Alternative ventilation strategies in U.S. offices: Comprehensive assessment and sensitivity analysis of energy saving potential

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ABSTRACT. Mature technologies exist to reduce the heating, ventilation, and air-conditioning (HVAC) energy associated with ventilation and use ventilation proactively to save energy. This study investigated the energy use impacts in U.S. office buildings of multiple alternative ventilation strategies that combined: economizing, demand controlled ventilation (DCV), supply air temperature reset (SR), and/or a doubled ventilation rate. We used energy simulations in a Monte Carlo analysis, sampling 17 building inputs and varying locations to match the climate zone distribution of the U.S. office stock. Results indicated the possibility for significant savings compared to a baseline that ventilated constantly at a minimum rate in both a small office type with a constant air volume (CAV) HVAC system and a medium office type with a variable air volume (VAV) system. In 95% of instances, HVAC source energy savings were 5–25% in the small-CAV office (median: 11%) and 6–42% in the medium-VAV office (median: 27%). In the small-CAV office, DCV typically saved the most energy, usually from heating, and heating degree days and occupant density were decisive influences. In the medium-VAV office, economizing and SR were most important, DCV usually only had minor impacts, and zone temperature setpoints, along with climate indicators, were the critical influences. Other than infiltration, envelope characteristics did not strongly influence energy impacts. The untapped primary energy savings of alternative ventilation strategies over the 74% of U.S. office floorspace reasonably represented by our modeling was estimated at 36 TWh per year, with an annual value of U.S. \$1.25 billion.

1 Introduction

Buildings consume about two-fifths of primary energy in the U.S., which is essentially evenly split between residential and commercial uses [1]. Heating, ventilation, and air-conditioning (HVAC) accounts

for 30–40% [2,3] of U.S. commercial buildings’ energy consumption, or 5–6% of all U.S. primary energy. Ventilation is the provision of outdoor air (OA) to an interior space to control contaminant levels, odors, humidity, or temperature [4,5], and it alone accounts for about one-fourth of U.S. commercial HVAC energy use [3,6]. Even that substantial fraction likely underestimates ventilation’s potential to impact heating, cooling, and fan energy consumption. Ventilation and infiltration are routinely identified as the most important variables in sensitivity analyses of total building energy use [7–10], and a next-generation optimized ventilation strategy could potentially reduce HVAC energy use by as much as half in some situations [11].

Currently, in most mechanically conditioned commercial buildings, the ventilation strategy is simply to supply a constant minimum ventilation rate prescribed by a standard [4]. However, a number of mature technologies that can save HVAC energy relative to a fixed minimum-rate baseline already exist. One of these is *demand controlled ventilation* (DCV), which dynamically modifies the OA flow based on current occupancy or a proxy for it. Studies have estimated DCV to save from about 10% of HVAC energy for offices in a variety of climates [12], to 20% for restaurants and retail even in mild climates [13]. Most of the savings come from heating, with 5–40% heating use reductions in offices [14,15], depending on location, occupant density, and control logic. One review concluded cooling savings were minimal in offices [14], but savings are available in other building types [15–17]. In general, savings may depend more on rightsizing ventilation for actual occupancy that is lower than design, rather than on dynamic control [12,15].

A second mature technology is *airside economizing*, which is a control sequence that introduces more OA when it can provide free cooling. Multiple simulated assessments in offices have found that 5–15% HVAC electricity savings are possible from economizing [15,18,19]. Installing economizers in the approximately half of U.S. offices that do not have them could save an estimated \$320 million in aggregate energy costs annually [6]. A third technology is *supply air temperature reset* (SR), or increasing the supply air temperature setpoint at part-load conditions to save compressor and reheat energy [20]. Though it does not manipulate OA flow explicitly, it interacts significantly with the economizer cycle; when both are installed, SR alters OA control and enhances energy savings [21]. A final possible way to modify a ventilation strategy is simply *changing the minimum or target ventilation rate*, which can have potentially large energy impacts [6], whose magnitude and even direction of change can vary greatly among buildings and locations [22].

Despite their maturity, these technologies appear to have low-to-medium market penetration [22]. The goal of this study, therefore, was to analyze which among, and in what situations, these technologies should be adopted, and to provide guidance to both decision-makers and policymakers. With U.S. offices as the focus, this investigation is comprehensive in terms of considering, in most cases for the first time,

(i) multiple component technologies and their combined effects, (ii) a wide array of building and climate parameters for more detailed impact understanding and prediction, and (iii) multiple building and system types, including variable air volume (VAV) systems. Furthermore, though this article focuses on energy impacts, a companion piece expands to a fourth dimension of comprehensiveness: consideration of energy along with a number of important indoor air quality impacts, including worker productivity [23], volatile organic compound concentrations [24], and pollutants introduced from outdoors [25,26].

To do so, we defined eight ‘alternative ventilation strategies’ that were combinations of economizing, DCV, SR, and doubled ventilation. We used Monte Carlo analysis and building performance simulation to evaluate energy impacts relative to a fixed minimum-rate baseline, for both a small office type with a constant air volume (CAV) HVAC system and in a medium office type with a VAV system. The only previous study to have thoroughly examined more than a single ventilation technology tested combinations of DCV and economizer use in single zone, for CAV mechanical systems in 20 locations [15], and concluded that the largest benefits of the two technologies are mostly mutually exclusive, especially in offices. Here, we re-examined that conclusion in light of interactions with additional technologies like SR, and in buildings with VAV systems.

Even more importantly, this work assessed variations among building, mechanical system, and climate parameters, whose strong influences on ventilation strategy energy impacts have not previously been studied or quantified. A Monte Carlo approach was used to construct datasets that climatologically represented of U.S. offices, with broadly but realistically varied building parameters, allowing the sensitivity of energy impacts to building and climate predictors to be evaluated. These methods were broadly in line with model-based sensitivity analysis of building performance [27], which has recently been applied to evaluate uncertainties in design inputs [7–9], prune non-influential model parameters [10], assess design impacts [28] and operational strategies [29], and identify favorable equipment implementation scenarios [30]. Though our application was somewhat different—i.e., understanding real variability among instances, not uncertainty in a single model—our goals were those of sensitivity analysis: relating output to input variables, identifying important regions of the input space, and, ultimately, using models and analysis to improve recommendations to decision-makers [31].

2 Methods

2.1 Building typologies and modeling

This study focused on offices, which are the largest users of U.S. commercial building floorspace [32], and for which building parameters are relatively well characterized and mechanical systems typical-

ly capable of using the strategies investigated. We conducted assessments in two office building types. The ‘small-CAV’ office was single story and small (325 m^2), with a single zone served by a packaged CAV HVAC system with a single-speed direct expansion (DX) cooling coil and a gas-fired heating coil. The ‘medium-VAV’ office was medium-sized ($4,982 \text{ m}^2$) with three stories, each with one core and four perimeter zones. Each floor had a VAV system that distributed air to modulable terminal units with hot water reheat coils in each zone. A central boiler supplied the building’s 15 reheat coils, as well as three central heating coils. Each VAV air handler cooled air with a two-speed DX cooling coil.

The goal in evaluating energy impacts in these two particular office buildings was to explore the range of size- and system-related effects likely to be observed in typical offices. The ratio of exterior surface area to building volume was much greater in the small building, driving infiltration and envelope thermal transfer. Internal gains, on the other hand, were expected to be more dominant in the medium building. At the same time, the two buildings’ HVAC systems differed in two key ways. First, the medium-VAV office’s HVAC system served multiple thermal zones with distinct loads, while the system in the small-CAV office only had a single zone. Second, the medium-VAV air handler could vary the supply airflow rate but not the supply air temperature, unless using a strategy that employed SR. The small-CAV system, by contrast, provided constant supply flow at variable temperature.

The office building models were implemented in the whole-building energy simulation program EnergyPlus [33]. We selected EnergyPlus because it is physics-based, is validated (e.g., to ASHRAE Standard 140-2011 [34]), allows modification of a wide array of parameters, has an active research and development community, and is in general the most mature research-grade whole-building energy simulation engine available. The office types were derived from existing EnergyPlus reference models [35] but underwent slight modifications, including adjustment of mechanical systems, elimination of the attic in favor of a flat roof in the small-CAV office, and slight alteration of schedules for consistency.

The most significant change we made in the reference models was implementing our own infiltration calculation routine, since infiltration can have a strong influence on ventilation control and its impacts. The original reference buildings’ infiltration was constant during the day and unaffected by outdoor conditions. It also assumed infiltration would be drastically and uniformly reduced during HVAC system operation, to an extent unlikely to be achievable in small buildings. Instead, our routine was based on first sampling the building envelope’s air-leakage coefficient C from a statistical model of commercial buildings [36], and then using a whole-building form of the LBL infiltration model [37] at runtime to determine infiltration airflows given time-varying temperatures and wind speeds. Infiltration reductions during system operation were based on the building pressurization achieved by returning less air (by a quantity that was either 10% of the supply flow, or the OA intake flow, whichever was smaller) from the building zones than the system supplied [38].

2.2 Ventilation strategies

We assessed a single Baseline and multiple alternative ventilation strategies in each office building (Table 1). The Baseline ventilation strategy used a fixed mechanical ventilation rate (VR) of 9.4 L/s per occupant (20 ft³/min/occ), the minimum rate specified by ASHRAE Standard 62-2001 [39]. The alternative strategies used combinations of economizer controls, DCV, SR, and a doubled constant mechanical VR (= 18.9 L/s/occ). Economizing could either be lockout, meaning it operated only when OA could meet the cooling load completely without any mechanical cooling, or integrated economizing that was based on the differential enthalpy (DE) difference between return and outdoor air. When DCV was used, it adjusted OA to not exceed a CO₂ setpoint in the critical (highest CO₂ concentration) zone. The setpoint was based on the steady state CO₂ concentration achieved with a VR of 9.4 L/s/occ (i.e., 950 ppm) for all strategies with D950 in their name, or of 18.9 L/s/occ (i.e., 675 ppm) for strategies with D675 in their name. In the medium-VAV office, all strategies with SR in their name allowed the supply air temperature to rise to the highest temperature capable of meeting the cooling load in all zones when VAV flows were at minimum, up to a maximum of 18 °C (64.4 °F). In all other strategies, including the Baseline, the supply air temperature was fixed at 12.8 °C (55 °F). (SR is not an applicable technology in the small-CAV office, where the HVAC system modulates the supply air temperature to meet the load by definition.)

Table 1 Evaluated Baseline and alternative ventilation strategies.

Strategy	Office type	Minimum VR (L/s/occ [cfm/occ])	Economizing	DCV CO ₂ setpoint (ppm)	Supply air temperature reset
Baseline	Both	9.4 (20)	No	-	No
EconLock	Both	9.4 (20)	Yes - Lockout	-	No
Econ	Both	9.4 (20)	Yes - DE	-	No
Econ+SR	Med-VAV	9.4 (20)	Yes - DE	-	Yes
D950	Both	-	No	950	No
Econ+D950	Both	-	Yes - DE	950	No
Econ+SR+D950	Med-VAV	-	Yes - DE	950	Yes
2×VR	Both	18.9 (40)	No	-	No
Econ+D675	Sm-CAV	-	Yes - DE	675	No
Econ+SR+D675	Med-VAV	-	Yes - DE	675	Yes

VR = ventilation rate; DCV = demand controlled ventilation; Lockout = no economizing when cooling coil is active; DE = (integrated) differential enthalpy controls

2.3 Varied building parameters

To assess these strategies' impacts over a wide range of situations, we conducted building energy simulations within a comprehensive Monte Carlo analysis, both by varying climates (described in the fol-

lowing section) and sampling 17 building parameters to determine each unique modeled instance. Table 2 lists the parameters, related details, and their sampling distributions. Every effort was made to match probability distributions to realistic values for U.S. offices, while at the same time to sample a broad enough parameter space to capture all effects of interest.

Table 2 Varied building parameters and their units, short names, and sampling distributions.

Parameter	Units	Short name	Distribution			Truncation	
			Type	<i>a</i>	<i>b</i>	Lower	Upper
Envelope air-leakage coefficient, small-CAV	$\text{m}^3/\text{s}/\text{m}^2/\text{Pa}^{0.65}$	-	<i>LN</i>	3.52E-04	2.3	-	-
Envelope air-leakage coefficient, medium-VAV	$\text{m}^3/\text{s}/\text{m}^2/\text{Pa}^{0.65}$	-	<i>LN</i>	2.81E-04	2.3	-	-
Wall insulation <i>U</i> -value	$\text{W}/\text{m}^2\cdot\text{K}$	wallU	<i>LN</i>	0.70	3.0	0.10	6.00
Roof insulation <i>U</i> -value	$\text{W}/\text{m}^2\cdot\text{K}$	roofU	<i>LN</i>	0.50	3.0	0.10	6.00
Wall thermal mass	$\text{kJ}/\text{K}\cdot\text{m}^2$	wallCT	<i>LN</i>	100	3.0	5	600
Window <i>U</i> -value	$\text{W}/\text{m}^2\cdot\text{K}$	winU	<i>U</i>	1.00	5.80	-	-
Window solar heat gain coefficient	-	SHGC	<i>U</i>	0.20	0.80	-	-
Day start	hour of day	dayStart	<i>U</i>	5.00	9.00	-	-
Day end	hour of day	dayEnd	<i>U</i>	18.00	24.00	-	-
Lighting power density	W/m^2	LPD	<i>N</i>	10.5	10.0	0.0	-
Equipment power density	W/m^2	EPD	<i>N</i>	2.7	5.0	0.0	-
Occupant density	occ per 100 m^2	occDens	<i>LN</i>	5.2	1.7	1.9	14.6
Zone heating setpoint	$^{\circ}\text{C}$	heatStpt	<i>N</i>	21.5	1.5	-	-
Zone cooling setpoint	$^{\circ}\text{C}$	coolStpt	<i>N</i>	24.5	1.5	-	-
Unoccupied period zone setpoint setback	$^{\circ}\text{C}$	stptSetback	<i>U</i>	0.0	5.0	-	-
Heating efficiency	-	heatEff	<i>N</i>	0.80	0.20	0.60	1.00
Cooling coefficient of performance	-	coolCOP	<i>N</i>	3.00	1.00	1.50	4.50
Fan efficiency	-	fanEff	<i>N</i>	0.70	0.20	0.40	1.00

LN = lognormal distribution, *a* = geometric mean, *b* = geometric standard deviation

U = uniform distribution, *a* = min, *b* = max

N = normal distribution, *a* = mean, *b* = standard deviation

The distribution for the building envelope air-leakage coefficient *C* was derived from an analysis of empirical air leakage data, which developed a regression model for the relation between leakage and a building's height and floor area [36]. Applying that model yielded a separate lognormal air-leakage coefficient distribution for each office type. For all other parameters, the two office types had the same distributions. For occupant density, we used a published distribution [29]. For heating and cooling temperature setpoints, we fit our own distributions to indoor temperatures reported by the U.S. EPA's Building Assessment Survey and Evaluation [40,41]. To do so, we assumed that the indoor temperature reflected an effective heating setpoint when it was higher than the outdoor temperature, and an effective cooling setpoint when it was lower than the outdoor temperature. There are no sources for statistical distributions in existing offices for envelope parameters, lighting and equipment power densities, and equipment efficiencies. For these, we relied on values used in previous sensitivity analyses [10,28], sector-wide assessments

[15,35], and industry references [37]. For day occupied start and end times and the unoccupied temperature setpoint setback, uniform ranges were selected to explore a reasonable space of interest.

Translating these scalar parameter values to EnergyPlus model descriptions required some additional implementation steps, a few of which are worth mentioning:

- Changing the start and end of the day required adjusting a number of other schedules, including occupancy, lights, equipment, and the operation of the HVAC system. A preprocessing routine left the fractional schedule values in middle of the day as in the default schedule, and applied appropriate stretching and truncation to the profiles at the beginning and end of the day to make all schedules consistent. The HVAC system always turned on one hour before the occupied day start.
- When the sampled value for heating setpoint exceeded that for the cooling setpoint, the average of the two was applied to both. In these instances, which were about 9% of the total, there was no zone setpoint deadband.
- The unoccupied period temperature setpoint setback was applied to both heating and cooling zone temperature setpoints when the HVAC system was off. It was added to the cooling setpoint and subtracted from heating setpoint.
- In the small-CAV office, heating efficiency corresponded to the gas burner efficiency for the furnace coil, while in the medium-VAV office it was the boiler thermal efficiency.
- For the two stage DX coils in the medium-VAV office, the cooling coefficient of performance (COP) was applied to the high-speed stage, and the low-speed COP was adjusted to always be 50% higher.

2.4 Locations and climate zones

Probably the most important dimension varied in the Monte Carlo analysis was climate. We conducted simulations in 18 locations spanning the IECC/ASHRAE 90.1 U.S. climate zones. Sampling from these locations was weighted so that the final datasets matched the geographic/climate distributions of U.S. offices. Fractional representation was first set for five broad climate categories defined by the Building America program [42], illustrated in Figure 1. According to the 2012 Commercial Building Energy Consumption Survey (CBECS) [43], the best available statistical model of the existing U.S. building stock, 13% of U.S. offices are in hot-humid areas, 14% are in mixed-dry or hot-dry ones, 31% are in mixed-humid climates, 3% are in marine zones, and 39% are in cold or very cold climates.

Figure 1 Building America climate zones. (Image courtesy of the U.S. Department of Energy’s Building America Solution Center.)

The fractional makeup of IECC climate zones within each Building America climate zone category was based on weights derived in a previous analysis of the office stock [44]. These fractions, which were very slightly different for the two building sizes, can be seen in Table 3 along with the cities used to represent each IECC zone and selected climate indicators for them.

Table 3 Fractions of simulations in each Building America climate zone category, and fractional makeup of those categories by representative IECC climate zone locations, along with selected climate indicators for the locations. Cooling degree days (CDD) and heating degree days (HDD) used a base of 18 °C. The CDD and summer enthalpy residuals are explained in Section 2.7.

Building America (BA) climate zone	Fraction of offices in BA zone	Location	IECC climate zone	Fraction of BA zone represented		HDD base 18 °C (K-days)	CDD base 18 °C (K-days)	Average summer enthalpy (kJ/kg)	CDD residual (K-days)	Summer enthalpy residual (kJ/kg)	Direct normal solar irradiance (W/m ²)
				Small offices	Medium offices						
Hot-Humid	12.7%	Miami	1A	7.3%	13.7%	73	2,476	73.0	743	4.0	200
		Houston	2A	92.7%	86.3%	786	1,667	72.4	212	9.7	186
Hot-Dry / Mixed-Dry	14.2%	Phoenix	2B	35.6%	28.0%	525	2,532	57.1	975	-11.2	239
		Los Angeles	3B	29.3%	34.3%	714	344	47.0	-1139	-8.2	208
		Las Vegas	3B	29.3%	34.3%	1,169	1,859	47.0	554	-16.0	232
		Albuquerque	4B	5.8%	3.5%	2,261	749	43.0	-129	-11.1	226
Mixed-Humid	31.2%	Atlanta	3A	50.7%	39.2%	1,497	1,024	62.0	-153	4.6	192
		Baltimore	4A	24.6%	30.4%	2,538	683	56.6	-86	3.6	170
		New York	4A	24.6%	30.4%	2,684	544	57.8	-168	5.8	163
Marine	3.0%	San Francisco	3C	38.8%	41.0%	1,504	80	36.4	-1094	-15.5	196
		Seattle	4C	61.2%	59.0%	2,626	99	37.7	-636	-11.8	141
Cold / Very cold	38.8%	Chicago	5A	29.7%	29.9%	3,506	470	52.7	79	3.0	160
		Boston	5A	29.7%	29.9%	3,122	417	49.4	-124	-0.8	160
		Denver	5B	20.8%	19.3%	3,302	431	40.6	-40	-9.4	190
		Minneapolis	6A	15.6%	16.8%	4,202	417	49.0	298	1.2	159
		Missoula	6B	1.9%	2.0%	4,157	162	35.3	26	-11.1	157
		Duluth	7	2.1%	1.9%	5,236	116	41.0	402	-2.7	153
		Fairbanks	8	0.3%	0.4%	7,516	40	33.2	1218	-5.0	108

2.5 Sampling, simulation, and data processing

The Monte Carlo analysis simultaneously varied all 18 inputs—i.e., the 17 varied building parameters plus the location. Such a multidimensional analysis produces more reliable and robust measures of impacts and sensitivity than investigations based on perturbing parameters one at a time [31]. For sampling, we used quasi-random low-discrepancy sequences, whose good space-filling properties become particularly important in high dimensional spaces. In addition, the Sobol sequences [45–47] that we used are conceptually simpler and perform slightly better than Latin hypercube sampling, another quasi-random approach, both in general [48] and in particular for building simulation applications [49].

Each instance of an office type was defined by a unique set of sampled building parameters and a location. For each instance, the Baseline strategy and the six or eight alternative strategies (for the small-CAV and medium-VAV offices, respectively; see Table 1) were instantiated from templates, written to EnergyPlus input format, and simulated. Mechanical system capacities for all strategies were determined automatically by EnergyPlus’ auto-sizing procedure applied to the Baseline strategy. Therefore, while coil and fan capacities varied among instances, each given instance had a single mechanical system that was used consistently to evaluate all ventilation strategies. In post-processing, each simulated strategy’s annual cooling electricity, fan electricity, and heating natural gas consumption were normalized by the office’s floor area to obtain annual energy use intensities in kWh/m². Then the change from the Baseline was calculated for each alternative strategy. These changes show the impact of an alternative ventilation strategy in terms of a single piece of information. Moreover, the study so-designed provides good observational power, with each instance representing a set of consistent experimental conditions under which the multiple ventilation strategies were tested and compared.

Tests indicated that sensitivity indicators had very good convergence properties for above approximately 500 unique simulations. We exceeded that significantly, conducting simulations for 3000 instances (with seven or nine ventilation strategies per instance) in each office type. These 3000 instances were sampled equally among the eighteen cities. In order to match the climate distribution of U.S. offices, the original simulations for each office type were bootstrap re-sampled 10,000 times with each location’s selection probability determined by the climate zone fractions listed in Table 3. The result was one 10,000-element, climate-weighted dataset for each office type. The weighted datasets were based on 2459 unique instances in the small-CAV office and 1650 in the medium-VAV office (where there were fewer usable instances because of the VAV control limitations discussed in the following section). The number 10,000 was selected as a round number that was a reasonable compromise between avoiding excessive duplication of unique instances and ensuring that climate zones with smaller fractional representation

would have more than a handful of data points. All analysis was conducted on the two climate-weighted datasets.

2.6 Outdoor air limitation under VAV control

In a substantial fraction of medium-VAV office instances, some alternative strategies did not operate as intended because they were, at times, limited by the total supply airflow determined by the VAV HVAC system. Deviation from design intent was clearest for 2×VR, and we classified instances as ‘VAV-limited’ if the annual geometric mean of the actual mechanical VR supplied by 2×VR was less than the specified mechanical VR of 18.9 L/s/occ. Compliance with design intent was harder to evaluate for dynamic strategies that included economizing and SR, but ability to meet the 2×VR strategy appeared to be a good surrogate for ability to provide higher flow rates generally. For example, implementing Econ+SR in San Francisco increased the VR by a median of 23.6 L/s/occ among instances that were not VAV-limited, but only by 3.7 L/s/occ among instances that were.

Just under 40% of medium-VAV instances were VAV-limited. As identified by logistic regression (Table 4), these were instances with high occupancy and frequently low cooling loads, due to some combination of relaxed cooling setpoints, lower internal gains, lower window solar gains, and milder outdoor temperatures. In other words, the systems that most frequently limited occupant-normalized OA flow rates (i.e., VRs) were those likely to have low occupant-normalized supply air flow rates. In these instances, standard methods for design and control of VAV systems usually permitted the minimum VR of the Baseline strategy to be met, but limited higher VRs. Further research is needed to determine the best ways to integrate control of OA flow, system supply air flow and temperature, and zone-level discharge air flows and temperatures to permit increased ventilation in such situations, without undesired energy or comfort consequences.

Table 4 Logistic regression model of the probability that ventilation changes in the medium-VAV office will be VAV-limited. $ELPD = EPD + LPD$.

$\text{logit}(\text{VAV-limited}) \sim 1 + \text{occDens} + \text{coolStpt} + ELPD + SHGC + CDD$				
	Coefficient (raw)	Coefficient (standardized)	Standard error (standardized)	p-value
(Intercept)	-39.42	-2.93	0.07	0.0000
occDens	153.2	3.58	0.09	0.0000
coolStpt	1.631	2.35	0.06	0.0000
ELPD	-0.2215	-1.99	0.06	0.0000
SHGC	-9.694	-1.66	0.05	0.0000
CDD	-0.002077	-1.34	0.05	0.0000

Percent correct: 87% for VAV-limited, 94% for as-intended, 91% overall

The scope of this investigation, however, was alternative ventilation strategies, so we only included the 60% of instances where OA control and VAV supply air control did not come into conflict, and in

which all ventilation strategies performed substantially as intended. Removal of VAV-limited instances was done before resampling to construct the medium-VAV office's weighted dataset, and as such ultimate parameter distributions were barely affected. The only meaningful exception was occupant density, for which removing VAV-limited observations reduced the mean from 5.8 to 4.5 occupants per 100 m², and nearly eliminated instances with more than 10 people per 100 m².

2.7 Defining sensitivity analysis predictors

We analyzed the sensitivity of alternative strategy energy impacts to predictors that in some cases differed from the directly sampled inputs listed in Table 2. Additional predictors were defined in order to represent climate attributes, improve model fits, and normalize inputs (usually by building volume) to make results more intuitive and generalizable. We also defined several lumped predictors, which enabled holistic recognition of some influences that appeared minor when spread among multiple inputs.

For climate, for which many annual measures are highly correlated, principal components analysis indicated three predictors were necessary; more would simply confound the analysis. We found heating and cooling degree-days (HDD and CDD), both calculated with a base balance temperature of 18 °C, and the average outdoor air enthalpy during the summer the best three metrics for capturing heating and sensible and latent cooling demands, respectively. In order to reduce confounding in sensitivity analysis, we allowed HDD to be the primary climate indicator, then successively defined linearly independent 'residual' CDD and summer enthalpy predictors. Thus the CDD residual (CDD_{res}) was the portion of CDD not explained by a linear regression of CDD against HDD, namely

$$\text{CDD}_{\text{res}} = \text{CDD} - (1762 - 0.3911 \cdot \text{HDD}) \quad (1)$$

and the average summer enthalpy residual (sumEnthpyRes) was the portion of average summer enthalpy not explained by HDD and CDD, or

$$\text{sumEnthpy}_{\text{res}} = \text{sumEnthpy} - (52.82 - 2.240 \cdot \text{HDD}/1000 + 5.792 \cdot \text{CDD}/1000) \quad (2)$$

The values of the CDD and average summer enthalpy residuals for the 18 locations are listed in Table 3. In general, CDD_{res} was negative in mild climates and positive in both hot and cold ones, while sumEnthpyRes was negative in dry climates and positive in humid ones.

Infiltration rate was used as a predictor, rather than the sampled envelope air-leakage coefficient C . It was calculated during post-processing of EnergyPlus results by averaging the time-varying infiltration air exchange rate (h⁻¹) over all hours of the year. Infiltration was a stronger explanatory predictor than C because it encapsulated not merely a building's envelope leakiness, but also the environmental and operat-

ing conditions to which the envelope was subject. Infiltration rate is also intuitive, and generalizes well because it is the air flow normalized by the building volume.

For envelope heat transfer, a lumped parameter K_{cond}/V (short name: KcondPerV; units: W/K/m³) was defined as the building conductive heat transmission coefficient K_{cond} (W/K) [50] normalized by building volume, or

$$\frac{K_{\text{cond}}}{V} = \frac{U_{\text{roof}}A_{\text{roof}} + U_{\text{wall}}A_{\text{wall}} + U_{\text{window}}A_{\text{window}}}{V} \quad (3)$$

where U and A refer, respectively, to individual component U -values (W/K·m²) and areas (m²). The use of KcondPerV, in addition to normalizing for component areas, made more apparent the influence of envelope conduction, which appeared trivial when split between individual components.

The window solar heat gain coefficient was replaced with a simple lumped parameter $Q_{\text{sol,window}}/V$ (short name: winSolarPerV; units W/m³), defined as the product of the solar heat gain coefficient (SHGC), the window area, and the annual average direct normal solar irradiance $\bar{I}_n$ (W/m²) available in weather files, normalized by the building volume, or

$$\frac{Q_{\text{sol,window}}}{V} = \frac{\text{SHGC} \cdot A_{\text{window}} \bar{I}_n}{V} \quad (4)$$

Finally, a summed equipment and lighting power density (ELPD) replaced separate equipment and lighting values, and a day length predictor replaced separate day start and end times. Both substitutions increased model simplicity and explanatory clarity, without meaningfully reducing predictive power.

Table 5 lists and summarizes the final 16 predictors used in the sensitivity analysis. The statistics are based on observations in both buildings, i.e., the merged 20,000 points of each building type's climate-weighted dataset. Only the four predictors included in Table 6 were meaningfully different in the two offices. That is, the infiltration rate, the building conductive heat transfer coefficient per volume, and the window solar gain per volume were all higher in the small-CAV office, because of its much greater envelope-to-volume ratio. Occupant density, on the other hand, was somewhat lower in the medium-VAV office because more densely occupied offices were more likely to be classified as VAV-limited and therefore removed.

Table 5 Building and climate parameters used as predictors in sensitivity analysis, with their units and short names. The mean, standard deviation (SD), and selected percentiles (prefix “p”) are shown for the combined dataset for both offices.

Parameter	Units	Short name	Mean	SD	p5	p25	Median	p75	p95
Heating degree days, base 18 °C.	K-days	HDD	2,308	1,221	530	1,156	2,566	3,267	4,147
Cooling degree days (base 18 °C) residual	K-days	CDDres	0	431	-1,024	-180	-14	203	797
Summer enthalpy residual	kJ/kg	sumEnthpyRes	0.0	7.6	-14.4	-6.0	2.1	5.3	10.1
Infiltration air exchange rate	h ⁻¹	infAER	0.38	0.38	0.04	0.12	0.25	0.50	1.16
Conductive heat transfer coefficient per volume	W/K/m ³	KcondPerV	0.45	0.33	0.14	0.23	0.35	0.57	1.13
Wall thermal mass	kJ/K-m ²	wallCT	136	125	16	45	93	186	414
Window solar gain per volume	W/m ³	winSolarPerV	3.8	1.5	1.6	2.6	3.6	4.7	6.5
Day length	hours per day	dayLen	13.9	2.1	10.4	12.4	13.9	15.5	17.4
Combined LPD and EPD	W/m ²	ELPD	19.3	9.0	6.1	12.6	18.5	25.1	35.1
Occupant density	occ per 100 m ²	occDens	5.1	2.3	2.3	3.4	4.6	6.3	9.9
Zone heating setpoint	°C	heatStpt	21.5	1.4	19.1	20.6	21.5	22.4	23.8
Zone cooling setpoint	°C	coolStpt	24.3	1.4	22.1	23.3	24.3	25.3	26.8
Unoccupied period zone setpoint setback	°C	stptSetback	2.5	1.4	0.3	1.3	2.6	3.8	4.8
Heating efficiency	-	heatEff	0.80	0.11	0.63	0.71	0.80	0.89	0.97
Cooling coefficient of performance	-	coolCOP	3.02	0.74	1.79	2.45	3.02	3.60	4.24
Fan efficiency	-	fanEff	0.70	0.15	0.46	0.59	0.70	0.81	0.95

Table 6 Statistics for each office type for the only four predictors that varied meaningfully between the two office types. These mean and standard deviation (SD) values were *not* used for standardization in regression models.

Parameter	Units	Short name	Office type	Mean	SD	p5	p25	Median	p75	p95
Infiltration air exchange rate	h ⁻¹	infAER	Small-CAV	0.53	0.46	0.06	0.18	0.39	0.72	1.51
			Medium-VAV	0.23	0.19	0.03	0.09	0.17	0.31	0.64
Conductive heat transfer coefficient per volume	W/K/m ³	KcondPerV	Small-CAV	0.64	0.36	0.25	0.39	0.55	0.80	1.36
			Medium-VAV	0.26	0.12	0.11	0.18	0.24	0.32	0.50
Window solar gain per volume	W/m ³	winSolarPerV	Small-CAV	4.4	1.6	1.9	3.0	4.3	5.6	7.1
			Medium-VAV	3.2	1.1	1.4	2.3	3.2	4.0	4.9
Occupant density	occ per 100 m ²	occDens	Small-CAV	5.8	2.6	2.5	3.7	5.2	7.3	11.1
			Medium-VAV	4.5	1.8	2.3	3.2	4.2	5.5	7.9

3 Results and discussion

The results are organized from general to specific, as follows. Section 3.1 briefly summarizes the Baseline strategy’s energy use intensity results for context. Section 3.2 provides an overview of the alternative ventilation strategies’ energy impacts, and Section 3.3 estimates the aggregate energy saving potential in a large segment of the U.S. office stock. Section 3.4 examines selected results by climate zone category. Sections 3.5–3.7 turn to detailed sensitivity analysis of climate and building parameters. Finally, Section 3.8 describes Supplementary Information available with the article, including a spreadsheet implementation of accurate models to estimate energy impacts, application of sensitivity analysis results to answer some specific ventilation strategy questions, and discussion of implications for high performance buildings.

Most discussion focuses on the principal strategies designed to save energy: Econ, D950, and Econ+D950 in the small-CAV office, and those three plus Econ+SR and Econ+SR+D950 in the medium-VAV office. Overview and sensitivity analysis results are given for EconLock, 2×VR, Econ+D675, and Econ+SR+D675, but they are discussed less. Economizing with lockout (EconLock) nearly always saved less than differential enthalpy economizing (Econ), and 2×VR would generally be implemented for work performance and absenteeism benefits [6], not energy savings. Both EconLock and 2×VR are discussed in in depth strategy analysis in the Supplementary Information. In terms of energy savings, Econ+D675 and Econ+SR+D675 never performed better than Econ+D950 or Econ+SR+D950, respectively, but provided a substantial fraction of the maximum savings, and are discussed in detail in a companion article that also considers other criteria like productivity and indoor air impacts.

For much of the treatment, HVAC natural gas and electricity energy use were combined into a single value for HVAC source (or primary) energy use. To do so, we used the national average site-to-source energy conversion factors used by the U.S. EPA, which are 3.14 and 1.05 source kWh per site kWh for electricity and natural gas, respectively [51]. Because in the U.S. the ratio of average site-to-source conversion factors for electricity and natural gas is nearly identical to the ratio of average electricity and natural gas prices—\$0.1086 per kWh for electricity and \$0.0375 per kWh natural gas, based on average consumption-weighted U.S. prices in all states from 2005–2014 [52–55])—changes in source energy use are a very good proxy for changes in energy operating costs. To estimate cost impacts from source energy impacts, one can multiply by \$0.035 per kWh, or estimate \$1 saved for every approximately 30 kWh of source energy reduction.

3.1 Baseline energy consumption

Table 7 summarizes the annual energy consumption of the Baseline strategy to provide context for the remainder of the paper. In general, the medium-VAV office consumed somewhat less energy. The largest and most consistent reason for this was less heating gas use, which accounted for 45% of HVAC source energy consumption in the small-CAV office type but only 25% in the medium-VAV office. In the hottest areas, the small-CAV office type also consumed more electricity for cooling. In both offices, total HVAC electricity consumption was about evenly split between cooling and fans.

Figure 2 illustrates the Baseline strategy natural gas and electricity annual use intensities in individual cities. For comparison, the background indicates the median (dark green line) and 25–75th percentile interval (green shading) of the use intensities derived from real consumption data in the 2003 CBECS, the most recent year for which energy consumption was available [56]. The CBECS data were restricted to offices and divided into the five broad climate classifications used in 2003, but not differentiated by size

(since that resulted in too few data points in some bins). Lack of size resolution probably helps explain why natural gas consumption was sometimes on the higher side of the CBECS reference range for the small-CAV office, and on the lower side of it for the medium-VAV one. There are many other good reasons to expect some differences between 2003 CBECS end-use intensities and our modeled results, such as independent variation of all parameters in our study, significant changes in lighting and equipment power density in the past thirteen years, and the uncertain assumptions in the CBECS end-use estimates themselves. Overall, though, the modeled baselines matched the reported office sector estimates quite well.

Table 7 Baseline ventilation strategy annual energy use intensity statistics for the two model typologies, for weighted datasets over the U.S. The prefix “p” indicates percentile.

	Baseline annual energy use intensity, kWh/m ²						
	Mean	SD	p5	p25	Median	p75	p95
<i>Small-CAV</i>							
HVAC natural gas	111	100	5	34	87	158	305
HVAC electricity	51	30	17	30	45	64	111
Cooling electricity	27	21	5	13	21	35	69
Fan electricity	24	13	9	16	22	30	48
HVAC site energy	162	103	43	89	140	210	353
HVAC source energy	278	137	96	185	254	349	523
<i>Medium-VAV</i>							
HVAC natural gas	45	38	1	15	37	65	115
HVAC electricity	48	20	23	34	44	59	87
Cooling electricity	26	14	11	17	23	32	52
Fan electricity	22	10	10	15	20	27	42
HVAC site energy	93	44	35	60	86	118	173
HVAC source energy	199	78	93	145	185	244	342

Figure 2 Boxplots of HVAC natural gas and electricity usage in the two offices by city. The green shaded area in the background shows CBECS 25–75th percentile span, and the line in the middle of it is the CBECS median. These references are the same in (a) and (b), and based on only offices and divided into the five broad climate bins used in 2003 CBECS.

3.2 Overview of alternative strategy energy impacts

Table 8 shows median and 95% data intervals for the changes in energy consumption intensity under the six strategy alternatives in the small-CAV office. Herein, the ‘95% data interval’ or 95% DI is the interval bounded by the 2.5th and 97.5th percentiles of a set of data. The D950 strategy saved the most natural gas but typically little electricity, while Econ saved some electricity but no natural gas. The combined Econ+D950 had the maximum source energy savings of any strategy 98% of the time. At the median, it saved 28 kWh/m² of source energy, and at the top of the 95% DI, it saved up to 72 kWh/m². In percent terms, Econ+D950 reduced HVAC source use intensity by 11% at the median (95% DI: 5–25% savings). The final row of Table 8 shows the fraction of maximum savings each strategy provided. On average, D950 alone achieved about two-thirds, and Econ alone about one-third, of the source energy consumption reductions of Econ+D950.

Table 8 For the small-CAV office, median and 95% data intervals (DI) for each strategy’s change from the baseline for natural gas, electricity, and source energy in annual kWh/m², as well as in percent of baseline for source energy. Negative changes indicate energy saved. Also shown are the frequency that each strategy yielded maximum savings in source energy and the average fraction of the maximum possible savings each strategy achieved.

	EconLock	Econ	D950	Econ+ D950	2×VR	Econ+ D675
Median (95% DI) natural gas change, kWh/m ²	1 (0, 2)	1 (0, 2)	-12 (-53, -1)	-12 (-53, 0)	16 (1, 72)	-5 (-37, 7)
Median (95% DI) electricity change, kWh/m ²	-2 (-8, 0)	-3 (-10, 0)	0 (-5, 1)	-4 (-13, -1)	1 (-2, 6)	-3 (-11, 0)
Median (95% DI) source energy change, kWh/m ²	-5 (-23, 0)	-7 (-32, 0)	-16 (-57, 0)	-28 (-72, -8)	21 (1, 75)	-18 (-54, 3)
Median (95% DI) source energy % change, %	-2 (-10, 0)	-3 (-16, 0)	-6 (-20, 0)	-11 (-25, -5)	9 (1, 29)	-7 (-18, 1)
Frequency strategy had maximum source savings	0%	0%	1%	98%	0%	0%
Average fraction of maximum savings	0.22	0.31	0.62	1.00	0.00	0.66

Table 9 lists analogous impacts in the medium-VAV office. As with the small-CAV office, the greatest energy savings nearly always came from the strategy with the most ventilation technology components. For the medium-VAV office, this was Econ+SR+D950, which substantially reduced both natural gas and electricity use, for a median total source use intensity reduction of 50 kWh/m² and reductions up to 124 kWh/m² within the 95% DI. In percent terms, Econ+SR+D950 saved 27% of HVAC source energy at the median (95% DI: 6–42% savings). Most savings could be realized without the use of the DCV component, however, with Econ+SR having a median and 95% DI only marginally lower than those of Econ+SR+D950, and capturing 84% of the savings of the more complex strategy on average.

Table 9 For the medium-VAV office, median and 95% data intervals (DI) for each strategy's change from the baseline for natural gas, electricity, and source energy in annual kWh/m², as well as in percent of baseline for source energy. Negative changes indicate energy saved. Also shown are the frequency that each strategy yielded maximum savings in source energy and the average fraction of the maximum possible savings each strategy achieved.

	EconLock	Econ	Econ+SR	D950	Econ+D950	Econ+SR+D950	2×VR	Econ+SR+D675
Median (95% DI) natural gas change, kWh/m ²	-1 (-4, 0)	-1 (-4, 0)	-13 (-36, 0)	0 (-5, 1)	-2 (-9, 0)	-18 (-42, 0)	4 (0, 24)	-13 (-38, 0)
Median (95% DI) electricity change, kWh/m ²	-5 (-15, 0)	-6 (-18, -1)	-9 (-27, -1)	1 (-3, 5)	-7 (-19, -2)	-9 (-28, -2)	0 (-3, 9)	-8 (-26, 1)
Median (95% DI) source energy change, kWh/m ²	-17 (-49, 0)	-22 (-61, -4)	-43 (-117, -4)	3 (-11, 14)	-26 (-65, -7)	-50 (-124, -9)	8 (-6, 31)	-41 (-115, 2)
Median (95% DI) source energy % change, %	-9 (-19, 0)	-11 (-23, -3)	-24 (-41, -3)	2 (-5, 6)	-14 (-24, -7)	-27 (-42, -6)	4 (-4, 15)	-23 (-40, 1)
Frequency strategy had maximum source savings	0%	0%	0%	0%	4%	95%	0%	0%
Average fraction of maximum savings	0.32	0.44	0.84	0.04	0.56	0.99	0.01	0.77

There were three important differences between the two offices types. First, economizing saved much more energy in the medium-VAV office, on the order of 2–3 times the savings observed in the small-CAV office. This greater savings potential was partially due to envelope-to-volume ratio differences, but mostly to the fact that supply air temperature is maintained consistently low in multizone air distribution systems, increasing opportunities for economizing. Second, SR was available as a strategy, and SR nearly always saved significant energy in both heating and cooling. Comparing Econ+SR to Econ, the addition of SR approximately doubled the source energy savings generated by an economizer alone. Third, DCV was not typically a useful strategy in the medium-VAV office. By itself, it was about as likely to increase source energy consumption as decrease it. Even with other components, DCV did not provide large additional energy savings, at least in terms of the median or average. In sum, the much greater savings from economizing, additional large savings from SR, and sharply reduced savings potential of DCV in the medium-VAV office combined to yield source energy savings opportunities that were about twice the magnitude of those available in the small-CAV office.

3.3 Aggregate office sector energy and expenditure savings

Before investigating the sensitivity of the energy savings to variations in the input parameters, we demonstrate the large potential of alternative ventilation strategies to save energy across the U.S. office sector. To do so, we used the small-CAV office results to represent the 296 million m² of floorspace in offices less than 930 m² (10,000 ft²), and the medium-VAV office to represent the 800 million m² of floorspace in offices between 930 m² and 18,590 m² (200,000 ft²) [32]. These two estimates cover 74% (or 1,095 million m²) of U.S. office floorspace in small to medium-large offices, but exclude possible benefits in the 26% of floorspace in high-rise and extremely large offices beyond the scope of our modeling domain. Under the Baseline strategy, this segment of the office sector was estimated to use 241 TWh of primary energy annually, at a total cost of \$8.4 billion (using average consumption-weighted electricity and natural prices in all U.S. states from 2005–2014 [52–55]). If all represented offices started from the Baseline and moved to the alternative with the greatest energy savings, the aggregate annual source energy savings would be 53 TWh, or a 22% reduction of all primary energy consumed by HVAC end-uses. Energy costs would be reduced by the same percent, at a value of \$1.84 billion.

Table 10 Aggregate impacts over all small to medium-large U.S. offices, which represent about three-quarters of office floorspace. Untapped savings account for technologies’ estimated current market penetration.

Aggregate U.S. small to medium-large office sector:	Sector total, under Baseline	Savings, starting from Baseline	Untapped savings
HVAC source energy consumed (TWh)	241	53	36
HVAC energy cost (billion \$)	8.43	1.84	1.25

Of course, not all offices currently operate with the Baseline strategy, so we also estimated the untapped market potential, only counting the portion of floorspace not yet penetrated by component technologies. Current economizer adoption rates, from CBECS 2012, were 9% for small offices and 44% for medium to medium-large offices [32,57]. For DCV and SR penetration, which CBECS does not ask about, we relied on survey information from building industry professionals, limited only those referring to offices ($N = 67$) [22]. These indicated 33% adoption for DCV and 37% for SR, among recent projects. There is more uncertainty in these adoption rate estimates for DCV and SR, given the small sample and the self-reported nature of the survey. Results indicated that most (68%) of the total theoretical savings potential judged against the Baseline strategy appeared to be untapped, with 36 TWh of annual primary energy savings still available across the sector even after accounting for current technology adoption rates. Such savings would represent 16% of all primary energy consumed by HVAC end-uses.

The small-CAV segment represented 27% of the small to medium-large stock's floorspace, and even more (34%) of baseline energy use. However, in terms of savings from alternative ventilation strategies, it was a significantly less attractive target, accounting for only 17% of theoretical savings (from the Baseline strategy) and 20% of untapped potential. Therefore, at the coarsest level, medium and larger offices with multizone distribution systems should be more immediate targets for market actors and policymakers interested in realizing energy savings from these alternative ventilation strategies.

3.4 Energy impacts by climate zone

Our Monte Carlo investigation also enabled much finer analysis, providing insights to target the most promising savings opportunities in both office types. We first examine the principal energy-saving strategies' results in each of the five broad Building America climate zone categories. For the small-CAV office, Figure 3 shows the ranges of annual HVAC source energy, natural gas, and electricity changes observed for Econ, D950, and Econ+D950. Economizer electricity savings were similar in hot-humid, mixed-humid, and cold climates, and substantially higher in hot-dry/mixed-dry and marine climates. Savings from DCV were almost entirely from natural gas for heating, and much greater in cold climates. Only in hot-humid locations did DCV consistently save electricity, and in all other climates it frequently increased electricity use by reducing free cooling.

Figure 3 Ranges of HVAC source energy, natural gas, and electricity from implementing three alternative ventilation strategies in the small-CAV office, divided by five broad Building America climate zones. (See Table 3 for cities in each zone.)

Combining economizer with DCV eliminated this unintended consequence, so Econ+D950 never increased energy use. The two components' source energy savings were largely additive. In hot-humid, mixed-humid, and especially cold climates, DCV made up the larger part of combined Econ+D950 source energy savings, and could potentially be more cost-effective to implement on its own. On the other hand, in hot-dry/mixed-dry and marine climates, D950 alone was less attractive, both because economizer was more beneficial and because DCV without economizer control override could increase energy use there.

For the medium-VAV office, Figure 4 shows the impacts of Econ, D950, Econ+D950, Econ+SR, and Econ+SR+D950. Comparison to small-CAV results in Figure 3 again confirms that alternative strategies in the medium-VAV office typically saved significantly greater source energy. (Note that source energy and electricity have larger scales in Figure 4 than in Figure 3.) This source energy difference was the combined effect of slightly smaller natural gas reductions and much larger electricity savings, due to the three important broad differences already identified between the two office types: in the medium-VAV office economizer saved much more energy, SR was applicable and saved significant energy, and DCV savings were minor (and, to an even greater extent than in the small-CAV office, D950 alone often increased electricity use by reducing free cooling.) Thus, for example, the combined Econ+D950 strategy happened to have similar source energy savings in both office types, but economizing and not DCV accounted for nearly all of them in the medium-VAV office—for which, in any case, the strategies Econ+SR and Econ+SR+D950 saved far more energy.

Within these broad conclusions, medium-VAV office impacts did vary by climate. Economizer and SR savings, both independently and together, rose consistently as the climate zones' cooling demands decreased. This was true for both natural gas and electricity savings from SR, reflecting significant potential for reducing both primary cooling and zone reheat energy in all but a small minority of instances in the very hottest climates. The potential benefits of moving from Econ+SR to Econ+SR+D950 were subtler, with small increases in electricity savings in hotter climates, and small increases in natural gas savings in colder ones. (More specific detail on the latter two questions can be found in the Supplementary Information.)

Figure 4 Ranges of HVAC source energy, natural gas, and electricity from implementing five alternative ventilation strategies in the medium-VAV office, divided by five broad Building America climate zones. (See Table 3 for cities in each zone.)

3.5 Sensitivity analysis tools

To quantitatively assess the influence of building and climate parameters on the alternative ventilation strategies' energy impacts, we turn to sensitivity analysis based on linear regression, which captures first-order effects well and is clear and intuitive. (More precise models that include nonlinear and interaction effects are available as in the Supplementary Information, as described in Section 3.8). The linear regression model with standardized predictors for response y is

$$y = \beta_0 + \sum_i \beta_i z_i + \varepsilon = \beta_0 + \sum_i \beta_i \frac{x_i - \mu_i}{\sigma_i} + \varepsilon \quad (5)$$

where ε is an error term, z_i is the standardized value of predictor x_i obtained by subtracting the mean μ_i and dividing by the SD σ_i . Sensitivity was assessed by the coefficient β_i , herein called the standardized effect. The constant term β_0 is the response when all predictors are at their means. Though separate regression analyses were conducted for each office, the same μ_i and σ_i values were used for both offices to

allow consistent comparisons. These μ_i and σ_i values are in Table 5, but are also provided in the result tables in this section for easy reference.

Here, the response y was the change from the Baseline in source energy use intensity owing to alternative strategy adoption, with positive changes indicating increased energy use compared to the Baseline strategy, and negative changes representing energy savings. Therefore, a negative constant term β_0 indicates the strategy saved energy when all predictors were at the standardizing mean values. A negative standardized effect for a predictor means that on average more energy was saved when that predictor had higher values. Further, as Equation (5) shows, β_i is the average change that a change of σ_i in predictor i has on source energy changes in real units of kWh/m² [58].

To make it clearer when parameters had truly negligible impact, a pruning routine tested the impact of removing each parameter from a regression model and did so if it increased the model’s root mean square error (RMSE) by less than 1%. To rank the influence of predictors, we used a sensitivity index (SI) based on the square of the standardized regression coefficient, which gives an estimate of the fraction of variance accounted for by variation in that parameter [31]. (For this statistic only, we used separate predictor standard deviations for each office type, rather than the ones for the combined dataset.) A ‘weighted SI’ combined results for the six or eight alternative strategies by averaging their SI values, with each strategy weighted by the variance of the energy changes it produced. These variance-based weights preserve the interpretation that the weighted SI indicates the fraction of variance, across all strategies, for which a predictor accounted. With coefficients of determination (R^2) between 0.6 and 0.8, the regression models accounted for 60–80% of the variance in source energy use intensity, depending on the strategy.

3.6 Small-CAV office sensitivity analysis

Table 11 shows the results of the regression sensitivity analysis for the small-CAV office. Seven building predictors—occupant density, the infiltration rate, the day length, ELPD, and heating and cooling setpoints and efficiencies—plus HDD explained 68% of the variance in ventilation strategy impacts. Occupant density and HDD alone accounted for nearly 40% of variance, because of their decisive influence on heating energy savings, which is illustrated in Figure 5a. Similarly, as Figure 5b shows, whether economizer saved significant energy could largely be predicted by internal gains and the cooling setpoint.

Table 11 Small-CAV office sensitivity analysis results. Values are coefficients of linear regressions against standardized predictors, and indicate the average change in a strategy's impact in kWh/m² produced by a change of σ in the predictor. Negative changes represent energy savings. The constant is the change in the outcome produced by the strategy when all predictors are at the values in the μ column.

Predictor	μ	σ	Weighted SI	Standardized effect size (kWh/m ²)					
				EconLock	Econ	D950	Econ+ D950	2×VR	Econ+ D675
Constant	-	-	-	-6.0	-8.3	-16.6	-26.9	22.8	-16.0
occDens	5.1	2.3	26%	-	-	-6.8	-7.6	12.0	-
HDD	2,308	1,221	13%	-	-	-6.2	-6.4	8.3	-3.2
infAER	0.38	0.38	8%	0.5	0.7	-3.7	-2.8	0.8	-6.7
dayLen	13.9	2.1	5%	-1.1	-1.2	-3.2	-4.7	4.2	-3.3
coolStpt	24.3	1.4	4%	2.6	3.4	-	4.2	-	3.6
ELPD	19.3	9.0	4%	-2.9	-4.0	1.8	-3.0	-1.7	-3.5
heatStpt	21.5	1.4	4%	-0.7	-1.1	-2.8	-4.1	3.7	-2.4
coolCOP	3.02	0.74	3%	2.2	2.8	-	3.9	-0.9	2.8
heatEff	0.80	0.11	2%	-	-	2.4	2.2	-3.1	1.2
KcondPerV	0.45	0.33	2%	-1.7	-2.2	-	-2.2	-	-2.2
sumEnthpyRes	0.0	7.6	1%	0.6	1.2	-2.6	-	2.9	-
CDDres	0	431	1%	1.0	1.7	-2.2	-	2.5	1.3
winSolarPerV	3.8	1.5	1%	-1.3	-1.9	1.2	-1.0	-1.4	-1.9
RMSE (R^2)	-	-	-	3.6 (0.68)	4.7 (0.70)	7.5 (0.74)	8.7 (0.74)	8.9 (0.80)	9.2 (0.62)
Weight	-	-	-	3%	6%	18%	23%	32%	18%

Note: the pruning routine eliminated wallCT, fanEff, and stptSetback from all strategies' models.

Figure 5 In the small-CAV office, (a) gas savings from D950, as a function of HDD and occupant density, and (b) electricity savings, as a function of the cooling setpoint and ELPD. Note the color scales are for site energy intensity units.

Detailed results, organized by predictor category, included:

- *Climate variables:* The number of HDD was so important because of its strong influence on heating energy, particularly on reductions from DCV and increases from doubling ventilation. In climates that were also hotter than average given HDD, and more humid than average given HDD and CDD, there were also fewer savings from economizing, more savings from DCV, and greater energy use increases from doubling ventilation. The residual climate effects not explained by HDD, however, were a small fraction of the effects associated with HDD.

- *Envelope:* Infiltration was an important influence on strategies with DCV, since, along with occupant density, it determined by how much mechanical ventilation could be reduced without exceeding the CO₂ setpoint. Other envelope characteristics, however, played a small role, with the lumped building conductive heat transfer coefficient and the window solar gain parameter (mostly based on the SHGC) ranked as the two least influential predictors that were not pruned, and the thermal mass of exterior walls pruned from all models.
- *Occupancy:* Along with HDD, occupant density decisively influenced heating energy changes, particularly for 2×VR and for strategies with DCV. (Occupant density also influenced increases in electricity use from doubling ventilation, but very weakly.) The length of the day was also quite important, with each ~2 hours of additional operating time increasing a given energy impact by about 20%, on average, for all strategies.
- *Gains:* The equipment and lighting power density was the most important single predictor of economizer savings, which increased as ELPD increased. Solar gains, via the lumped window solar gain, were also associated with economizer savings, but much less strongly. (Increases in both types of gains reduced DCV savings, too, but the effects were modest.)
- *Setpoints:* A tight control range for indoor temperatures increased the impact of alternative strategies on energy use. Lower cooling setpoints significantly increased savings of strategies with economizers, while higher heating setpoints enhanced energy-saving potential of strategies with DCV (and the energy impacts of doubling ventilation). As an example, an office with a zone temperature control range of 22–23 °C would save about 12 kWh/m² per year more on average from Econ+D950 than one with a more relaxed 20–25 °C allowable range. However, the unoccupied temperature setback had no meaningful influence on ventilation strategy impacts.
- *Efficiencies:* As would be expected, impacts were smaller on average for more efficient mechanical systems. Interestingly, cooling COP was most important, and heating efficiency much less so. Fan efficiency, in this CAV system, had negligible influence.

3.7 Medium-VAV office sensitivity analysis

Table 12 shows the results of the regression sensitivity analysis for the medium-VAV office. Because of the multizone distribution and VAV control of the building, and the fact that SR was a dominant energy-saving technology component, results were most sensitive to zone temperature setpoints and climate. Just five building predictors—the three setpoints, the cooling coil COP, and the infiltration rate—plus HDD accounted for 64% of alternative strategy impacts’ variance.

Table 12 Medium-VAV office sensitivity analysis results. Values are coefficients of linear regressions against standardized predictors, and indicate the average change in a strategy's impact in kWh/m² produced by a change of σ in the predictor. Negative changes represent energy savings. The constant is the change in the outcome produced by the strategy when all predictors are at the values in the μ column.

Predictor	μ	σ	Weighted SI	Standardized effect size, kWh/m ²							
				EconLock	Econ	Econ+SR	D950	Econ+D950	Econ+SR+D950	2×VR	Econ+SR+D675
Constant			-	-21.6	-27.6	-61.0	2.2	-33.4	-68.9	10.7	-59.6
heatStpt	21.5	1.4	17%	-5.0	-5.8	-14.2	0.9	-5.6	-14.0	-	-13.7
HDD	2,308	1,221	14%	-7.5	-7.4	-10.9	4.1	-6.1	-11.8	-	-10.9
stptSetback	2.5	1.4	13%	4.3	4.9	12.0	-	4.8	12.1	-	11.8
coolCOP	3.02	0.74	9%	4.3	5.8	9.2	-0.7	6.7	9.9	-	8.5
coolStpt	24.3	1.4	7%	4.0	4.7	8.6	-	5.2	9.0	-	8.0
infAER	0.38	0.38	3%	-	-	-8.5	-	-3.0	-11.9	-	-17.1
winSolarPerV	3.8	1.5	3%	-3.3	-4.6	-7.7	-	-4.4	-7.2	-1.4	-6.4
KcondPerV	0.5	0.3	2%	-4.9	-5.4	-15.5	-	-4.8	-15.0	-	-14.2
ELPD	19.3	9.0	2%	-2.3	-3.9	-3.2	-	-4.1	-2.8	-1.2	-3.7
CDDres	0	431	2%	-	1.0	4.0	-1.7	-	2.5	3.8	4.8
occDens	5.1	2.3	1%	1.5	2.0	2.8	-0.9	-	-	7.3	4.9
sumEnthpyRes	0.0	7.6	1%	-	2.0	2.0	-1.3	-	-	3.8	2.8
fanEff	0.70	0.15	1%	1.2	1.6	2.5	-	1.6	2.2	-	2.3
heatEff	0.80	0.11	0%	-	-	1.7	-	-	2.1	-0.8	1.5
dayLen	13.9	2.1	0%	1.3	-	-	-	-	-	1.3	-
RMSE (R^2)			-	6.5 (0.76)	7.0 (0.78)	14.5 (0.76)	3.5 (0.66)	7.0 (0.78)	14.3 (0.78)	5.9 (0.63)	14.6 (0.77)
Weight				5%	7%	25%	1%	6%	26%	3%	27%

Note: the pruning routine eliminated wallCT from all strategies' models.

Results for all predictors, by category, included:

- *Climate variables:* HDD was again a critical influence on potential heating and cooling savings, with greater savings from economizing and SR in colder climates. Furthermore, the CDD and average summer enthalpy residuals indicated that economizing and SR were even less effective (and doubling ventilation more energy intensive) in the hottest and most humid locations.
- *Envelope:* Infiltration was less influential overall than in the small-CAV office, but strategies with SR and DCV saved more heating energy in leakier buildings. The lumped building conductive heat transfer coefficient was more important in the medium-VAV office than in the small-CAV one, because less insulated envelopes (leading to greater load diversity among zones) were associated with greater SR savings.
- *Occupancy:* In a stark contrast to the small-CAV office, neither occupant density nor the length of the occupied day strongly influenced the medium-VAV alternative ventilation strategy energy impacts. The only exception was occupant density's influence on the energy impact of 2×VR.
- *Gains:* Higher solar gains were associated in particular with larger energy savings from SR, leading them to be more important than internal gains in the medium-VAV office (unlike in the small-CAV office). Solar gains only affect perimeter zones, and SR can typically save more energy in

situations where there is greater zone load diversity. Furthermore, although ELPD had almost the same standardized effect for Econ in both offices, it was much less relatively influential in the medium-VAV office because economizing did not require high internal gains to be beneficial.

- *Setpoints:* Higher heating setpoints, lower cooling setpoints, and smaller unoccupied period setbacks all led to larger alternative strategy impacts on energy use; together the three indoor air temperature control variables accounted for 38% of strategies' variance. Unlike in the small-CAV office, the zone temperature setpoint setback for unoccupied periods was influential, because the setback determined how frequently the HVAC system had to operate on weekends and holidays. (Unoccupied period control mattered little in the small-CAV office, where strategies' energy savings depended on occupants being present or high internal gains.)
- *Efficiencies:* Impacts were again smaller on average for more efficient mechanical systems, with cooling COP emerging as extremely important for both economizer and SR impacts. At least in this linear analysis, neither fan efficiency (despite the variable speed fan) nor heating efficiency (even though SR saved significant heating energy) registered as meaningful.

Figure 6 illustrates some of the most important influences for Econ+SR, which captured the bulk of the significant savings frequently available in the medium-VAV office. Figure 6a shows the influence of the heating setpoint and HDD on gas savings, which were greatest for buildings with heating setpoints greater than 20 °C in climates colder than about 1000 K·days. Figure 6b shows the role of CDD and COP on electricity savings, which were quite limited in the very hottest climates and also reduced with highly efficient cooling coils.

Figure 6 (a) Econ+SR gas savings vs. heating setpoint, colored by HDD; and (b) Econ+SR electricity savings vs. cooling COP, colored by CDD.

3.8 Detailed models and analysis as Supplementary Information

In addition to the linear regression models employed for the explanatory sensitivity analysis above, we also fit more detailed regression models, with interaction and quadratic terms, for changes in natural gas and electricity use separately. There are versions that include baseline consumption as a predictor, appropriate for retrofit evaluations when utility bills are available, and versions fit without baseline energy use, for use with new construction or other applications without existing energy histories. For both full versions, the fits were quite good, with every strategy and outcome having either $R^2 > 0.85$ or root mean square error (RMSE) $< 3 \text{ kWh/m}^2$, and often significantly better, as indicated in Table 13.

Table 13 Fit statistics for detailed prediction models available as a spreadsheet implementation in the SI.

Office	Outcome	Number of terms	RMSE in kWh/m ² (R^2)							
			EconLock	Econ	Econ+SR	D950	Econ+D950	Econ+SR+D950	2×VR	Econ(+SR)+D675
Small-CAV	Natural gas	32	0.5 (0.39)	0.5 (0.39)	-	4.1 (0.92)	4.2 (0.92)	-	4.6 (0.95)	4.1 (0.87)
Small-CAV	Natural gas, with BL	43	0.5 (0.47)	0.5 (0.47)	-	3.2 (0.95)	3.2 (0.95)	-	3.8 (0.96)	3.7 (0.89)
Small-CAV	Electricity	66	0.6 (0.90)	0.8 (0.91)	-	0.5 (0.89)	0.9 (0.93)	-	0.6 (0.91)	1.0 (0.89)
Small-CAV	Electricity, with BL	60	0.6 (0.93)	0.7 (0.93)	-	0.5 (0.90)	0.8 (0.95)	-	0.6 (0.92)	0.9 (0.91)
Medium-VAV	Natural gas	64	0.6 (0.72)	0.6 (0.73)	2.9 (0.92)	1.1 (0.63)	1.3 (0.73)	3.1 (0.93)	2.6 (0.85)	3.2 (0.91)
Medium-VAV	Natural gas, with BL	60	0.5 (0.74)	0.5 (0.75)	2.2 (0.95)	1.1 (0.64)	1.2 (0.76)	1.9 (0.97)	2.3 (0.88)	2.7 (0.94)
Medium-VAV	Electricity	70	1.2 (0.91)	1.3 (0.92)	2.1 (0.90)	0.6 (0.90)	1.3 (0.92)	2.1 (0.90)	0.7 (0.94)	2.2 (0.90)
Medium-VAV	Electricity, with BL	51	1.0 (0.94)	1.0 (0.95)	1.6 (0.95)	0.6 (0.89)	1.1 (0.94)	1.5 (0.95)	0.8 (0.93)	1.7 (0.95)

These detailed models are provided as Supplementary Information in a spreadsheet. There, in a simple interface, in a matter of minutes, a user can enter specific building and climate information and see estimates of all the alternatives' energy use impacts, with estimate uncertainties. Also available as a second supplement is a written document that addresses a series of specific strategy questions: when both economizing and DCV can be beneficial in the small-CAV office; when DCV should be added to Econ+SR in the medium-VAV office; when SR is inadvisable in the medium-VAV office; when integrated differential enthalpy economizing significantly outperforms EconLock; and how much additional energy 2×VR requires in each location. Implications for high performance buildings are also discussed.

4 Conclusions

Comprehensive simulations and sensitivity analyses were used to explore the energy saving potential of multiple alternative ventilation strategies relative to a Baseline strategy dictated by the ASHRAE minimum standard in a small office with a CAV HVAC system and in a medium office with a VAV system. Some of the most important results included:

- In the small-CAV office, DCV was usually the single component with the most energy savings, and most of its savings came from natural gas used for heating. However, combining economizer and DCV approximately doubled the median HVAC source energy savings of DCV alone, in part because an economizer prevented DCV from inadvertently reducing free cooling.
- In the medium-VAV office, economizer and SR were the dominant ventilation technologies recommended, and both heating (including reheat) and cooling savings were substantial. Adding DCV by itself usually saved little energy and was often counterproductive, but adding it to Econ+SR was often beneficial in colder climates.
- If the 74% of U.S. office floorspace reasonably represented by our modeling replaced the Base-line strategy with the best alternative, 53 TWh of primary energy annually would be saved, of which 36 TWh—with an annual value of U.S. \$1.25 billion—was estimated as still untapped given current technology adoption rates.
- In the small-CAV office, the most decisive factors influencing the alternative strategy energy impacts were HDD and occupant density. Those two predictors plus infiltration, the day length, ELPD, and heating and cooling setpoints and coil efficiencies explained about two-thirds of impact variance.
- In the medium-VAV office, zone temperature setpoints and HDD were the decisive influences. Along with the cooling coil COP and the infiltration rate, the heating setpoint, cooling setpoint, setpoint setback during unoccupied periods, and HDD explained about two thirds of impact variance.
- Other than the infiltration's influence on DCV savings in the small-CAV office, envelope parameters were not important predictors of alternative strategy impacts. However, the building conductive heat transfer coefficient did play a role in adjudicating some specific questions, like when both economizer and DCV were advisable in the small-CAV office, and when SR should be used in the medium-VAV office (in both cases, when the envelope was less insulated).
- Detailed models are supplied in the Supplementary Information in a user-friendly spreadsheet that allows fast estimation of energy impacts of alternative ventilation strategies for specific office buildings.

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