IMPACT OF DESIGN, COMMISSIONING, MAINTENANCE AND OPERATIONAL VARIABLES ON THE ENERGY PERFORMANCE OF OFFICE BUILDINGS

ABSTRACT

The study seeks to quantify the degree to which occupant behaviors affect building energy use, and compare these 'operational variables' to the relative impact of common variations in building design. Using eQUEST, a suite of 28 variables was selected to represent the physical features of a building; HVAC, lighting, control system, operations; tenant behavior; and climate. For each variable, a range of inputs was developed to represent the typical spread found in the field. The range of inputs for each variable was then applied to a prototype "medium" office building developed by NREL using the DOE2.2E batch processing module.

INTRODUCTION

This study compares 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 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 engineering judgment. The impact on total building energy use was evaluated as each variable was modified individually from low to high performance, while all other characteristics were kept at the baseline level. To more accurately represent interactive effects, packages of measures for both good and poor design and operational practices 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. Results of the analysis 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 it reflects an extremely inaccurate perception of how buildings actually 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 efficiency 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 which aspects of building energy performance deserve more attention in design, 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 existing building stock; 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 incentives, 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 evaluated building characteristics. However, in practice, energy modeling is seldom an accurate prediction of actual building energy use outcomes. 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 has implications for improving energy modeling accuracy. These results also serve as a way to prioritize various building performance upgrades 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 targets achieving net-zero annual energy use by 2030 for all new commercial buildings, 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 (see Figure 1 for details). 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 CBECS, the Pacific Northwest Baseline Analysis, ongoing PIER research and other research and field studies. (Additional information about sources can be found in Appendix A).

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 2 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. A full set of graphs for all of the cities analyzed can be found in Appendix B.

Application to Existing Buildings

This analysis describes energy impacts of a range of building physical features and operational practices, representing the energy use characteristics of buildings in operation. It is therefore anticipated that the performance of existing buildings could also be considered in the context of this analysis. More specifically, it might be possible to use this analysis to predict what aspects of existing buildings are having a significant effect on total building energy use. This information might also help inform the priorities of field investigation into performance of existing buildings. An exploration of this applicability is being conducted by NBI under a separate research project.

SETTING-UP THE ANALYSIS

This project began as an attempt to quantify the impact of building performance variables that are outside the scope of the typical design process and to demonstrate the relative impact of these factors on annual energy use in buildings. The analysis grew, in part, out of frustration with the disparity between energy modeling performance predictions by construction industry design professionals in forums like LEED and real-life energy use data reported in various databanks such as CBECs. Additionally, published energy simulations of the impact of improvements in various energy codes have tended to predict very low average energy use intensities compared to actual performance outcome. Another goal of the analysis is to better understand which aspects of building performance within the scope of the design team have the greatest impacts on energy use. These goals lead to several fundamental questions:

1. What building performance factors, including design, operational and tenant variables, represent the most significant impacts on potential building energy use?
2. How do these impacts vary by climate?
3. Which of these impacts are typically considered in the design and modeling process, and which are not?
4. What does the relative magnitude of the measure impacts evaluated suggest about processes and priorities in design, modeling and building operation?

By better understanding the energy impacts of design variables it is possible to focus design efforts and resources on issues with the largest potential energy benefit. At the same time, energy modeling could be improved if some common reasons why energy models fail to accurately predict performance outcome can be identified. And a better understanding of the potential impacts of operation strategies and tenant behavior can inform changes in the industry that would help buildings perform better.

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 (SHGC), 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, listed in Table 1, were modeled to address each of the following areas directly. Appendix C shows the values used for modeling schedule inputs for the baseline runs

The packages were developed by splitting the different modeling inputs into groups that were defined by whether they were controlled by the design team, the mechanical engineer specifically, occupant behavior patterns, or operator maintenance practices and commissioning. Some of the inputs overlapped between the packages, as they could be used to represent multiple areas. For instance, fan power was adjusted in both the Design packages and the CX+M packages as it could represent either duct design or maintenance practices. The variables analyzed, and the range of values for each are shown in Figure 1 and in Appendix A.

Prototype Description and Variable Range

Defining the baseline was a relatively straightforward process. The National Renewable Energy Laboratory (NREL) has developed a suite of 16 "benchmark" Energy Plus models that cover a range of building types, from small offices to fast food restaurants, intended to represent 70% of the commercial building stock in the U.S. (Torcellini et al., 2008). Updates to the original benchmark buildings were released in 2009, adjusting some of the inputs to the models. These prototypes have been developed to allow comparisons between results of different simulation studies. For this study, the medium office prototype was selected as a basis for the analysis. This prototype aligns with previous work done by NBI in developing the Core Performance Guide and with recent code performance analysis work. Although this analysis used the NREL Benchmark prototype as a starting point, baseline variables were modified in some cases to align with other data sets we consulted as representative of standard practice.

The basic geometry of the benchmark medium office building is shown in Table 2 and was held constant throughout the simulation process except for the aspect ratio and window-to-wall ratio, which were varied for two of the sensitivity runs. Figure 3 shows an image from the NREL documentation of the envelope.

The NREL benchmark models vary the thermal properties of the envelope to match the ASHRAE 90.1 code values for each climate. This study simplified the modeling process by using the same thermal properties across all 16 climates. As described above, three values were chosen for each variable to represent a low-performance, base-case and high-performance building. The low-performance envelope values were selected using data collected in the development of the 2002 Northwest Commercial Baseline Study performed by Ecotope (Baylon, Kennedy, and Borelli, 2001). The dataset included a sample of office buildings from the Pacific Northwest; the 10th and 90th percentile envelope values were used for most of the thermal properties of the various "low-performance" envelope constructions. The glazing u-value was chosen to represent single pane with a thermally broken aluminum frame. The 90.1-2007 values were used for the base-case building, assumed to be nominally code compliant new construction. ASHRAE 189 values were used for the high-performance building thermal properties. Table 3 shows the values used as modeling inputs in the envelope variables.

The prototype building internal gains are shown in Table 4. Plug loads were assumed at 0.75 W/sf for the base case. This value was used in some versions of the NREL analysis and aligns with current field work on plug loads being conducted by NBI. The baseline lighting load comes from ASHRAE 90.1-2007 table 9.5.1. The low- and high-performance values used in the analysis were the 90th and 10th percentile values from the 2002 baseline study.

The original benchmark models had 8-hour occupancy, plug-load, lighting- and HVAC schedules. This analysis used a 12-hour day as the baseline, as it seemed more realistic based on NBI and Ecotope's experience with real world buildings. In the version 1.3_5.0 medium office models, the benchmark operating hours were also increased to 12 hours, in part to address the difference between the benchmark modeling EUI predictions and actual billing data ("Baseline Variable Documentation?", 2010). A “low” energy use variant was included for the plug, lighting and occupancy schedules based on 8 daily hours of operation; a “high” energy use option used 16 hours of operation. Plug-load and lighting schedules were also modeled independently to determine the impact of leaving lights and computers on at night. Space temperature schedules were varied to show the impact of night setback and temperature settings. Appendix C can be referenced for more detail on the various schedules used in this analysis.

This analysis also focused on the effect of system type on EUI in addition to various other energy efficiency measures. Three systems were included as one of the sensitivity variables:

1. Single-zone packaged rooftop units with DX cooling and gas heat
2. VAV system with DX cooling and gas heat in the rooftop unit with electric heat in the boxes
3. Single-zone water to air heat pumps with ground loop heat exchanger

After looking at the most common system in the Commercial Baseline study, the single-zone packaged rooftop unit system was chosen to represent the baseline system, as it was the most common in the commercial sample for buildings similar in size to the benchmark medium office building (Baylon, Kennedy, and Borelli, 2001). Table 5 shows the basic modeling inputs for the system. Appendix A has additional detail for low and high performance input ranges, and includes data sources for the modeling inputs.

Modeling Limitations

eQUEST uses the DOE2.2e simulation engine which, while being a widely used tool, has several limitations that make it difficult to model certain systems in a batch process where hundreds of runs are automated. In particular, workarounds using eQUEST to model alternative distribution systems such as radiant and under-floor air supply are particularly cumbersome and difficult to implement with the batch processing tool. It is also very difficult to automate links between humidity control and climate. The options for humidity control methods are limited to re-heat for packaged single-zone systems, and systems with chilled water coils. Heat recovery systems are applied to 100% of the supply air flow, which makes modeling heat recovery on exhaust and outside air difficult.

The single most glaring limitation when developing the models was the difficulty in locating good baseline data to determine the range of modeling inputs for each modeling variable. Modelers without access to Ecotope’s various sources of information, from industry contacts to baseline audit data, would find it very difficult to determine the correct values for their building.

Recommended Additional Research

There were several steps taken in this analysis to limit the scope to simplify the amount of data produced and make the modeling more straightforward. This approach was due partly to time constraints, but also because it was unclear if interesting results would be generated. One of the most fundamental simplifications was to compare each variable’s impact to the baseline rather than modeling every combination of inputs. It is possible that interesting synergies of inputs that create lower energy options than the “package” models have been missed. Also, there is a chance that educational synergistic high energy use options haven’t been addressed. The output data from a full range of possible combinations could also be used to produce a web-based tool that would allow design teams or building occupants to play with various building energy variables to get a sense of what combinations of measures would have the most impact on reducing energy use.

A few things became clear during the energy model development process for the sensitivity analysis:

1. Energy modeling software HVAC system defaults can have drastic impacts on energy use.
2. Data on real-world ranges for schedules, occupancy and internal gains in buildings, particularly plugs loads, is difficult to come by and not widely agreed upon.
3. Broad data sets on real-world energy end-uses in buildings are also not current or widely available.
4. The DOE 2.2e simulation engine does not deal well with non-standard distribution systems for batch processing analysis.

Energy modeling software default assumptions can have large impacts on energy end-use. A useful second sensitivity analysis would focus on modeling software defaults to determine which can potentially have the largest effect on outcome if the values used are incorrect.

Regular research needs to be performed for a large sample of office buildings in a widespread range of climates with several different HVAC system types to determine accurate plug loads and end-use breakdowns. This data could be used to improve energy modeling accuracy and also help explain the widespread differences between energy modeling predictions and billing data. This data needs to be distributed in a format and forum that is easy for energy modelers and building science researchers to access.

Fan energy is a large portion of annual HVAC energy use, especially in mild and cooling-dominated climates. Alternative distribution systems such as raised floor or radiant systems can reduce or nearly eliminate this portion of the HVAC energy end-use. These variations are not well supported by this modeling tool; in order to determine the real potential impact of these technologies, the simulation must be performed with software that can accurately predict alternative distribution system performance.

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. A more thorough discussion of some of these climate-based design implications is also provided below.

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 gains. 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 sector. 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 yet-to-be-published study currently underway in the Pacific Northwest (Gowri, Winiarski, and Jarnagin, 2009). 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.

While modeling of building envelope variables is relatively simple, well developed and well understood, modeling of HVAC system effects is much less reliable. Modeling programs include numerous hidden assumptions and shortcuts for attempting to describe the control and performance of these systems under varying conditions. There is a trade-off between keeping the modeling input requirements simple enough to be understood and manageable by a wide range of modelers and making them detailed enough to more closely capture the actual performance. In an analysis such as this that specifically tries to attribute impacts to individual measures, these hidden assumptions can have unanticipated impacts on the results. Much more research is needed to fully develop the performance curves and ideal modeling parameters for a wide range of system and equipment types.

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 showed expected energy savings across all climates. Equipment efficiency has 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 offset 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 for 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 (see Table 1).

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 4). 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.

Occupant, Operations and Commissioning Effects

A huge fraction of the energy use of a commercial office building is not controlled by the building designers, rather it is driven by building operators or occupants. A key goal of this study is to quantify the building energy use impacts associated with occupancy and operations. 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 agent? (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 5, 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 30-60%.

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 occupants has a significant impact on overall building energy use. Figure 6 below shows the impact 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.

Combined Post-Construction Impacts

Taken together, the combined impacts of operation, maintenance, and tenant behavior practices represent the potential for a very substantial impact on overall building energy use. Figure 7 shows the combined impact of these variables by climate type.

As with other internal gain type loads, the occupant and operator factors are less important in the significantly colder climates (Fairbanks, Duluth, Chicago, Minneapolis) since the loads themselves offset some of the energy needed to heat the building. The impact of these factors is greatest in cooling climates since, like lighting energy, the increase in internal loads requires additional HVAC energy. In cooling climates the occupant and operations effects together can increase building energy use by about 80-140%, or conversely reduce energy use by about 30% in comparison to the typical baseline building.

The design team has the largest potential impact on total building energy use, and many of the decisions by the design team about building features also determine the degree to which operators, and to a lesser degree tenants, can successfully manage their own behaviors to achieve efficient building performance. It is also clear from the Figures 6 and 7 that once the building is constructed, the potential impact of operations and tenants has a much greater potential to adversely impact building energy use than to improve upon the original design characteristics.

Climate Responsive Approach

To deliver high levels of energy efficiency, building design and operations must be reflective of the particular climate. The results of the modeling runs offer important insights into the impact of various measures in different climates. The following sections discuss the results of the study in four different climate zones: Seattle as a mild maritime climate, Chicago as a cold climate, Phoenix as a dry hot climate, and Atlanta as a moist hot climate. The pie charts in Figure 8 show the distribution of energy end uses in the base-case building model in the various climates. The most obvious difference is in the fraction of energy going to space heating and space cooling. Note that the amount of energy going to plug loads or miscellaneous electric loads (MELs) and lights is nearly identical, but the percentages vary somewhat due to a varying total.

The base-case building with a PRTU heating system in Seattle has an EUI of about 60 kkBtu/sfsf/yr. The pie chart energy end use graph for Seattle shows where the energy is being used. Nearly 50% is used for the HVAC system, with the most energy going to heating (28%) and fan energy (17%). Note that cooling accounts for only about 3% of the total energy use. Lighting and plug loads (MELs) each account for about 22% of the energy use.

The base-case building in Phoenix has an EUI of about 61 kBtu/sfsf/yr, nearly identical to Seattle. However, the energy end use graph for Phoenix is much different than the graph for heating-dominated Seattle. HVAC energy still accounts for about 50% of the building energy use, but space heating represents less than 1%. Cooling, on the other hand, represents 28% of all energy used in the building. Lighting and MELs are about the same fraction as they were in Seattle. This indicates that the impact of measures effecting heating and cooling will be much different in the two different climates.

In Atlanta the HVAC energy is also about 50% of the total. Surprisingly, heating uses more energy than cooling. This is due to the fact that the heat is provided by gas at an efficiency of 80% while the cooling is supplied by a much higher efficiency refrigeration cycle. Also, heating is used in Atlanta for the dehumidification process.

Chicago is the most extreme thermal climate shown, with HVAC energy responsible for about 60% of the total energy use and a base EUI of 80 kBtu/sf/yr. It is obvious from the graph that measures targeting heating savings will have the biggest impact, while cooling, lighting, and plug-load reductions will be less important.

SEATTLE – MODERATE HEATING CLIMATE

Seattle has a relatively mild maritime climate characterized by a long, cloudy cool winter and a very mild summer with few hours over 80°F. As such, Seattle is heating dominated in terms of energy use, even in a relatively dense commercial office building. This has been widely misunderstood by much of the region's architectural and engineering community, who have assumed that office buildings are always cooling dominated, regardless of climate. This likely stems from confusion between peak load and annual energy use. The sizing of the HVAC system for an office building in Seattle is likely to be driven by the peak cooling load requirements of the building. However, those peak cooling loads are experienced for only a very few hours each year. The building is in heating mode for a much larger percentage of the time, so heating dominates the annual energy use.

Envelope

Figure 9 shows a graph of the relative impacts of envelope variables in Seattle shows a relatively significant impact of all insulation measures, but very little impact for building orientation, shading or Solar Heat Gain Coefficient. One interesting result is that there is still a significant amount of energy savings to be had through insulation exceeding current code levels (a reduction of up to 15% of total building energy use). This is in contrast to what many in the building industry believe about current envelope energy codes.

Another interesting result is that lower SHGC (0.38 to 0.15) actually causes buildings in Seattle to use more energy due to the reduction of useful solar gain in the winter. This indicates that regulating low SHGC in heating climates may be counterproductive.

Lighting

Since Seattle is a heating climate, there are not large gains to be made from better lighting or lighting controls beyond current code. This is because lighting savings during the heating season must be made up with additional heating energy. Significant lighting savings are only achieved during the non-heating season.

Note that this result is dependent on the heating system used. If electric heat or natural gas is used, then added lighting energy directly offsets heating for much of the year. However, if a high-efficiency heat pump system is used to provide heating, then lighting savings during the heating season become much more apparent.

Occupancy and Operations

An interesting aspect of the Occupancy variable graph (see Figure 10) for Seattle is that there is much more on the Red side of the graph then on the Green side. This shows that occupancy variables can add a significant amount of energy use to the building (data center, plug loads and thermostat settings), but it is much more difficult to obtain real savings below baseline from occupant choices. While high plug loads and a data center can add a significant amount of energy use to the building, much of the added energy offsets heating in the winter, so we will see a much larger impact of these measures in the cooling climates.

Note also that the assumptions about occupant behavior in the analysis reflect a somewhat optimistic baseline where controls work well and occupants are conscientious about turning off equipment in unoccupied hours. Less optimistic assumptions about base case behavior might alter magnitude of savings or energy penalty relative to the zero baseline, but will not change the overall significance of this behavior on total building energy use.

Thermostat settings have the largest impact of any measure for heating-dominated climates, with poor control resulting in a 35% increase in energy use and optimal controls resulting in a 12% savings over baseline. This indicates that significant focus should be devoted to occupant education and controls design in respect to thermostat controls and scheduling. Typical commercial programmable thermostats are difficult for the typical office worker to understand, and the clocks and setbacks are rarely optimally programmed except by the more sophisticated building operators.

HVAC

HVAC design decisions in a heating climate such as Seattle can have a huge impact on overall building energy use, both on the positive and negative side. The largest impact is on the selection of the HVAC system itself. Variable air volume (VAV) systems with terminal electric reheat in fan-powered terminal boxes has become the standard system for medium and large office applications in this region. In the Seattle climate, a VAV system will cause the building to use about 20% more energy than the same building with Packaged Rooftop Units (PRTU). VAV works well in cooling-dominated buildings as it can simultaneously supply a large number of zones with varying heating and cooling needs. However, in heating-dominated buildings VAV uses a great deal of heating energy as the central system supplies a minimum amount of cool air to the VAV boxes to meet minimum ventilation requirements, and electric coils in the boxes must then reheat the air to provide heating in the zones. Note that the predicted performance of the VAV system is very sensitive to modeling inputs related to minimum air settings on the VAV boxes, supply air reset temperatures and internal gains.

In contrast to the 20% increase due to a VAV system, a ground-source heat pump based system (or inverter-driven air source heat pump) can cause the building to use over 20% less energy than the base-case building due to the high coefficient of performance (COP) of a heat pump system.

HVAC system sizing can also have a significant impact on energy use in a heating climate, causing a 10% increase or decrease in the overall energy use. This is primarily the result of increased fan energy associated with larger equipment. Note that this has less of an effect in a heating-dominated climate using a standard 80% efficient gas furnace since increases in fan energy provide useful heating energy during the heating season.

Ventilation quantity and heat recovery also show small but significant impacts in this heating-dominated climate, as does HVAC distribution and heating efficiency.

Other

Miscellaneous direct loads were used to model exterior lighting for parking lots or parking garages, elevators, fans, etc. Figure 11 illustrates the HVAC and other measure impacts. These “other’ loads can have about a ±5% impact on the energy use of a building in Seattle for our assumptions about typical loads. Note that with poor design or specialized equipment requirements these miscellaneous loads could be quite large. For example a landscape water feature with large pumping requirements or a cell tower or satellite repeater on the roof.

PHOENIX: HOT DRY CLIMATE

Phoenix is used to demonstrate the impact of measures in a hot and dry climate. The weather is very sunny with a long hot summer. Phoenix typically experiences very large diurnal swings between daytime and nighttime temperatures. Temperatures can drop in the winter, but the vast majority of the very cold hours are at night when the ventilation systems are turned off. Figure 12 illustrates the envelope and lighting measure impacts in Phoenix.

Envelope

The envelope insulation variables are much less important in a cooling climate such as Phoenix than in a heating climate like Seattle. The significant envelope variables are all related to the glazing system and control over solar load. Large amounts of glazing can increase energy use by 15%, and less glazing and good solar shading can each save about 7% of the building energy. Varying the SHGC, which had almost no impact in Seattle, can affect the energy use by about +16 to -7% in Phoenix due to the impact on solar heat gain. High mass construction, which yielded significant gains in Seattle, did not show large savings in Phoenix due to the lack of heating load. However, the model did not attempt to capture the effect of night venting, which could effectively reduce cooling load in Phoenix with a high mass building due to typical low nighttime temperatures.

Lighting

Lighting measures have a much larger impact in Phoenix than in colder climates. Not only do they not provide any useful heating energy to the building, but almost every Btu of lighting energy put into the building becomes heat energy which must be removed with the cooling system.

Occupancy and Operations

Plug loads can increase the energy use of a building by 50% in Phoenix and are in the control of the occupants. Likewise, data centers are an increasingly common component of building operation and can come in many shapes and sizes. For this analysis we included a small data center representing about 1.5% of the total floor area, with an equipment load in that space of 100 W/sf.

The way the building occupants manage these two areas of building loads can overshadow many decisions made by the design team in relation to building envelope insulation, mass, shading and orientation. Furthermore it shows that the modeling estimates of energy use will be completely wrong if the modeler does not have an accurate estimate of these loads. Figure 13 shows the occupancy and operations measure impacts in Phoenix.

HVAC

The impact of radiant cooling (HVAC Distribution) in Phoenix is a very important measure that can reduce energy use in the building by 25%. This is primarily due to the large reduction of fan energy which also decreases cooling energy. The combination of a ground-source heat pump with radiant cooling could reduce energy use of the building by over 1/3. Similarly, HVAC sizing has a larger impact in Phoenix than in cooler climates due to the impact of additional fan energy on cooling load. Figure 14 shows the HVAC and other measure impacts in Phoenix.

ATLANTA: WARM MOIST CLIMATE

Since Atlanta does have a significant heating load and requires dehumidification, measures to reduce heating load and infiltration show up as important. Note that this is driven strongly by the choice of HVAC system. The base-case PRTU does not perform well in a climate requiring significant dehumidification; for the PRTU to dehumidify it must cool the entire airstream and then reheat it as needed (with gas in this analysis) to serve the space. The VAV system functions much better in Atlanta because the air conditioning system can be arranged to recapture the heat from the dehumidification process to reheat the air. This can be seen in the following graphic of the measure impacts in the Atlanta climate. The HVAC System variable shows only positive impacts because the base case system is the least efficient.

The HVAC Distribution variable shows a huge negative impact associated with going to an under-floor air system. This is due to the fact that the under-floor air is delivered at a higher temperature, so much more energy is needed to reheat the air during dehumidification. This anomaly is a result of the selection of a PRTU as the base-case system. It can be ignored in this case since it is unlikely that under-floor air would be used with PRTUs in a humid climate such as Atlanta. Note that the energy use of the HVAC systems is very sensitive to the humidity setpoint. 50% RH was selected here as the industry standard, but large savings are available by increasing this setpoint to 60-75% RH.

Where insulation, airtightness and mass had almost no impact in Phoenix, they have a notable impact in Atlanta because of the heat load of the base-case building. In the areas of occupant and operator control, the two climates look similar except that thermostat settings are much more important in Atlanta than in Phoenix, again due to the impact of the heating load. Figure 15 shows the impacts of all measures in Atlanta.

CHICAGO: COLD CLIMATE

Chicago is a much more extreme heating climate with nearly 6,500 heating degree days. As shown in the earlier pie charts of energy end uses, heating is 40% of the base building energy use in Chicago. As a result, the measures affecting heating energy will potentially have the greatest savings. The graph of measure impacts for Chicago is similar to the graph for Seattle, the other heating climate shown. Some of the pronounced differences are that heat recovery and airtightness are much more important, and controlling data center and plug loads is less important due to the colder winter temperatures and higher heating loads. The HVAC Distribution variable shows a large negative impact of under-floor air in Chicago. This is again due to the large cost of reheating air to a warmer delivery temperature for dehumidification with the PRTU system. Note that while VAV is a poor energy choice in Seattle, it is a better system in Chicago due to the ability to reheat with the air conditioning system for dehumidification. Figure 16 shows all measure impacts in Chicago.

MEASURE INTERACTIONS

The measures evaluated do not operate independently, with the exception of the direct loads (loads external to the building that do not impact heating or cooling). All of the other measures affecting internal gains in the building interact strongly with heating and cooling energy use. Every kWh of electricity used to power a computer or a lamp ends up as heat in the space and is either providing useful heating or increasing the cooling demands.

The magnitude of the interaction will be driven by the heating system type. For example, in the base-case building the heating is provided by a gas furnace at 80% efficiency. Therefore, in the context of this analysis, measures that reduce plug loads in a heating climate like Seattle are not highly effective since during much of the year the reduction in plug load energy must be made up by even more energy use from the lower efficiency gas furnace. This is demonstrated in the pie charts on Figure 17; reducing the plug loads causes the heating energy to expand.

The effect changes if the heat is being provided by a heat pump system with a COP of 3 or better. In the case of heat pump heating, the reduced lighting or plug heat is made up by a heating system operating at much higher efficiencies so real energy savings are achieved year-round.

ENERGY USE INDEX (EUI)

Table 6 shows the Energy Use Index (EUI) in kBtu/sf/yr for each of the climates shown above.

These results may appear slightly lower than typical buildings for a variety of reasons. The model predicts energy use from idealized new buildings; the entire envelope functions per code, the building shape is very simple with a relatively low surface-area-to-volume ratio, all setpoints and schedules are exactly as specified and everything works as designed. In the real world things never function quite so perfectly.

The modeled EUI's for Seattle and Phoenix are particularly low due to the selection of the base-case HVAC system. The PRTU functions much better in a heating climate than the more common VAV system. Table 7 shows the EUIs with a VAV system. Note that the energy use for Atlanta and Chicago do not change, but energy use in Seattle and Phoenix rises significantly. While less efficient, VAV systems have gained favor with HVAC designers in office buildings due to their ability to provide independent zone control.

The EUI predicted for the Seattle building with VAV system compares favorably to a recent survey of new commercial buildings in the Pacific Northwest. In that study, the average EUI in office buildings built between 2002-2004 was 72kBtu/sf/yr (Baylon, Robison, and Kennedy, 2008).

ENERGY CODES

Recent energy code development cycles by the IECC, ASHRAE 90.1, 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. To continue to increase building performance outcome through energy code improvements, the following three strategies will need to be considered.

Require Better Components

Each cycle of code development considers increases in the performance requirements of those aspects of buildings already regulated by codes. These may include higher insulation requirements, better glazing, lower lighting power densities, and a range of other performance enhancements. The results of this study show that there are still specific performance improvements available from continued tightening of these requirements, such as in the area of envelope insulation and air tightness. However, the amount of energy savings that can be obtained by increased component efficiency for any given building component is limited. As insulation values increase for example, the amount of energy lost through the building envelope is reduced, and each subsequent increase in insulation performance affects a smaller and smaller portion of total remaining building energy use. In this study, the end-use pie charts help demonstrate the theoretical limit to which improvements can be made to any given building component to achieve additional savings. At the same time, the potential for additional savings from improvements to specific components is shown by the magnitude of savings indicated in the measure bar charts. For example, it can be seen that continued improvement in building insulation performance can yield additional savings. In this case the values represented by the high-performance option are the insulation performance levels identified in the proposed ASHRAE 189 code standard. From this analysis, these insulation performance levels would result in significant additional energy savings. However it is also clear from these results that continued increases in the stringency requirements on components currently regulated by the code may not represent the largest potential energy performance improvements available.

Regulate More Components

Not all physical components of the buildings are regulated under current code practice. Figure 18 highlights those components analyzed in this study which are currently within the scope of codes, and those which are not. For example, there are significant savings to be had from better HVAC system selection, but current codes tend to be system-neutral, allowing the design team to select from HVAC systems with higher or lower efficiency without penalty. Even when projects are using energy modeling to compare their design strategy to a baseline building, system alternatives are often not considered as a basis for performance improvements beyond code. A more comprehensive discussion of these issues can be found in *The Future of Codes*, NBI, 2010.

In the case of glazing area, codes do tend to require increased thermal performance as window area increases, but they do not specifically limit glazing areas, nor do the increases in thermal performance in current codes fully make up for the adverse energy performance impact of increased glazing area.

Figure 18 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.

Expanded Codes to Include Post Construction Characteristics

Current code structures only regulate physical features of the building which can be addressed during the design and construction process. Once the building is completed, the manner in which the building is operated and occupied is not within the scope of current energy codes. This represents an increasingly significant limitation to the ability of energy codes to affect building energy use, especially at the aggressive performance targets being set for codes.

In this analysis, the relative impact of post-construction variables are compared to the kinds of efficiency strategies more commonly considered in the design process. A key finding of this study is just how significant occupancy factors are relative to design features. It is clear that in order to achieve more aggressive code targets, codes will increasingly need to address post-construction energy loads. This represents a substantial change to code and enforcement structures as increasingly higher building performance outcomes are targeted.

CONCLUSION

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 measures 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.

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Category	Variable	LOW Performance	BASE CASE	HIGH Performance
Envelope	Square Footage	52630	52630	52630
	Number Of Floors	3	3	3
	Thermal Zoning	Core zone w/ 4 perimeter zones on each floor	Core zone w/ 4 perimeter zones on each floor	Core zone w/ 4 perimeter zones on each floor
	Perimeter Zone Depth	15'	15'	15'
	Floor to Floor Height (ft)	13	13	13
	Floor to Ceiling Height (ft)	9	9	9
	Aspect Ratio & Orientation	N/S 2.5-1	1.5-1 S	E/W 2.5-1
	Mass	wood frame (no slab)	4" slab	12" slab
	Insulation	R-11 metal frame	ASHRAE 90.1-2007 Seattle	ASHRAE 189
	Glazing Area	60%	33%	20%
	Shading	NONE- SHGC: .38	NONE- SHGC: .38	FIXED 3' HORIZONTAL, SHGC: .38
	SHGC	SHGC: .76	SHGC: .38	SHGC: .15
	Glazing U	0.93	0.48	0.28
	Air Tightness (ACH)	Idesign (Natural)	0.29	0.182728551
Lighting	Lighting LPD	1.3 W/SF	1.0 W/SF	.7 W/SF
	Lighting Control	60% ON AT NIGHT - see schedules for details.	TIMECLOCK - See Schedules for details	TRACKS OCCUPANCY - see schedules for details
Occupancy	Occupant Density	130 SF/PERSON	200 SF/PERSON	400 SF/PERSON
	Occupant Schedule	16 HOUR WD + 12 HOUR SAT (30%)	12 HOUR WD + 6 HOUR SAT	8 HOUR WD + 4 HOUR SAT (30%)
	Plug loads	2W/sf	.75 W/SF	.4 W/SF
	Plug Schedule	80% AT NIGHT	40% AT NIGHT	5% ON AT NIGHT
	Data Center	**yes - 1.5% floor area, 100 W/SF**	**Base=no, .75 W/SF**	**yes - 1.5% floor area, 35 W/sf**
Operations	Daylight controls	None	None	CONTINUOUS DIMMING 30 FC CONTROL POINT 10% MINIMUM TURN DOWN RATIO 93% OF LIGHTING ON DIMMING CONTROLS 3% SKYLIGHT IN ROOF-TOP ZONES
	Economizer	FIXED OA PERCENTAGE (MINIMUM OA) NO ECON, ALL SYSTEMS	PRTU: 50% MAX OA FLOW FOR ECON	PRTU: 100% functioning (MAX OA PERCENTAGE = 85%)
	Thermostat Settings	Tight range w/o setback: **74 Cool** 72 heat	ASHRAE55 base w/ setback: **76 Cool (6 am to 8 pm),78 Set-up unoccupied** 70 heat (6am-8pm), 65 Set-back unoccupied	ASHRAE55 expanded w/ setback: **80 Cool (6 am to 8 pm), 82 Set-up unoccupied** 68 heat (6am-8pm), 60 Set-back unoccupied
Other	Direct Loads	High - big parking lot (1/500 SF) = 104 spots, or 23,712 SF @ .3 W/SF = 7.1 kW 15 HP Elevator w/ standard office elevator schedule 5.4 kW Misc loads for fans, façade lighting, etc (on exterior)	Standard Garage (1/1000 SF) = 52 spots, or 11,856 SF @ .3 W/SF = 3.6 kW 15 HP Elevator w/ standard office elevator schedule 3.6 kW Misc loads for fans, façade lighting, etc (on exterior)	15 HP Elevator w/ standard office elevator schedule 1.8 kW Misc loads for fans, façade lighting, etc (on exterior)
HVAC	HVAC System	VAV RTU, DX cooling, Gas Preheat, standard VAV boxes, w/ elec heat at the perimeter boxes	Single Zone PRTU w/ DX cooling & gas heat.	GSHP: Single zone water to air heat pumps with vertical ground loops for heat balance Ground Loop Sizing: 32 min LWT, 95 Max LWT
	HVAC Distribution	PRTU W/ UFAD: 1. Supply fan static reduced to .25" 2. Supply air temp raised to 62 F. 3. Lighting head load sent to plenum	Equest defaults for over-head, plenum return.	PRTU W/ radiant w/ vent fan: 1. Supply fan static zeroed out 2. Ventilation air provided with exhaust fans sized for max vent load with 1.0" of static
	Heat Efficiency	PRTU .72 AFUE	PRTU .78 AFUE	PRTU .80 AFUE
	Cool Efficiency	PRTU .37EIR	PRTU .31 EIR	PRTU .307 EIR
	Heat Recovery	None	None	COUNTER FLOW ENTHALPY WHEEL 76% LATENT EFF. 74% SENS EFF. OPERATES DURING HEATING & 5 DEGREE F DELTA-T ONLY ADDS .000054 kW/CFM OF STATIC TO SUPPLY FAN
	Ventilation	27.3 CFM/PERSON	NREL base schedule (21 CFM/PERSON)	14.7 CFM/PERSON, EQUEST DEFAULTS FOR DCV-RETURN-SENSOR
	Fan Energy	.000498 kW/CFM	.000376 kW/CFM	.000358 kW/CFM
	HVAC Sizing	**3.0 AUTOSIZE**	**2.0 AUTO-SIZE**	**1.0 AUTO-SIZE**

Figure 1: Variable List and Range

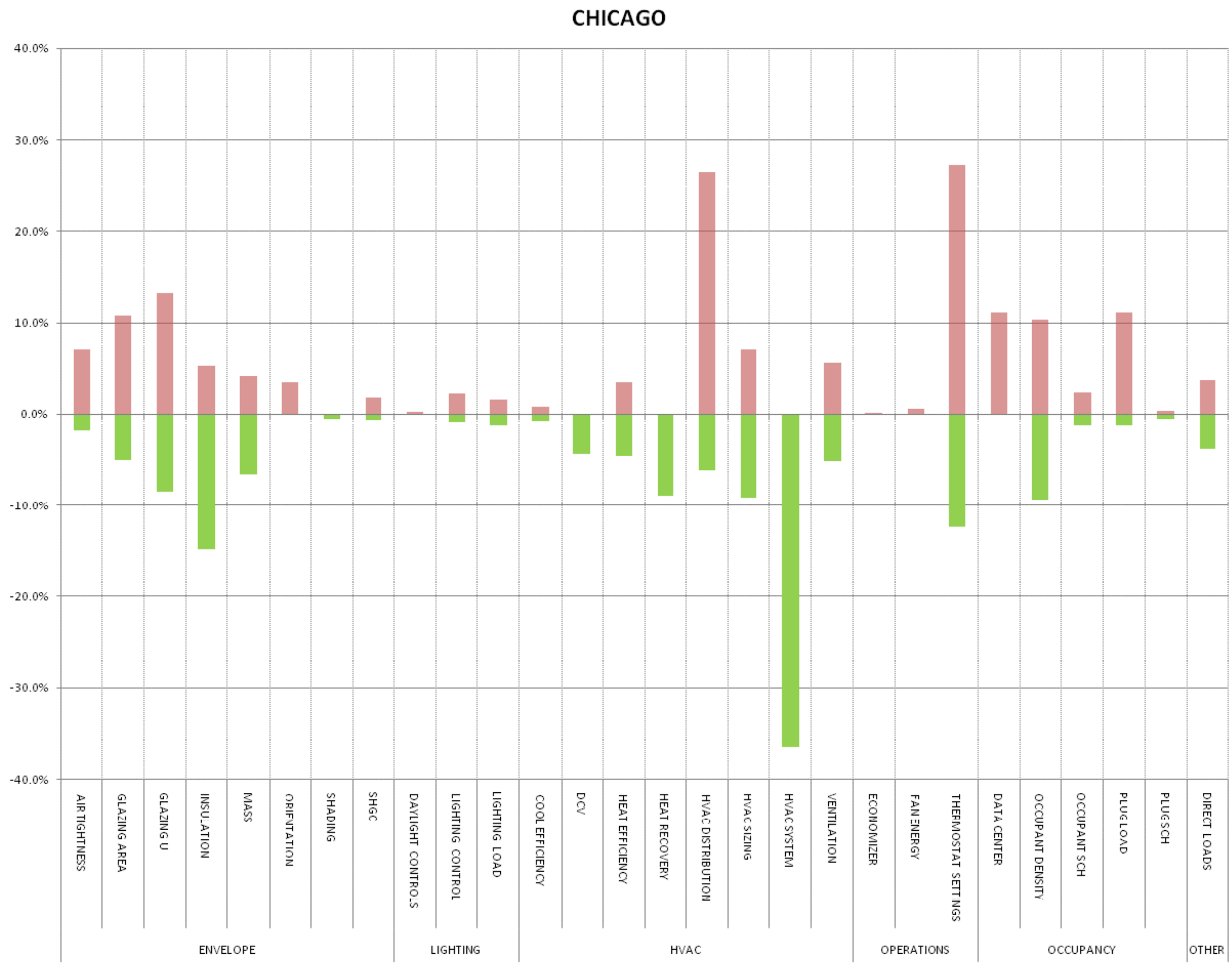


Figure 2: Measure Energy Sensitivity for Chicago

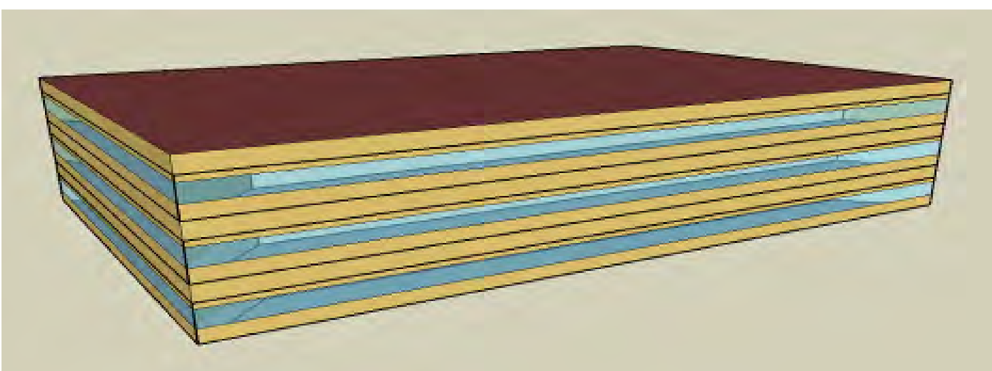


Figure 3: Building Geometry for Office Prototype

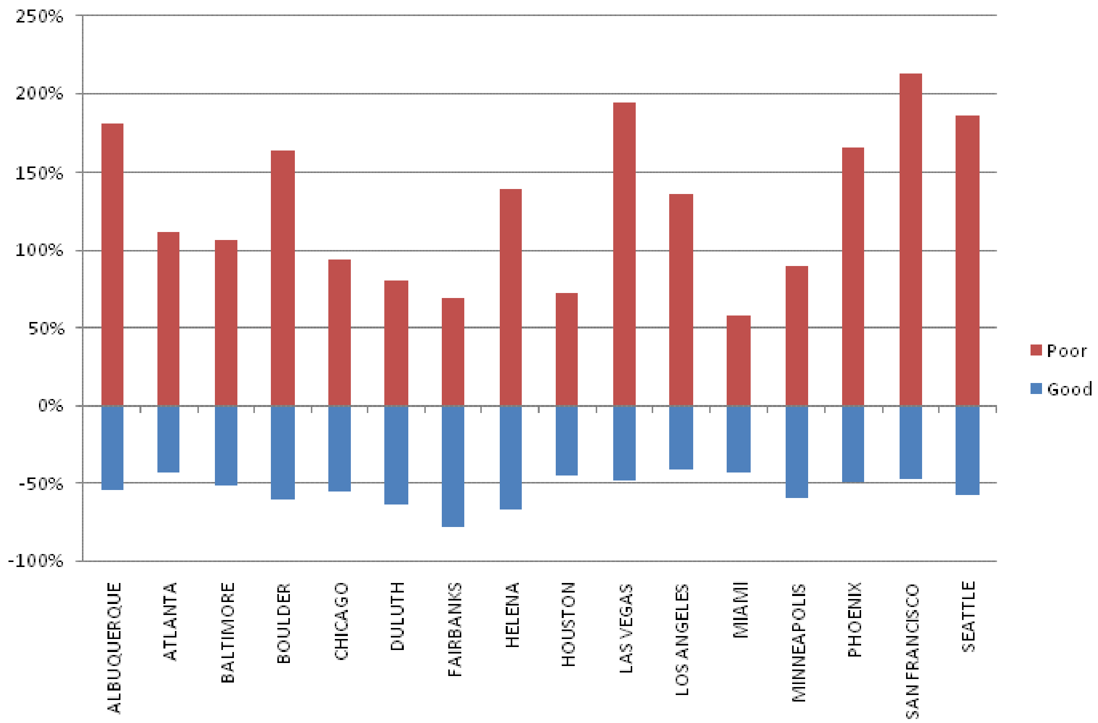


Figure 4: Relative Impact of All Variables Controlled by Design Team

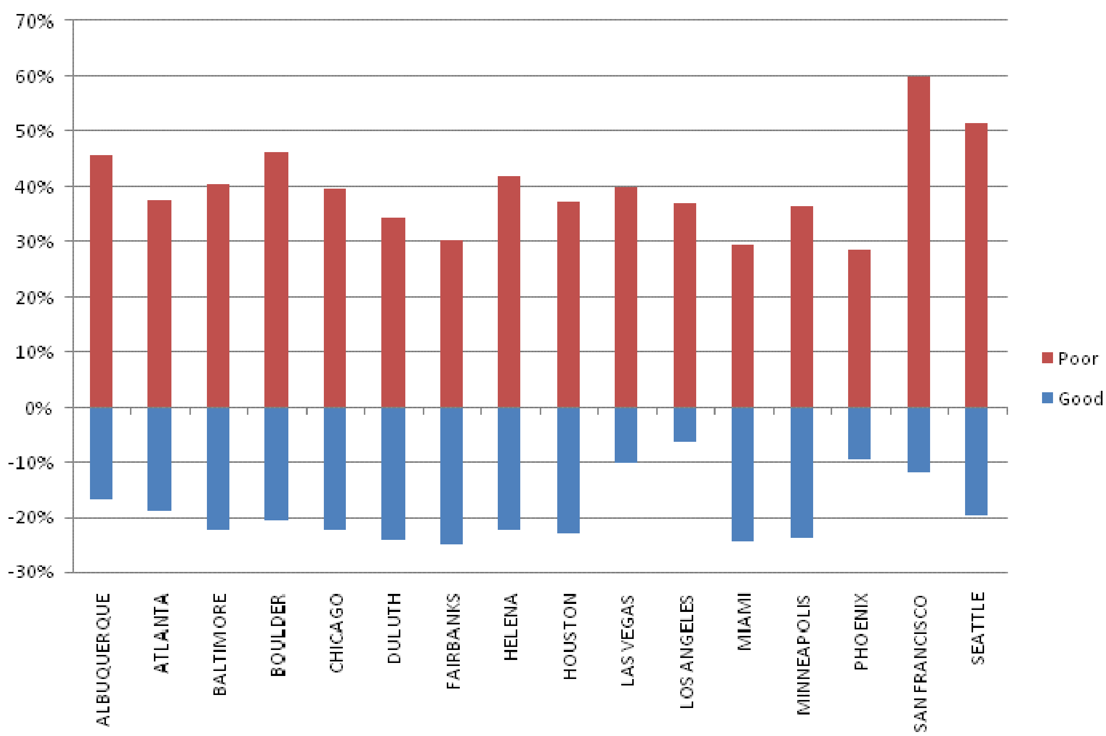


Figure 5: Impact of Variables Associated with Commissioning, Operations, and Maintenance

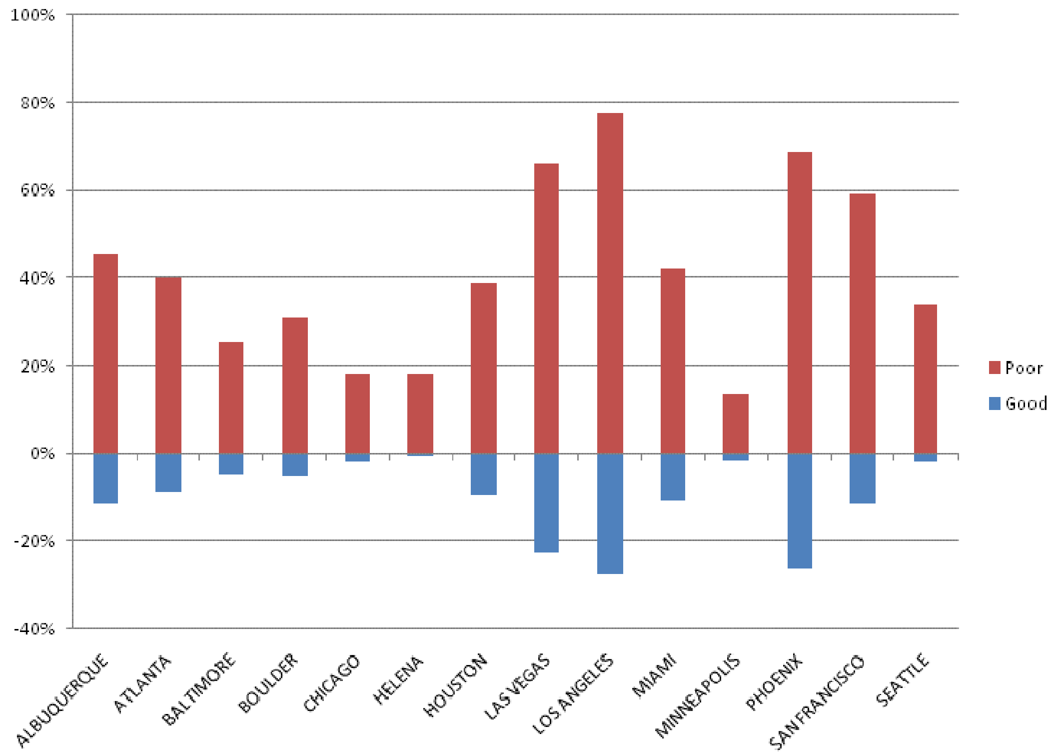


Figure 6: Impact of Variables Controlled by Tenants Only

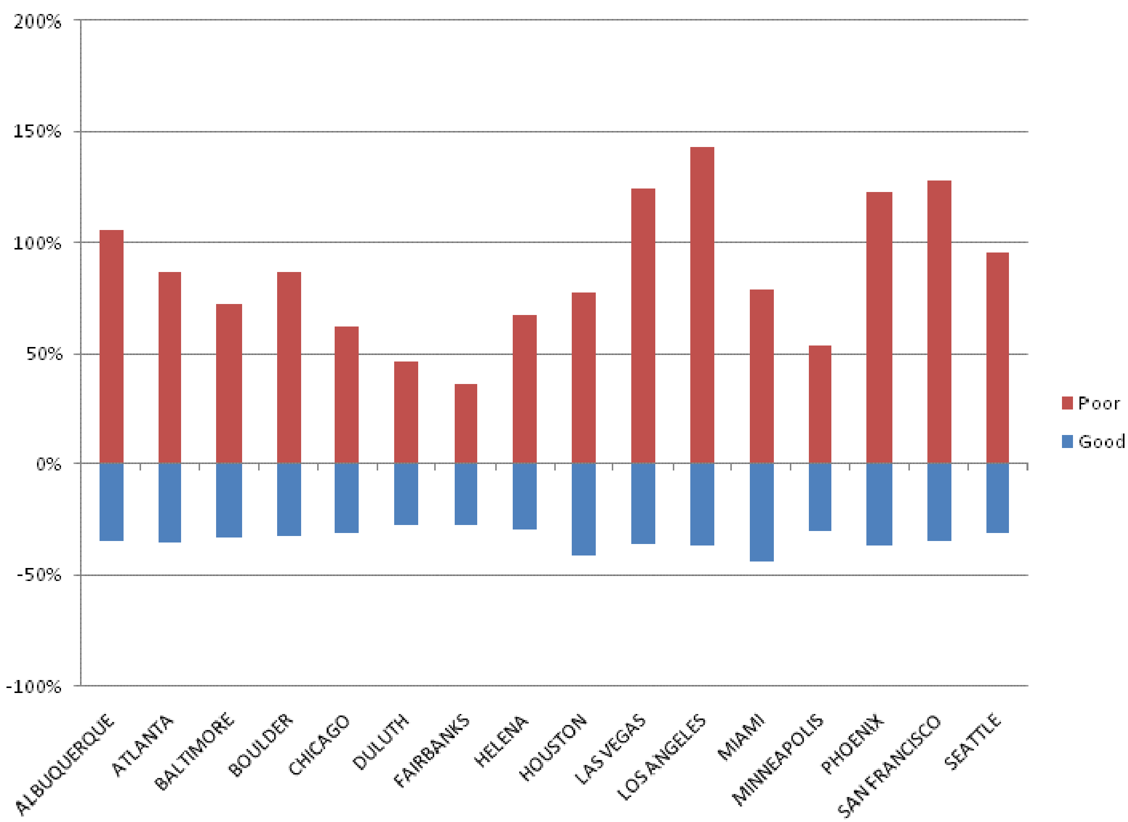


Figure 7: Impact of All Variables of Operation and Tenants Combined

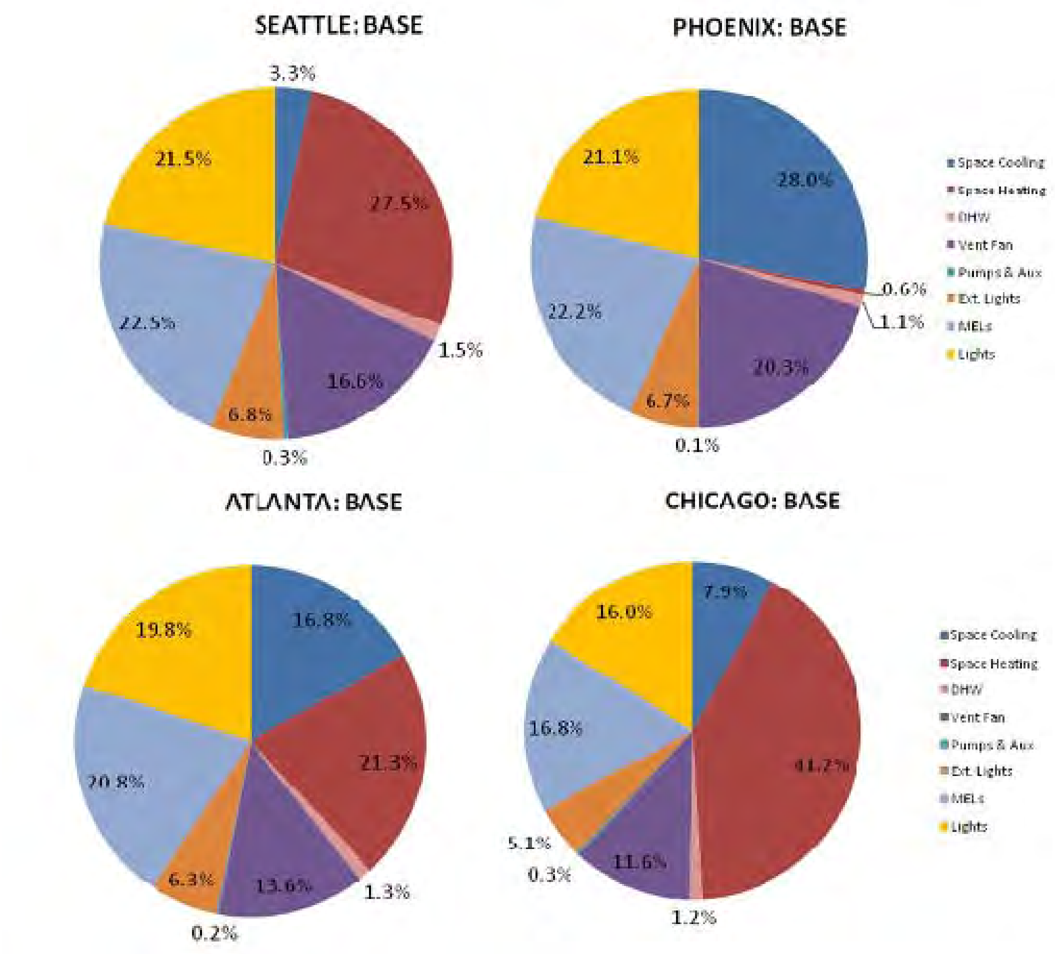


Figure 8: Base Case Energy End Use Breakdowns for Four Representative Climates

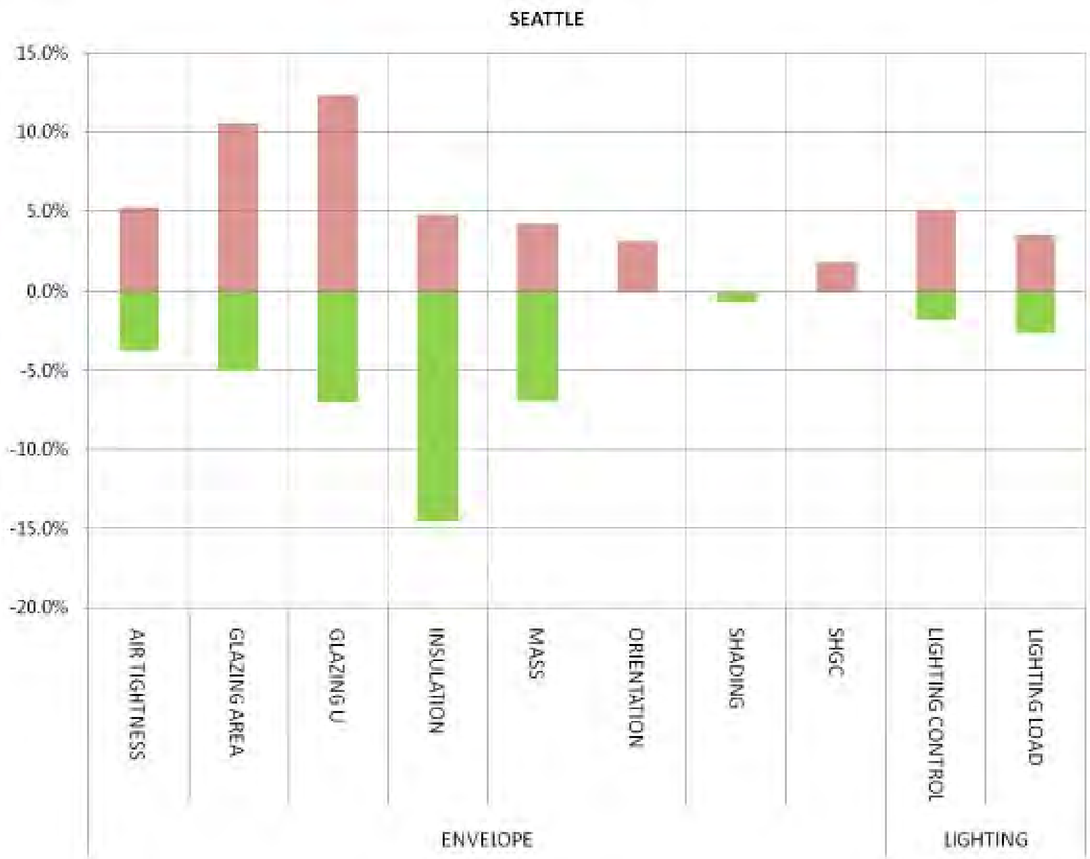


Figure 9: Seattle Envelope Measure Impacts

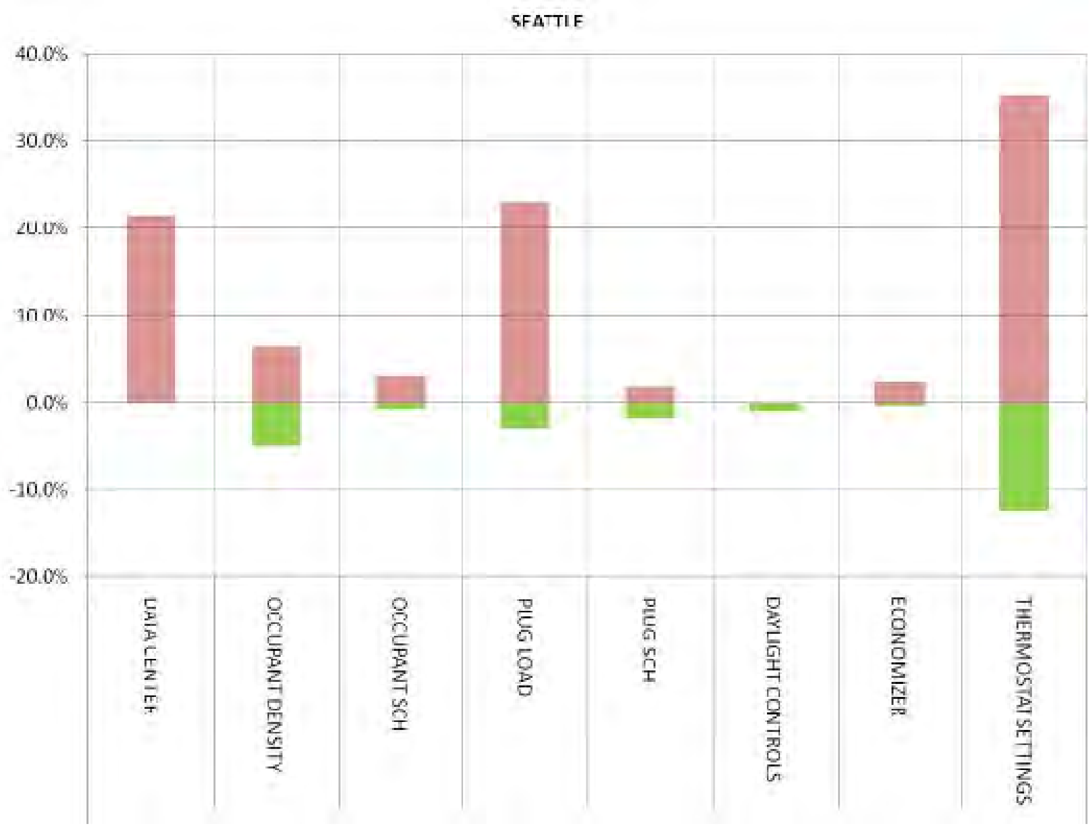


Figure 10: Seattle Occupancy and Operations Measure Impacts

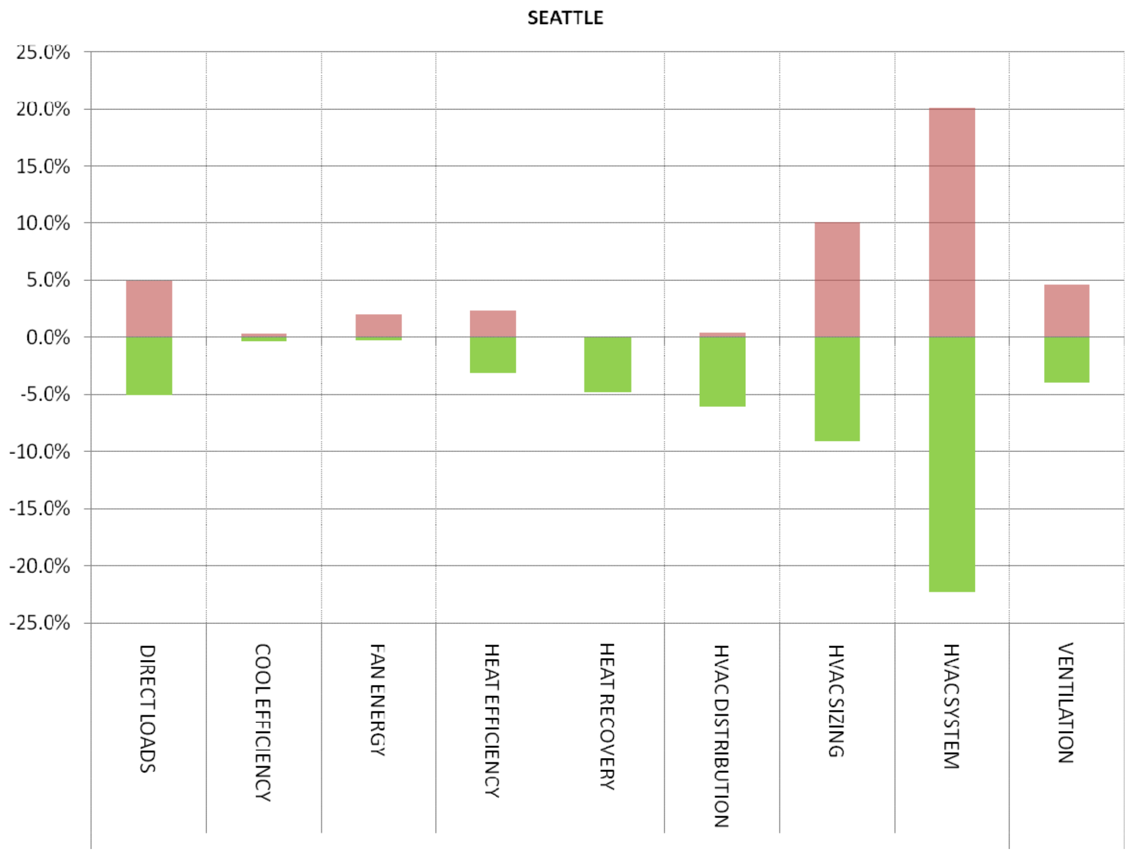


Figure11: Seattle HVAC and Other Measure Impacts

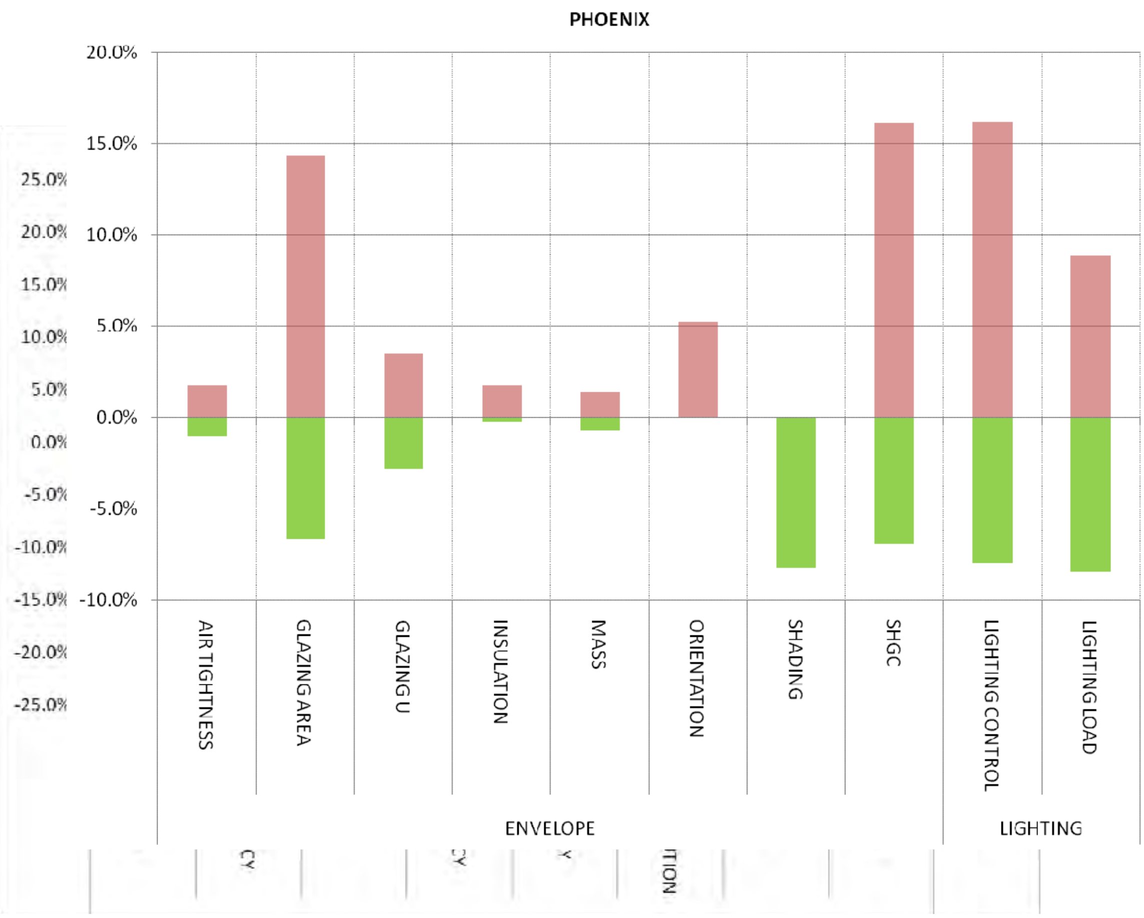


Figure 12: Phoenix Envelope and Lighting Measure Impacts

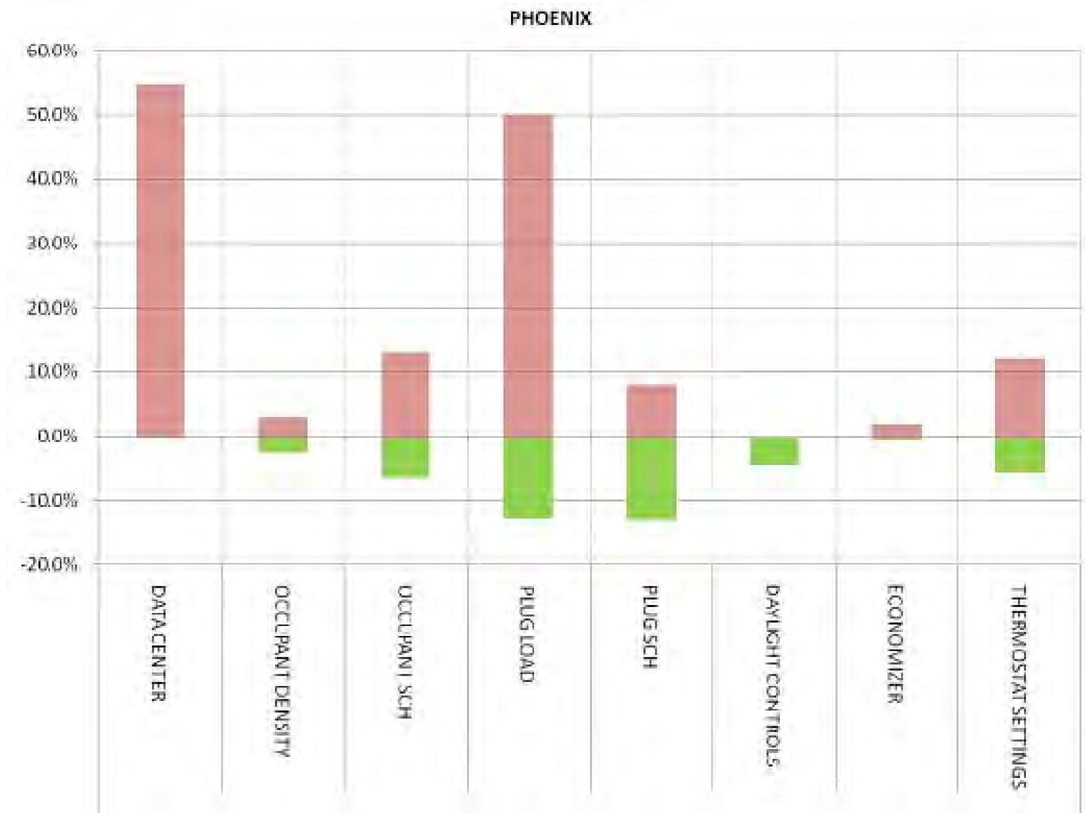


Figure 13: Phoenix Occupancy and Operations Measure Impacts

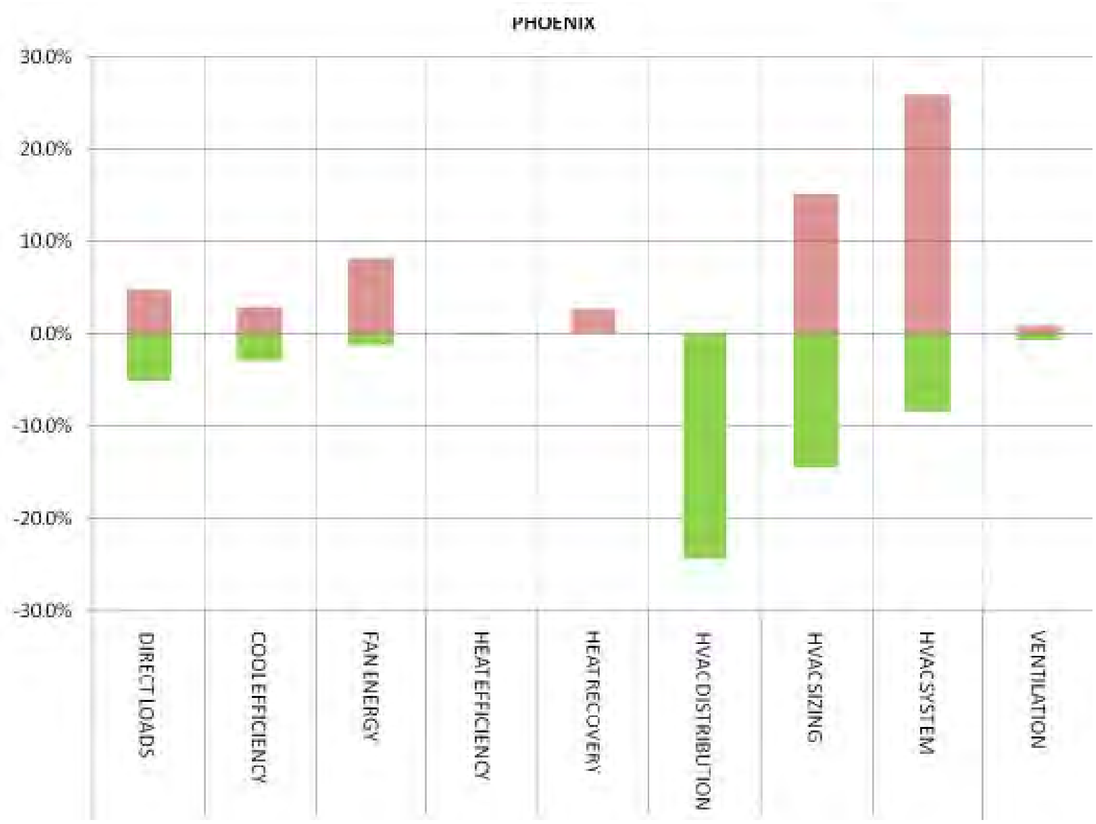


Figure 14: Phoenix HVAC and Other Measure Impacts

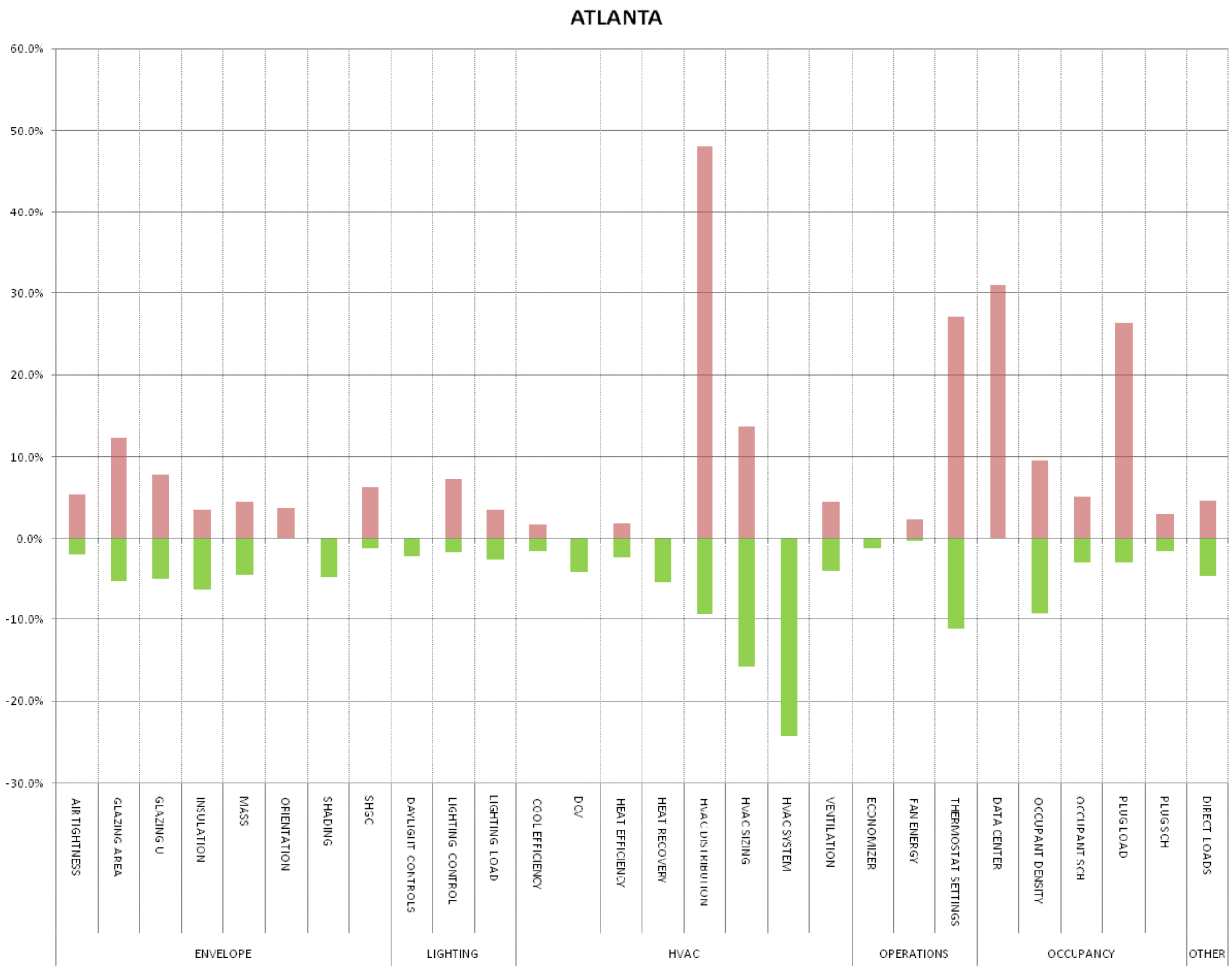


Figure 15. Atlanta Measure Impacts

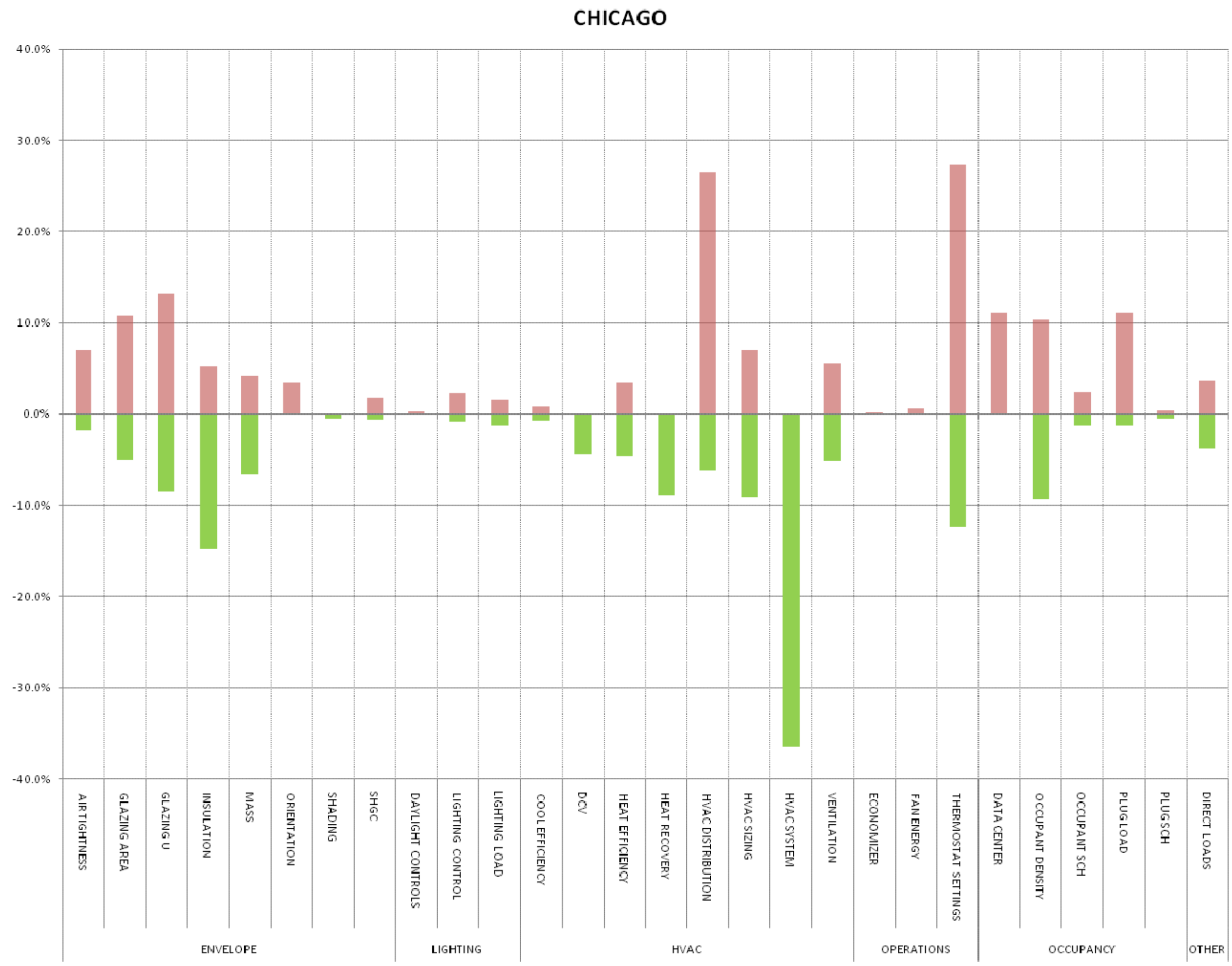


Figure 16. Chicago Measure Impacts

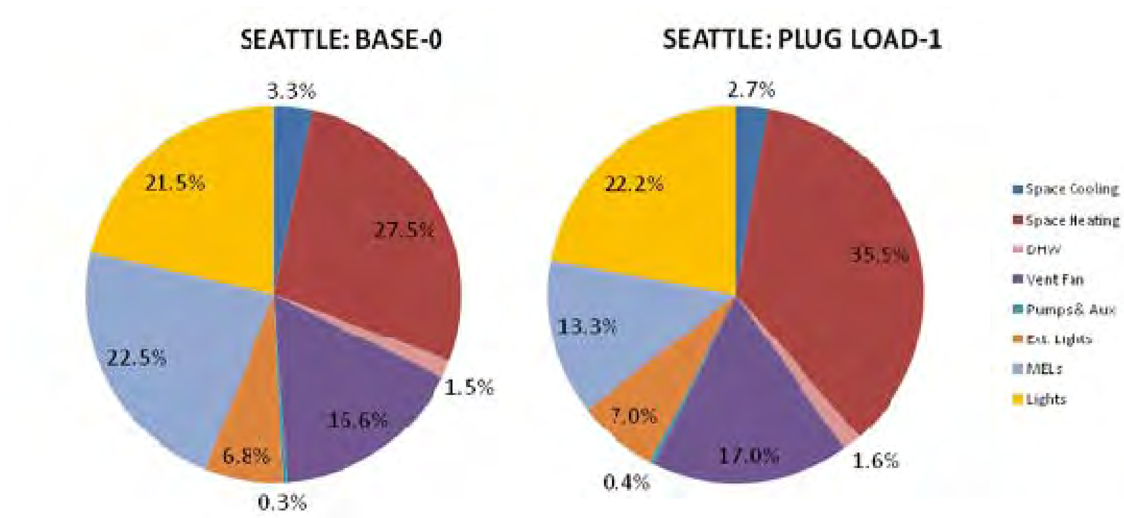


Figure 17. Seattle Plug Load Interactions

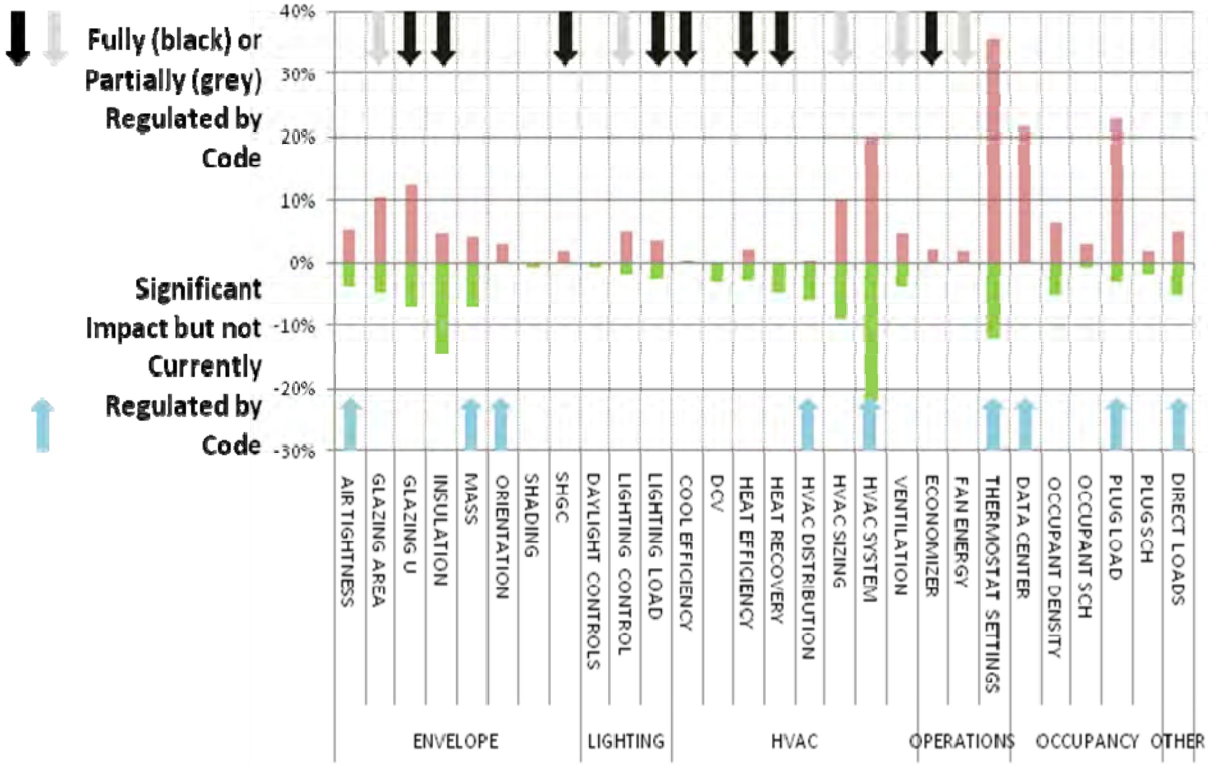


Figure 18. Components Regulated or Unregulated by Typical Energy Codes

Table 1: Measure Bundles for Package Analysis

Commissioning and Maintenance	Commissioning, Maintenance, and Operations	Operations Only	Daylighting	Design and HVAC System	HVAC System Only
Heat Efficiency	Occupant Schedule	Occupant Schedule	Orientation/ Aspect	Orientation/ Aspect	System/ Distribution
Cool Efficiency	Plug Loads	Plug Loads	Glazing Area	Mass	DCV
Ventilation	Plug Schedule	Plug Schedule	Shading	Envelope Insulation	Fan Energy
Fan Energy	Heat Efficiency	Lighting Control	Glazing U	Glazing Area	HVAC Sizing
Economizer	Cool Efficiency		Daylight controls	Shading	
Combined Setpoint Range & Setback	ventilation			Glazing U	
	Fan Energy			Air Tightness	
	Economizer			Lighting LPD	
	Lighting Control			Daylight controls	
	Combined Setpoint Range & Setback			System /Distribution	
				DCV	
				Fan Energy	
				HVAC Sizing	

*Table 2: Building Geometry**
**NREL, Building Summary Medium Office New Construction (benchmark-new-v1.2_4.0-medium_office_si)*

Total Area	53,625	sf
Number of Floors	3	
Aspect Ratio	2:1	
Floor to Floor Height	13	ft
Floor to Ceiling Height	9	ft
Window to Wall Ratio	0.33	

Table 3: Thermal Properties

Variable	Low Performance	Base Case	High Performance
Mass	wood frame (no slab)	4" slab	12" slab
Insulation Levels	R-11 metal frame walls R-19 steel framed roof No slab insulation	ASHRAE 90.1-2007 Seattle	ASHRAE 189
Shading	NONE- SHGC: 0.38	NONE- SHGC: 0.38	FIXED 3' HORIZONTAL, SHGC: 0.38
SHGC	0.76	0.38	0.15
Glazing U	0.93	0.48	0.28
Air Tightness (ACH)	0.62	0.29	0.01

Table 4: Internal Gains

Variable	Low Performance	Base Case	High Performance
Plug Loads	2.0 W/sf	0.75 W/sf	0.4 W/sf
Lighting Loads	1.3 W/sf	1.0 W/sf	0.7 W/sf
Occupant Density	130 sf/Person	200 sf/Person	400 sf/Person

Table 5: HVAC System Modeling Inputs

Variable Name	Base Case Input
Systems/Zone	1
HVAC System Type	Pkgd Single Zone (PRTU)
Sizing Ratio	2
Fan Control	Constant (Occupied Hrs)
Supply kW/cfm	0.000376
Min Supply Temp (F)	55
Max Supply Temp (F)	120
Cool Sizing Ratio	1
Cooling EIR	0.31
Cooling Performance Curves	eQUEST Defaults
Humidity Control (RH)*	50%
Heating Sizing Ratio	1
Heating AFUE	0.78
Heating Performance Curves	eQUEST Defaults
Economizer Control	OA Temperature
Economizer High-limit (F)	65
DCV	No
Water-side Econ	No
Heat Recovery	No
Baseboard Heat	No
Evaporative Cooling	No

*Only included for cities located in ASHRAE's "humid" climate zones

Table 6: Base-Case Energy Use Index (EUI) for Four Representative Climates

Climate	Seattle	Phoenix	Atlanta	Chicago
Base Case (PRTU) EUI (kBtu/sf/yr)	60	61	65	80

Table 7: Energy Use Index (EUI) for Four Representative Climates with VAV Systems

Climate	Seattle	Phoenix	Atlanta	Chicago
VAV EUI (kBtu/sf/yr)	68	76	65	79

APPENDIX A

Variables and References

Category	Variable	Low Performance	Base Case	High Performance	References
Envelope	Building Area (SF)	52630	52630	52630	1
	Number Of Floors	3	3	3	1
	Thermal Zoning	Core zone w/ 4 perimeter zones on each floor	Core zone w/ 4 perimeter zones on each floor	Core zone w/ 4 perimeter zones on each floor	1
	Perimeter Zone Depth	15'	15'	15'	1
	Floor to Floor (ft)	13'	13'	13'	1
	Floor to Ceiling (ft)	9'	9'	9'	1
	Aspect Ratio & Orientation	N/S 2.5-1	E/W 1.5-1	E/W 2.5-1	1,9
	Mass	wood frame (no slab)	4" slab	12" slab	1
	Insulation	R-11 metal frame	ASHRAE 90.1-2007 Seattle	ASHRAE 189	2, 9, 14
	Glazing Area	60%	33%	20%	1, 9
	Shading	NONE	NONE	FIXED 3' Horizontal	2
	SHGC	0.76	0.38	0.15	2
	Glazing U	0.93	0.48	0.28	2
	Air Tightness (ACH)	0.013	0.29	0.62	1, 15
Occupancy	Occupant Density	130 SF/Person	200 SF/Person	400 SF/Person	1, 16
	Occupant Schedule	16 Hour WD + 12 Hour SAT	12 Hour WD + 6 Hour SAT	8 Hour WD + 4 Hour SAT	1, 7
	Plug loads	2.0W/sf	0.75 W/SF	0.4 W/SF	1
	Plug Schedule	80% on at Night	40% on at Night	5% on at Night	1
	Data Center	1.5% of floor area, 100 W/SF	None	1.5% of floor area, 35 W/sf	
HVAC	HVAC System	VAV RTU, DX cooling, Gas Preheat, standard VAV boxes, w/ elec heat at the perimeter boxes	Single Zone PRTU w/ DX cooling & gas heat.	GSHP: Single zone water-air heat pumps with vertical ground loops. Ground Loop Sizing: 32 min LWT, 95 Max LWT	9
	HVAC Distribution	PRTU W/ UFAD: 1. Supply fan static .25" 2. Supply air temp 62 F. 3. Lighting heat load to plenum	Equest defaults for over-head, plenum return.	PRTU W/ radiant w/ vent fan: 1. Supply fan static =0 2. Ventilation air provided with exhaust fans sized for max vent load with 1.0" of static	
	Heat Efficiency	PRTU .72 AFUE	PRTU .78 AFUE	PRTU .80 AFUE	3, 13
	Cool Efficiency	PRTU .37EIR	PRTU .31 EIR	PRTU .307 EIR	4, 11, 12
	Heat Recovery	None	None	Counter Flow Enthalpy Wheel. Adds 0.054 W/CFM to Supply Fan	20
	Ventilation	27.3 CFM/PERSON	21 CFM/PERSON	14.7 CFM/Person w/ DCV (eQuest Defaults)	1
	Fan Energy	0.498 W/CFM	0.376 W/CFM	0.358 W/CFM	6
	HVAC Sizing	3.0 AUTOSIZE	2.0 AUTOSIZE	1.0 AUTOSIZE	
Lighting	Lighting LPD	1.3 W/SF	1.0 W/SF	0.7 W/SF	5, 9
	Lighting Control	60% on at Night	Timeclock	Tracks Occupancy	17
Operations	Daylight controls	None	None	Continuous Dimming to 30 FC 10% Min Turn Down Ratio. 93% of Lighting on Dimming Controls. 3% Skylights in Top Floor Zones.	
	Economizer	None	PRTU: 50% Max OA Flow	PRTU: 85% Max OA Flow	8
	Thermostat Settings	Tight range w/o setback: 74 Cool 72 heat	ASHRAE55 base w/ setback: 76 Cool (6 am to 8 pm),78 Set-up unoccupied 70 heat (6am-8pm), 65 Set-back unoccupied	ASHRAE55 expanded: 80 Cool (6 am to 8 pm), 82 Set-up unoccupied 68 heat (6am-8pm), 60 Set-back unoccupied	1
Other	Direct Loads	104 parking spots, or 23,712 SF @ .3 W/SF = 7.1 kW, 15 HP Elevator w/ standard office elevator schedule, 5.4 kW Misc loads for fans, façade lighting, etc (on exterior)	52 parking spots, or 11,856 SF @ .3 W/SF = 3.6 kW, 15 HP Elevator w/ standard office elevator schedule, 3.6 kW Misc loads for fans, façade lighting, etc (on exterior)	No Parking, 15 HP Elevator w/ standard office elevator schedule, 1.8 kW Misc loads for fans, façade lighting, etc (on exterior)	18, 19

References:

1 NREL Benchmark Medium Office Version 1.2_4.0: "Establishing Benchmarks for DOE Commercial Building R&D and Program Evaluation", P. Tocellini, B. Griffith, M. Deru - 2006

2 ASHRAE Standard 90.1-2007 table 5.5-4

3 ASHRAE Standard 90.1-2007 table 6.8.1E

4 ASHRAE Standard 90.1-2007 table 6.8.1B

5 ASHRAE Standard 90.1-2007 table 9.5.1

6 Trane Precedent Product Catalogue: "RT-PRC023-EN", June 2010

7 refbldg_mediumoffice_new2004_v1.3_5.0_SI input spreadsheet

8 Robert Davis, et. al. "Enhanced Operations & Maintenance Procedures for Small Packaged Rooftop HVAC Systems". 2002. Ecotope Inc. Prepared for Eugene Water and Electric Board.

9 Ecotope. Non-residential data from "2002 commercial baseline study for Pacific NW", ,10%-90% range of office buildings > 7500 square feet, none of the office buildings less than 100,000 square feet had multi-zone systems

10 ASHRAE 62.1-2001, table 2, Extimated max occupancy

11 ASHRAE 189-2009, Table C-2

12 ASHRAE Standard 90.1-2004 table 6.8.1B

13 Discussions with several manufacturers, this is the highest efficiency available

14 ASHRAE-189-2009, Table A-4

15 Gowri, Winiarski, Jarnagin. "Infiltration Modeling Guidelines for Commercial Building Energy Analysis" Sept 2009.

16 Communication from Seattle Office Building Developer

17 Communication from Chris Meeks of Seattle Integrated Design Lab

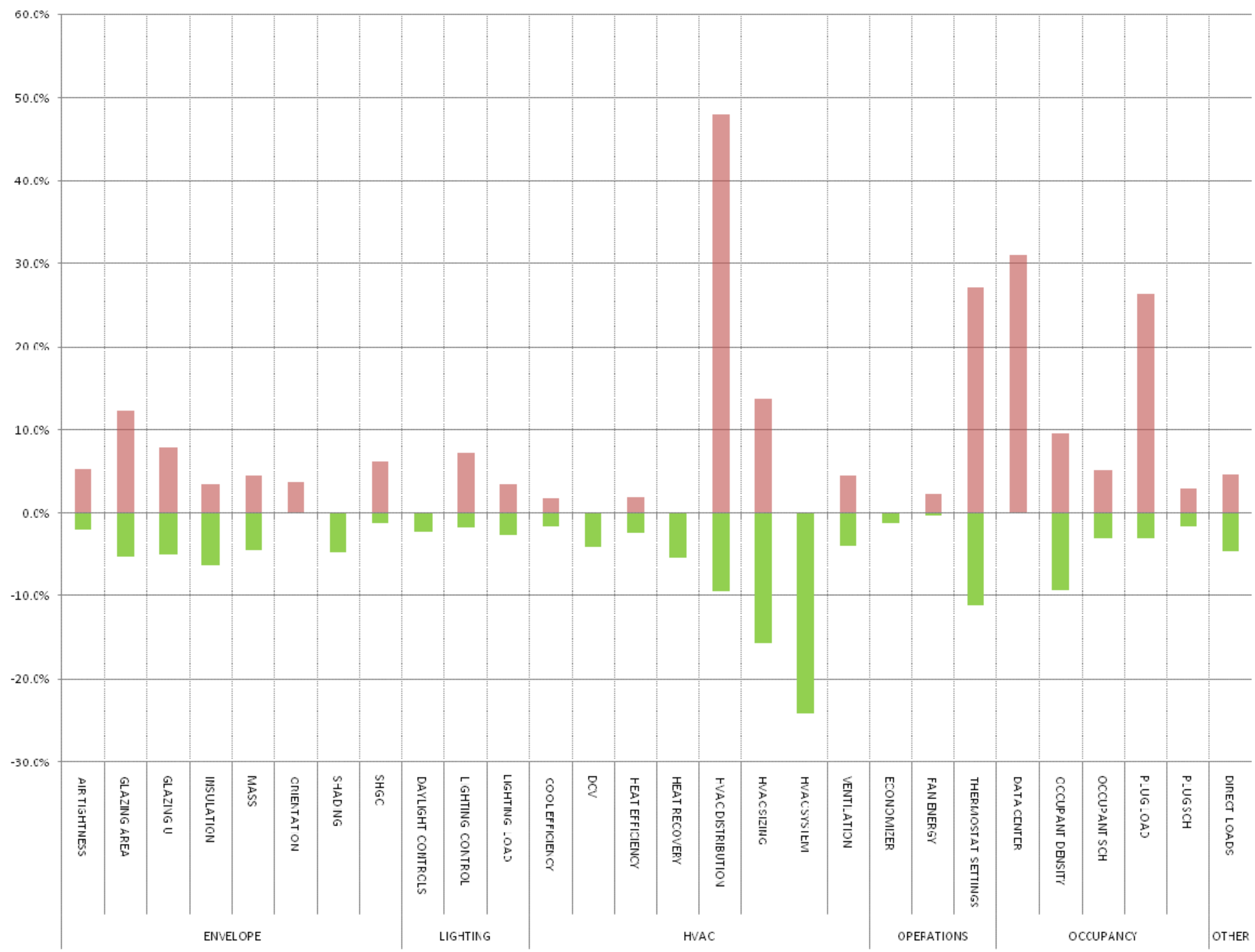
18 Seattle Municipal Code 23.54.015

19 Elevator Manufacturer's Data

20 ERV Manufacturer's Data for 6,000 CFM unit

APPENDIX B

ATLANTA



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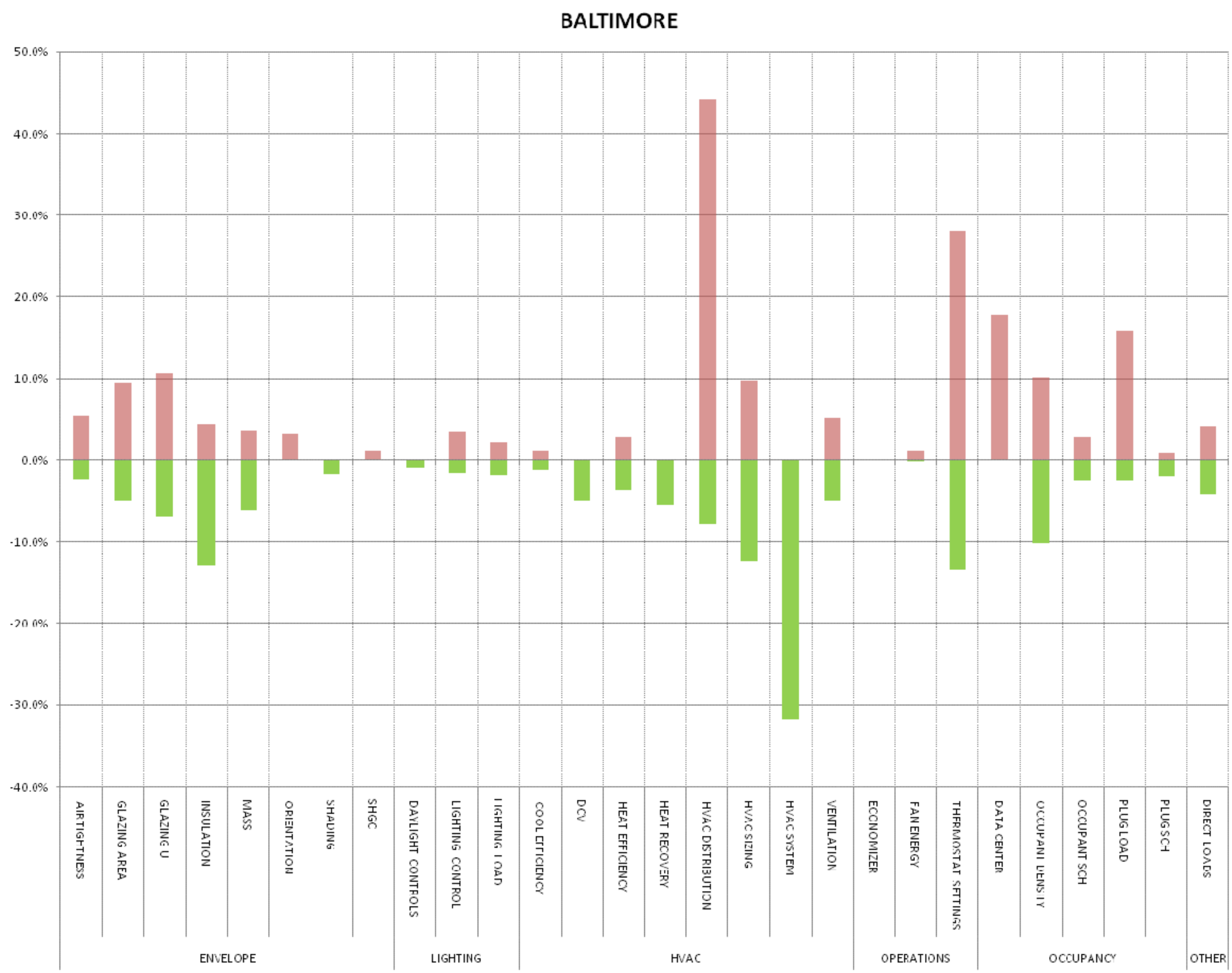

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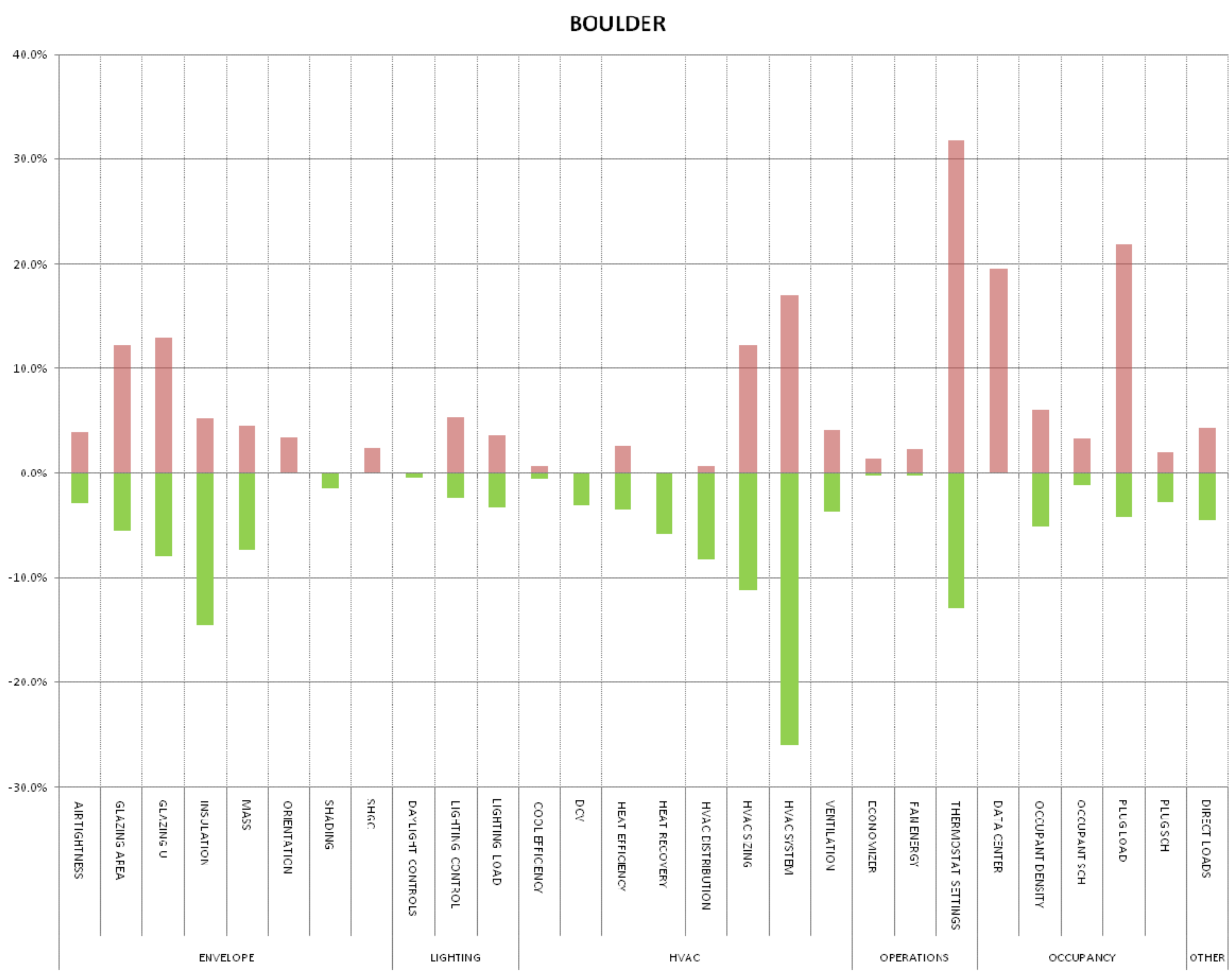

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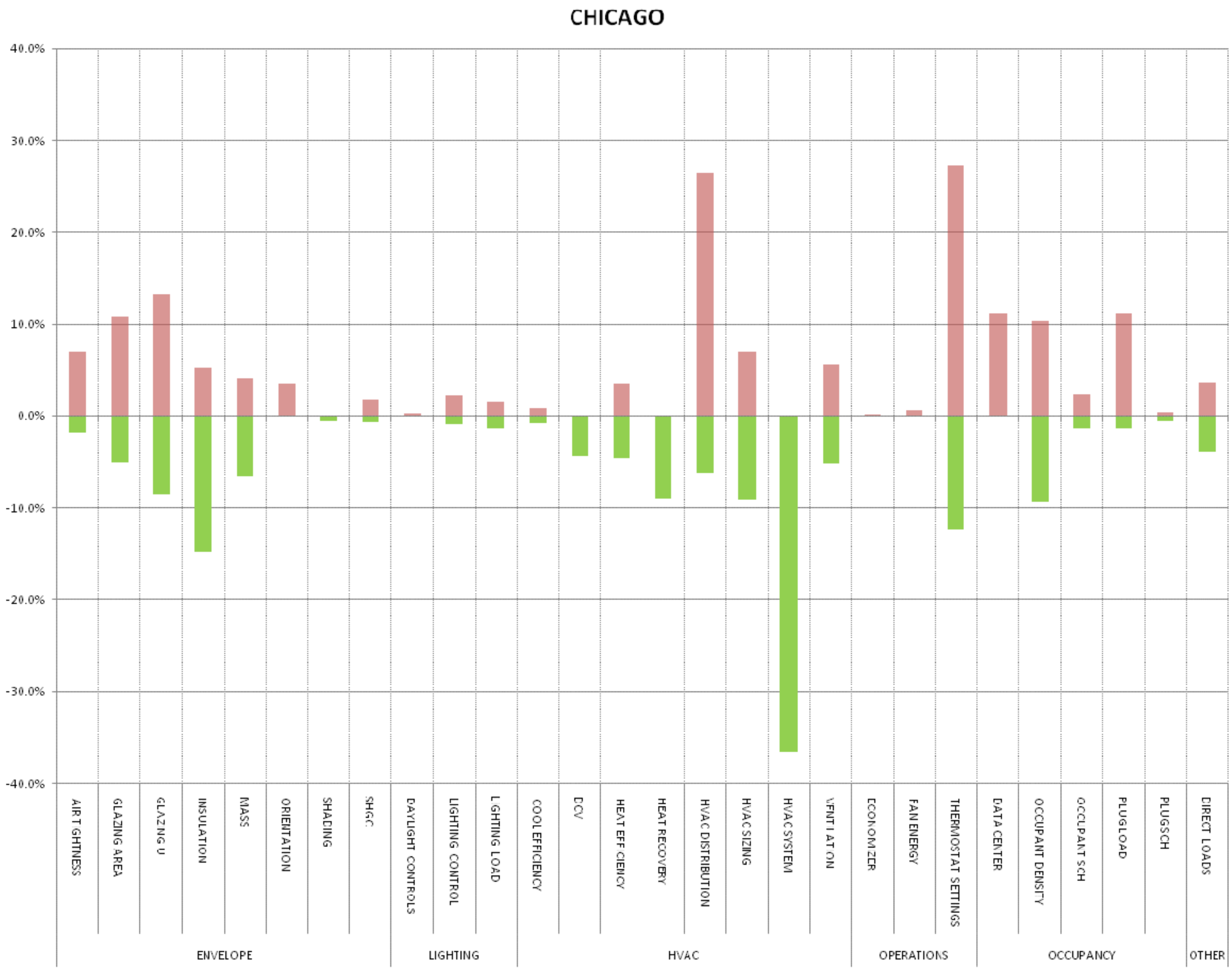
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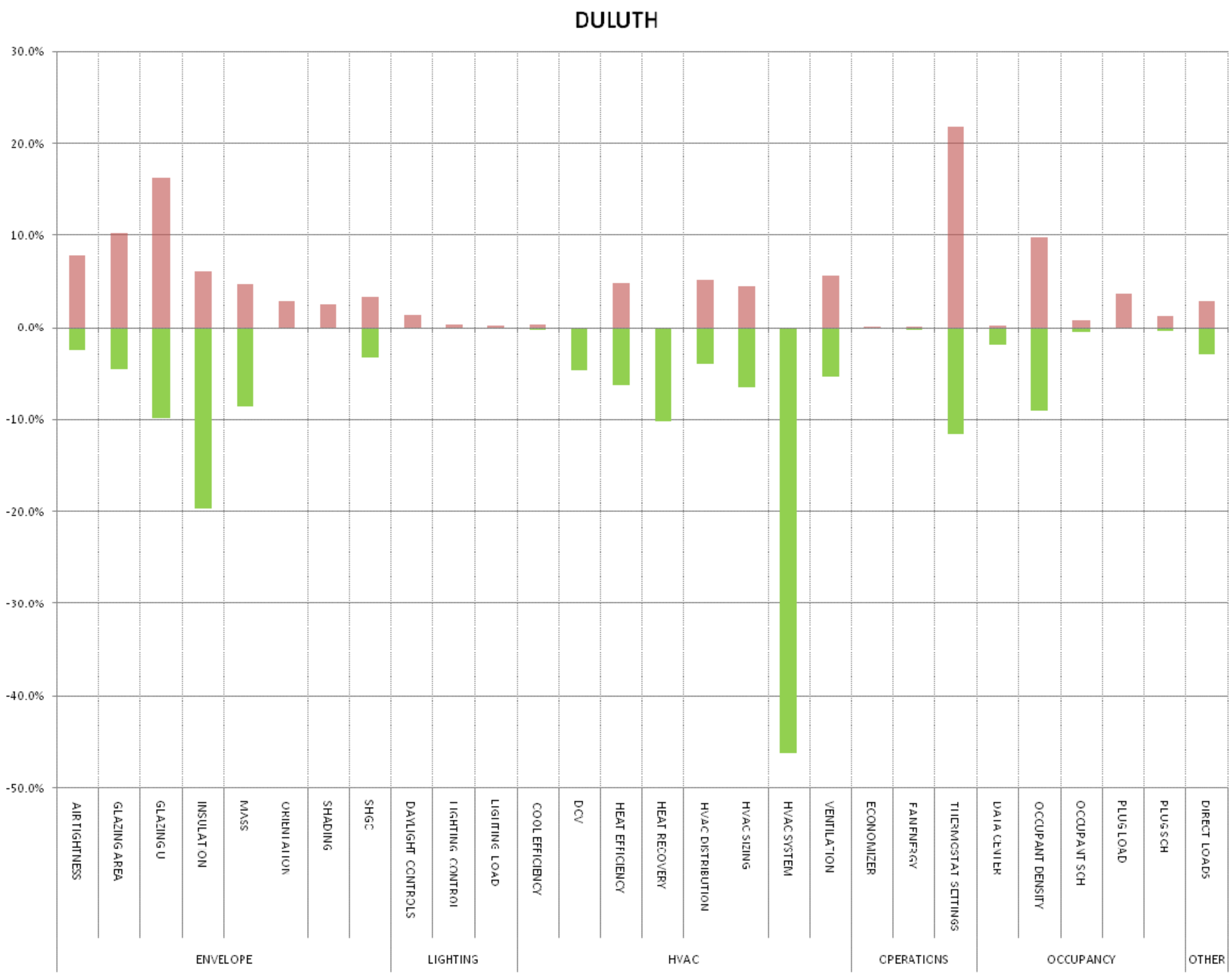

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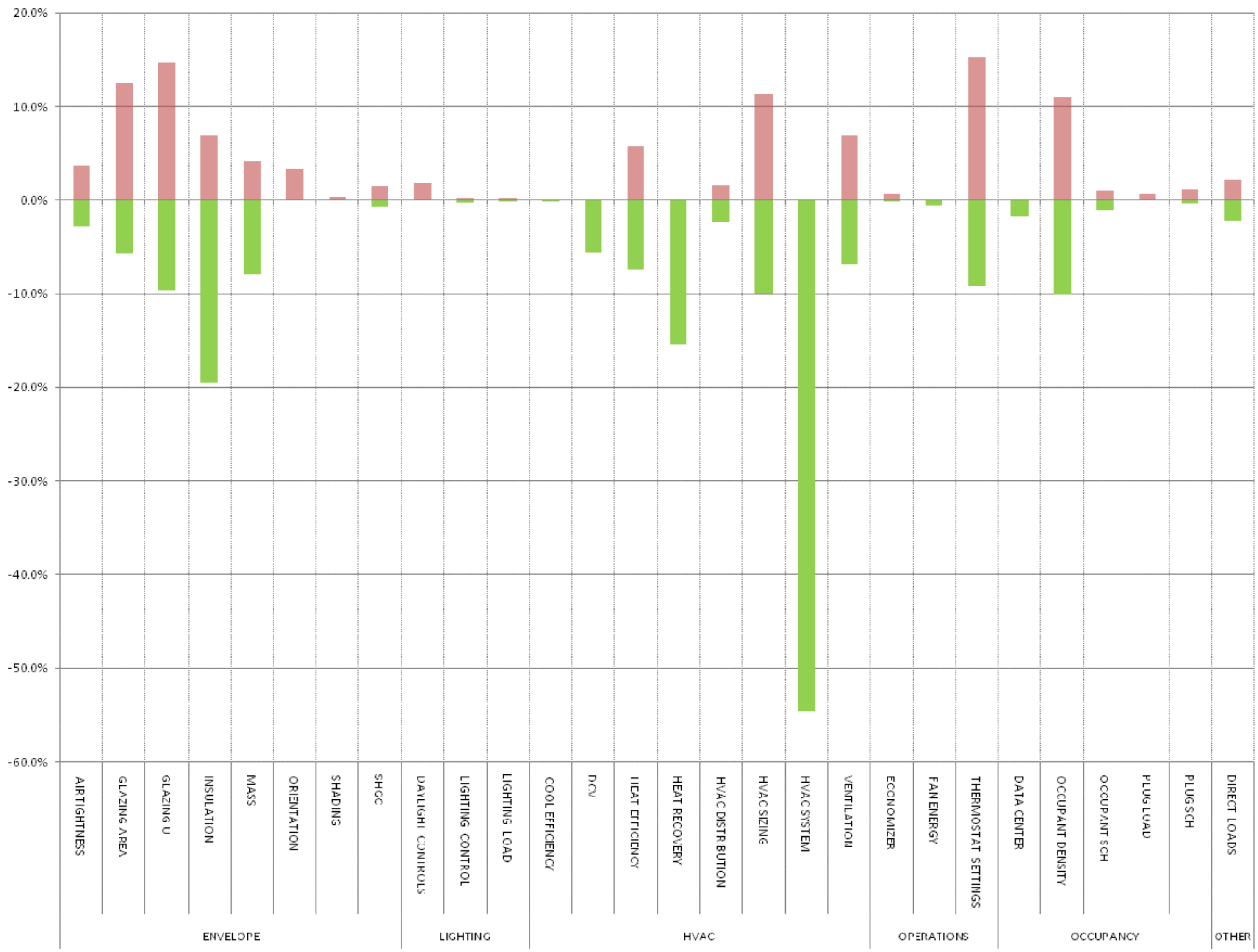

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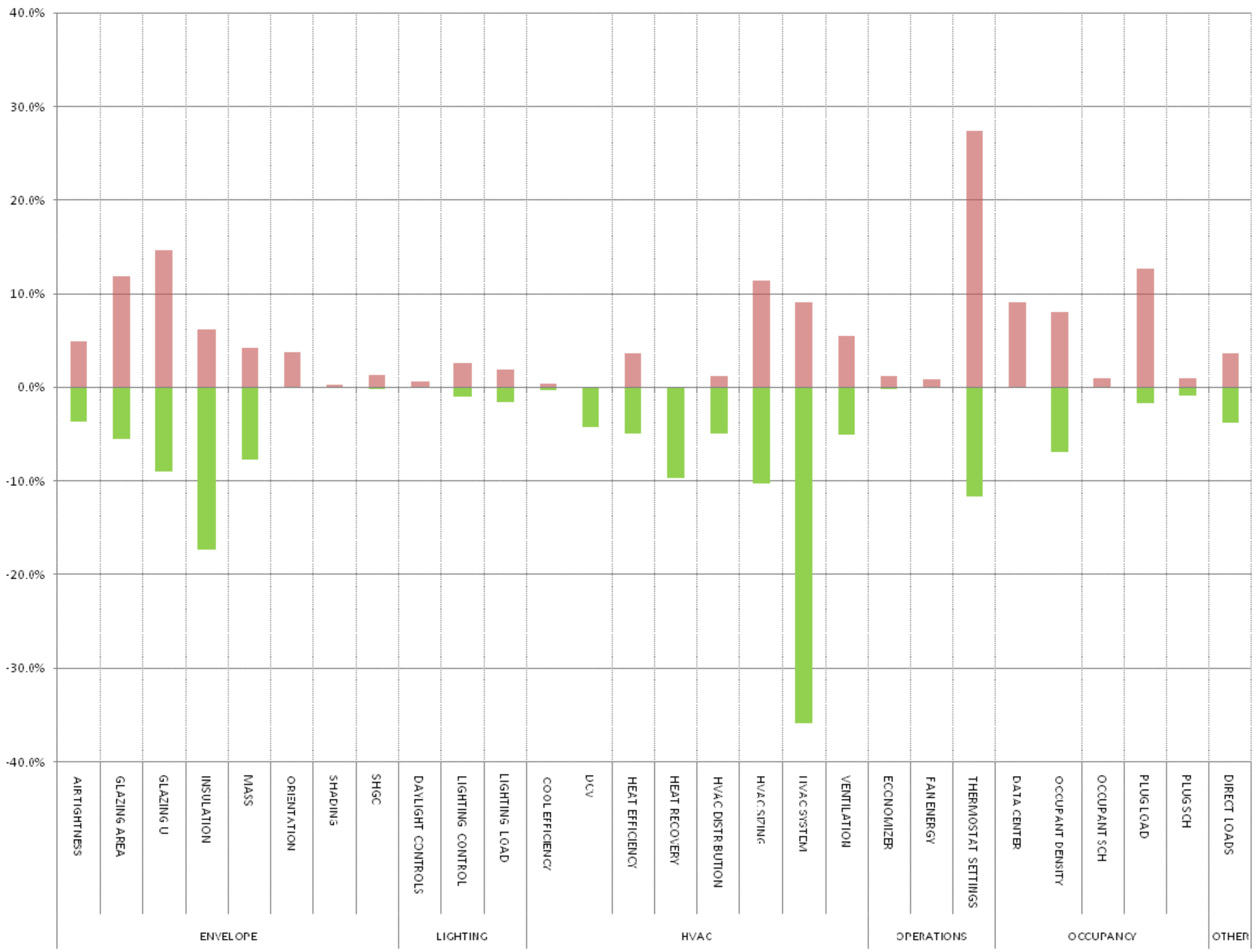

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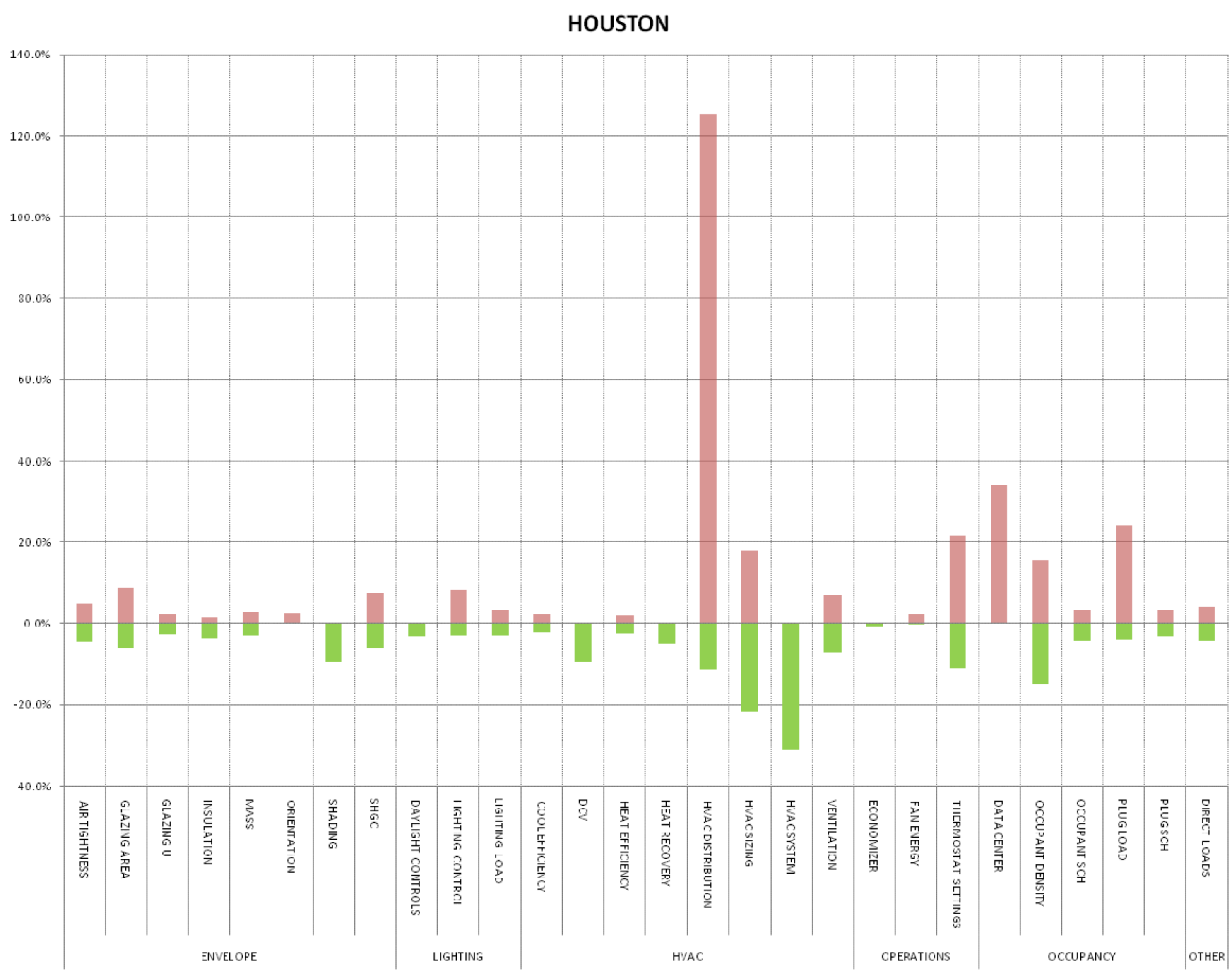
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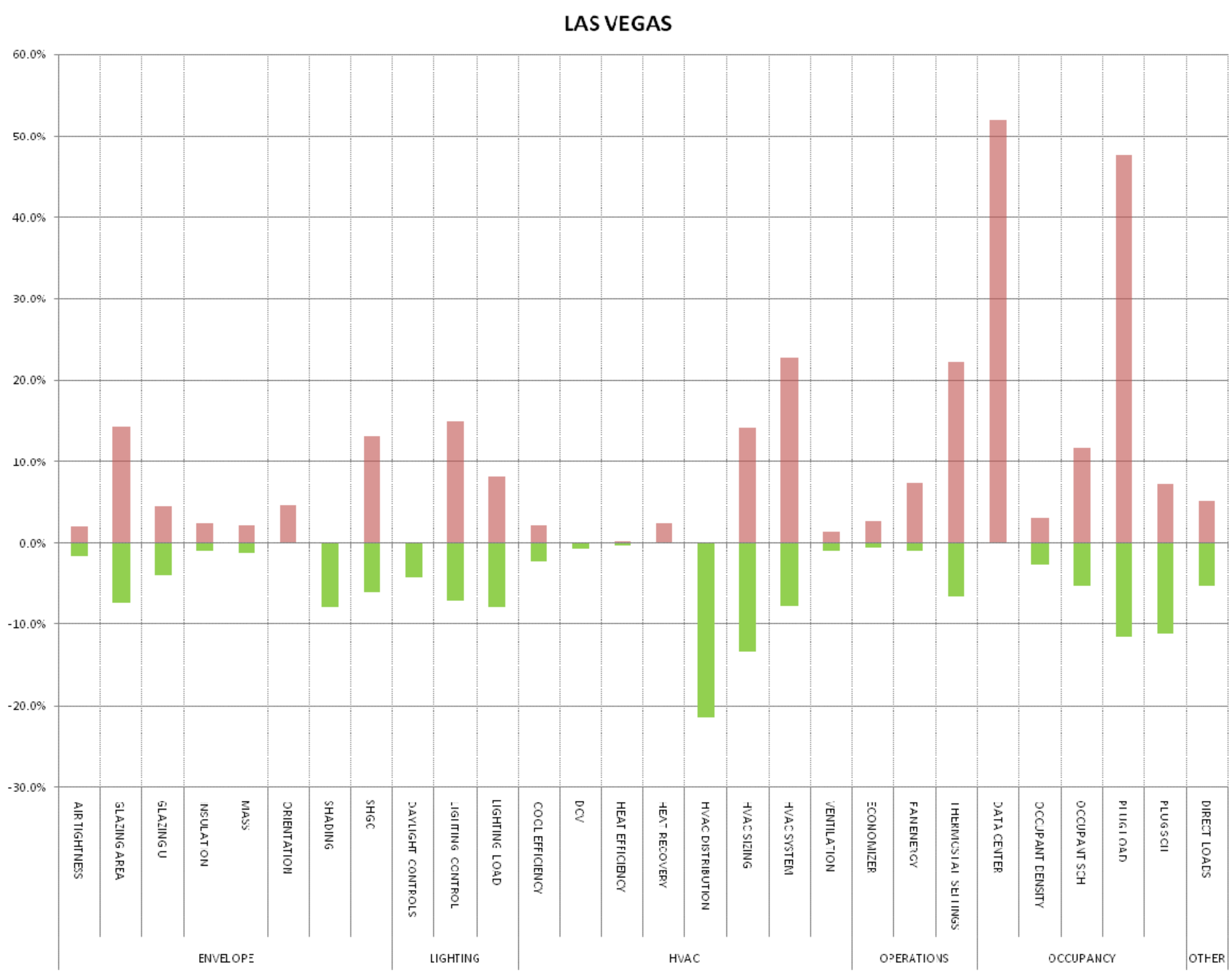

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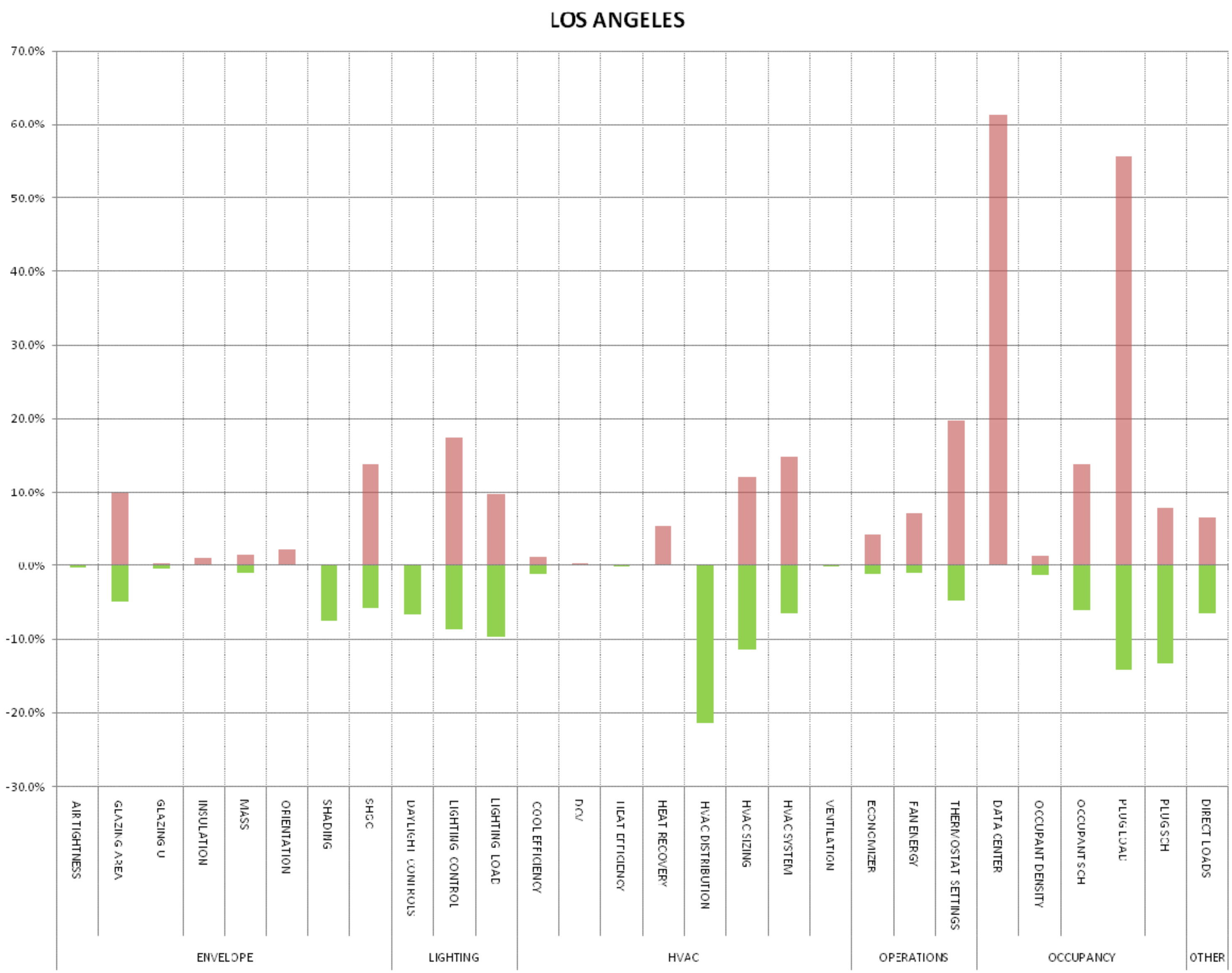
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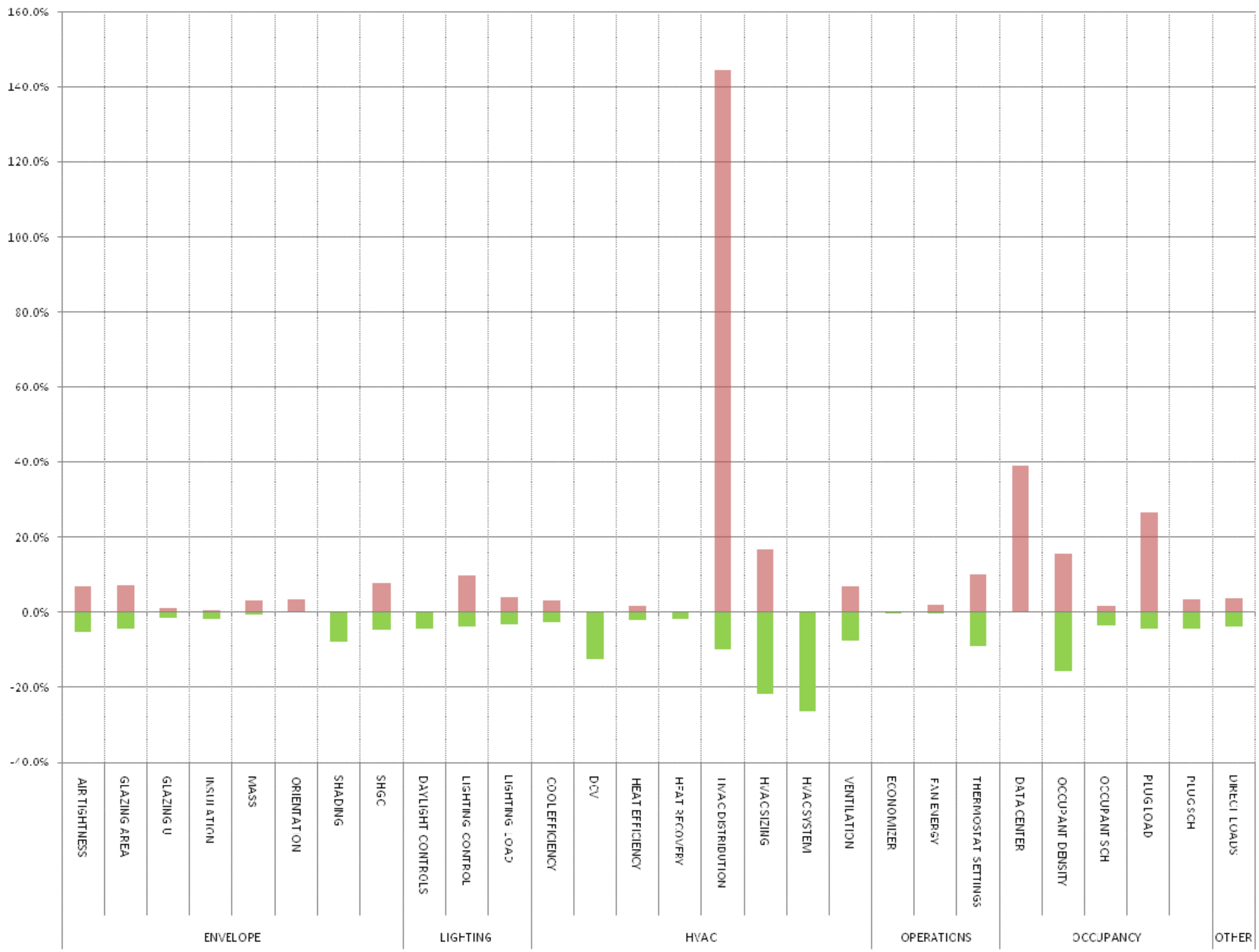

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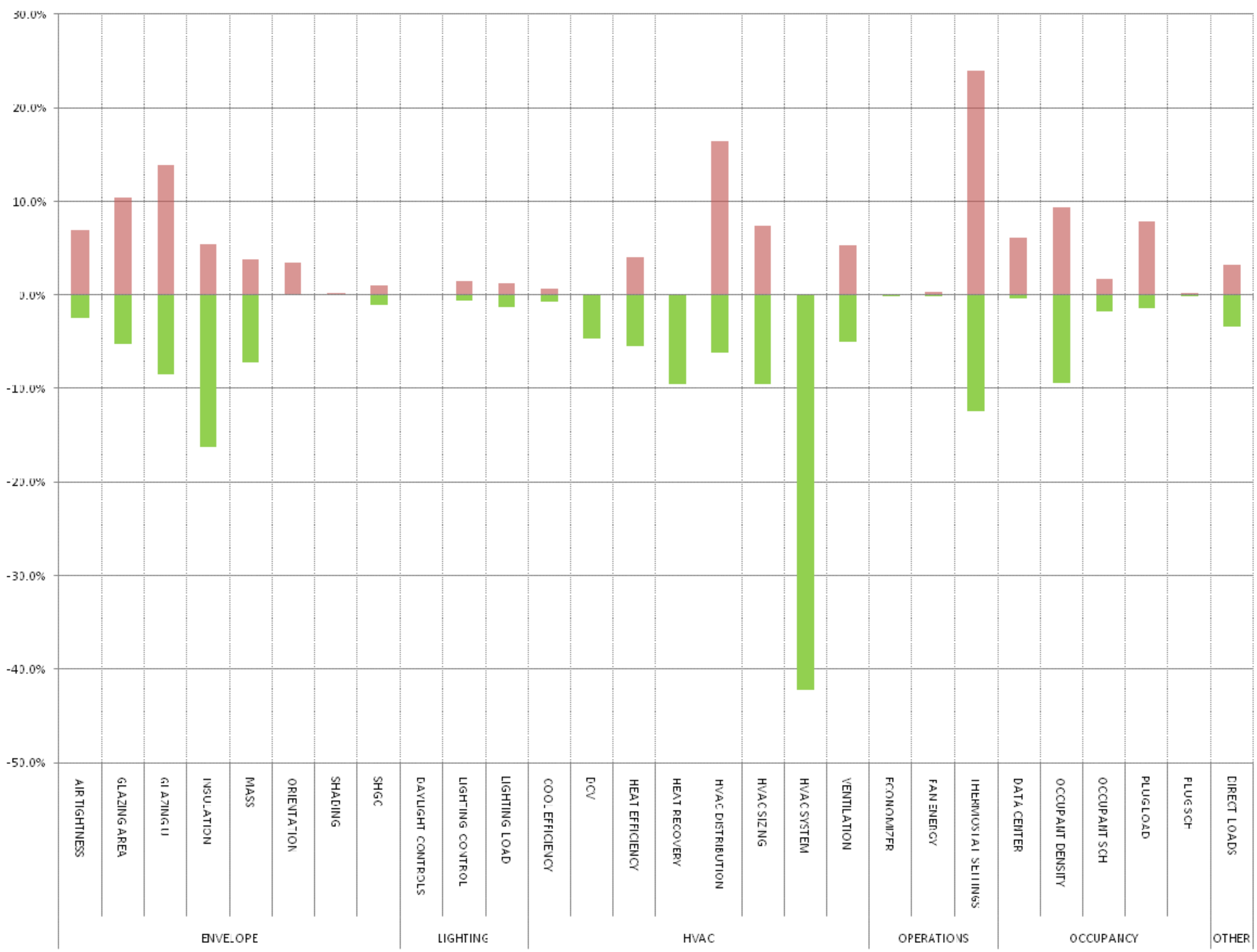

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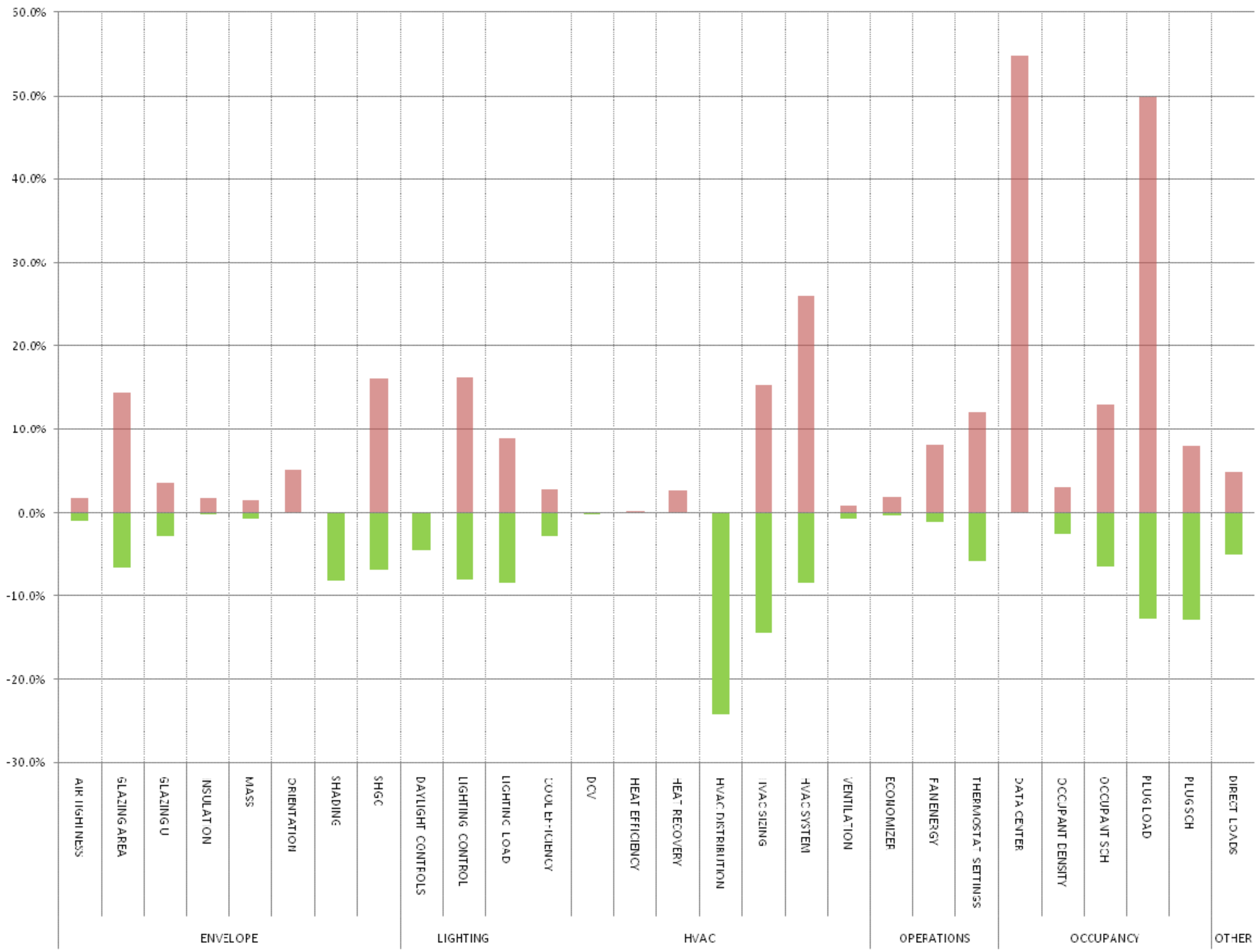

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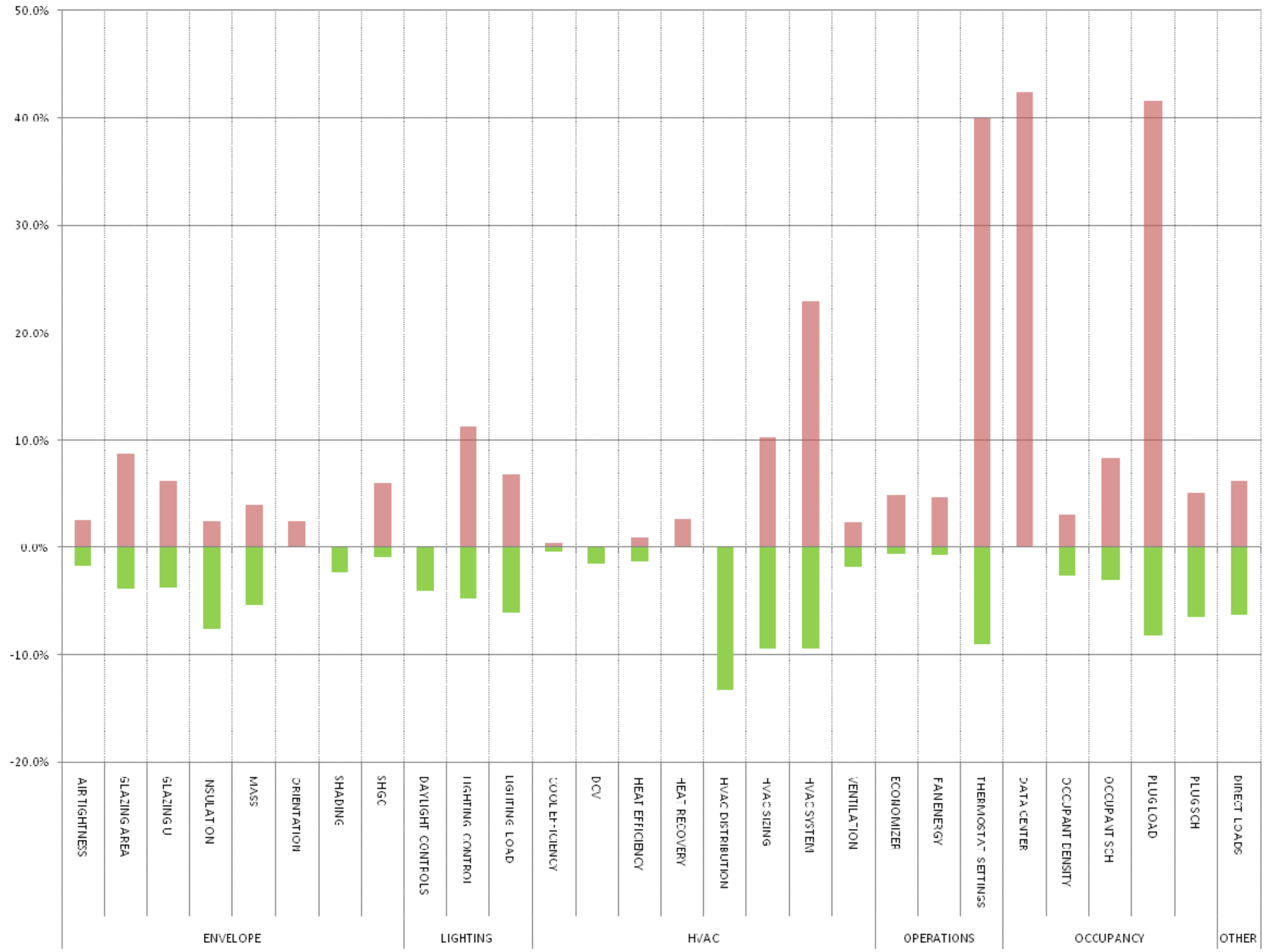
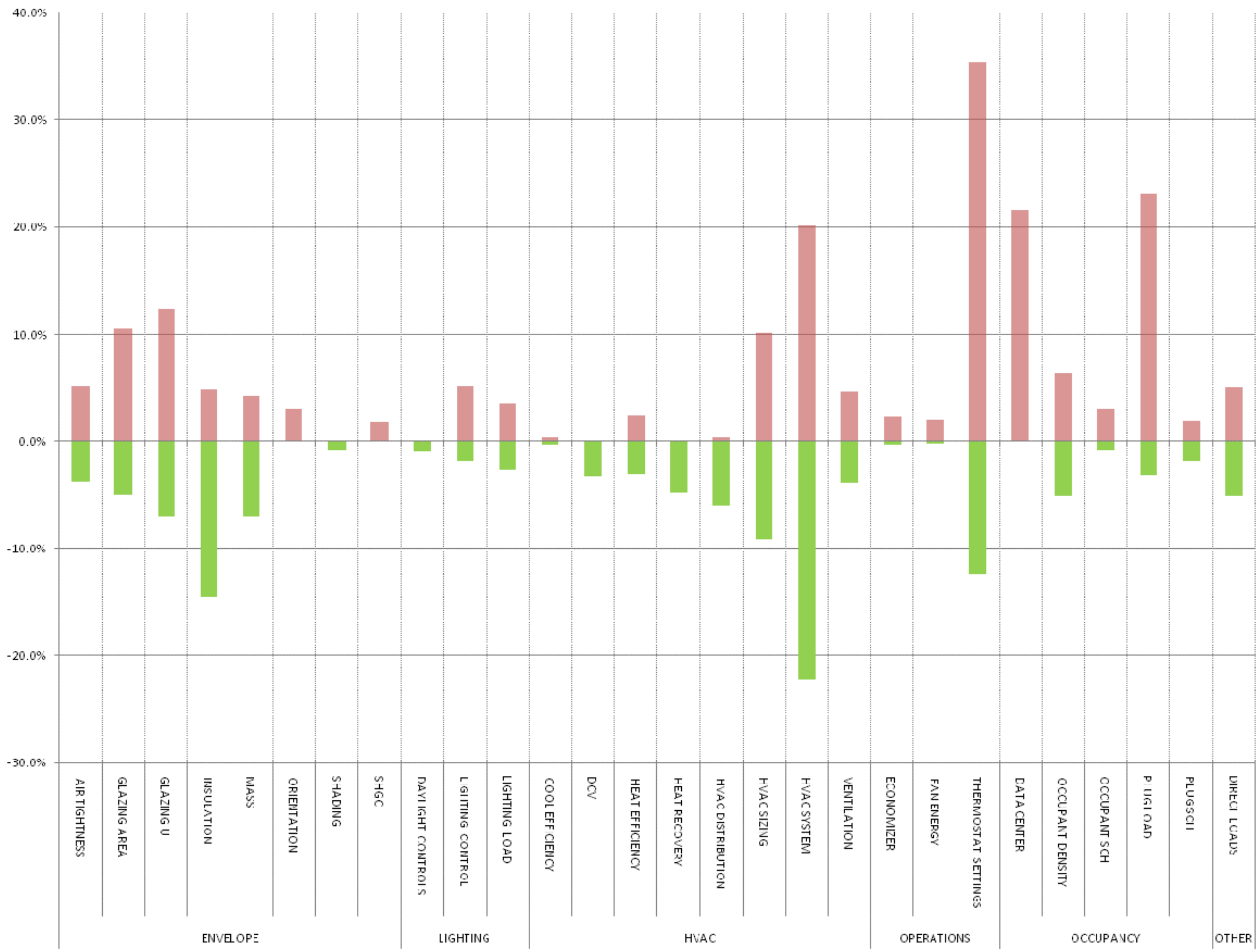
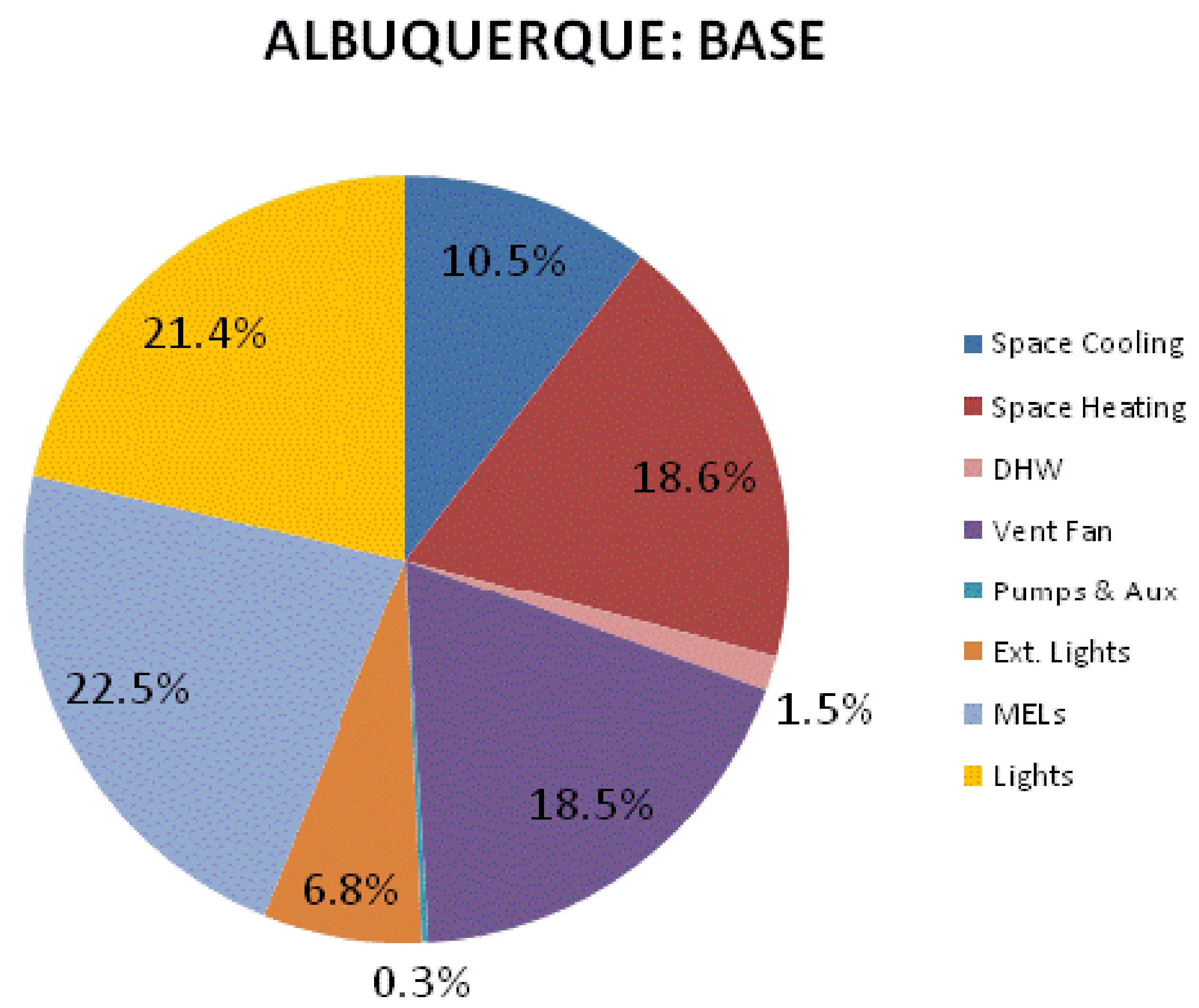


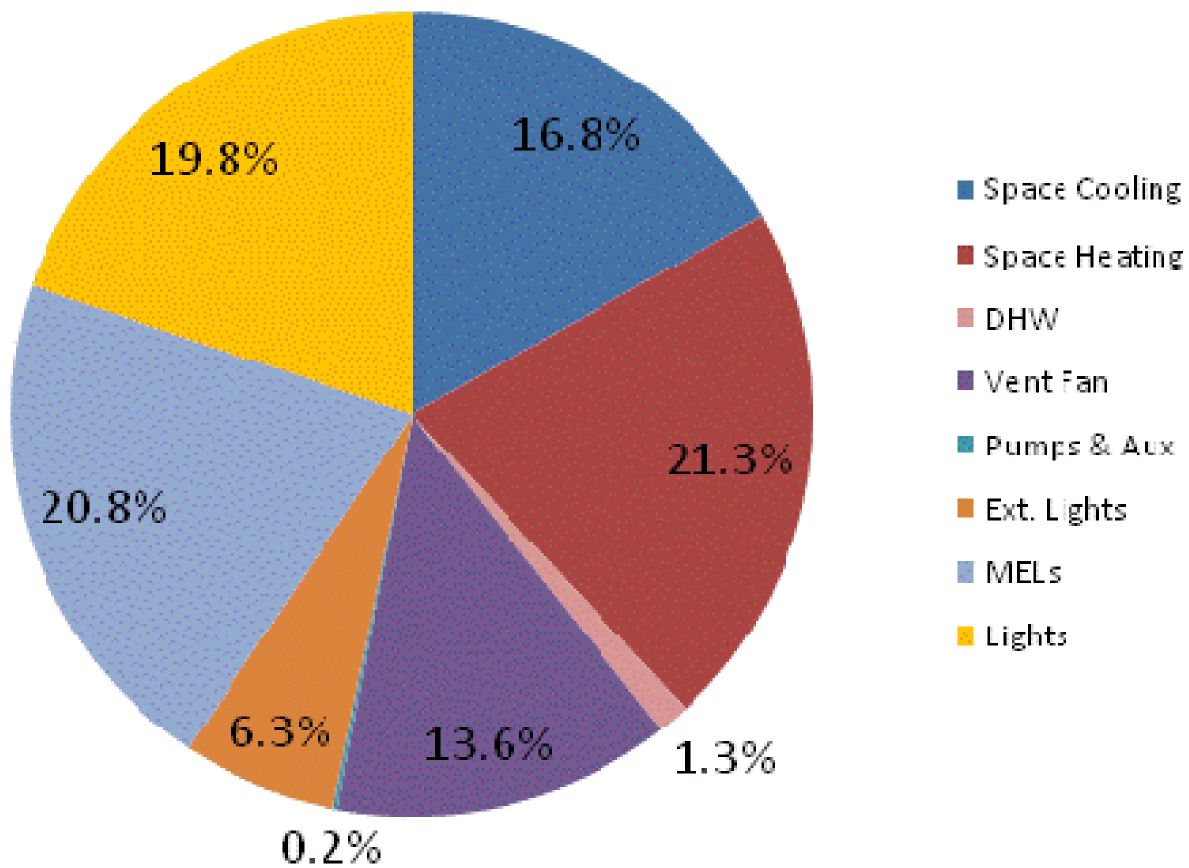
SEATTLE

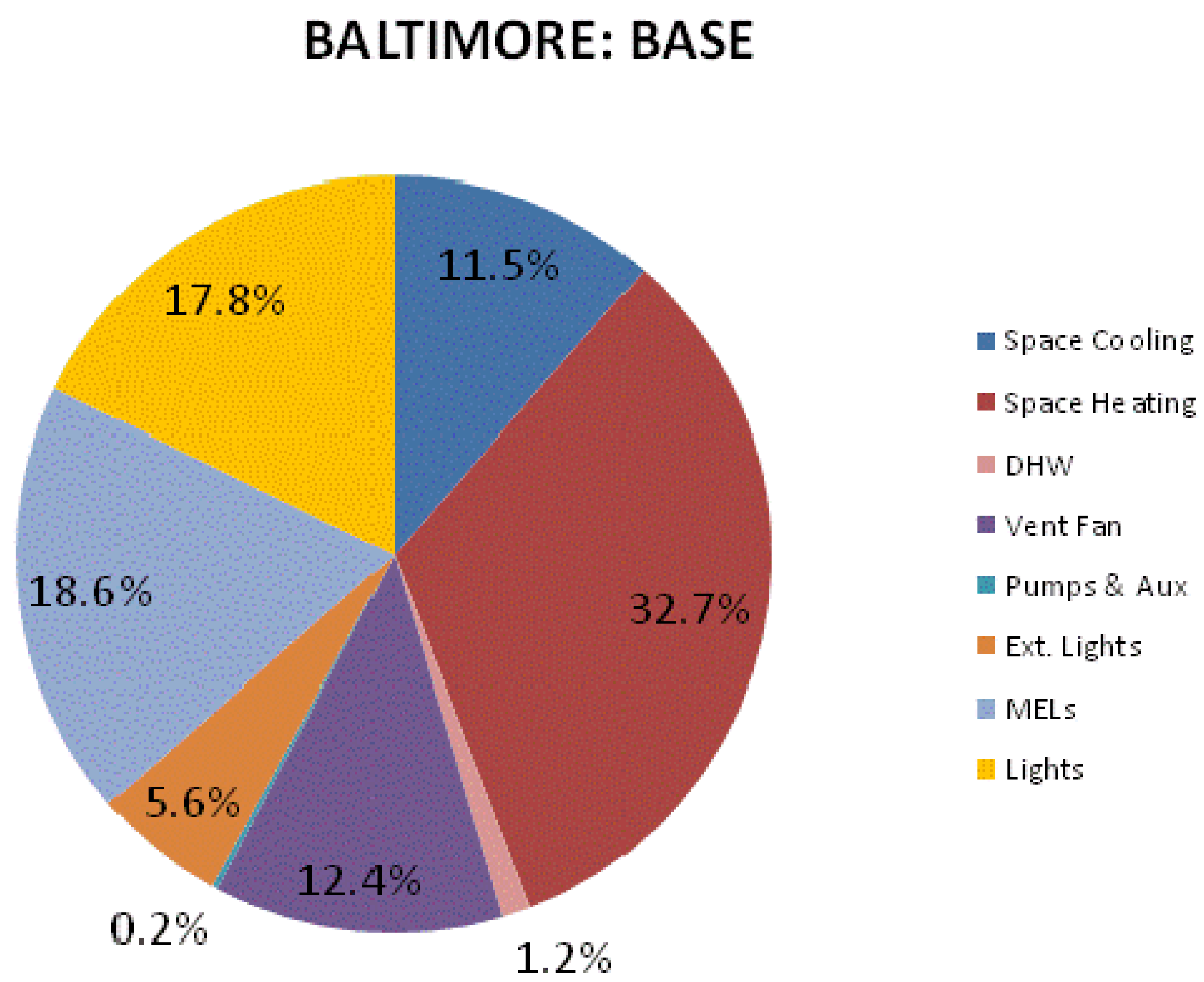


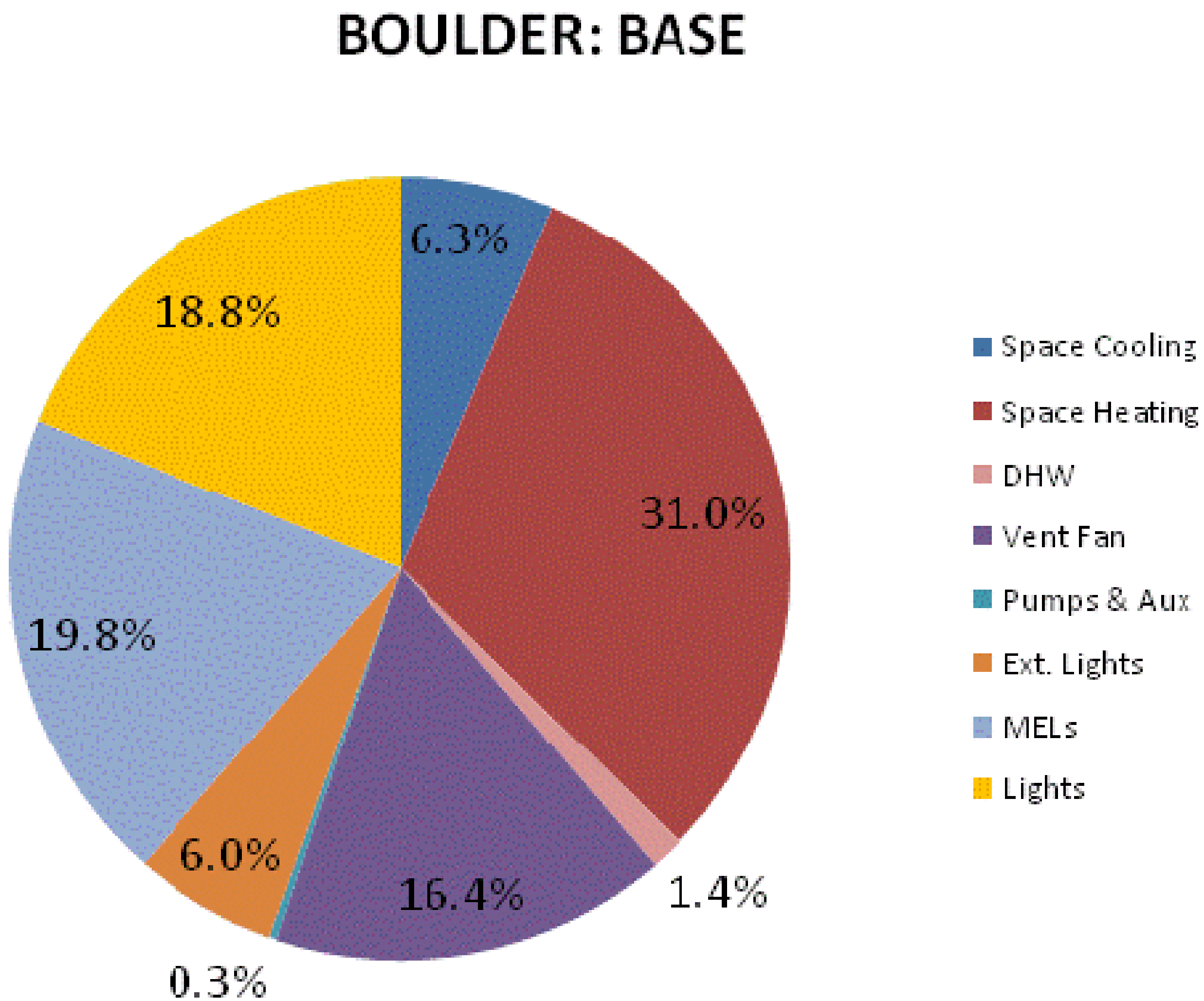
40.0%
30.0%
20.0%
10.0%
0.0%
-10.0%
-20.0%
-30.0%
AIR TIGHTNESS
GLAZING AREA
GLAZING U
INSULATION
MASS
ORIENTATION
SHADING
SHGC
DAYLIGHT CONTROLS
LIGHTING CONTROL
LIGHTING LOAD
COOL EFFICIENCY
DCV
HEAT EFFICIENCY
HEAT RECOVERY
HVAC DISTRIBUTION
HVAC SIZING
HVAC SYSTEM
VENTILATION
ECONOMIZER
FAN ENERGY
THERMOSTAT SETTINGS
DATA CENTER
OCCUPANT DENSITY
OCCUPANT SCH
PLUG LOAD
PLUG SCH
DIRECT LOADS
ENVELOPE
LIGHTING
HVAC
OPERATIONS
OCCUPANCY
OTHER

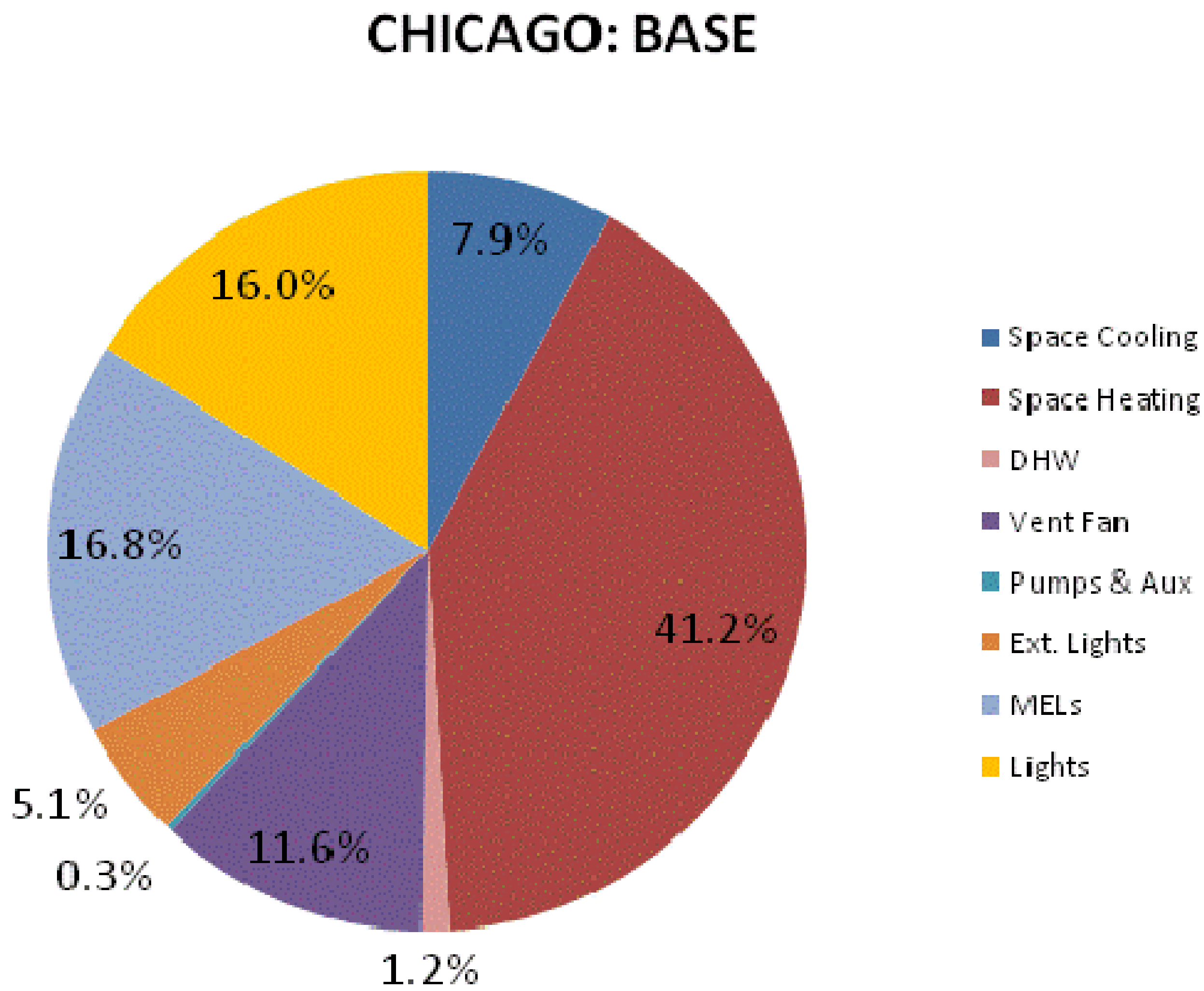

ALBUQUERQUE: BASE
10.5%
18.6%
1.5%
18.5%
0.3%
6.8%
22.5%
21.4%
Space Cooling
Space Heating
DHW
Vent Fan
Pumps & Aux
Ext. Lights
MELs
Lights

ATLANTA: BASE

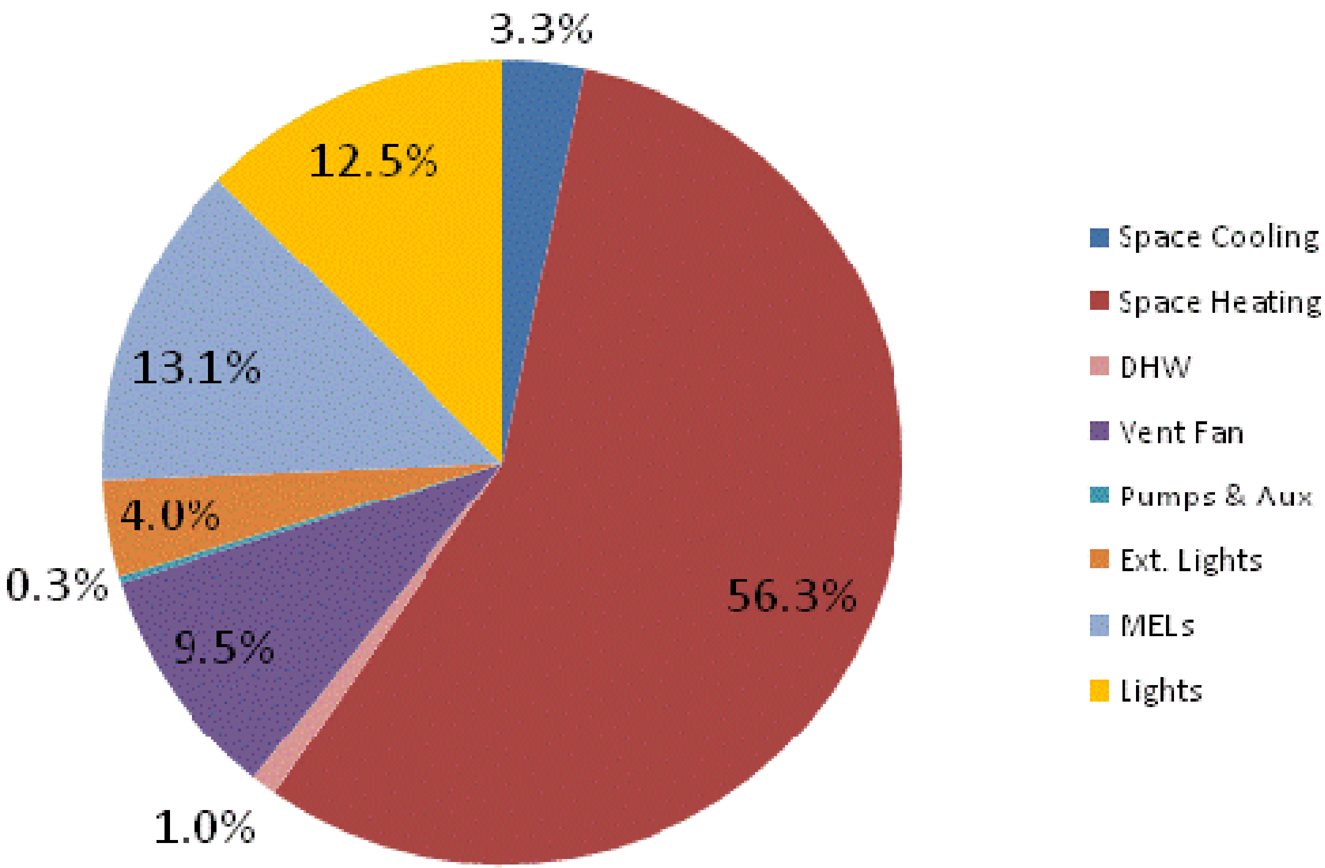


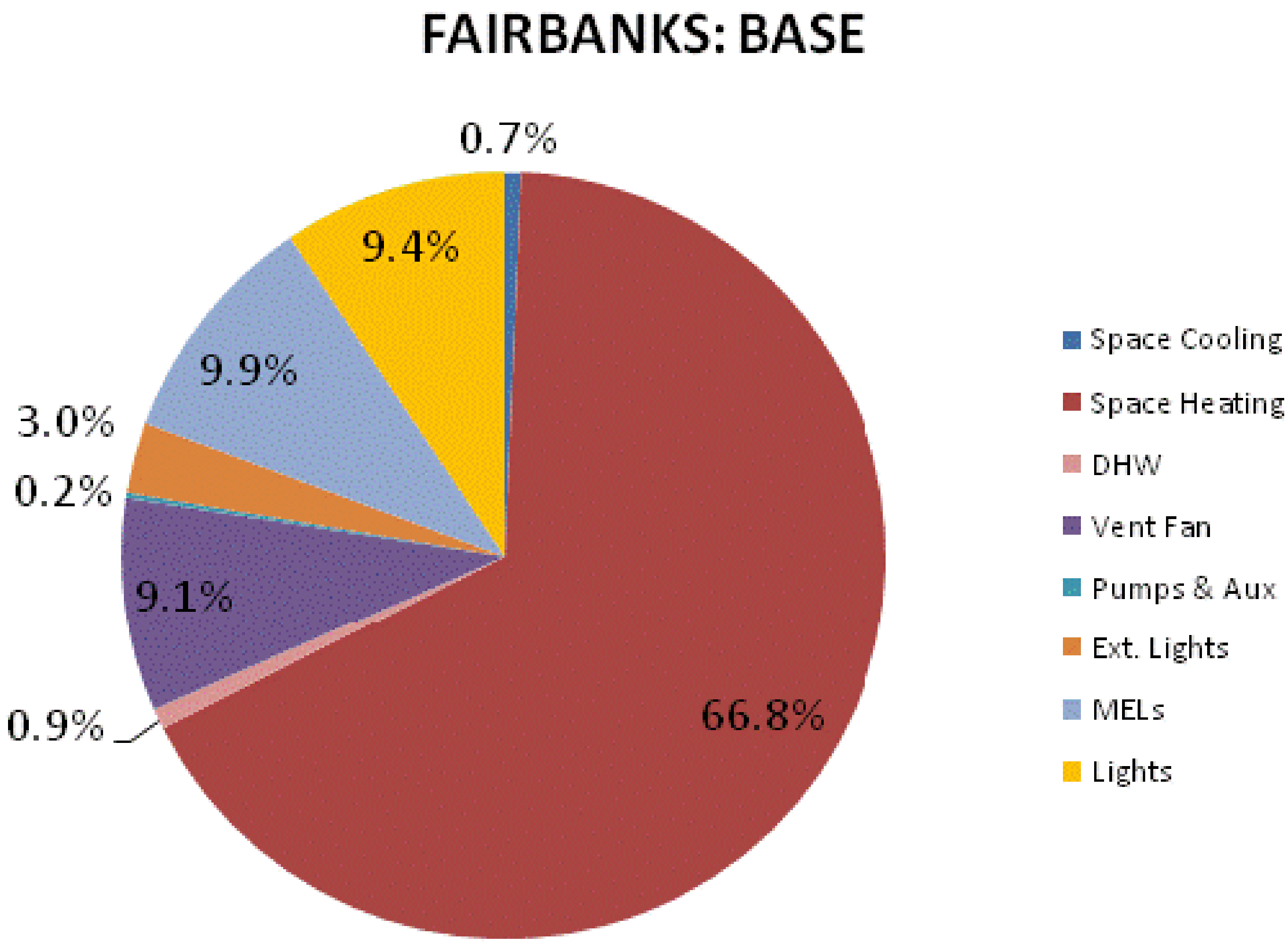

BALTIMORE: BASE
11.5%
32.7%
1.2%
12.4%
0.2%
5.6%
18.6%
17.8%
Space Cooling
Space Heating
DHW
Vent Fan
Pumps & Aux
Ext. Lights
MELs
Lights

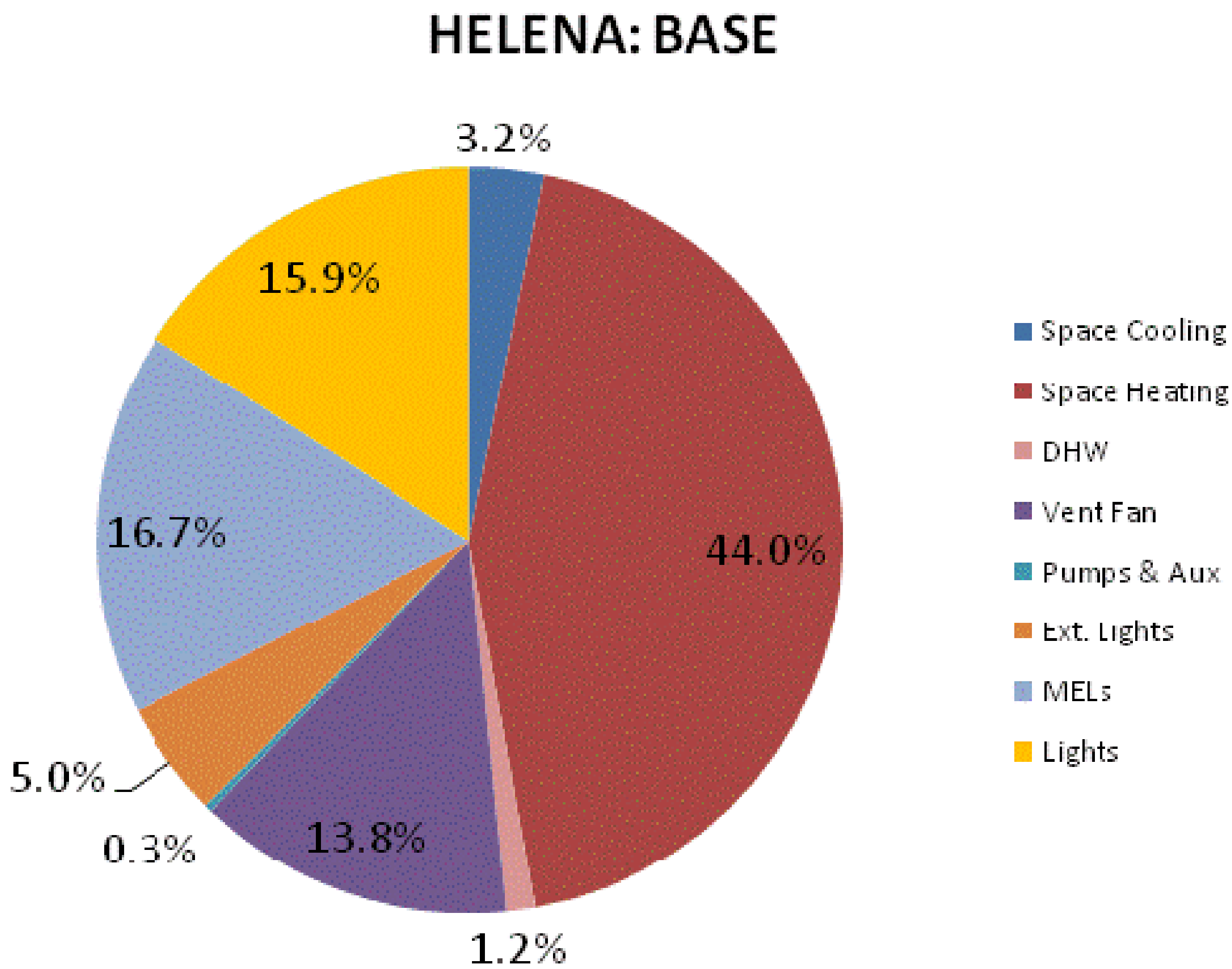

BOULDER: BASE
6.3%
31.0%
1.4%
16.4%
0.3%
6.0%
19.8%
18.8%
Space Cooling
Space Heating
DHW
Vent Fan
Pumps & Aux
Ext. Lights
MELs
Lights

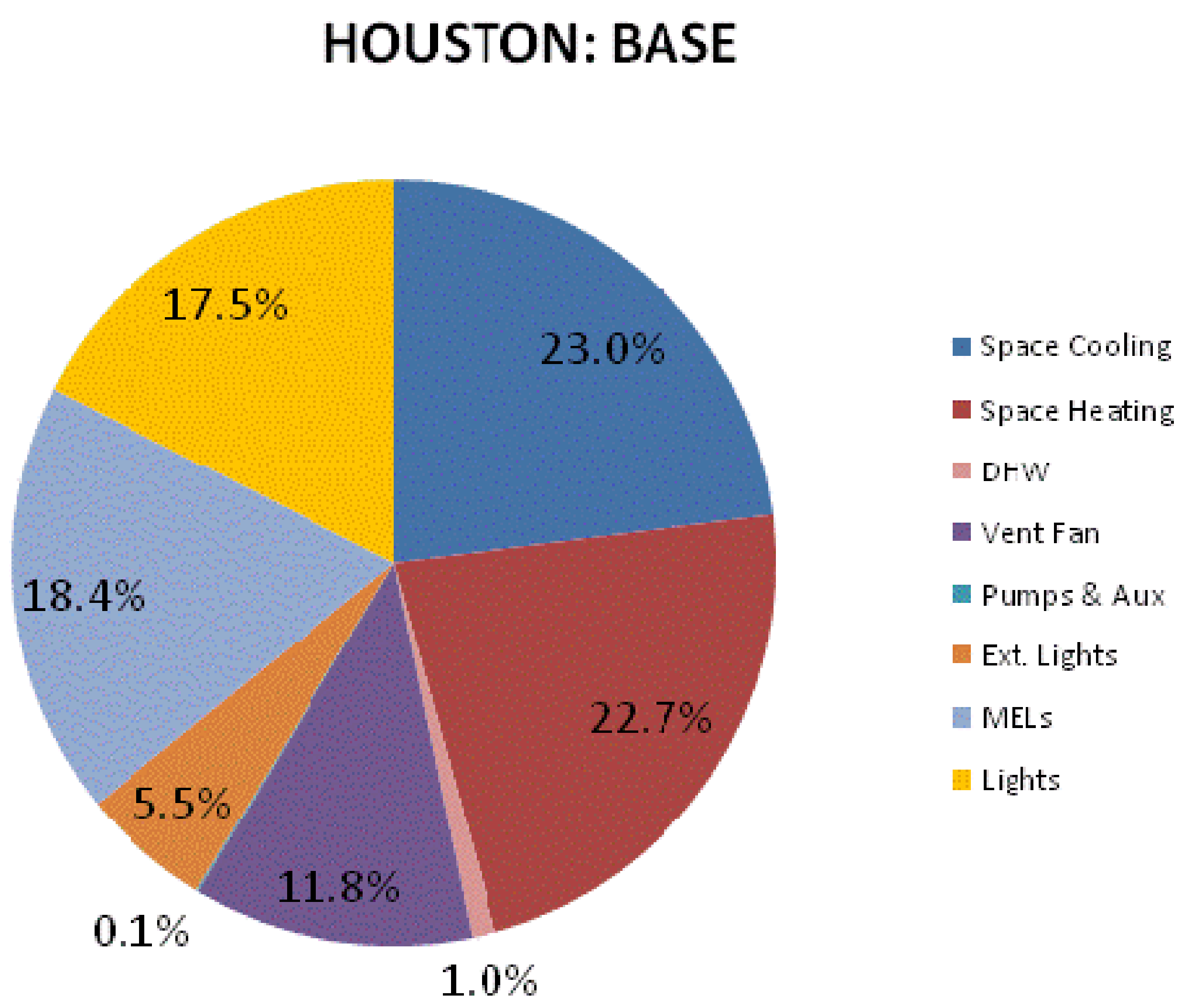

CHICAGO: BASE
7.9%
41.2%
1.2%
11.6%
0.3%
5.1%
16.8%
16.0%
Space Cooling
Space Heating
DHW
Vent Fan
Pumps & Aux
Ext. Lights
MELs
Lights

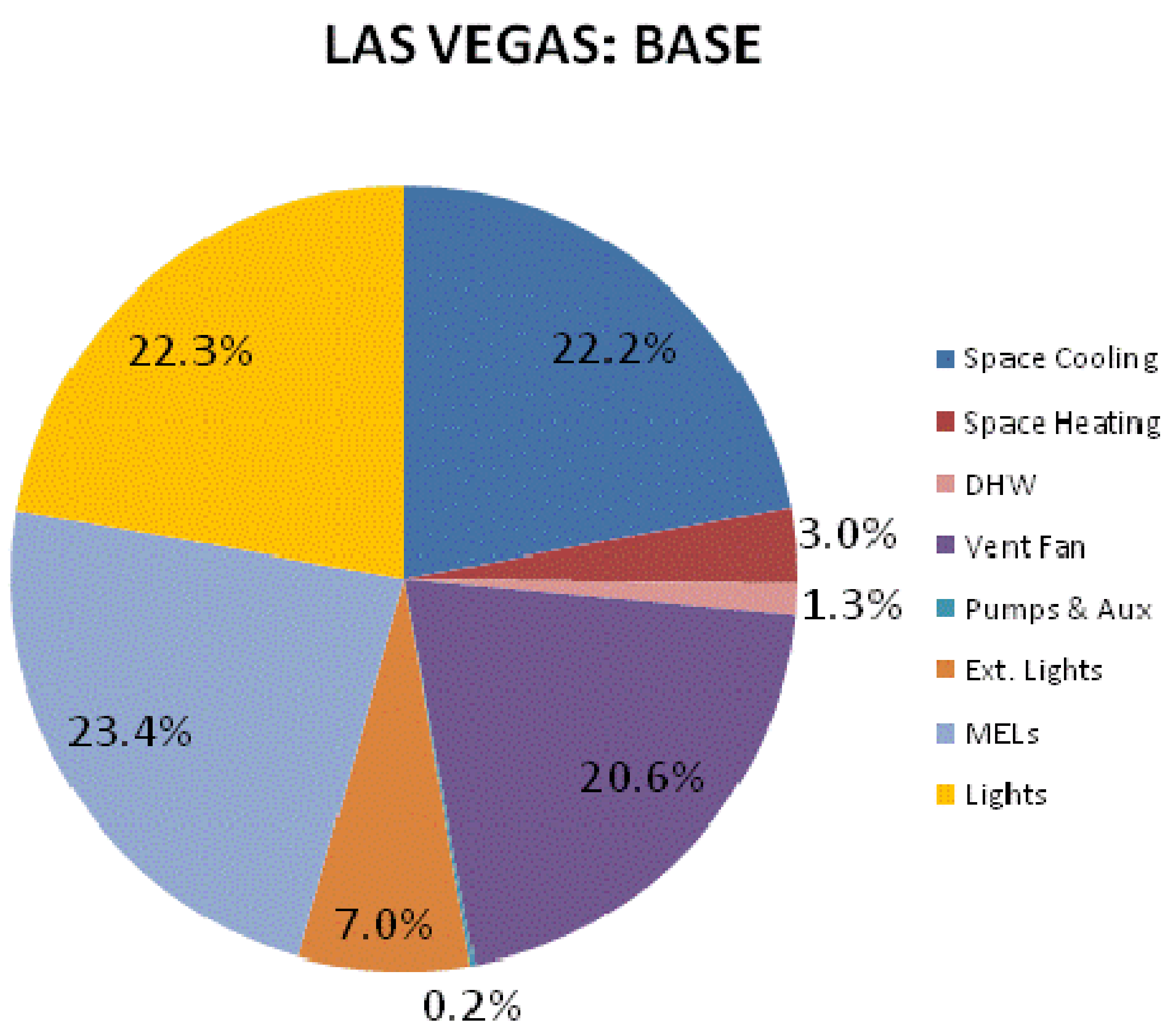
DULUTH: BASE

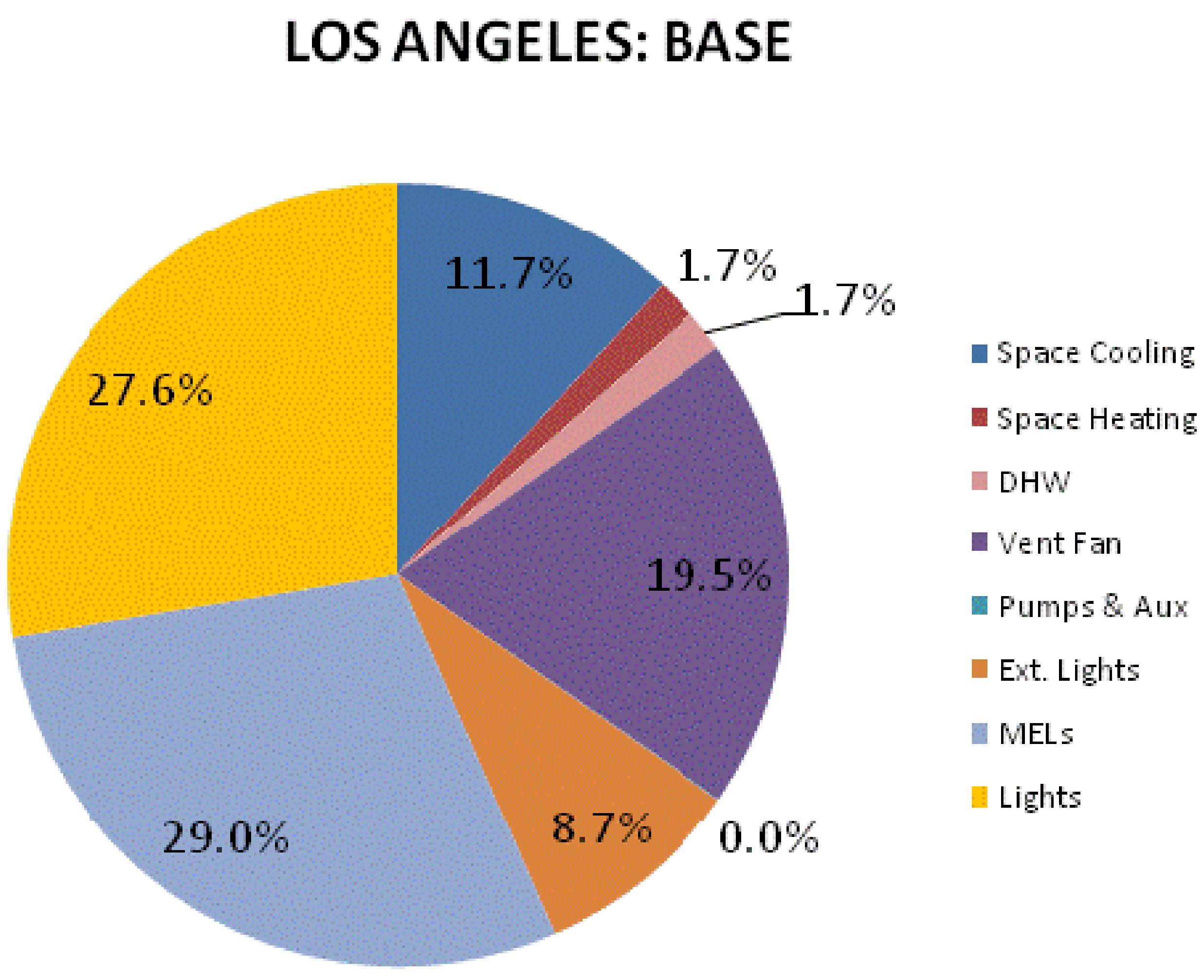

3.3%
12.5%
13.1%
4.0%
0.3%
9.5%
1.0%
56.3%
Space Cooling
Space Heating
DHW
Vent Fan
Pumps & Aux
Ext. Lights
MELs
Lights


FAIRBANKS: BASE
0.7%
9.4%
9.9%
3.0%
0.2%
9.1%
0.9%
66.8%
Space Cooling
Space Heating
DHW
Vent Fan
Pumps & Aux
Ext. Lights
MELs
Lights

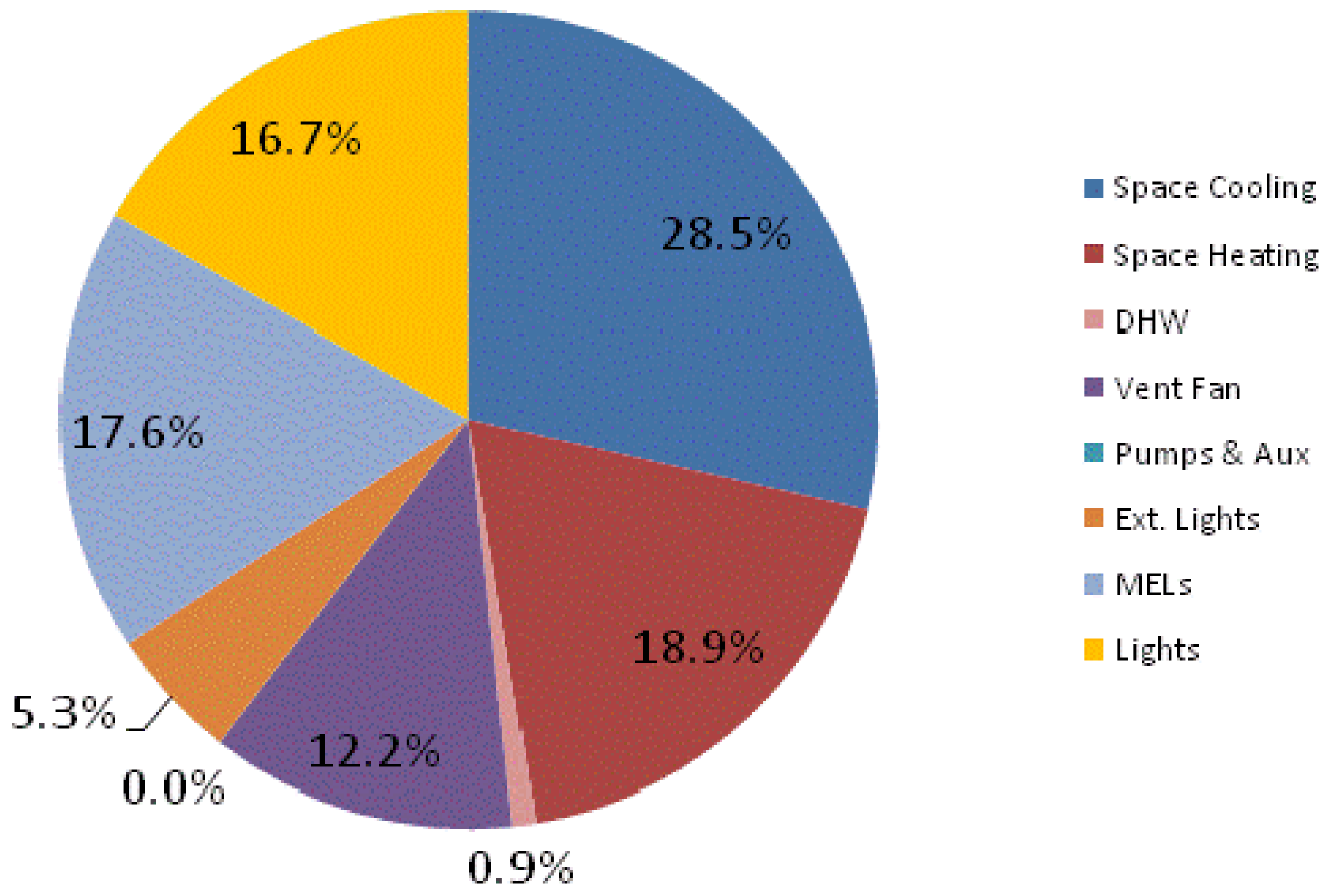

HELENA: BASE
3.2%
15.9%
16.7%
44.0%
5.0%
0.3%
13.8%
1.2%
Space Cooling
Space Heating
DHW
Vent Fan
Pumps & Aux
Ext. Lights
MELs
Lights

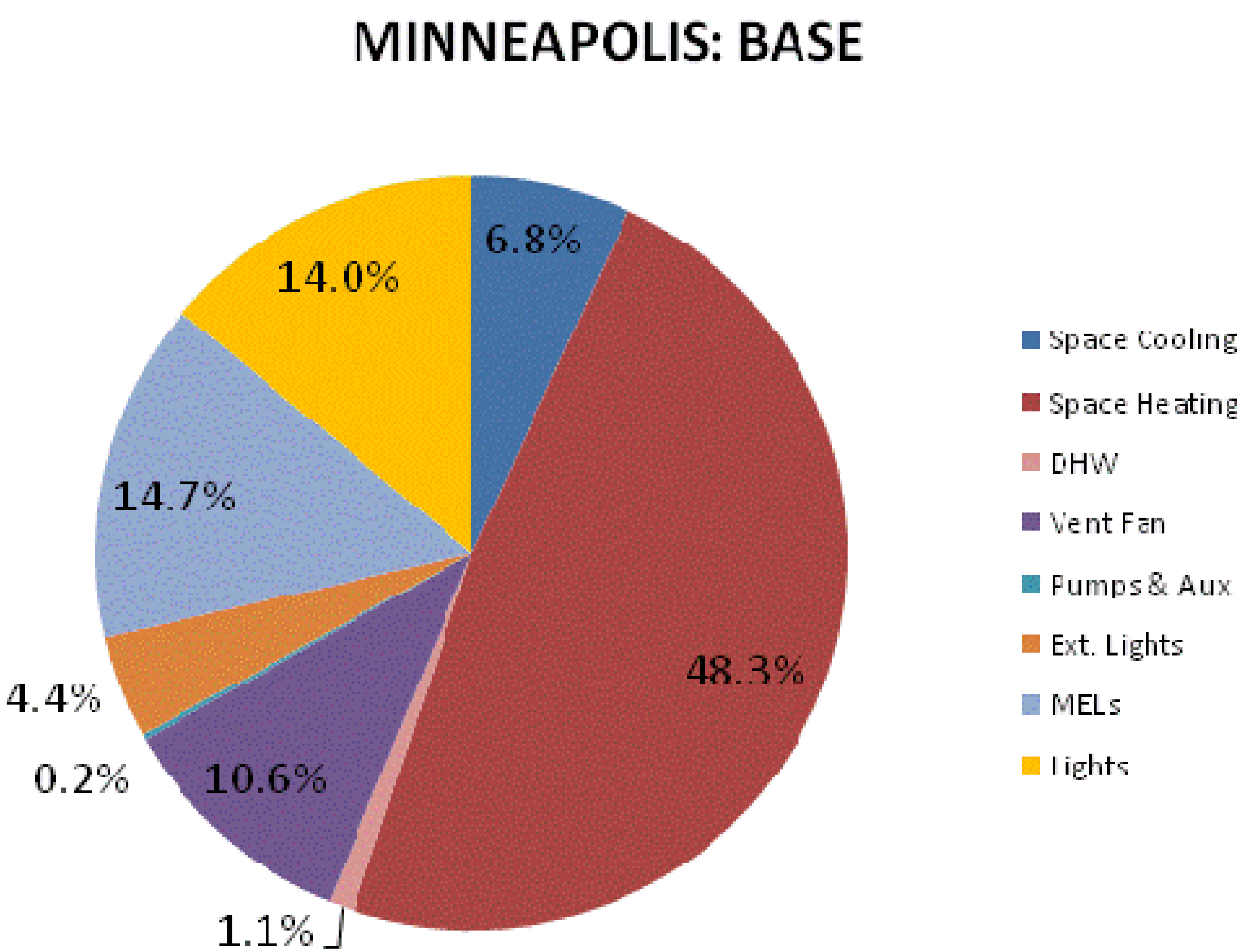

HOUSTON: BASE
23.0%
22.7%
1.0%
11.8%
0.1%
5.5%
18.4%
17.5%
Space Cooling
Space Heating
DHW
Vent Fan
Pumps & Aux
Ext. Lights
MELs
Lights

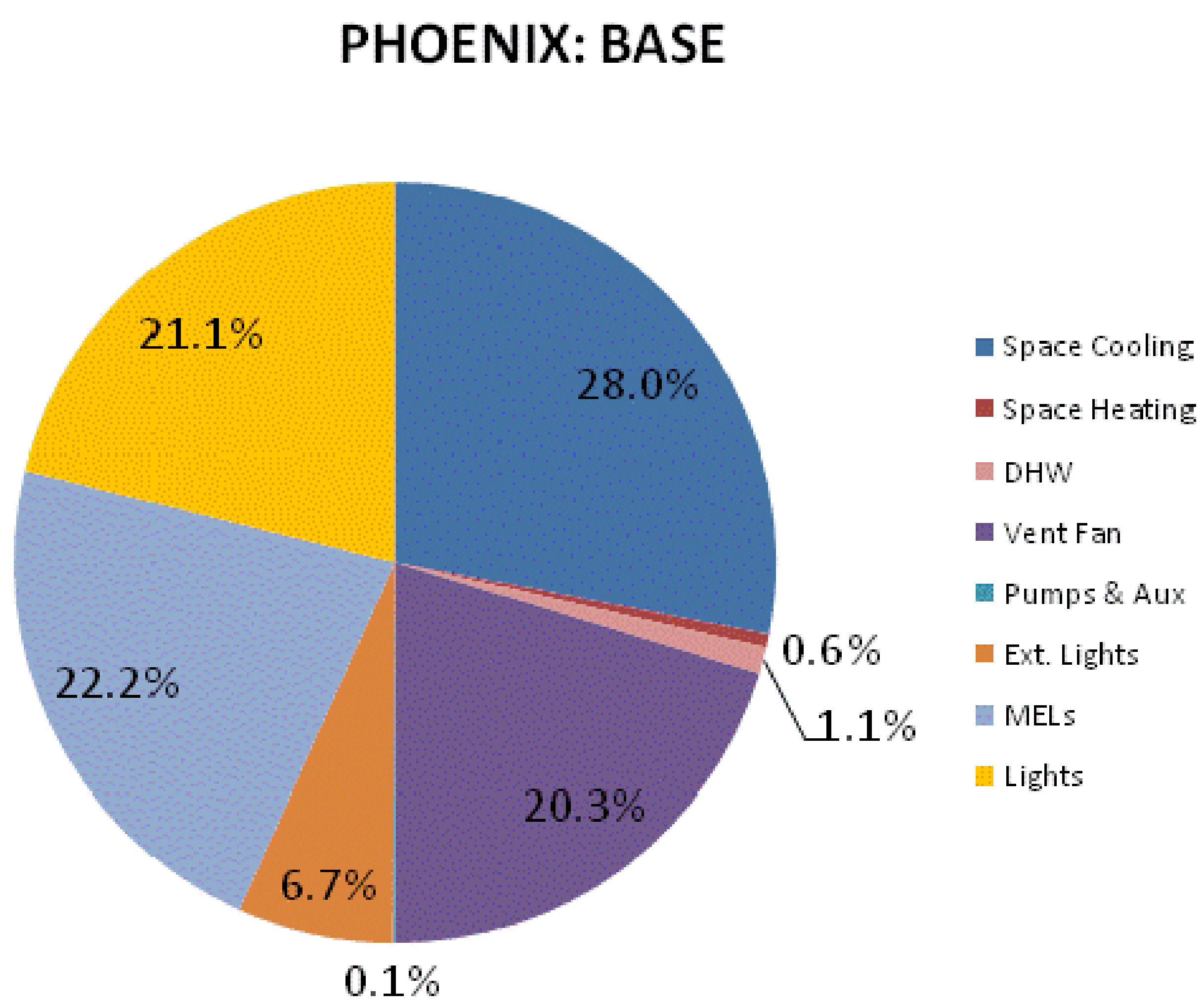

LAS VEGAS: BASE
22.2%
3.0%
1.3%
20.6%
0.2%
7.0%
23.4%
22.3%
Space Cooling
Space Heating
DHW
Vent Fan
Pumps & Aux
Ext. Lights
MELs
Lights

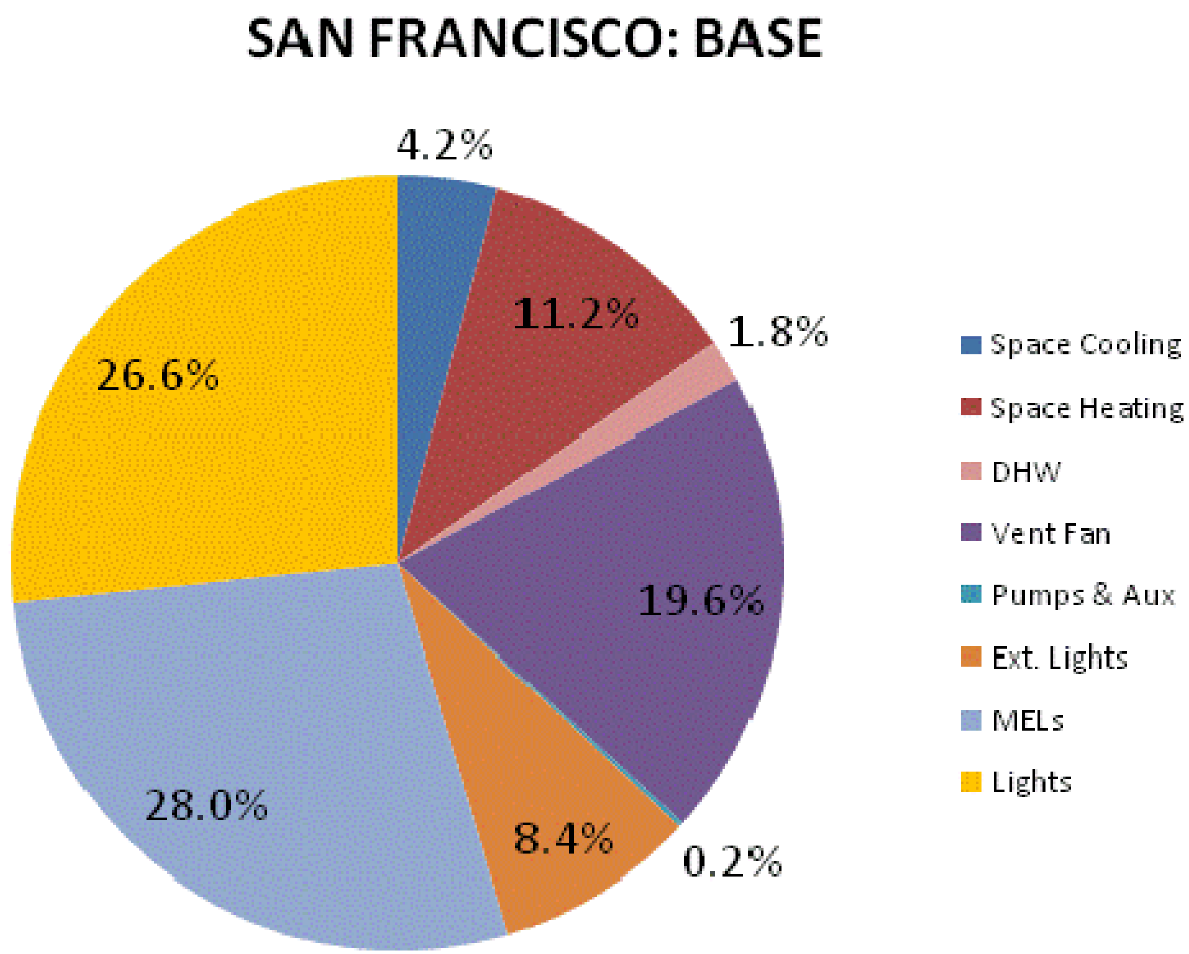

LOS ANGELES: BASE
11.7%
1.7%
1.7%
27.6%
19.5%
29.0%
8.7%
0.0%
Space Cooling
Space Heating
DHW
Vent Fan
Pumps & Aux
Ext. Lights
MELs
Lights

MIAMI: BASE

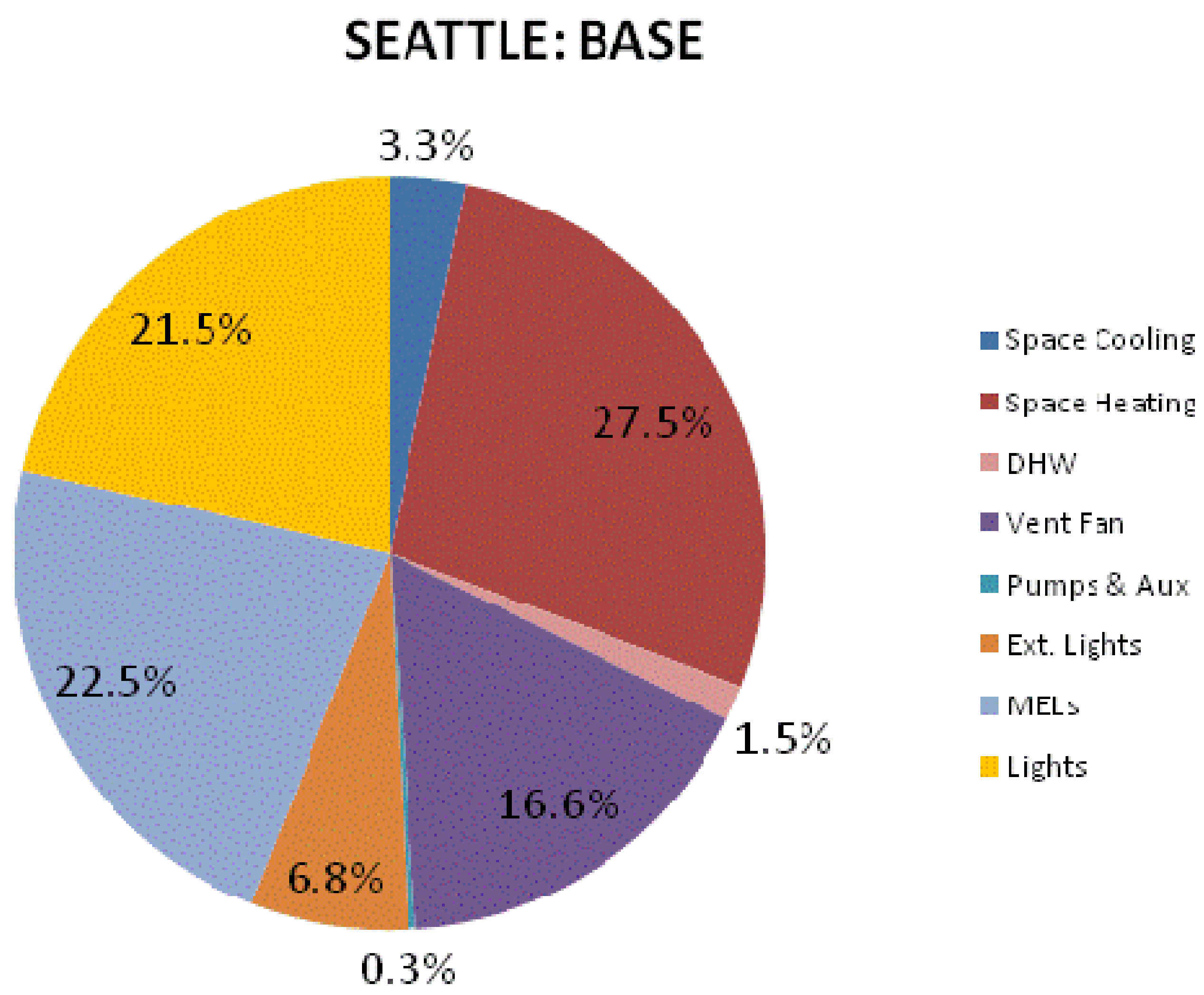

28.5%
18.9%
0.9%
12.2%
0.0%
5.3%
17.6%
16.7%
Space Cooling
Space Heating
DHW
Vent Fan
Pumps & Aux
Ext. Lights
MELs
Lights


MINNEAPOLIS: BASE
6.8%
48.3%
1.1%
10.6%
0.2%
4.4%
14.7%
14.0%
Space Cooling
Space Heating
DHW
Vent Fan
Pumps & Aux
Ext. Lights
MELs
Lights


PHOENIX: BASE
21.1%
28.0%
22.2%
0.6%
1.1%
20.3%
6.7%
0.1%
Space Cooling
Space Heating
DHW
Vent Fan
Pumps & Aux
Ext. Lights
MELs
Lights



SAN FRANCISCO: BASE
4.2%
11.2%
1.8%
26.6%
19.6%
28.0%
8.4%
0.2%
Space Cooling
Space Heating
DHW
Vent Fan
Pumps & Aux
Ext. Lights
MELs
Lights


SEATTLE: BASE
3.3%
27.5%
1.5%
16.6%
0.3%
6.8%
22.5%
21.5%
Space Cooling
Space Heating
DHW
Vent Fan
Pumps & Aux
Ext. Lights
MELs
Lights

APPENDIX C

Baseline Schedules:

Schedule	Day of Week	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
Base Lighting Schedule	WD	0.2	0.2	0.2	0.2	0.2	0.2	0.5	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.5	0.3	0.3	0.2	0.2	0.2	0.2
	Sat	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	Sun, Hol, Other	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	WinterDesign	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	SummerDesign	0.2	0.2	0.2	0.2	0.2	0.2	0.5	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.5	0.3	0.3	0.2	0.2	0.2	0.2
Base Equipment Schedule	WD	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.9	0.9	0.9	0.9	0.8	0.9	0.9	0.9	0.9	0.9	0.5	0.4	0.4	0.4	0.4	0.4	0.4
	Sat	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.5	0.5	0.35	0.35	0.35	0.35	0.35	0.3	0.3	0.3	0.3	0.3	0.3
	Sun, Hol, Other	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	WinterDesign	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	SummerDesign	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.9	0.9	0.9	0.9	0.8	0.9	0.9	0.9	0.9	0.9	0.5	0.4	0.4	0.4	0.4	0.4	0.4
Base Occupancy Schedule	WD	0	0	0	0	0.1	0.2	0.3	0.95	0.95	0.95	0.95	0.95	0.5	0.95	0.95	0.95	0.95	0.95	0.3	0.1	0.05	0.05	0.05	0.05
	Sat	0	0	0	0	0	0	0.1	0.1	0.3	0.3	0.3	0.3	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0	0	0	0	0
	Sun, Hol, Other	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WinterDesign	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	SummerDesign	0	0	0	0	0.1	0.2	0.3	0.95	0.95	0.95	0.95	0.95	0.5	0.95	0.95	0.95	0.95	0.95	0.3	0.1	0.05	0.05	0.05	0.05