Design for Off: Key Mechanical Engineering Design Features for Significant Energy Savings

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ABSTRACT

In spite of energy code and technology changes over the last 30 years, the energy use of office buildings in the Pacific Northwest has barely changed since the mid-1980s.[1] While energy codes have made undeniable progress regulating the work of architects and lighting designers, they have made very little progress influencing the work of mechanical engineers. The code has regulated the efficiency of equipment specified by engineers, but has had little impact on the energy use of buildings. To make further significant progress, changes must be made in some important HVAC design features.

Ecotope recently provided engineering for two 36,000SF office buildings which use about 1/3 the energy of a typical office building with EUIs of 22 and 26 KBtu/ft2/yr. The success of these designs can be duplicated. The key mechanical design strategies used to achieve these results were the following:

1. **Dedicated Outdoor Air Systems** (DOAS) with either Energy Recovery Ventilation (ERV) or Demand Controlled Ventilation (DCV).
2. **Complete zoning** using heating and cooling equipment that can be completely shut off at the individual zone level.
3. **Low energy fan selection** targeting a minimum of 1.5CFM/Watt.
4. **Right sizing HVAC systems** with ventilation levels at no more than 130% of ASHRAE 62.1 and heating and cooling equipment sized at no more than 120% of the ASHRAE design loads.

Introduction

Over the last 30 years significant progress has been made to improve the efficiency of commercial buildings with a combination of codes and standards, improved technology, and design evolution. For example,

- The changes in lighting efficiency have been dramatic. Audits from the mid-1980s document new office lighting power density (LPD) at about 2 W/sf (Katz 1989, Palmiter 1987). In the 2002-2004 NEEA baseline of new buildings, the office LPD was about 1.0 W/sf (or less) (Baylon 2008). There is no doubt that this transformation reduced the energy impact of lighting and along with code-required lighting controls lighting energy reductions over this period may have exceeded 60%.

[1] Energy use in this paper will be normalized on a per square foot of conditioned floor area basis and reported as an annual Energy Use Intensity (EUI) in KBtu/ft^2/yr.

- Envelope and window performance provides another success. Envelope insulation has been steadily increasing over the last 30 years driven largely by code requirements. Codes and technology improvements have driven significant efficiency improvement in windows. The standard window glazing is now almost exclusively double glazed with high quality low-ϵ coatings. These window types have been substituted for single glazing with shading films. Average window thermal performance has improved by at least a factor of three in this period. Unfortunately, architectural practice has resulted in larger window areas which partly counter the effects of the improved performance.
- HVAC equipment technologies and efficiencies have also improved during this time period with new heat pump technologies coming on the market and incremental improvements in combustion, fan, and motor efficiency requirements.

In spite of these changes (and many others) the EUI of office buildings has barely changed since the mid-1980s. A sample of 25 office buildings from the period (in Seattle, Bellevue, and Portland) showed an EUI of slightly more than 75 kBtu/sf (Katz 1989). In the 2002-2004 new building baseline, the average office EUI was 72 and the average of the Commercial Buildings Stock Assessment (CBSA) was 82 (Baylon 2008, Cadmus 2009). This doesn't indicate much progress.

The lack of progress in reducing EUIs in commercial buildings has been attributed to a range of factors, from the advent of plug-in heaters under desks to the ubiquitous presence of servers and computers. That said, in 1988 a typical server used 40-50 kW and took most of a floor. Now it uses 5 kW and takes up a small closet. The desk computer of 1990 drew about 300 W while current models are about 100 W and have the computing power of the 50 kW server of the late 1980s. So, while we have many more computers and servers we have also seen dramatic reductions in energy use for these devices. As for the plug-in heaters, there was probably never a time when that was not a standard part of office work areas.

If building envelopes and lighting systems have improved dramatically, HVAC equipment efficiencies have increased incrementally, and internal equipment loads have not increased substantially, why hasn't the energy use of commercial buildings gone down significantly over the last 30 years? The answer has to lie with the design of building mechanical systems. The actual explanation is likely a combination of changing engineering standards around ventilation and comfort, an increasing willingness to size HVAC equipment at a level several times the design requirements to improve the perception of future occupant comfort, flexibility, and an increasing tendency to design to prevent litigation risk. In short the evolution of the design of mechanical systems has been moving toward designs that require more rather than less energy use over the last two or three decades.

Over the last decade Ecotope mechanical engineers have been involved in the design of several dozen commercial buildings and have done detailed auditing in several dozen more. This experience has afforded us some perspective on the disconnect between engineering practices and efficiency. The Ecotope-designed buildings are routinely using about 1/3 the total energy of a typical building. We call our overall approach "Design for Off" in recognition of the fact that there is no more efficient mechanical system than one that is turned off. Our goal is to design the system so that equipment is turned off or down whenever possible as opposed to the typical commercial HVAC system design which is running at full capacity during all occupied hours.

The mechanical design strategies which are critical to the high performance achieved are:

1. **Dedicated Outdoor Air Systems** (DOAS) with either Energy Recovery Ventilation (ERV) or Demand Controlled Ventilation (DCV).
2. **Complete zoning** using heating and cooling equipment that can be completely shut off at the individual zone level.
3. **Low energy fan selection** targeting a minimum of 1.5CFM/Watt.
4. **Right sizing HVAC systems** with ventilation levels at no more than 130% of ASHRAE 62.1 and heating and cooling equipment sized at no more than 120% of the ASHRAE design loads.

These design elements could be replicated in most new construction and retrofits and have a significant impact on overall building energy use.

Dedicated Outdoor Air Systems (DOAS)

The most common modern HVAC systems in commercial buildings combine all HVAC functions (heating, cooling, and ventilation) in a single system. Often this single system (such as VAV) serves the entire building or very large portions of the building. This requires the entire system to be energized whenever the building is occupied to provide conditioning and ventilation even if only a single zone is occupied. When a single system is used to supply heating, cooling, and ventilation, the fans must be sized to provide for the largest demand (typically cooling).

When we split the ventilation system from the heating and cooling system (DOAS), we allow for significant energy savings. The fan and ducts can now be sized only as large as necessary to carry the ventilation air. This is typically only a fraction of the fan size necessary for cooling or heating[2]. The heating and cooling equipment can now be turned off unless there is a call for thermal conditioning. Ductless systems can be used to deliver heating and cooling such as is available with Variable Refrigerant Flow (VRF) systems, ductless heat pumps (DHP), radiators, passive chilled beams, or radiant panels. These systems greatly reduce or eliminate fan energy associated with heating and cooling. The cost of splitting the systems into their functional parts is made up in the significantly reduced size of the fans, ducts, diffusers, soffits, mechanical spaces, etc…

To further reduce the energy use associated with ventilation, Energy Recovery Ventilation (ERV) or Demand Controlled Ventilation (DCV) should be part of system design. For spaces with predictable occupancy such as offices or classrooms, energy recovery ventilation should be used in heating climates to temper the incoming ventilation air and reduce heating energy demand. If very efficient heat exchangers are used (>70% sensible effectiveness), there is no need for auxiliary tempering of ventilation air even in relatively extreme heating climates.

In zones with irregular occupancy, such as conference rooms or auditoriums, DCV can be used to dramatically reduce fan energy and conditioning energy. If zones are empty or lightly occupied, properly designed DCV will cut ventilation air delivery to a fraction of the fully occupied levels. Typically this is accomplished with sensors which use CO_2 concentration as a proxy for occupancy and with variable speed fans (VFD) to provide a minimum level of ventilation during occupied hours and increase fan speeds to maintain a CO_2 setpoint (e. g. <1000 ppm).

[2] Significantly reduced duct installation costs are an additional benefit of this strategy.

Zoning

Typical commercial central HVAC systems (such as VAV systems) include equipment that runs continuously during all occupied hours regardless of space occupancy or thermal conditioning requirements. Furthermore many systems supply the entire building-- or large portions of the building--continuously even if there is only occupancy in a single zone. Significant savings are attainable by zoning the heating and cooling equipment to provide individual temperature control to each zone. A zone in this sense is any area in the building separated by walls and/or doors from other areas of the building.

Coupled with the other measures mentioned above, this simple concept of separate zoning leads to large energy savings. With a DOAS system, only ventilation air is being continuously supplied during occupied hours (with either heat recovery or CO_2 control). All heating and cooling equipment is then small zonal equipment that can provide heating or cooling to a single smaller zone and will only operate if there is a call for heating or cooling in that zone. This eliminates large, continuously operating fan systems. It also eliminates central systems that swing back and forth between heating and cooling in an attempt to satisfy different zones in the building (or different portions of the same zone).

Examples of equipment that can easily meet this zoning intent include ductless heat pump or VRF fan coils, 4-pipe fan coils with 2-way valves and pump controls, chilled beams, and radiators. The case study examples below show how we have applied these design principals with extremely good results in creating low energy buildings.

Fan Selection

Fan energy can make up a significant fraction of total building energy in typical commercial building HVAC design. The measures noted above will dramatically reduce fan energy. In addition to these measures the design should be targeted to reduce static pressure and to use efficient fans. We propose a "rule of thumb" maximum fan energy of 0.66Watt/CFM for ventilation air delivery.

Reducing air supply to only what is needed to meet ASHRAE 62.1 requirements can leave some spaces with little air movement and a difficult distribution problem. For added comfort, destratification, and air mixing we propose the use of ceiling fans specified at 300 CFM/watt to provide for the desired air movement at a fraction of the energy use.

System Sizing

Typical engineering design tends to be extremely conservative when sizing HVAC equipment. Undersized equipment (ventilation air volumes and conditioning capacity) can lead to poor thermal comfort, poor indoor air quality, and lawsuits. Oversized equipment can lead to noise and comfort problems, excessive energy use, and higher cost, but rarely leads to lawsuits (though it has been associated with inadequate humidity control in warm humid climates).

Load calculations are often done early in the design process when usage and final design are not settled and it is customary for engineers to include "safety factors" to account for unknowns such as future changes in use or occupancy. Ventilation rates are often specified as percent of total flow and damper settings often get set to guarantee at least that amount of air. Furthermore, ventilation and thermal load calculations are done using conservative 'worst case' assumptions. For example, cooling load calculations assume full occupancy on the hottest day of the year with the sun streaming in and all lights and appliances running. In practice it is not at all uncommon to see ventilation rates and installed conditioning capacity of over twice what would be arrived at using careful calculations done to ASHRAE standards. The result is excessive mechanical system usage (including fan and thermal energy). Significant savings can be achieved simply by constraining equipment sizing to near 100% of the ASHRAE-calculated heating, cooling, and ventilation loads. The design can accommodate potential future expansion by allowing for additional capacity to be added in various ways without oversizing the equipment originally installed.

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Costs

Typical HVAC systems are comprised of a primary air handler, heating and cooling production equipment and heat exchangers, distribution ductwork sized for peak cooling, economizer systems and a digital control system. Typical current cost for a zoned VAV system is about $20/sf for office buildings.

Proposed systems would trade off potentially more expensive heating and cooling plants and Energy Recovery Ventilation systems for less expensive distribution systems, deletion of economizer systems and stripped down controls. The HVAC systems for the two office building case studies below were installed for $10/sf for the RFM office building and $14/sf for the King County Housing Authority (KCHA) office building.

Office Buildings

In 2011-2013 Ecotope provided mechanical engineering for two 36,000 SF office buildings. The first was a redevelopment of an old warehouse for an architectural firm, Rice-Fergus-Miller (RFM) in Bremerton, WA. The second was an office rehab of an old strip mall retail building for the KCHA in Tukwila, WA. Both of these buildings incorporated the "Design for Off" strategies and were designed around a VRF system with a dedicated outside air energy recovery ventilation system. The overall measured performance for the RFM project is about 22 KBtu/ft^2/yr for the first three years that the building has been in operation. This does not include the impact of a 9 kW PV array that is installed on the building (Oram 2013a). The KCHA building has a measured EUI of about 26 KBtu/ft^2/yr over the first 1.5 years of operation. The HVAC construction budget in both of these buildings was a remarkably low $15/sf (Oram 2013b).

The RFM building included very high levels of thermal insulation and an innovative "passive/active mode" natural ventilation and natural cooling system. Some of the energy savings can be attributed to those measures. However, the KCHA building is good indication of the impact of our proposed measures alone on a typical office building. Other than the extremely low energy use, this building is otherwise unremarkable. The thermal envelope is mediocre, not even meeting the requirements of current energy codes, and no operable windows are available for natural ventilation. It is very much a typical small office with typical occupancy and office equipment, very similar to the tenant's other office building across the parking lot which has a VAV system and uses three times as much energy (EUI=80 KBtu/ft^2/yr) (Oram 2013b).

The end use breakdown for a typical office from the 2003 CBECS is shown below in Figure 1 compared to the RFM Office. Note that the HVAC energy end uses are nearly eliminated with lights and plugs the only significant remaining end uses in the highly efficient office.

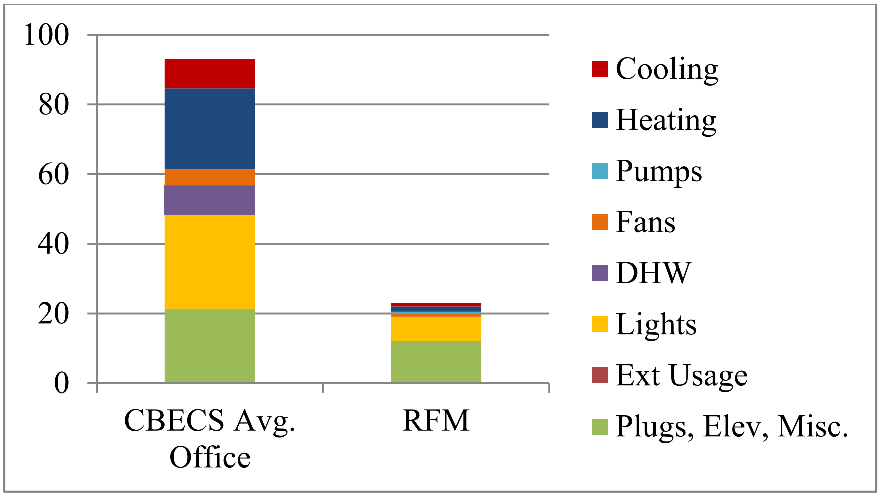

Figure 1. End use breakdown of typical office vs. RFM office in EUI (kBtu/SF/yr).

The experience with these two buildings is in sharp contrast to the typical office buildings in regional baseline studies. Figure 2 below shows the site energy use of regional and national office buildings in comparison with our two case studies. (Uhlig 2013, Cadmus 2009, Oram 2013a, Oram 2013b, USEIA 2003).

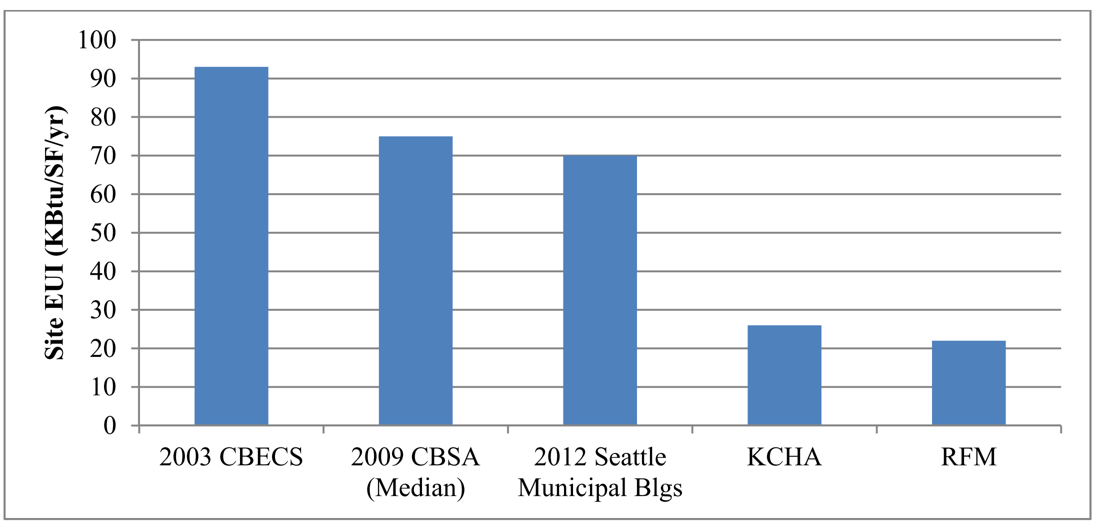

Figure 2. Energy performance of national and regional office buildings.

Modeling and billing analyses have indicated that well over half of the energy use in a typical office building in the Pacific Northwest is associated with HVAC (Heller 2011). Regional office buildings that we have audited tend to have oversized fan systems operating continuously during occupied hours; often with fixed damper settings and relatively large zones. In many of these systems simultaneous heating and cooling is common across zones during the heating season. Often these systems will switch back and forth between heating and cooling throughout the day in an attempt to keep various zones satisfied (Heller 2013a).

Fire Stations

In 2009, Ecotope provided mechanical systems design for a new fire station, FS72, for the City of Issaquah WA; an 11,000 SF facility, to achieve high efficiency and LEED platinum status. The overall EUI of this building over the first two years of operation was just 28 KBtu/ft^2/yr. After the impact of a rooftop PV array is accounted for, the station has an EUI of 22 KBtu/ft^2/yr (70% less than a typical regional fire station). The mechanical system incorporated the concepts noted above in the form of zoned radiant slabs and 4-pipe fan coils and heat recovery ventilation. The building is highly insulated and the heated and chilled water and domestic hot water are supplied by a small ground source heat pump (GSHP) system. The combination of these measures reduced fan energy to a very low level and nearly eliminated heating and cooling energy requirements. (Heller 2013b).

In contrast, there were six fire stations built in the city of Seattle in the last five years. These are modern fire stations with roughly the same size and occupancy as the Issaquah station. Ecotope audited three of these stations and collected billing data for about 30 of the Seattle fire stations, including these newer stations. The average EUI for the new fire stations is about 100 KBtu/ft^2/yr, nearly four times the Issaquah station built at about the same time and with similar budgets. The average of existing Seattle fire stations built or rehabbed before 1995 is also about 100 KBtu/ft^2/yr.

A neighboring fire station of the same size operated by the same jurisdiction was used as a basis for design analysis. The building was occupied two years earlier and earned a LEED Silver certification. It has an annual EUI of about 96 KBtu/ft^2/yr based on the energy bills for the first two years of occupancy. A detailed audit was completed on this existing fire station and an eQuest model was built and calibrated to predict actual energy bills to within 10%. The annual energy end use fractions predicted from this model are shown in the figure below. HVAC energy use makes up well over 50% of the total energy use of the fire station. Some savings could be obtained through additional lighting efficiency or controls and through better thermal insulation or higher efficiency equipment. However, large savings could only be achieved with a significant change to the HVAC system design.

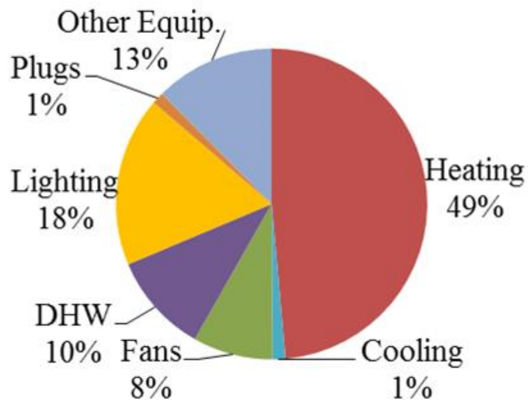

Figure 3. Energy end use breakdown for typical regional fire station.

Figure 4 below shows the performance of FS72 compared to other regional and national benchmarks for fire stations (Uhlig 2013, NBI 2013, Cadmus 2009, Heller 2013a, Heller 2013b, Baylon 2008, USEIA 2003)

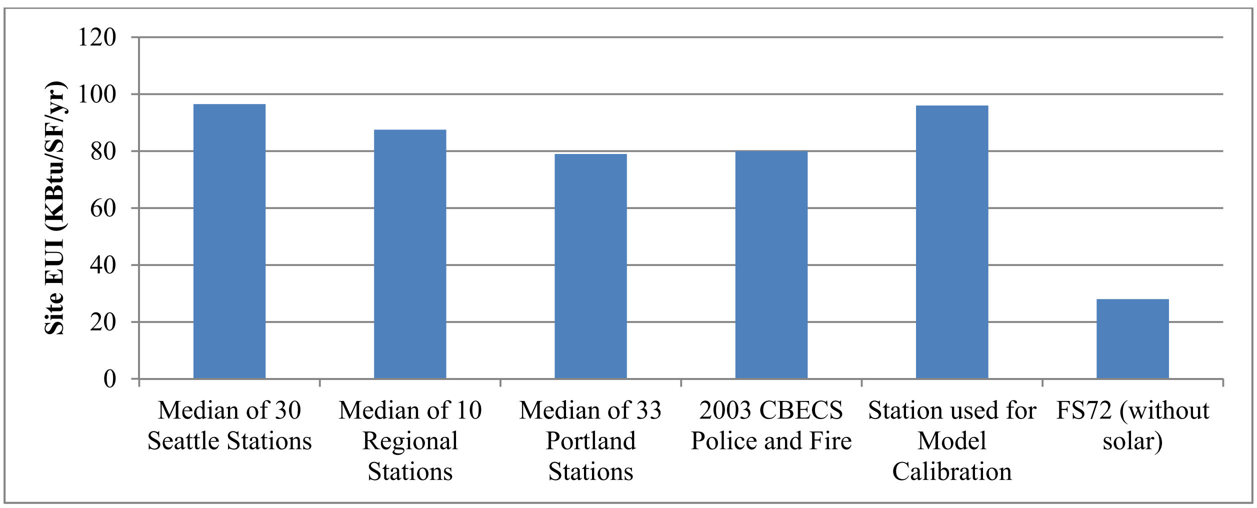

Figure 4. Energy performance of national and regional fire stations.

Some of the remarkably low energy use of FS72 is associated with the high levels of thermal insulation and the highly efficient heat pump system. However, the majority of the energy reductions in comparison to the typical regional station can be attributed to the HVAC design concepts listed above. While a GSHP system can be a relatively expensive option, the system for this building is relatively small due to the various optimization measures taken to reduce system capacity requirements; it has an installed ground loop capacity of only about 1-ton per 1200ft^2 of conditioned building area. The high degree of envelope insulation coupled with heat recovery ventilation and careful sizing to the 100% design loads allowed for only eight 300ft vertical wells to be drilled in the parking area and three residential scale 5-ton water-to-water heat pumps to provide domestic hot water, heating, and cooling. This is a 24-hour facility, but the only HVAC equipment that runs continuously is the energy recovery ventilator.

In contrast, the other fire stations audited by Ecotope all included large ducted HVAC systems with continuously operating fans and fixed outside air damper settings. Two of these facilities were awarded LEED Gold ratings, but have measured EUIs of greater than 100KBtu/SF/yr. Both of these facilities included VRF heat pump technology, but they both were integrated with oversized ventilation systems without heat recovery. In all cases the HVAC equipment was oversized and the ventilation rates were oversized in comparison with ASHRAE Standard 62 calculations. Note that these stations had all received commissioning services and were operating per the design intent (Heller 2013a).

Quantification of Savings

It is difficult to reliably quantify savings achievable through incorporation of the "Design for Off" measures identified here. To do so with a modeling study would require a huge number of prototype buildings and broad assumptions regarding the base case building systems. There are not enough buildings incorporating these design features to develop a savings estimate based on a statistical survey. However, a savings prediction based on a comparison of our case studies to the large-scale samples of buildings available in national and regional studies referenced above indicates that average reductions of 50% or more are achievable.

Ecotope developed a "Sensitivity Analysis" modeling study for the New Buildings Institute to explore the energy impact of a wide range of design and operations variables on the performance of medium office buildings in various climate zones across the country (Heller 2011). The goal was to identify those measures with the highest potential impact.

A parametric modeling study (using the NREL medium office prototype) was undertaken using eQuest. The base case was modeled to ASHRAE 90.1 2007 standards. Design and operational variables affecting energy use were identified and varied one at a time to identify the relative impact of each. The base case model was run with the variables at ASHRAE 90.1 2007 levels, at a "high performance" level defined by typical best current practice or aspirational standards (eg. ASHRAE 189), and again at a "low performance" level defined by typical poor practice or indicative of older existing buildings.

The results of the modeling matrix for the Seattle climate are shown in the figure below. The zero line indicates the performance of the baseline building (with an EUI of about 60 KBtu/ft^2/yr). The red bars indicate the percentage increase in energy use if that variable were to be of a "low performance" condition. The green bars indicate the percentage energy reduction in total building energy use associated with a "high performance" condition of that variable.

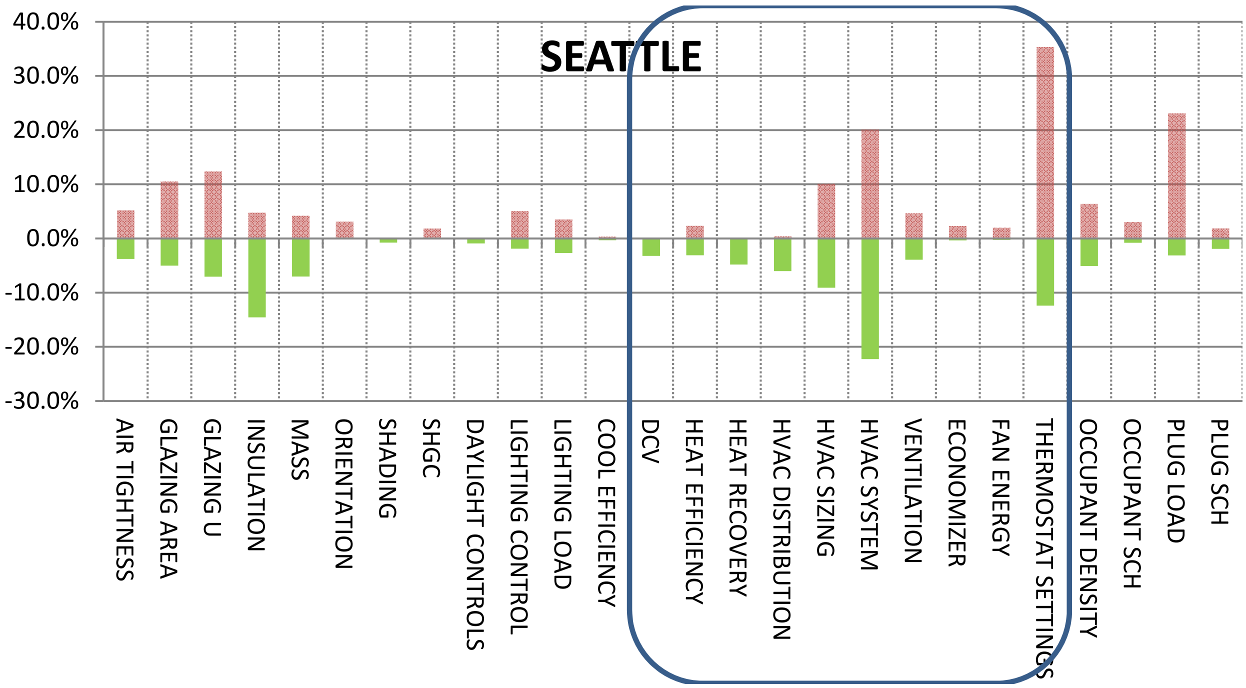

Figure 5. Sensitivity analysis of impact of individual variables on the performance of a medium office prototype in the Seattle climate.

Some variables are relatively unimportant in a typical office in the Seattle climate. Window shading, Solar Heat Gain Coefficient, and cooling efficiency all have very little impact. Significant savings are still available by moving the thermal envelope of the building closer to the high levels of efficiency targeted by the ASHRAE 189 standards. The other obvious area that this sensitivity analysis identifies as critical for building performance in the Seattle climate is the HVAC design (noted inside the rectangle in the figure above).

This study was not intended to quantify actual savings, but to provide an indication of the level of impact that each of these measures can have alone on the performance of buildings. The HVAC measures modeled in this study were not designed to model the impact of the Design for Off strategies (DOAS is not modeled). Even still this study shows that large savings are available in the HVAC system design area.

The variable labeled “HVAC System” is a Packaged Rooftop unit in the base case, a zoned heat pump system in the “high performance” case, and a VAV system in the “low performance” case. This captures some of the impact of a zonal system. Note that the difference between the VAV system and the zonal heat pump system is about 40% of the total building energy use. The variable labeled “Thermostat Setting” also captures some of the effects of zoning as it shows the effect of central system cycling on a building with tight thermostat deadbands. This study shows that the combined effects of all of these HVAC design measures is a more than 50% reduction in the total energy use of the building.

Implications

Some HVAC system types are much more easily adapted to comply with our proposed “Design for Off” measures. Ductless VRF heat pumps, chilled beams, or radiant panels coupled with a ducted heat recovery ventilation system work very well. Ducted VAV systems and most packaged rooftop equipment designs cannot be easily adapted to comply. This implies a significant shift in typical HVAC mechanical engineering design practice. Most engineering firms have not been designing in this manner and it will take considerable outreach and training to change this. The current HVAC equipment and distribution channels in the USA are not oriented around the equipment best suited to this design paradigm. However, many product representatives and distributors are rolling out new products that can meet these criteria. As the market shifts, these people will play a significant role in providing the outreach and education needed to get these newer products and methods incorporated into new designs.

Our experience with the case studies noted above is that this "Design for Off" approach can be carried out for the same mechanical system budget as other typical HVAC approaches while yielding large operational cost savings. It does, however, imply that the design process and approach must change from current typical design. This design approach requires very careful sizing and selection of ventilation and conditioning equipment coupled with more attention to controls and occupancy schedules. Separate systems must be designed for ventilation supply and for heating and cooling.

Conclusions

While significant effort has been put into codes and standards and technologies to reduce energy use in commercial buildings over the last 30 years, the results have not been dramatic. To achieve large reductions in energy use we must make a shift from focusing on the efficiency of the parts and pieces of the buildings to focusing on the integrated design elements. Specifically the HVAC systems require a commitment to design approaches that integrate these systems with both building design and building occupancy. Ecotope has demonstrated in case study buildings that it is possible to reduce the total energy use by about a factor of three through careful design. The primary features of our "Design for Off" approach can be replicated in most commercial buildings with little impact on the overall HVAC budget.

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