling 72°F Heating (night and weekend setback 62°F)	Identical to strip store
Internal Loads	1.9 W/sq.ft lighting 0.5 W/sq.ft equipment	2.5 W/sq.ft lighting 1.0 W/sq.ft equipment
HVAC	2 packaged rooftop single-zone, variable air volume, direct expansion units. Minimum fan ratio is 0.3.	Dual-duct variable air volume. Minimum fan ratio is 0.2.
Fan Efficiency	0.47 for inlet vane, 0.51 for ASD.	0.51 for inlet vane, 0.55 for ASD.
Economizer	62 F, dry bulb.	Identical to strip store.
Minimum Outside Air	5 cfm/person.	Identical to strip store.
Heating Plant	Electric resistance baseboard.	1 Gas-fired hot water generator (eff. 75%)
Cooling Plant	Reciprocating compressor with air cooled condenser (COP 2.4).	1 hermetic centrifugal chiller and cooling tower. Chiller COP is 4.5 for conventional and 4.3 for ASD control (does not include electricity used for cooling tower and pumping).

conventional variable-air-volume package unit. The schedules are taken from a library of "typical" schedules [7]. They specify 12 h of operation six days per week, and 10 h of operation on Sundays and holidays.

Our evaluation for this prototype consists of two sets of simulations. The first modulates air flow with inlet vanes; the second uses an ASD. Fig. 1 compares the performance of these two techniques for flow modulation. The full-load efficiency of ASDs is higher, in spite of losses in the ASD unit, since they avoid the high static pressure drop associated with inlet vanes. We assumed an overall full-load fan efficiency of 47 percent for inlet vanes and 51 percent for ASD. An ASD for the cooling system was not evaluated for the strip store because the small size of these units rarely warrants the relatively high first cost ($/hp) of ASD controls.

The second prototype is a medium office building. This building, too, is based on an existing structure and has also been modified to comply with ASHRAE Standard 90-1975. The HVAC system for this prototype is a variable-air-volume dual-duct system. The conversion of this kind of system from constant volume to variable air volume has been a very popular retrofit. The building is operated 10 h/day during the week, with limited occupancy on Saturdays, and is closed on Sundays and holidays. Full-load overall fan and motor efficiency was specified to be 51 percent for inlet vane control and 55 percent for ASD. The chiller for this prototype is a hermetic centrifugal chiller and cooling tower. The full-load coefficient of performance (COP) for the chiller alone (not including electricity for operation of the cooling tower and pumps) is set at 4.5 for a conventional chiller and 4.3 for control with an ASD. For chillers, ASD control adds losses that are not compensated for, since ASD control is used in addition to (rather than in place of) inlet vane control. Fig. 2 compares the part-load performance of both a conventional chiller and one controlled with ASDs. On this graph the loads have not been normalized (as in Fig. 1) and clearly illustrate the performance penalty for ASDs at full-load.

The evaluation for the medium office building prototype consists of three simulations. The first controls air volumes with inlet vanes and provides cooling with a conventional chiller. The second uses ASDs to control fan operations. The third combines ASD fan controls with ASD chiller control. This ordering replicates the likely stages for retrofit: first fans, then chillers.

We did not oversize the equipment, in order to ensure that our estimates of the benefits from ASDs would be conservative. For both building prototypes the sizing of fan and chiller is determined by a separate design calculation for each location. In each case the installed size for a fan or chiller is exactly the peak or maximum expected load condition. Real-world sizing practice, by contrast, is based on an assumed oversizing factor of, say, ten percent, for safety and may be increased further by the availability of equipment. For example, a 100-ton design load may become a 110-ton load for safety and then a 125-ton unit since this is the next incremental size chiller available. In these circumstances, equipment will rarely operate at full-load conditions, so the importance of efficient part-load operation is highlighted.

FIVE U.S. CLIMATES

The prototypes were simulated with weather data for five U.S. climates. The climates were chosen to represent a range of combinations for hot and cold, wet and dry U.S. conditions. Briefly, El Paso, TX, represents a hot and dry climate. Lake Charles, LA, represents a hot and humid climate. Madison, WI, represents a climate with mild summers and very cold winters. Seattle, WA, represents a mild climate with wet summers and cold winters. Washington, DC, represents an intermediate climate, with humid summers and mild winters. Table II summarizes heating and cooling degree-days to base 65°F for each location.

We used Weather Year for Energy Calculation (WYEC) weather data tapes to represent each climate in our simulations [8]. These tapes were developed specifically for building energy simulation analyses and include detailed meteorological data such as solar insolation. The tapes were created from many years of historical weather measurements and have been designed to represent long-term averages for each site.

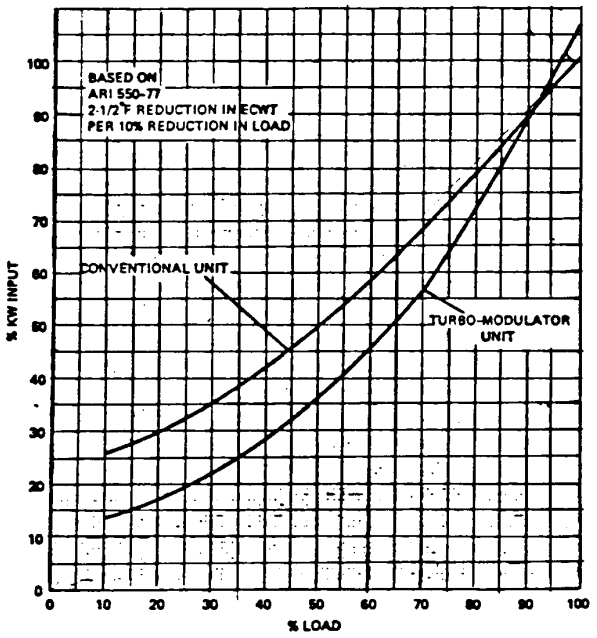

Fig. 2. Part-load performance comparison for ASD versus conventional chiller control. (Source: York International Corp. [13].)

TABLE II
CLIMATE PARAMETERS[a]

Site	Heating Degree-Days	Cooling Degree-Days
El Paso TX	2,689	2,129
Lake Charles LA	1,535	2,696
Madison WI	7,710	447
Seattle WA	5,223	97
Washington DC	4,236	1,425

[a]All degree-days calculated to base 65°F.

Building Energy Simulation Model

We use the DOE-2 building energy analysis program (version DOE-2.1C) to study the additional energy savings from ASDs compared to conventional methods for flow modulation. The DOE-2 program was developed by the Lawrence Berkeley and Los Alamos National Laboratories for the Department of Energy to provide architects and engineers with a state-of-the-art tool for estimating building energy performance [9]. The DOE-2 program has been extensively validated [10].

Three features make DOE-2 particularly applicable to the study of variable-flow devices for commercial buildings.

1) Heating and cooling loads are calculated on an hourly basis.
2) The structure and operation of a building can be entirely specified by user inputs.
3) A special input processor allows for the incorporation of manufacturer's data on equipment performance at part-loads.

Energy Performance

We present the results of our simulations in Tables III and IV for the strip store and medium office building, respectively.

TABLE III
ENERGY RESULTS FOR STRIP STORE

Site	Base Case	ASD Fans (Δ)	ASD Fans (Δ %)
El Paso TX			
Electricity (MWh)	173.4	12.1	7
Fan (MWh)	42.3	11.2	27
Cooling (MWh)	31.1	1.0	3
Peak Demand (kW)	47.5	0.9	2
Lake Charles LA			
Electricity (MWh)	183.2	11.9	7
Fan (MWh)	40.8	10.9	27
Cooling (MWh)	42.5	1.0	2
Peak Demand (kW)	48.2	0.9	2
Madison WI			
Electricity (MWh)	168.8	7.5	4
Fan (MWh)	40.9	7.4	18
Cooling (MWh)	17.1	0.8	4
Peak Demand (kW)	73.5	0.0	0
Seattle WA			
Electricity (MWh)	157.5	8.1	5
Fan (MWh)	43.8	7.3	17
Cooling (MWh)	13.4	0.9	7
Peak Demand (kW)	50.5	0.0	0
Washington DC			
Electricity (MWh)	171.4	9.2	5
Fan (MWh)	44.0	8.6	20
Cooling (MWh)	26.3	0.7	3
Peak Demand (kW)	56.3	0.0	0

TABLE IV
ENERGY RESULTS FOR MEDIUM OFFICE[a]

Site	Base Case	ASD Fans (Δ)	ASD Fans (Δ %)	ASD Fans & Chiller (Δ)	ASD Fans & Chiller (Δ %)
El Paso TX					
Electricity (MWh)	741.2	34.0	5	43.0	6
Fan (MWh)	113.2	29.0	26	29.0	26
Cooling (MWh)	126.7	5.3	4	14.2	11
Peak Demand (kW)	295.5	4.3	1	1.2	0
Natural Gas (MBTU)	358.5	(14.3)	(4)	(14.3)	(4)
Lake Charles LA					
Electricity (MWh)	766.9	34.7	5	47.8	6
Fan (MWh)	110.9	29.7	27	29.7	27
Cooling (MWh)	155.7	5.2	3	18.3	12
Peak Demand(kW)	304.8	6.5	2	2.4	1
Natural Gas (MBTU)	255.4	(10.6)	(4)	(10.6)	(4)
Madison WI					
Electricity (MWh)	686.6	35.0	5	42.1	6
Fan (MWh)	107.7	32.6	30	32.6	30
Cooling (MWh)	74.8	2.6	3	9.7	13
Peak Demand (kW)	296.5	5.6	2	0.2	0
Natural Gas (MBTU)	729.1	(15.0)	(2)	(15.0)	(2)
Seattle WA					
Electricity (MWh)	671.6	33.0	5	41.0	6
Fan (MWh)	109.7	30.2	28	30.2	28
Cooling (MWh)	57.9	3.1	5	11.1	19
Peak Demand (kW)	286.8	5.5	2	0.0	0
Natural Gas (MBTU)	767.2	(20.8)	(3)	(20.8)	(3)
Washington DC					
Electricity (MWh)	723.5	33.7	5	44.4	6
Fan (MWh)	114.0	30.2	27	30.2	27
Cooling (MWh)	106.6	3.5	3	14.1	13
Peak Demand (kW)	296.5	5.6	2	0.2	0
Natural Gas (MBTU)	599.4	(5.2)	(1)	(5.2)	(1)

[a]All savings are calculated relative to the base case.

For both prototypes, electricity consumption by fans is relatively stable across climates and often exceeds electricity consumption by the cooling system. For the base case strip store, fan electricity consumption represents 22 percent (Lake Charles, LA) to 28 percent (Seattle, WA) of annual electricity consumption. Cooling for the base case strip store represents 8 percent (Seattle, WA) to 23 percent (Lake Charles, LA) of annual electricity consumption. For the medium office building the corresponding ranges for the base case are 14 percent (Lake Charles, LA) to 16 percent (Madison WI, Seattle, WA, and Washington, DC) for fans and 9 percent (Seattle, WA) to 20 percent (Lake Charles, LA) for cooling, where cooling includes cooling tower and pump operation in addition to the chiller.

For the strip store the use of ASDs reduces fan electricity consumption by 17–27 percent. The largest savings occur in the warmer climates (El Paso, TX and Lake Charles, LA). These results indicate that these climates require longer hours of fan operation at low load conditions. Since decreased fan losses (higher overall fan efficiencies) lower heat gains to the air flows, small cooling energy savings are also realized. Chiller energy savings range from 2 to 6 percent. Differences in the change in total electricity consumption compared to the change in electricity consumption for cooling and fans combined often exceeds the change in total electricity consumption (see, for example, the results for Madison, WI, on Table III). The difference is additional electric heat required due to the more efficient fans under ASD control. Less efficient fan controls contribute heat to the air, which must be replaced during the heating season when ASD controls are used.

For the medium office building, introduction of ASD fan controls saves relatively more electricity than the strip store but exhibits less variation across climates as internal gains tend to dominate. The range of fan savings is 26–30 percent. No clear pattern emerges linking the level of savings to a given climate. Recall that the range of variation in fan energy consumption in the base case was small. The associated chiller electricity savings are again small but noticeable, ranging from 3 to 5 percent of total cooling electricity consumption. The combination of ASD fan and chiller controls does not alter fan savings but increases cooling electricity savings 11–19 percent. In this case the mildest cooling climate (Seattle, WA) produces the largest percentage savings. Again, additional heat is required during the heating season to compensate for the more efficient ASD controls versus inlet vanes for fans. In this case the additional heat is generated from natural gas.

Our simulations for both the strip store and medium office indicate small reductions in peak demands for ASDs for fan control because of higher full-load efficiencies relative to the base case. For the medium office these savings are offset by the lower full-load efficiency of ASD controls for the chiller. Variable-flow controls (inlet vane and ASDs) do not, as a rule, reduce peak electrical demands since the benefits stem from greater overall efficiencies at part-load conditions.

In closing we reiterate the significance of our conservative equipment-sizing assumption. This conservative assumption tends to result in understated savings for ASDs. We would expect even greater savings from an analysis that more closely followed conventional sizing practices.

Economic Analysis

The electricity savings from adjustable-speed drives are only valuable if these savings meet or exceed the additional cost of the drives. Our analysis uses payback time as a simple figure of merit for making comparisons. As a rule of thumb, paybacks of less than three years indicate a good investment opportunity, independent of such important considerations such as the time value of money and taxes.

Tables V, VI, and VII summarize the results of our payback analyses. Payback times have been calculated assuming a low and high electricity price ($0.07 and 0.10 per kWh) and, for the medium office, a constant natural gas price ($3.50/MBtu). Similarly, the cost of ASDs has been estimated in the form of ranges. Based on informal surveys of manufacturer's literature (summarized in [11]), we assumed a low cost of $150/hp, and a high cost of $300/hp. These costs are intended to reflect the full installed cost of an ASD, which include labor and, in the case of retrofit, the salvage value of a conventional motor starter. Of course these are only estimates; actual costs and energy prices may vary considerably. A well-known cause for such variation is the added costs that may be required to mitigate harmonic problems induced by the ASD controls. Generally speaking, higher cost estimates can also be anticipated for the more sophisticated variable-frequency controls required for ASD chiller control. Our sole intent is to present results for a likely range of these uncertainties in order to identify the boundary of favorable economic conditions.

The results for the strip store indicate that ASDs are generally cost effective for either electricity price, with the low ASD cost (see Table V). With the high ASD cost, the investment is marginal though still somewhat attractive. Payback times are around five years with the high electricity price.

The results for ASD fan control in the medium office building are also encouraging (see Table VI). Again the investment is generally acceptable with the low ASD cost but is not acceptable with the high ASD cost. ASD controls for both the fan and chiller in the medium office building are much less cost effective (see Table VII). None of the sets of economic conditions evaluated yield paybacks of less than five years for this combination.

ASD fan controls are more cost effective than ASD chiller controls because fans operate all year while the majority of chiller operation is concentrated in the summer. In general, longer hours of operation would make the investments more attractive for both prototypes. We would expect, for example, that ASD chiller controls would be much more cost effective for applications which operate 24 h/day. In this case, nighttime operation under usually relatively low load conditions would enhance savings greatly.

Conclusion

We have completed a set of parametric computer simulations to evaluate the cost effectiveness of ASD controls for commercial building fans and chillers. The evaluations exam-

TABLE V
PAYBACK ANALYSIS FOR STRIP STORE—ASD FANS

Equipment Cost ($/horsepower)	150		300	
Electricity Price ($/kWh)	0.07	0.10	0.07	0.10
El Paso TX	2.9	2.0	5.7	4.0
Lake Charles LA	2.8	2.0	5.6	3.9
Madison WI	3.8	2.7	7.6	5.3
Seattle WA	3.6	2.5	7.3	5.1
Washington DC	3.5	2.4	7.0	4.9

TABLE VI
PAYBACK ANALYSIS FOR MEDIUM OFFICE—ASD FANS[a]

Equipment Cost ($/horsepower)	150		300	
Electricity Price ($/kWh)	0.07	0.10	0.07	0.10
El Paso TX	4.2	2.9	8.4	5.8
Lake Charles LA	4.0	2.8	8.1	5.6
Madison WI	3.9	2.7	7.8	5.4
Seattle WA	4.4	3.1	8.8	6.1
Washington DC	4.3	3.0	8.6	6.0

[a]Natural gas price is $3.5/MBtu.

TABLE VII
PAYBACK ANALYSIS FOR MEDIUM OFFICE—ASD FANS AND CHILLERS[a]

Equipment Cost ($/horsepower)	150		300	
Electricity Price ($/kWh)	0.07	0.10	0.07	0.10
El Paso TX	8.3	5.8	16.6	11.6
Lake Charles LA	7.7	5.4	15.4	10.7
Madison WI	8.6	6.0	17.1	11.9
Seattle WA	8.7	6.0	17.4	12.1
Washington DC	8.7	6.0	17.3	12.1

[a]Natural gas price is $3.5/MBtu.

ined the additional electricity savings of ASDs compared to conventional flow modulation (inlet vanes) for two prototypical commercial buildings in five U.S. climates. ASD controls for fans were found to be generally cost effective for the low set of ASD costs and either set of electricity prices evaluated. ASD controls for chillers were not found to be cost effective. Our sizing assumptions for the fans and chillers were strict compared to conventional practice and tend to understate the benefits of ASD controls.

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