Benefit-Cost Analysis of Reduced Ventilation in a University Laboratory Building

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Introduction

Laboratory fresh-air ventilation rates on the University of Texas campus can be as high as 12 air volume changes per hour (12/hr), significantly increasing the energy required to heat and cool facilities. Maintaining such a high ventilation rate for laboratories ensures the safety of the occupants against harmful vapors and aerosols, however, it comes with a steep energy penalty. Since all of the ventilation air is exhausted into to the atmosphere, all fresh air brought into the building must be re-conditioned at a significant cost in the form of additional fan energy, chilled water usage, and reheated supply air in the building's heating, ventilation, and air conditioning (HVAC) system. According to the Design Guide for Energy-Efficient Research Laboratories1, "Laboratories typically consume 300,000 to 400,000 British Thermal Units (BTUs) per square foot per year or more, six to ten times the number of BTUs consumed in a typical office building." In an effort to reduce energy usage in campus buildings, the University of Texas at Austin Green Fee Committee funded a research project to estimate energy savings due to reduced ventilation rates in a laboratory on campus. As a parallel research focus, indoor air quality in the laboratory was also evaluated under baseline and reduced ventilation conditions to ensure that the health and safety of the building's occupants would not be compromised under reduced ventilation scenarios.

Need for research on energy usage and impacts on indoor air quality:

The U.S. Energy Information Administration estimates that energy used in buildings accounts for 40 percent of energy usage nationwide.1 Since buildings account for such a large amount of energy usage, a considerable amount of effort towards designing more sustainable and energy efficient buildings has gained traction, especially with the growing popularity of building rating systems such as the Leadership in Energy and Environmental

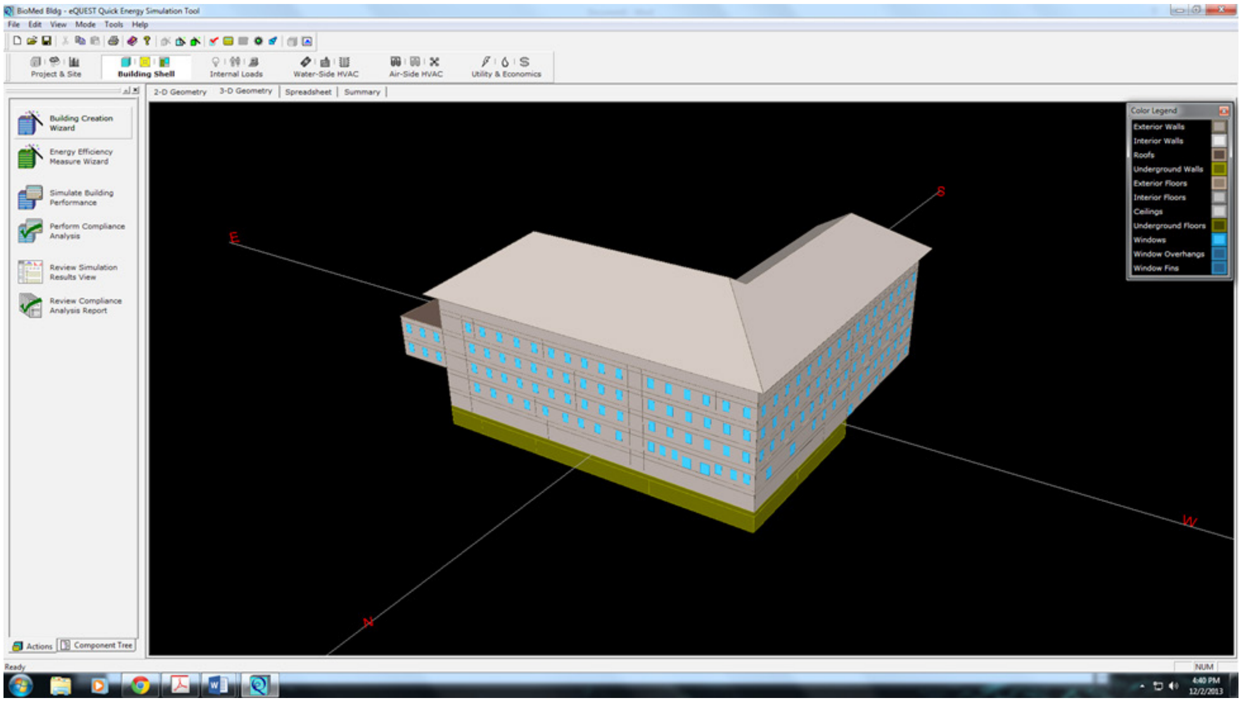

Figure 1: BME Building Modeled in eQuest.

Design (LEED) system. Many green building rating systems weigh points more heavily towards energy usage rather than towards indoor air quality. When evaluating the points awarded for the LEED Commercial Interiors v3 (110 points total), up to 37 points are awarded for energy savings measures and up to 17 points are awarded for indoor environmental quality, of which 10 points will impact indoor air quality (e.g., low emitting building materials and additional ventilation). 1 As buildings become more energy efficient, they are typically less well ventilated and indoor concentrations of harmful pollutants can be much higher indoors than outdoors.1 Since the average American spends up to 90 percent of their lives indoors,1 exposure to indoor pollutants is a major health concern. In fact, several researchers have quantified the chronic health impacts1 and life cycle costs1 of exposure to indoor air pollutants and the projected health benefits of improving indoor air quality can be substantial.1 Reducing energy usage in buildings is important, but it is essential to remember that building energy usage and indoor air quality and the health of the occupants are intrinsically linked. As such, we must explore these connections and evaluate buildings from a holistic point of view.

Developing an energy model of the Biomedical Engineering building

The Biomedical Engineering (BME) building on the UT Austin campus is a 142,000 square foot research facility that was constructed in 2008 and was certified as LEED Silver. Approximately 35,000 square feet of floor space was added to the BME building last year with a south expansion that was certified as LEED Gold. The building has six primary floors, with the top floor acting as mechanical spaces for the facility. The first floor is entirely below grade and the second floor is partially below grade. The BME building has nine air-handling units and dozens of heating, ventilation, and cooling (HVAC) zones, each with multiple purposes and heating loads. Three of the air-handling units are dedicated to teaching and research labs. These are supplied 100 percent by outdoor air and have flow rates of up to 40,000 cubic feet per minute (cfm). Because of the large demand for fresh air in laboratories, the three laboratory air-handling units are much larger than the other six air-handling units that serve office spaces. These labs have ventilation rates above four air changes per hour and sometimes as high as 12 air changes per hour.

The building was modeled using custom options in eQuest software (version 3.64), a free software program developed by the U.S. Department of

Energy.1 Modeling parameters were entered manually and were derived directly from the building blueprints and specifications. Internal building loads were unknown and varied by laboratory function, so all non-HVAC interior end uses were included in the model and default values were used when the true value was unknown. A schematic of the BME building shell created in eQuest is shown in Figure 1 below. Due to the complexity of the mechanical systems, only zones serviced by a single air-handling unit (AHU-1) were considered in the energy analysis. Using AHU-1 for modeling and experiments incorporates thermal zones on every floor of the building and in multiple spatial locations (e.g., south facing windows, below grade, etc.), in addition to multiple laboratory uses (lasers and optics, teaching classrooms, and working biology labs), providing an adequate sample to model the heating and cooling energy profiles throughout the building. The biggest limitation of this method is that heating and cooling (as well as indoor air quality) is dependent on building occupancy and occupant behavior, which is difficult to capture on a macro level. However, future field experiments will evaluate the effects of human behavior on energy usage and indoor air quality at a much smaller time interval.

As expected, reduced ventilation rates did result in annual energy savings compared to the baseline condition. Overall, the total reduction in outdoor supply air (i.e., make-up air) supplied by AHU-1 was 5,120 cfm, which resulted in 47,200 kWh of electric power saved due to space cooling and heat rejection. Additionally, 18,000 kWh of electric power was saved due to reductions in fan energy within the air-handling unit. Finally, 300-million BTUs of natural gas were saved due to reduced heating load. This was likely attributed to a lower heating demand during VAV reheat operations. The University of Texas at Austin has chillers with a coefficient of performance (COP) of approximately 4.5. The eQuest model used a default COP of 5.2 (electric input ratio of 0.19 BTU/BTU) and the eQuest model provided space-cooling energy in electric power. However, it does not explicitly determine how much chilled water is required to meet the cooling energy demands in the building (although it can be calculated with some effort from the detailed hourly reports). The cooling energy of the chilled water used in the cooling coils can be calculated using electric power and the COP of the chiller as shown in Equation 1.

The University of Texas pays an average cost of $0.165 per ton-hour of chilled water, so a savings of 69.8K ton-hours of chilled water is approximately equal to $11,500 per year. Electricity costs are approximately $0.055 per kWh, so the reduction in fan energy (18,000 kWh) saves approximately $1,000 per year. Assuming that the natural gas boiler has an efficiency of 1.0 and that energy from the natural gas is fully converted to steam, a natural gas savings of $5,500 per year and total overall energy savings of $18,000 per year across the 40 rooms served by AHU-1 can be expected.

Field measurements of energy usage
Several rounds of field measurements were organized to determine overall energy costs at baseline ventilation conditions as well as at a lower ventilation rate. Five rooms on four different floors serviced by AHU-1 were considered for the analysis and field measurements were collected during the academic year (i.e., building was occupied) in the winter, spring, and summer seasons. The BME building is equipped with a building automation system (BAS) that collects airflow and temperature data with sensors located throughout the building. Airflow measurements from the BAS were verified with field measurements with an airflow capture hood (Airflow Instruments Prohood). Temperature and relative humidity were verified with data loggers (Onset U12-006) placed in the five rooms. During the field experiments the BAS was used to collect temperature and relative humidity data before and after the glycol heat recovery system (pre-heat coil), the heating coil, and the cooling coil in the air-handling unit. Temperature and relative humidity measurements were also collected before and after the reheat coil in the supply ducts servicing each room. Finally, airflow measurements from the BAS were collected for each room (supply and return).

Each ventilation scenario was run for between one and two weeks and in sequence with one another in order to use similar outdoor meteorological conditions. Heating and cooling energy use was determined by airflow rates and equations for latent and sensible heat for ventilation air passing through the three heat exchangers in the air-handling unit. Electrical fan energy use was collected from the BAS system. During the winter test experiments, it was determined that the glycol recovery heat exchanger was fully operational and was effectively pre-heating cold outdoor air using recycled exhaust air. The hourly energy savings in the five labs from using the glycol heat recovery unit ranged from $1.60 to $3.30 per hour depending on the ventilation flow rate. In addition, average hourly energy costs for the five labs decreased by 35 percent (ρ <0.00001) during the ventilation reductions, as shown in Figure 2 below.

Estimated annual energy savings in the

$Q_{chiller}$	=	COP * P_{elec} (Eqn. 1)
$Q_{chiller}$	=	chilled water energy [kWh]
COP	=	coefficient of performance = (electric input ratio)$^{-1}$ [kWh/kWh]
P_{elec}	=	electric energy required for cooling [kWh]
$Q_{chiller}$	=	5.2 * 47,200 kWh = 245,440 kWh = 69,790 ton-hour of chilled water required

40 rooms supplied by AHU-1 approach $31,000 per year. The difference in energy costs between the eQuest model and the field measurements is likely due to differences in internal heat sources in the laboratories (defaults were used in the eQuest calculations) and because eQuest uses typical meteorological year (TMY2) data for modeling outdoor meteorology, whereas the field experiments incorporated measured outdoor temperatures and relative humidity.

Field measurements of indoor air quality
Indoor air quality measurements were collected in parallel with the energy field measurements. Pollutants of concern included volatile organic compounds (VOCs) and ozone. Volatile organic compounds were collected using Tenax-TA with thermal desorption and gas chromatography/mass spectrometry. Quantities of compounds were estimated by using an internal standard of 4-Bromofluorobenzene and an assumed response ratio of 1.0. Samples were collected using a sampling rate of 25 milliliters per minute for four hours and were collected in accordance with U.S. Environmental Protection Agency methods (TO-17). Ozone was measured with a portable UV-absorbance ozone analyzer. All indoor air quality measurements were made concurrently with outdoor measurements in the air-handling unit fresh air intake.

Quantification of individual VOCs was difficult because of their low concentrations, even after the ventilation rate was reduced. Therefore, a total VOC (TVOC) concentration was used to quantify volatile organic compounds. Concentrations of TVOC were estimated using the total mass under the mass spectrometry spectra curve from a retention time of 6 to 16 minutes, and then using the molecular weight of toluene to convert to a concentration in parts per billion (ppb). An average increase of 72 percent ($\rho < 0.05$) in TVOC was observed when the ventilation rate was reduced. Although TVOC concentrations increased under the reduced ventilation scenario, all of the measurements closely mimic outdoor air and were far below 53 parts per billion, which is considered an 8-hour exposure limit for sensitive individuals.

The indoor/outdoor ozone concentration ratio (Figure 3) increased by 23 percent ($\rho < 0.05$) under the reduced ventilation scenario and the average measured indoor ozone across the five rooms increased by roughly 10 parts per billion or 56 percent ($\rho < 0.05$). The increase in ozone in the laboratories under reduced ventilation conditions is likely due to decreased ozone deposition to surfaces due to a lower air velocity in the room . This phenomena will be further explored in future field

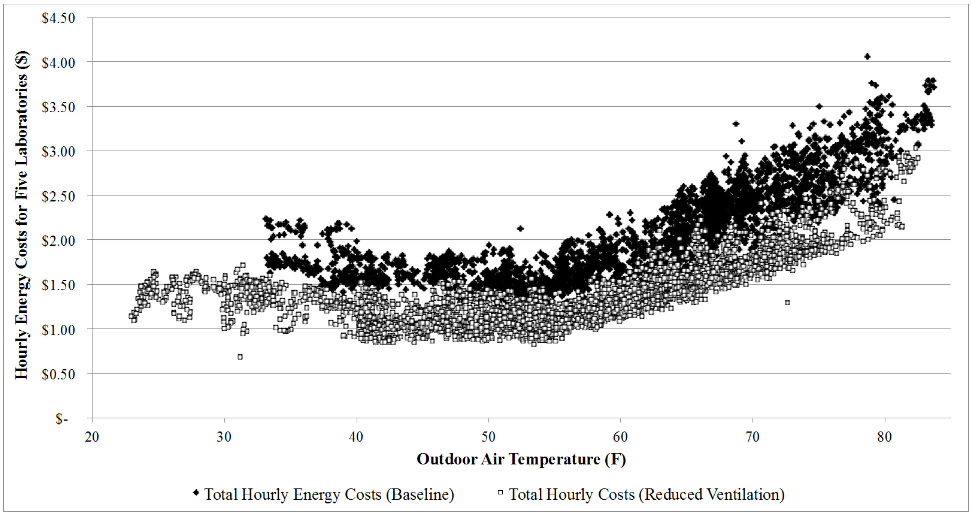

Figure 2: Measured hourly heating and cooling energy costs in five labs in the BME building under high and low ventilation conditions.

experiments. Ozone exposure has been linked to respiratory related mortalities and hospital admissions and a recent study linked indoor ozone exposure to ozone-related mortalities at very low ozone concentrations . Therefore, the increase in indoor ozone exposure under the reduced ventilation scenario is the greatest cause for concern for the health of the occupants in the BME building.

Predicted benefits and costs

The predicted health costs of increased ozone exposure in the BME building can be estimated using the CO3B-Calc model. The CO3B-Calc model uses health-impact functions used in analyses by the U.S. Environmental Protection Agency to determine the economic costs of exposure to harmful air pollutants such as ozone. The health impacts are converted to disability-adjusted life-years (DALYs), which can be quantified with a monetary values. Assuming that the BME building labs are regularly occupied by 300 people ranging in age from 18 to 24 who are in the labs 20 hours per week for 30 weeks per year (typical academic year), the increased number of ozone-related annual DALYs due to reduced ventilation is about 0.01 DALYs per year. Each DALY is equal to $150,000 per DALY, which results in an increased health burden of $1,600 per year. The health burden due to ozone exposure can be significantly reduced with the addition of activated carbon filters in the air-handling unit. Using the CO3B-Calc model and assuming that the carbon filters have a single pass removal efficiency of 80 percent results in a 79 percent reduction in indoor ozone concentration. This, in turn, results in an average health benefit of 0.02 DALYs per year or approximately $3,100. Installation of the carbon filters in one BME air-handling unit would cost about $10,000 for the filter and labor and the initial pressure drop across the filters is nearly the same as the existing bag filters, which eliminates the energy penalty. When combining the energy savings with the improved health benefits and the additional costs of the filters, the net benefit (or total monetary savings) for AHU-1 in the BME building is $24,000 per year. Limitations of this analysis include the health impacts of aerosols and chemical compounds under the two ventilation scenarios and the carbon filter scenario. A more in-depth analysis on this topic will be explored in more detail after the next round of field experiments.

Conclusion

In conclusion, ventilation reductions paired with carbon filtration in the BME building could net significant energy savings and health benefits. This strategy could be implemented in newer laboratory buildings on campus that allow for the automated control of ventilation air such as the new Dell Medical School or the Engineering Education and Research Center. Additional field experiments are currently planned for August and September 2014 and will include field-testing of activated carbon filters to determine the operational characteristics of the filters and the impacts on indoor air quality when compared the baseline and low ventilation conditions without carbon filters.

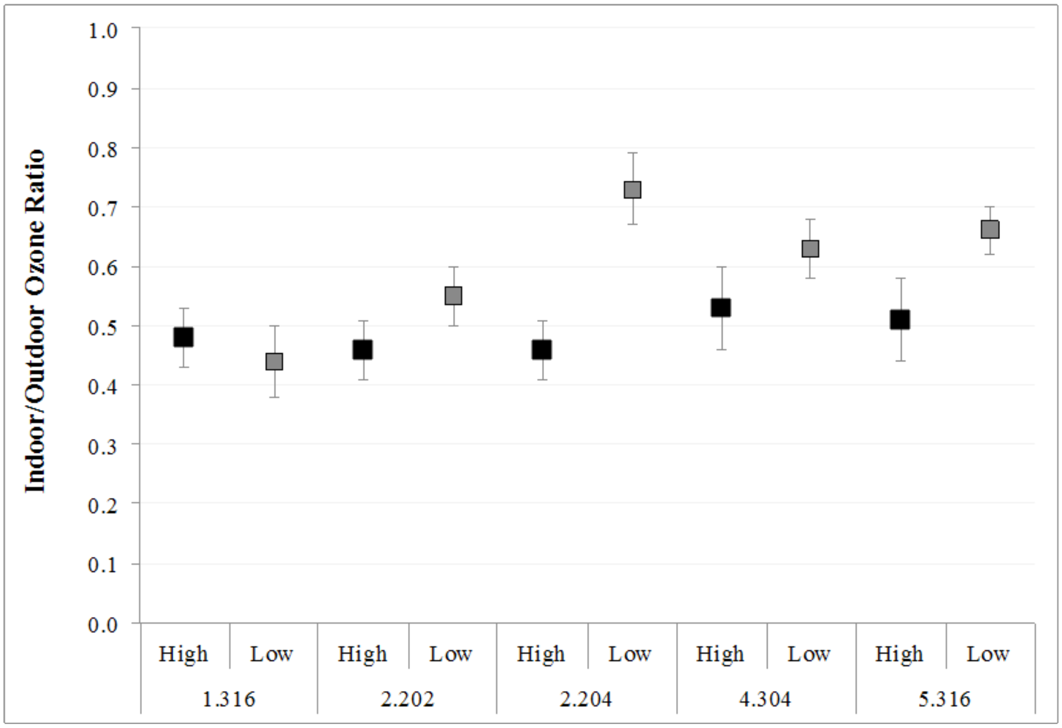

Figure3: Measured indoor/outdoor ozone ratios under high (baseline) and low ventilation conditions (numbers below the high and low measurements are the lab room numbers in the BME building).

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