Sensitivity Analysis: Relative Impact of Design, Commissioning, Maintenance and Operational Variables on the Energy Performance of Office Buildings

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ABSTRACT

The goal of this study is to compare the magnitude of energy impact that modifications to design, operation and tenant behavior characteristics have on total building energy use. The DOE/NREL mid-size office prototype[1] was used as a representative building type for this analysis. A set of 28 distinct building features was identified representing physical and operational characteristics of buildings that affect total building energy use. For each characteristic, a range of performance values was identified representing poor, baseline and good practice with respect to building energy performance. These values were determined from a range of published building characteristic studies, field research currently underway, and professional judgment[2]. The impact on total building energy use was evaluated as each variable was modified from low to high performance individually, while all other characteristics were kept at the baseline performance level. To more accurately represent interactive effects, good and poor practice packages of measures were also analyzed to represent various combinations of these strategies. The analysis was conducted using weather data from 16 different cities to represent the range of climate types identified by DOE/ASHRAE for US design criteria[3]. The work was completed jointly by Ecotope and NBI. Results of this analysis demonstrate that building operating strategies and tenant behavior represent significant impacts on building energy use. In order to achieve significantly increased levels of building efficiency the role of tenants and operators on building energy use will need to be systematically addressed. The study also demonstrates the potential impact of continued efforts to mandate or deliver increased energy efficiency through the design process. These results are summarized in the overview below, and in the accompanying report.

Overview

Although nearly everyone interacts with buildings on a daily basis, if you were to ask most people about building energy efficiency, the vast majority would describe physical features like insulation, efficient HVAC and lighting, or alternative energy systems. The perception in the market is that the responsibility for building energy performance is in the hands of architects and engineers and is relatively set once the building is constructed. This perception represents a significant barrier to broad societal goals to substantially improve building energy performance and reflects an extremely inaccurate perception of how buildings work. In fact, a significant percentage of building energy use is driven directly by operational and occupant habits that are completely independent of building design, and in many cases these post-design characteristics can have a larger impact on total energy use than many common variations in the design of the building itself.

This study was designed to try to quantify the degree to which operational energy-use characteristics affect building energy use and compare these variables to the relative impact of what are typically considered building design characteristics. While the results of this study are informative to the design community in prioritizing energy strategies for buildings, they have even more significant implications on how buildings are operated and occupied and on how design teams should communicate information about building performance to building owners, operators and occupants. The results of this study can provide a broader perspective on how buildings use energy and on what aspects of building energy performance deserve more attention in design, operation, operation and policy strategies.

The analysis demonstrates the relative impact of a range of variables affecting building design and operation on building energy performance. These variables include physical features of the building; HVAC, lighting and control system characteristics and efficiencies; operational strategies; tenant behavior characteristics; and climate, all of which affect building energy use. For each variable, a baseline condition was defined based on typical building characteristics. A range of outcomes that represent good and poor responses to these variables was identified. All of the variable ranges used in this study are based on research and field observations of actual building performance characteristics that can be found in the building stock today; they do not represent extreme or theoretical conditions.

Energy Modeling

One of the most important design tools used to make informed decisions about energy efficient design strategies is energy modeling software. Energy models are used to decide between energy performance features and options, to demonstrate code compliance, to qualify for utility incentive payments, to target specific high-performance goals and even to distribute responsibility for energy bills among tenants. Energy modeling was used in this study to compare the significance of the building characteristics evaluated here. However, in practice, energy modeling is seldom an accurate prediction of actual building energy use outcome. Conventional energy modeling is typically only used to tell part of the story of building performance, and the results of energy modeling are often misinterpreted in the context of actual outcome. The results of this study demonstrate that energy modeling can be more accurate and more informative if greater attention is paid to the operational characteristics of the building. The study therefore has implications for improving modeling accuracy. These results also serve as a way to prioritize various building performance upgrades even before a modeling exercise is undertaken.

Codes

Energy codes have been widely adopted to set a minimum performance level for building energy efficiency. Recently, a great deal of attention and effort has gone into developing and adopting increasingly stringent energy code requirements. However, energy codes only regulate certain aspects of building performance, and this study demonstrates that there are significant opportunities for building performance improvement in aspects of building energy use that are not currently regulated by code. The study also demonstrates that there are opportunities for climate-based improvements in code strategies that would be more effective than some of the current climate-neutral regulations in the codes. The results of the study also highlight areas where additional code improvements in currently regulated areas might be effective.

Operation/Occupancy

The design community (architects, engineers, government and supporting organizations) has widely adopted aggressive goals for building performance improvement over time. For example, the 2030 Challenge is a specific goal developed by the Architecture 2030 organization that prescribes that all new commercial buildings will achieve net-zero annual energy use by 2030, with significant improvements in the existing building stock in the same time frame. These goals have led to significant attention on high-performance building design strategies, along with the growing realization that building design characteristics alone cannot achieve these goals. A key focus of this study is on the 'operational variables' that affect building performance after the building is designed, built and occupied. While design characteristics have a significant impact on long-term building energy use, building maintenance, operation and occupancy strategies are absolutely critical to the long-term performance characteristics of buildings. The results of this study show that a range of occupancy factors can result in a range of impacts on energy use that equal or exceed the significance of many design decisions on building energy use. This demonstrates how critical it is to engage building operators and tenants in any long-term strategy to manage and improve building energy performance.

Climate Response

It is intuitive that climate and weather conditions affect building energy use, but the degree to which climate itself is impacting building performance characteristics is not always obvious in the design process. For example, designers often target reduced lighting loads as an energy efficiency strategy but seldom recognize how much more critical this strategy is when buildings are located in a cooling climate as opposed to a heating-dominated building where the lights are contributing useable heat to the building. This analysis was conducted for 16 different climate zones, representing the range of climates identified as distinct by ASHRAE. The results of this study provide perspective on how the relative importance of different efficiency strategies varies by climate. This information not only serves to focus design strategies on more critical issues but can also inform improvements to code and incentive programs that support improved building performance.

Defining the Measures

A set of 28 building characteristics was identified to represent the variables analyzed in this study. These characteristics represent a key set of building features and operational characteristics that impact building energy use and can be broken down into three categories: design variables, operating characteristics and tenant behavior impacts. In the operating characteristics category, some of the variables identified represent proxies for the anticipated impacts of a set of operation and maintenance practices on system performance. In these cases proxies were used because the modeling software could not specifically address O&M issues. For example, a variation in duct static pressure was used to represent the impact of clogged air filters from poor maintenance practices as well as duct design characteristics.

For each performance variable, a baseline condition was identified to represent a typical building stock characteristic. A low and high range for each variable was also identified to represent relatively poor and very good design/operating practices for each case. These performance values were gathered from a variety of reference sources, including the 2003 Commercial Building Energy Consumption Survey (CBECS), the Pacific Northwest Baseline Analysis[4], ongoing PIER research on plug loads, and other field studies currently underway.

Defining the ranges for low and high performance for each variable is a key aspect of this study. In the case of variables with large impacts, the definition of the range itself can significantly alter the conclusion, while for other variables the results are less dependent on the range assumptions. For example, the presence of even a small data center has a huge impact on total building energy use, so assumptions about data center operating characteristics become critical to the analysis. On the other hand, the range of outcome for heating equipment efficiency is less significant, and bound by the availability of equipment in the marketplace. The relative range of outcome shown for each variable therefore represents not only the importance of this variable to overall building performance, but also the importance of understanding the nature of these loads and characteristics in the design process.

Sample Results Summary

When viewed graphically, the results of this analysis provide a quick, intuitive understanding of the relative significance of the building characteristics considered. Figure 1 below shows an example of the data output for a single city, Chicago.

Each building characteristic is represented by a single bar on the chart, listed individually along the X-axis. Values on the Y-axis represent the impact on total building energy use of the changes to the measure listed at the bottom of the graph. Values below zero (green bars) on the Y-axis represent reduced energy use from the high-performance option for that variable, while values above zero (red bars) represent increased energy use associated with the low performance option. For certain building variables, such as shade coefficient, the sign of the energy savings may change from positive to negative between climate types. Subsets of this graph, and those for other cities, are presented throughout this report.

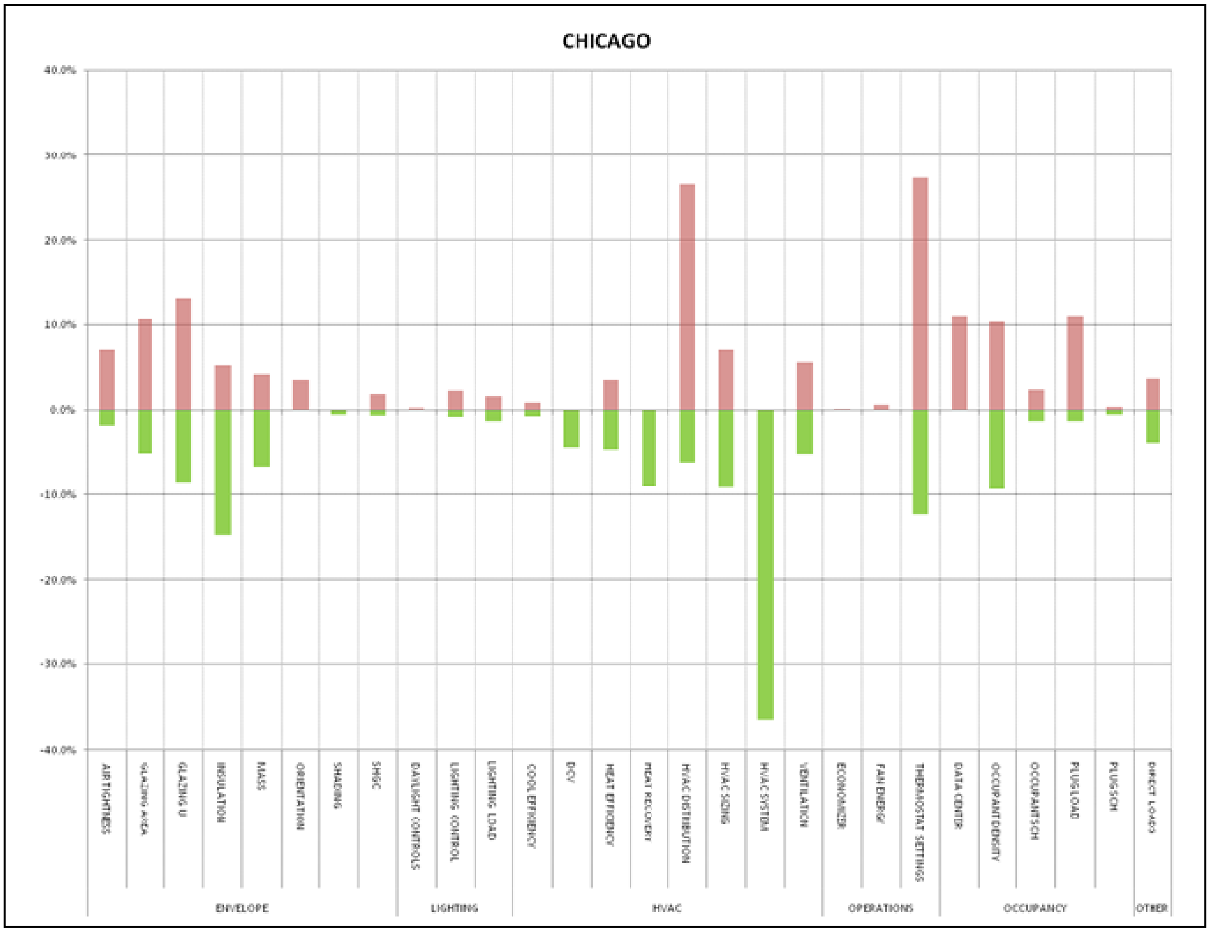
Variable Selection and Modeling Procedure

A set of 28 variables was identified to represent the range of building features in this analysis. The variables represented a series of building characteristics that can be affected by design strategies, operational practices and tenant behavior. The impact of climate was also represented by comparing results in different cities.

In selecting the modeling inputs to mimic various aspects of building systems, an effort was made to bracket the range of values found in real-world buildings. The sensitivity of building energy use for each variable was determined by establishing a baseline, high-performance and low-performance condition for each variable. Some variables, such as Solar Heat Gain Coefficient, actually switched from high to low performance depending on the climate. The ranges for each variable were modeled individually, across each of the 16 climates. For instance, to determine the effect of glazing area on building energy use, the model was run with a low value for the window-to-wall ratio (20%) and a high value (60%) while keeping the rest of the baseline inputs constant. With 28 variables, some of which only had a “low” or a "high" option, the final simulation ended up requiring 848 individual runs. This would be an onerous task if performed manually, so the *DOE2.1E* batch processing tool was used along with a spreadsheet automation tool developed for use with eQUEST.

The first goal of the analysis was to identify the relative impact of each variable in isolation. (Although the modeling analysis did account for the impact of each change on the performance of other systems.) This approach doesn't capture the full range of possible combinations of modeling inputs, as each variable is compared individually to the baseline. Because some synergistic combinations of variables might be missed with this approach, several packages of variables were modeled to address interactive effects

Figure 1. Measure Energy Sensitivity for Chicago



Observations on Results

There are many implications of an analysis of this type on building design and operation, code and policy, and performance analysis strategies. This report has chosen to focus on a subset of these implications for a more thorough discussion. In particular, a key aspect of this work is to identify the degree to which different parties are responsible for on-going building energy performance. Although the market generally assigns responsibility for building energy performance to the design team, this study shows that operational and tenant practices have a very significant impact on building energy use, and this issue is discussed more fully in the following section.

The analysis also suggests that there are a range of climate-driven performance features that are not fully recognized in current design practice, or in the energy codes that regulate these features.

Building and System Designers

Generally, primary responsibility for building energy performance is ascribed to the design team, and it is true that the features and systems designed into the building have a critical role in overall building performance. In this analysis, design variables can be broken into three categories: envelope, HVAC system and lighting system features. The design team is responsible for determining the characteristics of these variables and thus sets the stage for the long-term performance of the building. But many of the features designed into the building must also be operated and maintained properly, so there is overlap between design variables and operational impacts.

The envelope variables modeled in this analysis are generally in the control of the architect. For this analysis these included insulation levels, glazing amount and glazing properties, as well as thermal mass. Also in this category is building air tightness, since careful construction details need to be developed in order to produce an airtight building. The commonly accepted industry belief is that office buildings are dominated by internal loads, even in heating climates, and envelope improvements beyond code aren't cost effective. In actuality, this study shows that envelope efficiency can have a dramatic impact on overall energy use in all climates. Wall, roof and floor insulation levels alone can have large impacts on overall energy use in heating-dominated climates (±10%).

Glazing U-value improvements and glazing area reductions show savings across all climates. Glazing area has a particularly large impact. Increasing glazing from a base case of 33% to 60% of the wall area increases overall energy use by more than 10% in all climates. Glazing U-value is very important in heating climates, causing energy use to increase by about 15% by going from a high quality double glazed window to a single-pane window. Glazing U-value is less important in cooling-dominated climates (Phoenix, Atlanta, etc.). Decreasing the SHGC only saves energy in cooling-dominated climates, and actually increases energy use in heating-dominated climates by limiting useful solar gain. This indicates that energy code regulations enforcing low SHGC values across all climates may be counterproductive.

Increasing mass in buildings surprisingly saves energy in all climates, even if there isn't a large diurnal temperature swing in the heating season (e.g. Seattle, San Francisco). Mass extends the amount of time before the systems have to turn on to maintain the setback temperatures and buffers the extreme daily temperatures, thus reducing HVAC energy use.

Building air tightness also saves energy in all climate zones. Tight building construction has received a great deal of attention in the last 20 years in the residential sector, and a significant amount of research has been done to understand the issue. However, this aspect of building efficiency has yet to gain much attention in the commercial building industry. The common belief is that in office buildings the mechanical system is typically balanced to create a small amount of positive pressure in the building, thus eliminating infiltration as an energy issue. This is almost certainly not the case in practice, but there is very little existing research upon which to draw. This analysis used high and low infiltration values from a study providing modeling guidelines on infiltration in commercial buildings[5]. It is unclear the degree to which this range represents common practice, because widespread representative data simply does not exist.

Finally, in the category of factors controlled by the architect, this study examined the effect of orientation and massing, or aspect ratio. When modeled in isolation, the ideal aspect ratio is 1 to 1, or a square, because the surface-area-to-floor area ratio is the smallest (smallest UA). Solar gain and daylight utilization can have significant impacts on building performance, but in order for the orientation of the glazing and the aspect ratio of the building to save energy, the measure has to be implemented in concert with other measures such as daylighting and glazing optimization or passive solar design. Therefore changes to the aspect ratio in isolation do not accurately reflect the anticipated energy impact of this variable. To address this, some packages representing measure combinations were evaluated, as discussed in the following section.

The selection of HVAC system type, distribution type, equipment and duct sizing, system efficiency, and ventilation damper settings and control strategies are all controlled by the HVAC system designer and have a huge impact on the energy use of the building. This study included comparison of a baseline packaged rooftop single-zone gas system (PRTU) compared to a high-efficiency ground source heat pump system (GSHP) and a variable air volume system with terminal electric reheat (VAV). In addition, it examined the relative distribution efficiency of overhead ducts, under-floor air distribution or radiant hydronic distribution with natural ventilation.

The impact of HVAC system variables is very sensitive to other variables such as fan power, internal heat gain and occupancy levels. Ground-loop heat exchanger systems with water-to-air heat pumps saved energy in all climates, but the effect was greater in heating climates. VAV systems increased the energy use in all dry climates due to increased re-heating demands and fan energy. Energy use for VAV systems shows a savings in humid climates due to the ability of VAV systems to be set up to capture heat from the air conditioning system to reheat air during dehumidification. The greatest increase is shown in hot dry climates where fan heat from VAV operation increases cooling loads. However, this result is very sensitive to fan power, internal gain, humidity setpoint and minimum primary air-flow settings. Note also that this analysis treats gas and electric heat equally so it does not address energy cost or carbon impacts of fuel and system choices.

Heating and cooling equipment efficiency improvements caused the expected energy savings across all climates. This is a relatively small impact on overall energy use of the building except in the extreme climates. Increasing the ventilation rate also predictably uses more energy across all climates, but more so where outside air needs tempering to match interior conditions.

Duct sizing or fan power mimicked the internal gain variable results with increased fan power using more energy except in extremely cold climates where the fan heat was off-setting the relatively less efficient gas heating. Right-sizing HVAC equipment saved energy across all climates. Larger HVAC systems use more fan energy and have reduced part-load efficiency impacts for heating and cooling. This result is sensitive to system type. On a VAV system with variable speed fan control, over-sized fans have smaller impacts on the energy use.

Lighting measures modeled included reduced installed lighting power as well as lighting controls from occupancy and daylight sensors. Lighting energy impact differs greatly in different climates. In cooling climates, extra energy used for lighting not only increases the lighting energy budget, but also increases the HVAC cooling energy budget. In heating climates, lighting savings are significantly diminished because savings in lighting energy require an increase in heating energy. The lighting power measures are relatively easy to model; however, daylight availability and controls are not well developed within *eQUEST*, and there is disagreement about the accuracy of results.

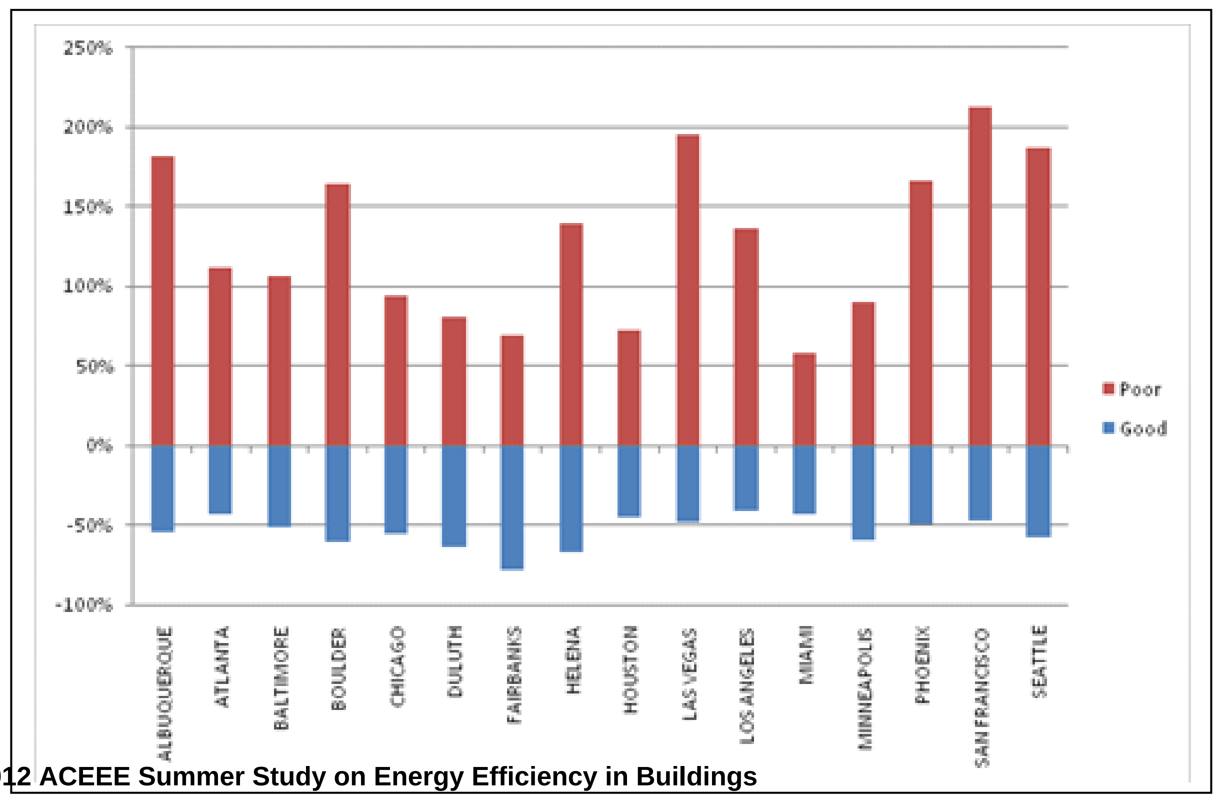
Decisions about lighting power density are fully under the control of the designers, but while the existence of control systems are the responsibility of the designers, the ultimate effectiveness of the lighting controls are more in the hands of building operators and occupants. While the absence of good lighting controls certainly reduces the potential for efficient building operation, the presence of controls alone is no guarantee of efficiency.

Bundling Design Impacts

Although this analysis focuses on the impact of individual measures relative to each other, it is also useful to consider the cumulative impacts of variables within the control of different building performance participants. To address this, certain packages of measures were combined to represent the range of performance that might be expected from a combination of design, operating or tenant behavior decisions.

Building envelope, HVAC and lighting systems are the primary areas where the design team can impact the building efficiency. Taken together as a package, best practices in envelope and lighting design can save about 40% of total building energy use; poor practices can increase energy use by about 90% in all climate zones. When the effects of HVAC system selection are added, best design practices can lead to about a 50% savings, and worst practices can lead to a 60-210% increase in energy use, depending on climate (as shown in Figure 2). Although some of the design variables listed in the poor performance category represent strategies that do not meet current codes, examples of all of these strategies can be found in existing buildings, or in new buildings built in areas with limited energy code enforcement.

Figure 2. Relative Impact of All Variables Controlled by Design Team



Occupant, Operations and Commissioning Effects

A huge fraction of the energy use of a commercial office building is not controlled by the building designers, but rather is driven by building operators or occupants. A key goal of this study is to quantify the building energy use impacts associated with operations and tenancy. From the analysis, it is clear that post-construction building characteristics can have a major impact on total building energy use, and these variables must be considered in the context of successfully managing and reducing building energy use. There are also implications for the design process if the team wants to successfully deliver a high-performance building.

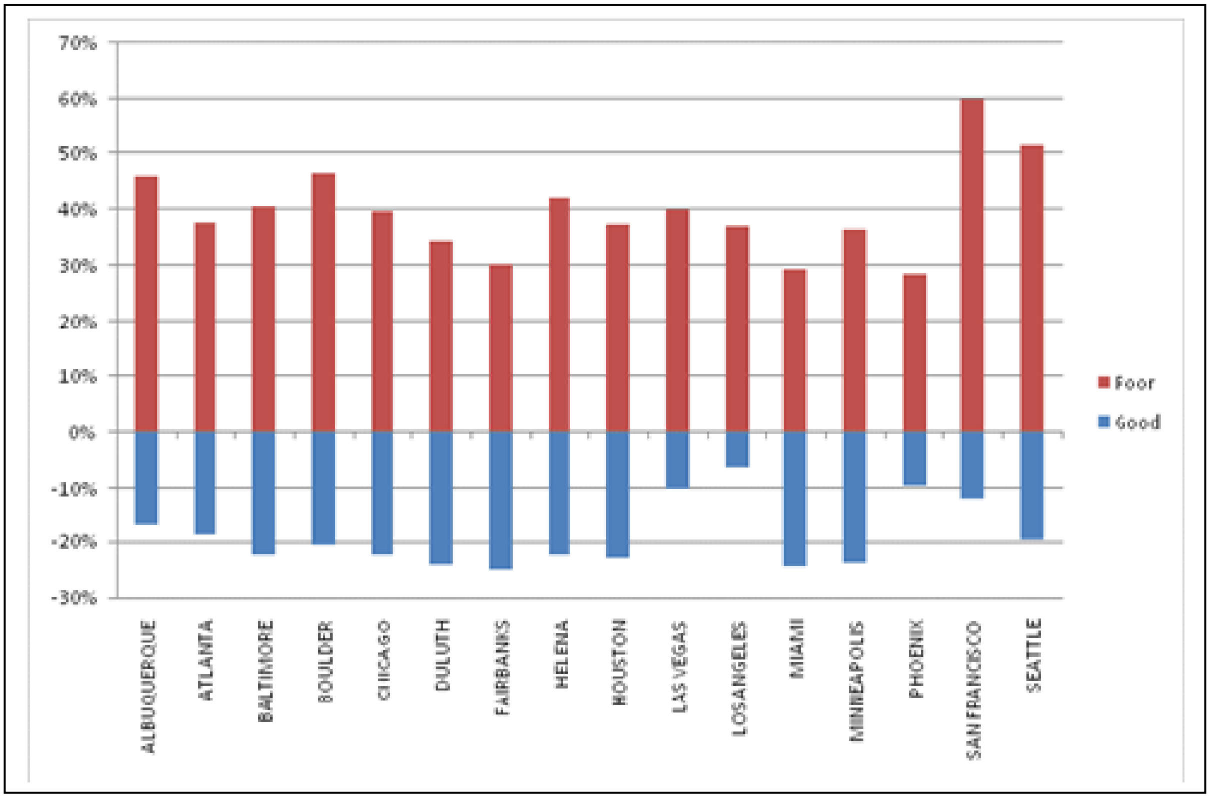
The range of post-construction building performance factors considered in this analysis include occupant density and schedule, plug and portable equipment loads and use habits, and maintenance and operational practices. Some of the variables, such as fan energy use and lighting controls, can be considered design variables as well, but may also represent proxies for building operational characteristics, such as poor filter maintenance. In general, these variables can be further divided into those impacted primarily by operational practices, like fan energy, and those impacted by occupant behavior, such as plug-load density and night use. In some cases such as occupant schedule, temperature setpoints and lighting control effectiveness, the variables can be affected by both these groups.

Building Operations

While some non-design aspects of buildings are more controlled by the occupants themselves, others are controlled by the building operators, maintenance staff, the controls programmer or commissioning (or lack thereof). The variables assumed by this study to be in this category include HVAC systems setpoints and schedules, economizer operation, ventilation controls and settings, and to some degree HVAC system efficiency and fan power (in that these variables can act as surrogates for adequate maintenance and balancing of the HVAC system).

As shown in Figure 3, best practices in this area are shown to reduce energy use 10-20% across all climate zones. In contrast, bad practices in this area can increase energy use by 30-60%.

Figure 3. Impact of Variables Associated with Commissioning, Operations & Maintenance

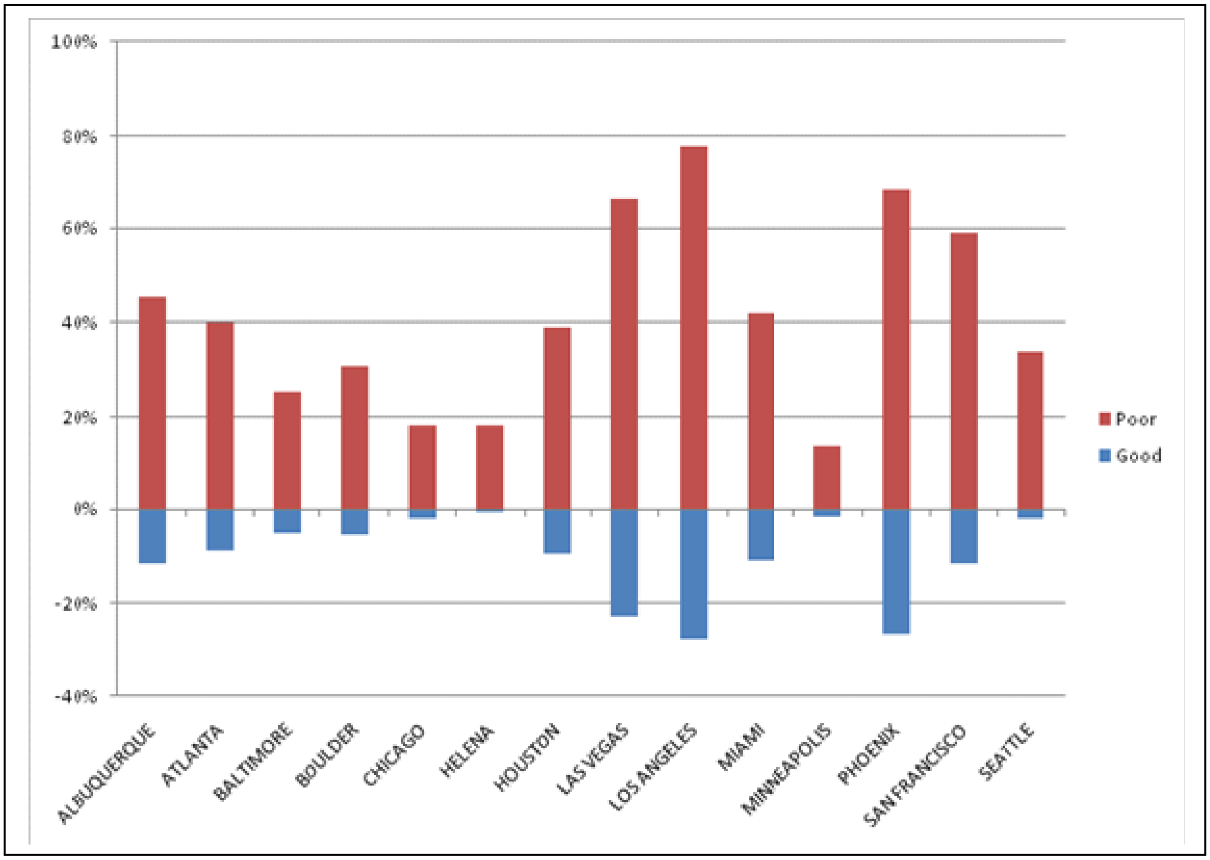


The design team may be able to affect these loads by incorporating building operations and maintenance staff into the design process so they better understand building operation, or by developing effective building operations and training programs in conjunction with building commissioning and start-up procedures.

Tenant Impacts

On the tenant side, the behavior of building tenants also has a significant impact on overall building energy use. Figure 4 below shows the impact on total building energy use of variables directly controlled by the tenants such as schedules, increased plug loads, poor management of night plug loads and lighting controls. Building tenants are seldom in a position to recognize the direct impact they have on total building energy use. The installation of submetering and energy-use dashboards can contribute to effective strategies to help building tenants understand and reduce their building energy use.

Figure 4. Impact of Variables Controlled by Tenant Only

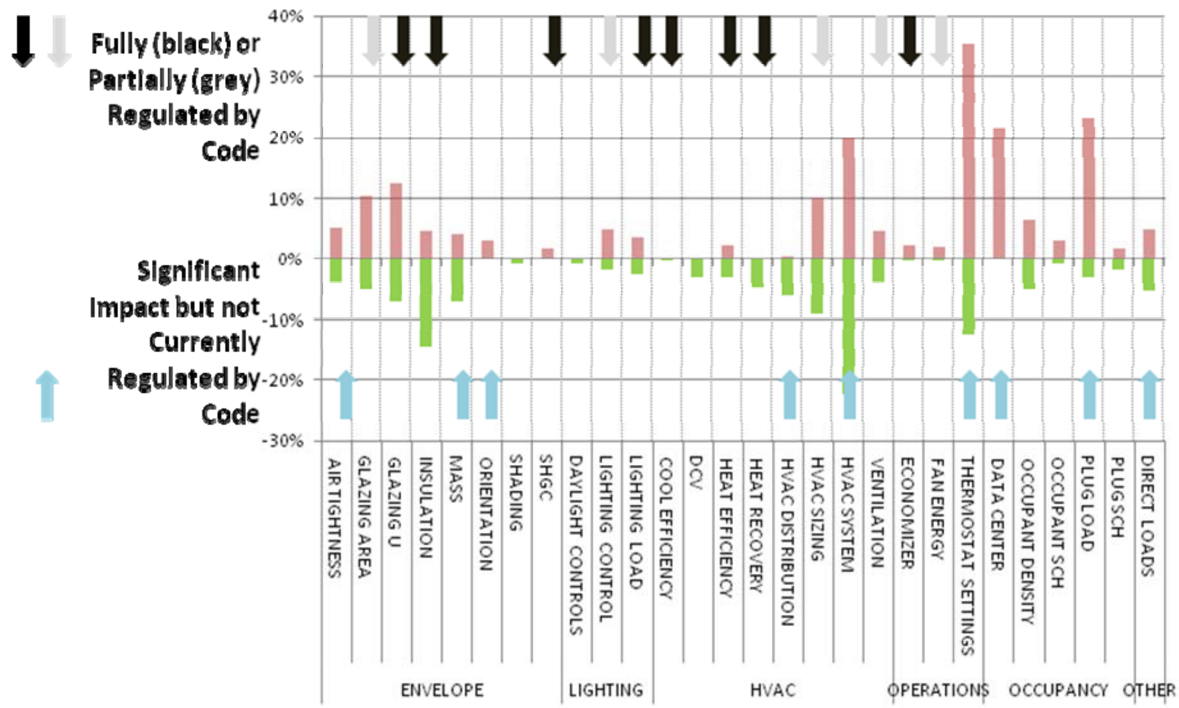


Energy Codes

Recent energy code versions such as the IECC-2012, ASHRAE 90.1-2010, and various regional jurisdictions have targeted substantial efficiency increases of up to 30% more stringent than code baselines from only a few years ago. These significant stringency increases are a response to aggressive policy goals such as the 2030 Challenge which targets improvements in new building efficiency of 50% better than a CBECS 2003 baseline by 2010, increasing to net zero by 2030. But the potential impact of increased code stringency is limited by three important factors: 1) The amount of energy savings available from improvements to any given building component is limited, 2) not all physical components of buildings are regulated by code, and most importantly 3) code language and enforcement mechanisms are focused on building physical characteristics, but a significant portion of building energy use is driven by operational characteristics and tenant behavior. The results of this analysis demonstrate the importance of all of these issues in considering future increases in code stringency.

Figure 5 shows the variable sensitivity graphic for one of the cities in this analysis (Seattle). This graphic indicates which aspects are fully or partly regulated by code (black and grey arrows) and which aspects of building performance are not regulated by energy codes. Significant unregulated components are highlighted with blue arrows. From this graph it is clear that additional savings opportunities are available in the regulated and partially regulated aspects of code, but significant savings opportunities exist that are currently outside the scope of energy codes.

Figure 5. Components Regulated or Unregulated by Typical Energy Codes



Summary

While the set of building features and characteristics generated in the design process have a major impact on total building energy use, operational and tenant characteristics also have significant impact. This analysis shows that long-term, significant reductions in building energy use will require significant attention to post-construction building characteristics and operation that are currently outside the scope of energy codes, policy initiatives, and general perceptions in the building industry.

The study also demonstrates that while there remain opportunities for further improvement in energy code stringency within current code structure, new mechanisms and code structures will be needed to capture savings from some of the larger remaining savings streams in building performance.

There is also an opportunity for more attention to climate-specific impacts on building performance, with a goal of improving the degree to which building design and operation responds to specific climate conditions.

The information generated by this work can be used to guide design and energy modeling priorities, and to help educate the design community about strategies to improve long-term building operation. At the same time the information can serve to educate building operators and tenants on strategies to reduce building energy use, and as a basis for codes and policies that focus on significant energy savings opportunities that exist downstream of the building design process.

References

[1] NREL Benchmark Medium Office Version 1.2_4.0: "Establishing Benchmarks for DOE Commercial Building R&D and Program Evaluation"

[2] The authors have been involved in extensive field research and data evaluation, published in various papers and studies, reflecting evaluation of building characteristics from several thousand buildings over the past two decades.

[3] Normative Appendix B from ASHRAE Standard 90.1-2010; Building Envelope Climate Criteria

[4] Cadmus and Ecotope, Pacific Northwest Commercial Building Stock Assessment, 2009

[5] Gowri, Krishnan, Winiarski, David, and Ron Jarnagin. 2009. *Infiltration Modeling Guidelines for Commercial Building Energy Analysis*.