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Simulation-based assessment of the energy savings benefits of integrated control in office buildings

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Energy Simulation Tools for Buildings: An Overview

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ABSTRACT

The purpose of this study is to use existing simulation tools to quantify the energy savings benefits of integrated control in office buildings. An EnergyPlus medium office benchmark simulation model (V1.0_3.0) developed by the Department of Energy (DOE) was used as a baseline model for this study. The baseline model was modified to examine the energy savings benefits of three possible control strategies compared to a benchmark case across 16 DOE climate zones. Two controllable subsystems were examined: 1) dimming of electric lighting, and 2) controllable window transmission. Simulation cases were run in EnergyPlus V3.0.0 for building window-to-wall ratios (WWR) of 33% and 66%. All three strategies employed electric lighting dimming resulting in lighting energy savings in building perimeter zones ranging from 64% to 84%. Integrated control of electric lighting and window transmission resulted in HVAC energy savings ranging from -1% to 40%. Control of electric lighting and window transmission with HVAC integration (seasonal schedule of window transmission control) resulted in HVAC energy savings ranging from 3% to 43%. HVAC energy savings decreased moving from warm climates to cold climates and increased when moving from humid, to dry, to marine climates.

Keywords: daylighting, energy conservation, energy management systems, energy efficiency, energy consumption, lighting control systems

1. INTRODUCTION

1.1. Background

Windows and daylighting controls can play a significant role in the road toward net-zero energy buildings as they have the potential to reduce cooling, heating, and lighting energy use in buildings. (Arasteh et al. 2006; Apte and Arasteh 2006) used DOE-2.1E (DOE-2.1E 1995) to estimate the energy savings potential of deploying various window technologies in the U.S. commercial building stock. (Lee and Selkowitz 2006) demonstrated via field measurements 50 to 60% lighting energy savings in office buildings through daylighting control systems in New York and (Li and Lam 2001; Li et al. 2004) showed 30 to 50% savings in Hong Kong. (Roisin et al. 2008) studied different lighting control systems in several European locations and showed 45 to 61% savings in lighting energy via DAYSIM (DAYSIM 2003) analysis. (Athienitis and Tzempelikos 2002) demonstrated 76 to 92% lighting energy savings in an office space via daylighting controls through a combination of field tests in Montreal and simulation. (Lee et al. 2002) studied the effects of electrochromic windows and daylighting controls on lighting and space conditioning energy in prototypical large and small office buildings of old and new vintages in two New York state locations via DOE2.1E analysis. (Lee at al. 2004) showed 10 to 28% total primary energy savings by using electrochromic windows and daylighting controls in five U.S. climate zones and 16 California climate zones. (Guillemin and Morel 2001; Guillemin and Morel 2002) studied integrated control of electric lighting, daylighting, and heating systems via Simulink (Simulink 2009) and field tests in office spaces in Switzerland and showed 19% to 25% total energy savings compared to traditional control systems.

The purpose of this study is to perform a simulation-based assessment of the energy savings benefits of integrated control applied to existing commercial buildings across the complete range of U.S. climate zones. The study focused on control of electric lighting and window transmission and their impact on building energy consumption using building simulation models that are statistically representative of the U.S. installed base. Office buildings were chosen based on data from the EIA 2003 CBECS indicating that office buildings are the most common building type, comprise the largest floor area, and consume the most energy in the commercial building sector. Office buildings represent roughly 17% of the buildings, floorspace, and energy use in the commercial building sector (Energy Information Administration 2003). By basing the simulation study on office buildings, the results will be representative of a portion of the U.S. new commercial building base.

1.2. Base simulation model

EnergyPlus (U.S. Department of Energy 2008) is a building energy analysis and thermal load simulation program which provides integrated (simultaneous loads and systems) simulation for accurate temperature and comfort prediction. The loads are calculated by a heat balance engine and then passed to the building systems simulation module which calculates the heating and cooling system, and plant and electrical system response (Crawley et al. 2005). This integrated simulation approach allows for accurate space temperature prediction and also enables realistic controls systems simulation. EnergyPlus also has flexible features for modeling the performance of windows and daylighting controls, which makes it especially well-suited for a study of this type.

The U.S. DOE developed a set of 15 commercial building benchmark models across 16 DOE climate zones for whole building energy analysis using EnergyPlus. The benchmark buildings are intended to form the basis for research on building technologies, energy code development, appliance standards, and measurement of progress toward the DOE energy goals. These models are representative of 70% of the new commercial building stock in the U.S. in terms of building types, sizes, and locations, and meet the minimum prescriptive requirements of ASHRAE 90.1-2004. The derivation of these models was based on the CBECS 2003 data for buildings constructed from 1994 to 2003, along with 2002 Economic Census data and Typical Meteorological Year 2 (TMY2) weather sites (Deru et al. 2006; Torcellini 2008).

This study used the medium office benchmark V1.0_3.0 (DOE 2008) as a starting point for the various simulation cases. A rendering of the building is shown in Figure 1. The benchmark medium office building has three floors and 15 occupied thermal zones covering a total floor area of 4,982m^2. The building is rectangular in shape with an aspect ratio of 1.5. Each floor consists of a core zone covering approximately 60% of the floor area and four perimeter zones covering approximately 40% of the floor area. The window-to-wall ratio is 33% with window U-values and solar heat gain coefficients (SHGC) meeting ASHRAE 90.1-2004 minimums (ASHRAE 2004). There is also a single plenum zone for each floor, which differs from the previous V2.0 benchmark model. Exterior walls are steel frame construction with a slab on grade foundation (no basement) and built up flat roof with insulation entirely above deck. Interior partitions are 2x4 steel frame with gypsum board. Each thermal zone also contains an appropriate wood thermal mass corresponding to furniture. For different climate zones, the building form, size, internal loads, operating schedules and mechanical system types stay the same, but the envelope criteria varies according to ASHRAE 90.1-2004. The HVAC system is a packaged multi-zone variable air volume (VAV) system without air-side economizer. There are local VAV boxes for each thermal zone served by hot water reheat coils. The HVAC equipment is autosized to meet peak cooling and heating loads. Designed internal gains include interior lights at 10.76W/m^2, electric plug loads at 8.07W/m^2, and occupancy of 195 total (3.91/100m^2). The heating setpoint is 21°C with setback to 13°C during unoccupied hours. The cooling setpoint is 24°C with setback to 30°C during unoccupied hours.

EnergyPlus does not simulate the specifics of electric lighting distributions. Electric lighting is specified primarily in terms of power allocated to lighting per thermal zone. For this simulation model the lighting follows the prescriptive requirements of ASHRAE 90.1-2004. For office buildings the whole building lighting power density (LPD) specification is 10.76W/m^2 which is a design level meant to encourage energy efficient lighting design while meeting the required lighting levels for the given activity. EnergyPlus does require specification of the fraction of lighting energy radiated as visible (short-wave) radiation, radiated as long-wave (thermal) radiation, and in some cases the fraction of heat in the zone return air (for return-air ducted luminaire configurations). These parameters are dependent on the specific lighting source and luminaire. From the benchmark model parameters and from calculations based on data from various sources (Navigant Consulting, Inc. 2002) the lighting specification in this simulation model is consistent with F32T8 fluorescent lighting with return air plenum.

1.3. Scope

The principal objective of this study was to perform an EnergyPlus simulation assessment of the energy savings benefits of integrated control using the medium office building benchmark model (as a baseline starting point) across 16 DOE climate zones. For reference, a map of the DOE climate zones is shown in Figure 2. The 16 specific cities representing these zones are listed in Table 1. Generally speaking, the climate zones are divided in two ways. The first is by temperature with one being the warmest to eight being the coldest, which loosely represents South to North. The second is by climate type, A – humid, B – dry, and C – marine, which loosely represents East to West. This is a simplified description of the climate zones and more information can be found in (Briggs et al. 2002).

Two controllable subsystems were examined: 1) dimming of electric lighting, and 2) controllable window transmission. The effects of different window-to-wall ratios were studied by looking at two ratios, 33% from the base model and 66% to be representative of highly glazed facades. Further details are provided in the next section.

2. METHODOLOGY

This section describes modifications to the benchmark medium office building model and simulation details for this study including a description of the controllable subsystems, a description of each control strategy, a brief description of the metrics, and a brief description of the weather files used.

2.1. Controllable subsystems

2.1.1. Dimming of electric lighting

The electric lighting is the first controllable subsystem and is controlled to maintain an illuminance setpoint at the specified reference points by dimming the electric lighting in response to the available daylight. Only the perimeter zones of the medium office building receive daylight. In each perimeter thermal zone, a single reference point was located in the center of the zone, two thirds deep into the perimeter space (approximately 3m from the windows), and at a workplane height of 0.8m. Figure 3 shows the building plan, which is identical for all three floors, with the locations of the reference points. The illuminance setpoint for all reference points was 500lux and 100% of the lighting in each thermal zone was controllable.

An idealized approach to the control was used in order to identify the upper bounds of energy savings. Both the light output and input power were controllable over the full linear range from 0 to 100%. The maximum available electric lighting at any given time is subject to a schedule which essentially follows the building occupancy schedule. The schedule is a full year specified hourly for all days taking into account weekdays, weekends, and holidays.

2.1.2. Controllable window transmission

Windows employing switchable glazing technologies offer potential energy savings due to auto-shading and daylight harnessing capabilities without sacrificing thermal or visual comfort. Again, an idealized approach to the control of window transmission was used in this study to identify the upper bounds of energy savings. For this reason, electrochromic windows were used because they provide linear control of visible transmittance and solar heat gain between fully clear and fully dark states. Slat angle control of venetian blinds is limited in EnergyPlus, complex, and not an ideal choice for this study.

For simplicity, typical commercially available electrochromic windows were used for all windows in all climates. The properties of the electrochromic windows were fully spectrally characterized and created using the WINDOW software tool (LBNL 2006, WINDOW website) from Lawrence Berkeley National Laboratory and data from the International Glazing Database (IGDB) (LBNL 2008, IGDB website). These properties were then imported into EnergyPlus input files. The windows have a U-factor of 1.40W/m^{2}K in both clear and dark states, a visible transmittance (VT) of 0.562 in the clear state and 0.018 in the dark state (dynamic range approximately 30:1), and a SHGC of 0.397 in the clear state and 0.066 in the dark state (dynamic range approximately 6:1). By keeping the same U-factors for all electrochromic windows the differences in energy consumption will explicitly relate to the window shading controls.

Strictly speaking, the chosen electrochromic windows in the fully clear state do not meet ASHRAE 90.1-2004 standards for SHGC in climate zones 1A through 3C for WWR 33%. There are no specifications for vertical glazings greater than 50% (beyond 50% an energy cost budget method must be used to determine compliance). However, the benchmark medium office model, and ASHRAE 90.1-2004, should be considered only a starting point for these studies.

Glare control was not active in these simulations in order to focus the results solely on energy considerations which serves to provide the maximum limits of energy savings. Overheating, or driving the HVAC system into cooling mode during normally heating periods, was not taken into consideration. In the public release of EnergyPlus V3.0.0 it is not possible to model overheating control directly because run-time feedback of this information is not available.

2.2. Control strategies

There were four cases, Reference, DimLights, DimLightsWindows, and SeasonSchedule, simulated for each climate and for each WWR. The following is a description of each control strategy including its purpose and its implementation.

2.2.1. Reference

The Reference simulation case was performed to establish baseline results for energy consumption. In this case the controllable subsystems are not controlled and are simply maintained in their benchmark states. There is no dimming of electric lighting, but rather the lighting follows the lighting schedule. The electrochromic windows are kept in the fully clear state at all times.

2.2.2. DimLights

The DimLights control strategy is the next incremental step in control and activates control of the electric lighting by making use of available daylight and dimming the electric lighting to maintain the illuminance setpoint in each perimeter thermal zone. The electrochromic windows are not controlled and are kept in the fully clear state at all times. Under this control strategy, the electric lighting energy will be minimized, resulting in a corresponding decrease in building cooling energy as well as a corresponding increase in building heating energy.

2.2.3. DimLightsWindows

The DimLightsWindows control strategy is the next incremental step in control and integrates the control of lighting and window transmission. Dimming of electric lighting to maintain the illuminance setpoint is active. In addition, the window transmission is controlled by dimming the electrochromic windows to meet the illuminance setpoint. In simple terms, daylight entering the perimeter zones is maximized in order to offset electric lighting energy. When more than enough daylight is available, the electrochromic windows are dimmed so that the illuminance setpoint is met (offsetting all electric lighting energy) while blocking additional solar heating gains. This control strategy results in the same savings of electric lighting energy as in the DimLights case, but further reduces building cooling energy due to rejection of additional solar heating gains. This strategy also results in a corresponding increase in building heating energy.

2.2.4. SeasonSchedule

The SeasonSchedule control strategy is the next incremental step in control. In this case, dimming of electric lighting to maintain the illuminance setpoint is active. However, whether or not the window transmission control is active is subject to a season schedule. During heating months, the electrochromic windows are kept in the fully clear state to maximize solar heating gains in order to offset building heating energy. During cooling months, the electrochromic windows are actively dimmed to meet the illuminance setpoint to reject additional solar heating gains and reduce building cooling energy.

The season schedule was determined for each climate and WWR by simulating each case under the DimLightsWindows control strategy and comparing monthly heating and cooling energy. If the monthly heating energy was greater than the cooling energy, that month was marked as a heating month and vice versa. The heating months and cooling months were the same in all climates for both the WWR 33% and 66% cases and are shown in Table 2.

It should be noted that the SeasonSchedule control approximates the control of electric lighting and window transmission with HVAC integration. A truly integrated control would share explicit run-time knowledge of the HVAC system heating or cooling mode with the shading control system. However, it is not possible to simulate this level of control integration in the public release of EnergyPlus V3.0.0 which does not make available the necessary run-time feedback. Nonetheless, the SeasonSchedule control strategy is one approximation to HVAC integrated control that can be simulated in EnergyPlus V3.0.0. A summary of the control strategies is given in Table 3.

2.3. Performance metrics

For this study the primary metrics were site energy consumption by end use and peak electrical demand for the entire facility. Particular focus was placed on the components of site energy consumption affected by the proposed control strategies, namely interior lighting energy and all components of HVAC energy. Site energy was used in order to avoid fuel factor conversion issues in deriving source energy.

2.4. Weather files

For this simulation study, Typical Meteorological Year 3 (TMY3) (Wilcox and Marion 2008) weather data was used, as opposed to TMY2. TMY3 represents hourly solar radiation and meteorological elements for a one year period, derived from weather data from the 1991 to 2005 National Solar Radiation Data Base archives. TMY2 represents older weather data from 1961 to 1990. The TMY3 weather files represent typical hourly weather for a given location over a time period of one year. Extreme weather conditions are not represented and therefore worst-case scenarios will not be represented in this data. The TMY3 data set is a concatenation of 12 typical meteorological months whereby each month is statistically chosen from the relevant data pool as a representative month. Thus each month in the TMY3 data set represents a true time series of actual weather data and real weather dynamics are preserved which would otherwise be lost if data averaging methods were applied.

3. RESULTS

3.1. Total site energy

Figure 4 shows the total site energy consumption for one year by climate for the Reference cases and the SeasonSchedule cases for WWR 33%. These results are given to show how the baseline site energy consumption varies by climate, and also to give an indication of how much site energy can be reduced by using the most integrated (SeasonSchedule) control strategy. The total site energy consists of many end uses that are not affected by the control strategies simulated which specifically target interior lighting energy and HVAC energy.

Similar results for WWR 66% are given in Figure 5. Note that when increasing the WWR from 33% to 66%, the total site energy for the Reference case increased by a mean of 17% across all climates. In contrast, the total site energy for the SeasonSchedule case increased by a mean of 4% across all climates which indicates that integrated control with larger window areas can result in a broader range of energy savings. The following sections will focus results on interior lighting energy and HVAC energy.

3.2. Dimming of electric lighting (DimLights)

The effects of simply adding dimming of electric lighting to make use of daylight can be studied by examining the Reference and DimLights control cases. The daylighting potential of a building depends largely upon the building plan. For the benchmark medium office building approximately 40% of the floor area is windowed perimeter space. The electric lighting power distribution is the same in both the perimeter spaces and the core spaces at $10.76 W/m^2$. So if all lighting requirements in the perimeter space could be met solely by natural daylight, the electric lighting energy would be reduced by 40%. Obviously, because of limitations in the actual availability of daylight it is not possible to achieve 40% reduction in lighting energy. The actual savings in lighting energy relative to the Reference case when applying the DimLights control for both WWR 33% and 66% and for all climates is shown in Figure 6. Lighting energy savings in the perimeter zones ranged from 64% to 82% for WWR 33% and 67% to 84% for WWR 66%. When expressed as a percentage of the total building lighting energy, these savings translate to 26% to 34% for WWR 33% and 27% to 34% for WWR 66%. The lighting energy savings is relatively constant over all climate zones with the exception of Fairbanks, AK where the availability of daylight is lower. Increasing the WWR from 33% to 66% has a minor effect on lighting energy savings, which may imply that for daylighting benefit, a WWR of 33% is adequate.

Reducing the energy consumed by the electric lighting has the effect of decreasing building cooling energy and increasing building heating energy since the electric lighting represents a heating source or internal gain. Generally speaking, as cooling energy decreases the fan energy will decrease. As heating energy increases the pump energy will also increase. Fan energy is tied to both cooling and heating functions, while the pump energy is tied only to heating (specifically the hot water reheat coils). Overall HVAC energy is the sum of all heating and cooling related energy. In EnergyPlus for the benchmark medium office this includes heating energy, cooling energy, fan energy, and pump energy. Savings in total HVAC energy for the DimLights control relative to the Reference case are shown in Figure 7.

There is generally a net savings of HVAC energy in most climates after making use of daylight to dim the electric lighting. In heating-dominated climates there may actually be a net increase in HVAC energy. It should be reiterated that no window transmission control has been applied and the windows in both the Reference and DimLights cases are always in the fully clear state.

3.3. Integrated control

In all three control cases – DimLights, DimLightsWindows, and SeasonSchedule – the reduction of electric lighting energy in response to daylight is identical. The DimLights control dims the electric lighting in response to daylight but does not employ any window transmission control. The DimLightsWindows control integrates control of window transmission via the electrochromic windows, however the use of daylight and resulting electric lighting energy consumption remains the same as in the DimLights case. The SeasonSchedule control essentially operates like the DimLights control strategy during heating months and operates like the DimLightsWindows control strategy in cooling months. Again, the resulting lighting energy consumption remains the same.

The performance of the control strategies differs only in the impact on HVAC energy consumption. Therefore, most of the subsequent results will use the DimLights case as the baseline for comparisons. Comparing the DimLightsWindows and SeasonSchedule controls to the DimLights case assesses the impact of different window transmission controls on HVAC energy consumption.

Figure 8 shows the HVAC site energy consumption for each control case and WWR 33% across all climates. The results for WWR 66% are shown in Figure 9. Figure 10 and Figure 11 show the percentage savings in HVAC site energy for WWR 33% and 66% respectively. The HVAC savings are relative to the DimLights control case.

For the WWR 33% cases, the DimLightsWindows control strategy resulted in HVAC energy savings ranging from -1% (actually an increase in HVAC energy) in Duluth to 22% in San Francisco. The SeasonSchedule control strategy resulted in HVAC energy savings ranging from 3% in Fairbanks to 25% in Seattle. For the WWR 66% cases, the DimLightsWindows control strategy resulted in HVAC energy savings ranging from 6% in Fairbanks to 40% in San Francisco. The SeasonSchedule control strategy resulted in HVAC energy savings ranging from 11% in Fairbanks to 43% in Seattle.

In general, there were two main climate-based effects observed in HVAC energy savings. First, the HVAC energy savings decreased moving from warm climates to cold climates (South to North). Second, the HVAC energy savings increased when moving from humid, to dry, to marine climates (East to West).

In all cases, the SeasonSchedule control saved more HVAC energy than the DimLightsWindows control. For Miami and Los Angeles, which were always in cooling months, the SeasonSchedule and DimLightsWindows controls operated the same and thus the HVAC energy savings were the same. There are generally high savings in the warm climates since the primary means of achieving HVAC energy savings is by rejecting solar heat gain and reducing cooling loads. However, during heating periods it is advantageous to allow additional solar heat gains in order to offset heating energy loads. The SeasonSchedule control achieves this, albeit on a monthly level of granularity. The difference in performance between the DimLightsWindows and SeasonSchedule controls was generally larger in the cold climates and smaller in the warm climates. This was expected since with fewer heating months in warmer climates the SeasonSchedule control operationally approaches the DimLightsWindows control.

The results for WWR 66% show that a larger range of control of HVAC energy is possible with greater window area. This observation should be tempered by the fact that increasing window area also has the effect of increasing baseline energy consumption.

3.4. Peak demand

Also of interest is the reduction in peak demand of electricity since peak demand is one criteria used by utilities in determining electricity rates. Since strategies to reduce peak electricity demand include reduction of electric lighting energy and the electricity components (primarily cooling) of HVAC energy, results are given here for the three control strategies relative to the Reference case. The results for WWR 33% and 66% are presented in Figure 12 and Figure 13 respectively.

As can be seen, the DimLights control, which only addresses reduction of lighting energy, results in reduction of peak demand relative to the Reference case of 7% to 13% for WWR 33% and 9% to 12% for WWR 66%. For most cases, both the DimLightsWindows and SeasonSchedule controls result in the same reduction of peak demand relative to the Reference case, ranging from 15% to 22% for WWR 33% and 18% to 30% for WWR 66%. Peak demand typically occurs during times of high cooling loads where the DimLightsWindows and SeasonSchedule controls operate identically.

4. DISCUSSION AND CONCLUSIONS

This study presents a simulation-based assessment of the energy savings benefits of integrated control for a medium office building across 16 climate zones. Although the medium office building is a theoretical building that is statistically representative of new commercial office buildings in the U.S., it still represents one specific building case. Changes in geometry, orientation, climate, construction, etc. will change results. The simulated control cases represent integrated control of electric lighting and window transmission and an approximation of controls integrated with HVAC. This study has focused primarily on energy as a metric of performance. The impact of the controls on occupant thermal and visual comfort was beyond the scope of this study.

The DimLights control simulated the use of daylight to dim the electric lighting. There was no control of window transmission. The DimLightsWindows control simulated integrated control of electric lighting and window transmission. The two subsystems worked together to maximize daylight in order to reduce electric lighting energy while rejecting additional solar heating gains to minimize cooling loads.

EnergyPlus V3.0.0 does not have run-time feedback of information available to integrate HVAC system information with the lighting and window transmission control used in this study. The SeasonSchedule control is one approach to approximating integration of controls with HVAC by identifying when the HVAC system is predominantly in heating or cooling mode on a month by month basis. However, it is only an approximation and thus represents a limitation of this study. Determining the season schedule itself is a moving target, since under different control strategies the heating and cooling energy balances will be different. It is expected that a truly HVAC integrated control could result in more energy savings than the approximation presented in this study. However this would have to be verified for the medium office model across all climate zones.

The three control strategies employed electric lighting dimming resulting in lighting energy savings in building perimeter zones ranging from 64% to 84%. These results fall in the upper ranges of results reported in the literature (Floyd and Parker 1995; Lee and Selkowitz 2006). Integrated control of electric lighting and window transmission (DimLightsWindows) resulted in HVAC energy savings ranging from -1% to 40%. Control of electric lighting and window transmission with HVAC integration (SeasonSchedule) resulted in HVAC energy savings ranging from 3% to 43%. The additional efficacy of HVAC integration was highly dependent on climate. In hot climates with little HVAC heating, the SeasonSchedule control offered marginal benefits over the DimLightsWindows control. For climate zones 1A to 3C the SeasonSchedule control saved between zero and 4% more HVAC energy than the DimLightsWindows control. In colder climates with more HVAC heating, the SeasonSchedule control offered more benefit over the DimLightsWindows control. For climate zones 4A to 8A the SeasonSchedule control saved between 4% and 11% more HVAC energy than the DimLightsWindows control. These results are summarized in Figure 14.

Although this study focused on site energy consumption as a metric, it should be noted that the control strategies described here are also effective at addressing environmental impact by reducing greenhouse gas emissions. Emissions are reduced by reducing electricity usage in lighting and cooling at the expense of increased heating, which is natural gas-based. Electricity requires far higher source energy and emits more pollution compared to natural gas. To estimate environmental impact, the source energy must be estimated and the emissions from the energy production, distribution and use must be estimated. Electricity energy is sourced from a combination of fossil fuels, nuclear generation, and renewable generation. The specific combination of fuel sources is region dependent and is given in (Deru and Torcellini 2007) for each state in the U.S. Total emissions from electricity are based on combustion and pre-combustion emissions. Emissions from natural gas include pre-combustion emissions based on the sourcing of the fuel as well as on-site combustion emissions.

For a specific emissions example, the DimLights control strategy results in a reduction of electric lighting energy, and a resulting decrease in HVAC cooling energy and increase in HVAC heating energy. In very cold climates, this results in a negative HVAC energy savings, particularly in Duluth, MN and Fairbanks, AK (see Figure 7 for WWR 33%). However, overall there is a 9% savings in carbon dioxide (CO_2) equivalent emissions in Duluth (264 metric tons) and a 7% savings in emissions in Fairbanks (137 metric tons) compared to the respective Reference cases. Perhaps even more interesting is comparing the DimLightsWindows control to the DimLights control in the Duluth and Fairbanks cases. With the DimLightsWindows control there is not only a negative savings in HVAC energy compared to the DimLights control (see Figure 10), but the total site energy increases as well (see Figure 8). However, source energy actually decreases and CO_2 equivalent emissions are reduced by 5% in Duluth (137 metric tons) and by 5% in Fairbanks (147 metric tons). These examples illustrate control strategy benefits that extend beyond site energy consumption.

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TABLES

Zone	*City*	*Zone*	*City*
1A	Miami, FL	4B	Albuquerque, NM
2A	Houston, TX	4C	Seattle, WA
2B	Phoenix, AZ	5A	Chicago, IL
3A	Atlanta, GA	5B	Boulder, CO
3B-CA	Los Angeles, CA	6A	Minneapolis, MN
3B	Las Vegas, NV	6B	Helena, MT
3C	San Francisco, CA	7A	Duluth, MN
4A	Baltimore, MD	8A	Fairbanks, AK

Table 1. DOE climate zones and representative cities.

Climate zone and location	**Heating months**
1A Miami	None
2A Houston	January – February, December
2B Phoenix	January – February, December
3A Atlanta	January – March, November – December
3B Los Angeles	None
3B Las Vegas	January – March, December
3C San Francisco	January – March, December
4A Baltimore	January – April, November – December
4B Albuquerque	January – March, November – December
4C Seattle	January – April, October – December
5A Chicago	January – April, October – December
5B Boulder	January – April, October – December
6A Minneapolis	January – April, October – December
6B Helena	January – April, October – December
7A Duluth	January – May, September – December
8A Fairbanks	January – May, September – December

Table 2. Heating months by climate zone used to develop SeasonSchedule control.

Control strategy	Electric lighting	Window transmission
Reference	No dimming	Fully clear
DimLights	Dimming	Fully clear
DimLightsWindows	Dimming	Dynamically controlled to meet illuminance setpoint
SeasonSchedule	Dimming	Dynamically controlled in cooling months, fully clear in heating months

Table 3. Summary of control strategies.

FIGURES

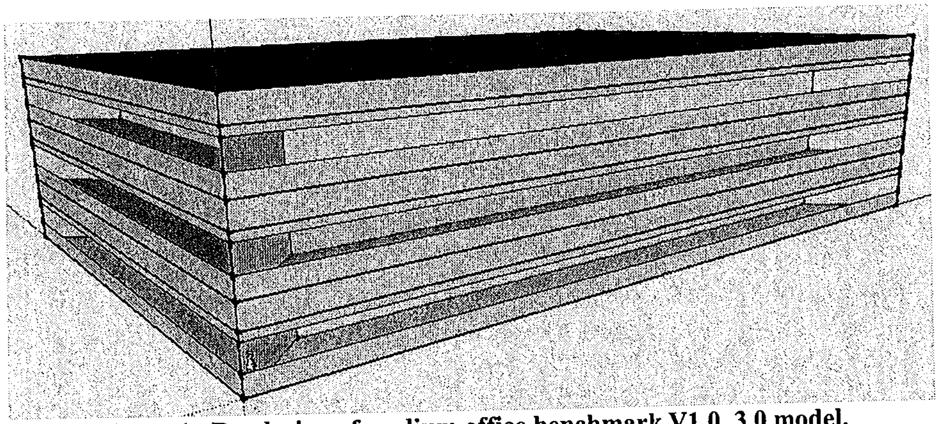

Figure 1. Rendering of medium office benchmark V1.0_3.0 model.

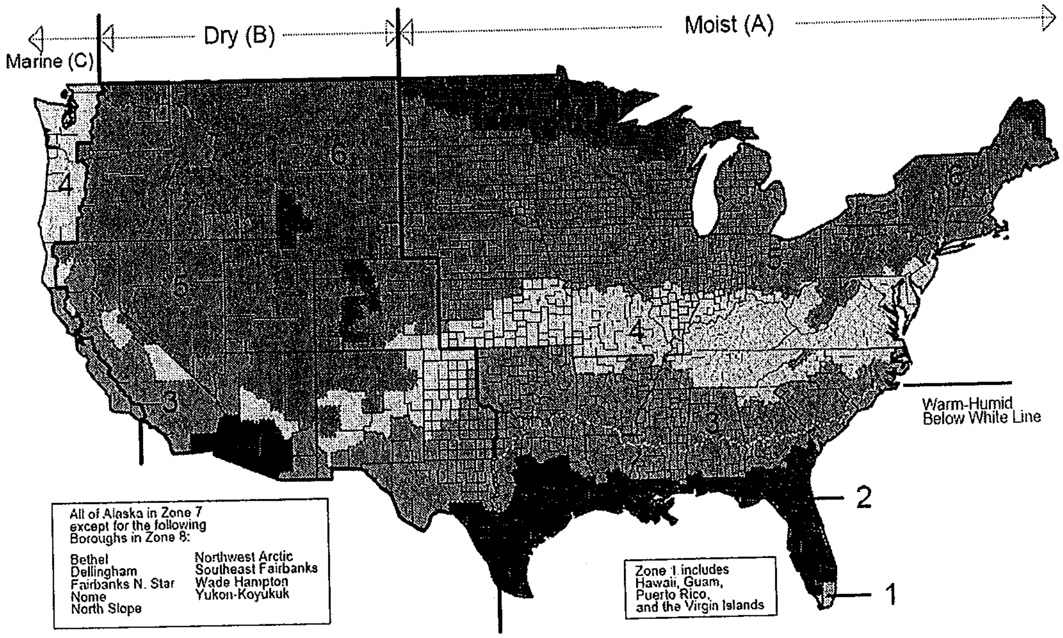

Figure 2. DOE climate zones (source: http://www.energycodes.gov/implement/pdfs/color_map_climate_zones_Mar03.pdf)

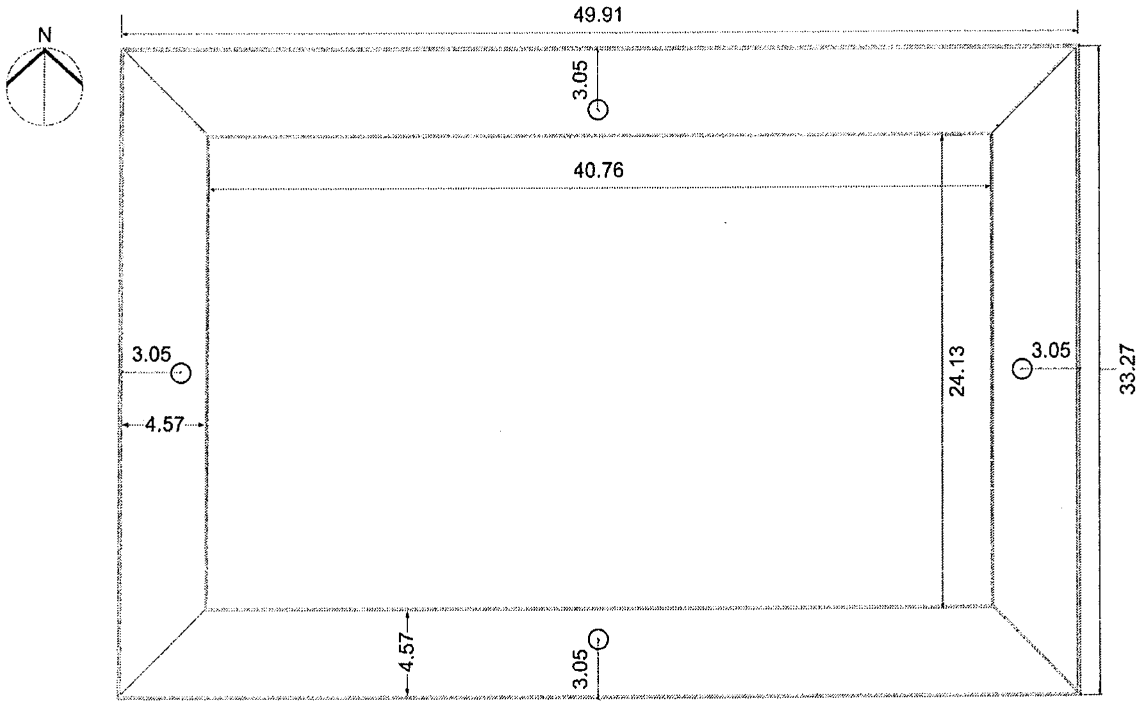

Figure 3. Building plan showing locations of reference points (3.05m from windows) in perimeter zones.

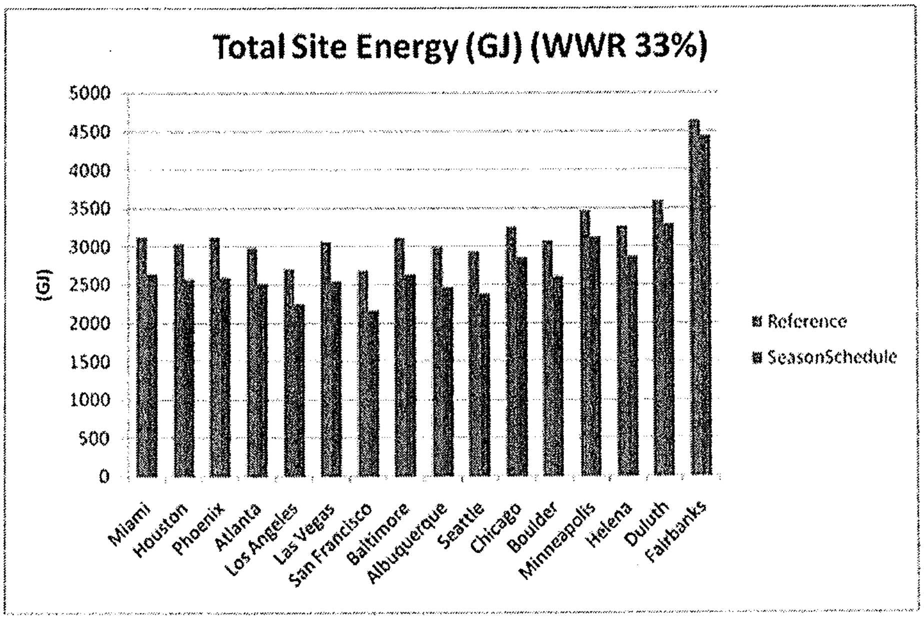

Figure 4. Total site energy (GJ) for Reference and SeasonSchedule cases and WWR 33%.

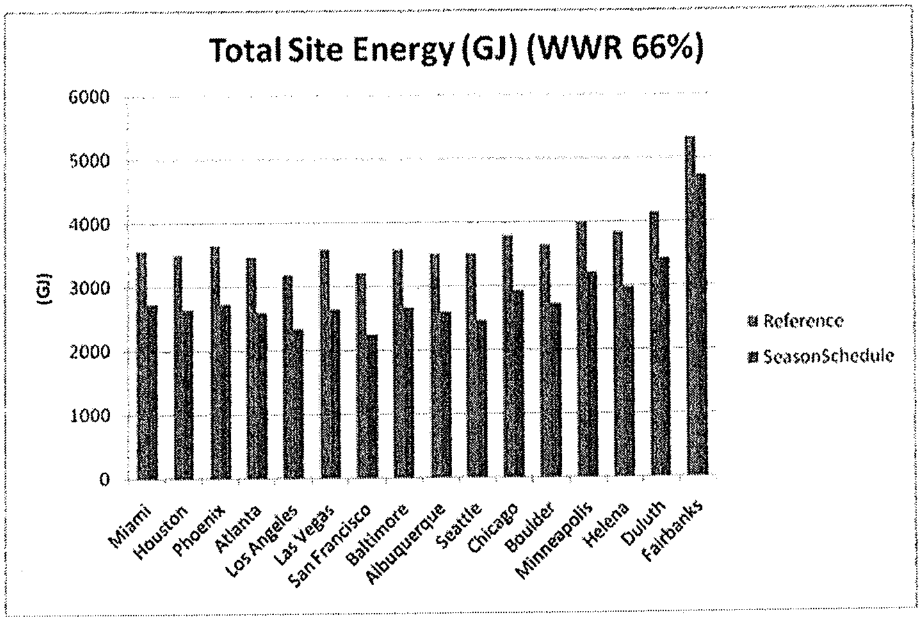

Figure 5. Total site energy (GJ) for Reference and SeasonSchedule cases and WWR 66%.

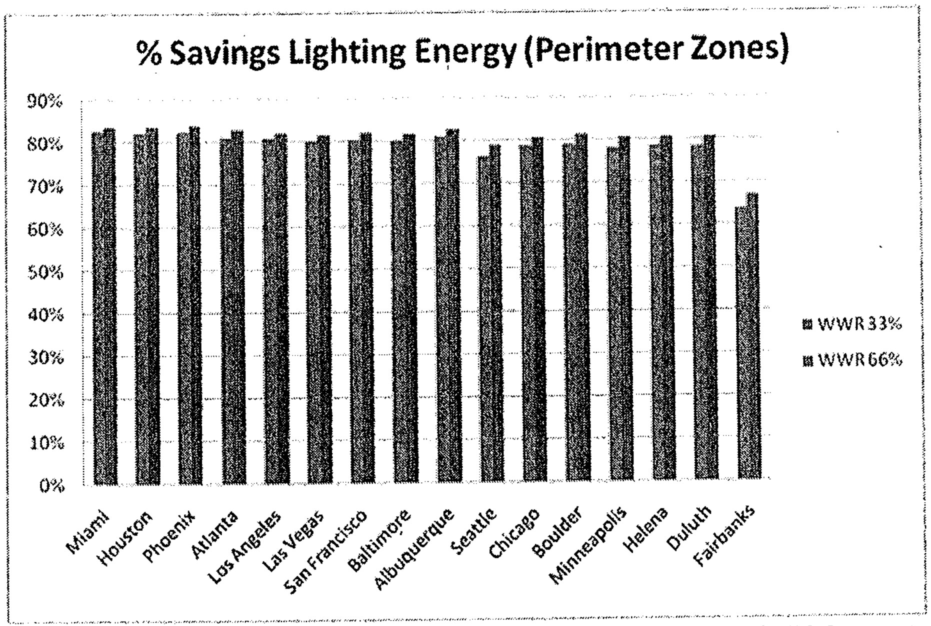

Figure 6. Percent savings in lighting energy in perimeter zones for DimLights control.

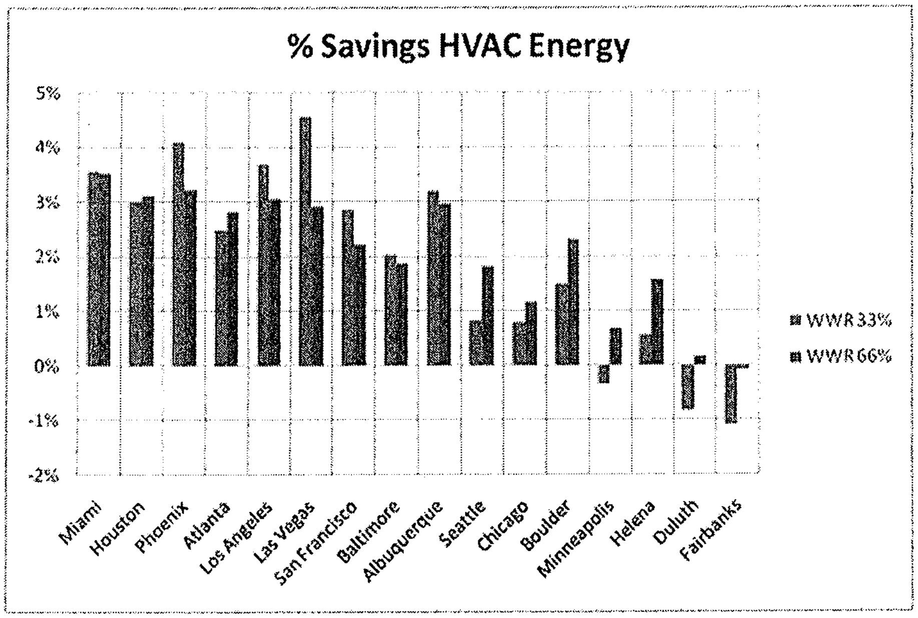

Figure 7. Percent savings in HVAC energy for DimLights control.

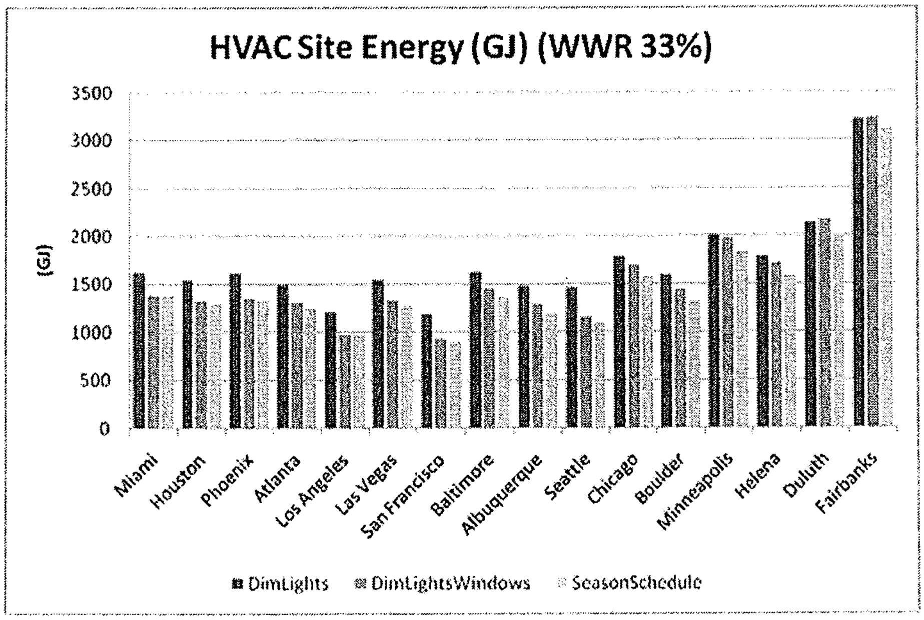

Figure 8. HVAC energy for three control cases and WWR 33%.

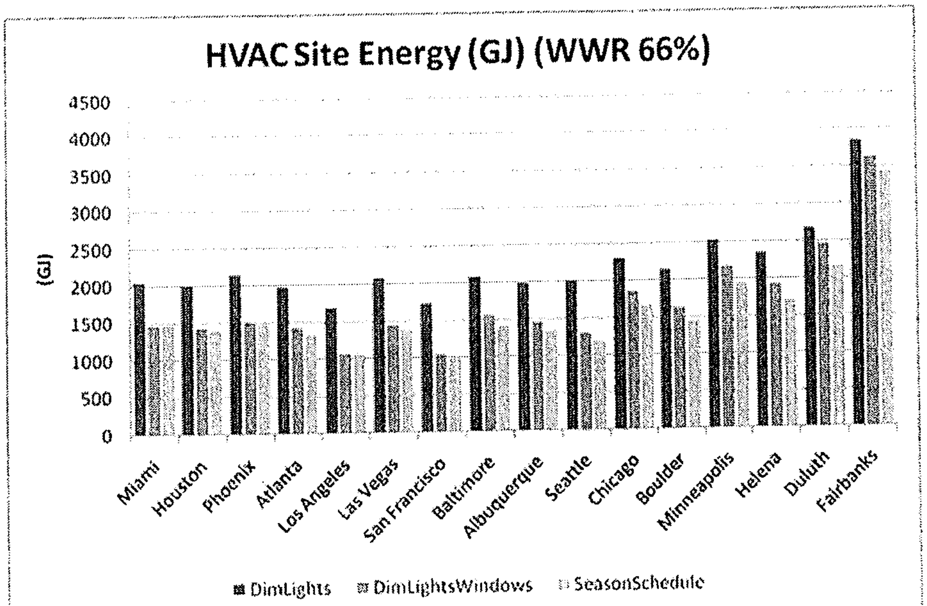

Figure 9. HVAC energy for three control cases and WWR 66%.

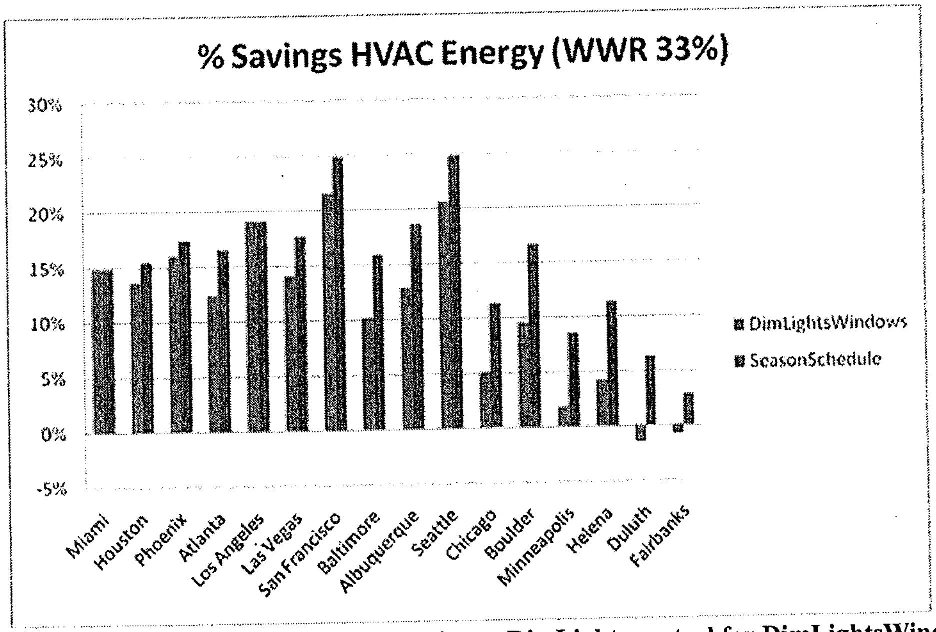

Figure 10. Percent savings HVAC energy relative to DimLights control for DimLightsWindows and SeasonSchedule controls, WWR 33%.

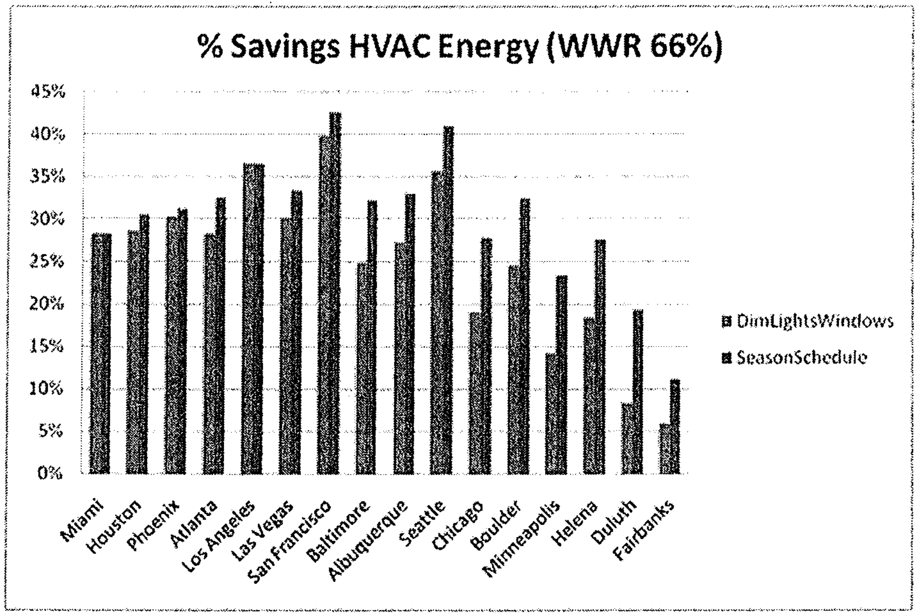

Figure 11. Percent savings HVAC energy relative to DimLights control for DimLightsWindows and SeasonSchedule controls, WWR 66%.

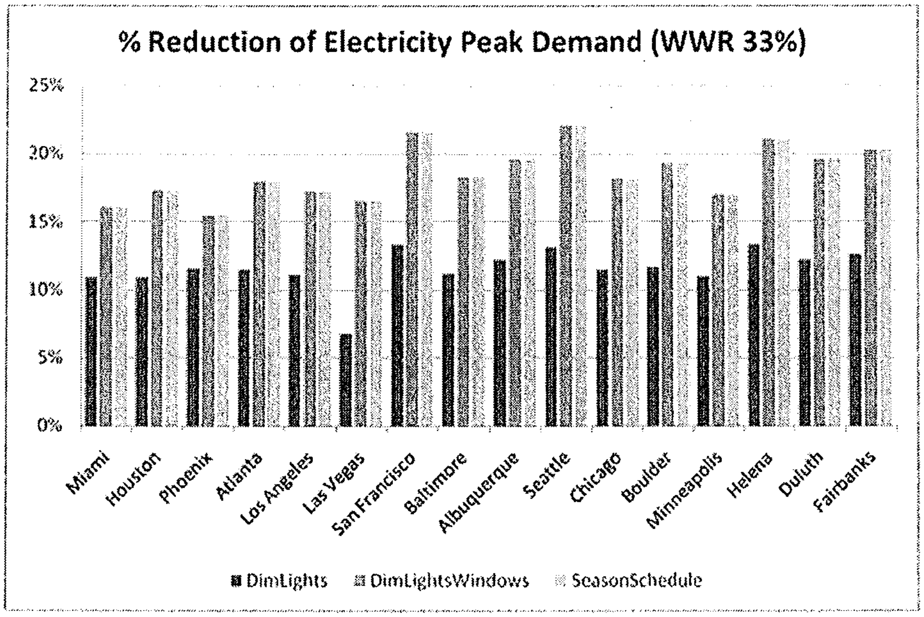

Figure 12. Percent reduction of peak electricity demand relative to Reference for WWR 33%.

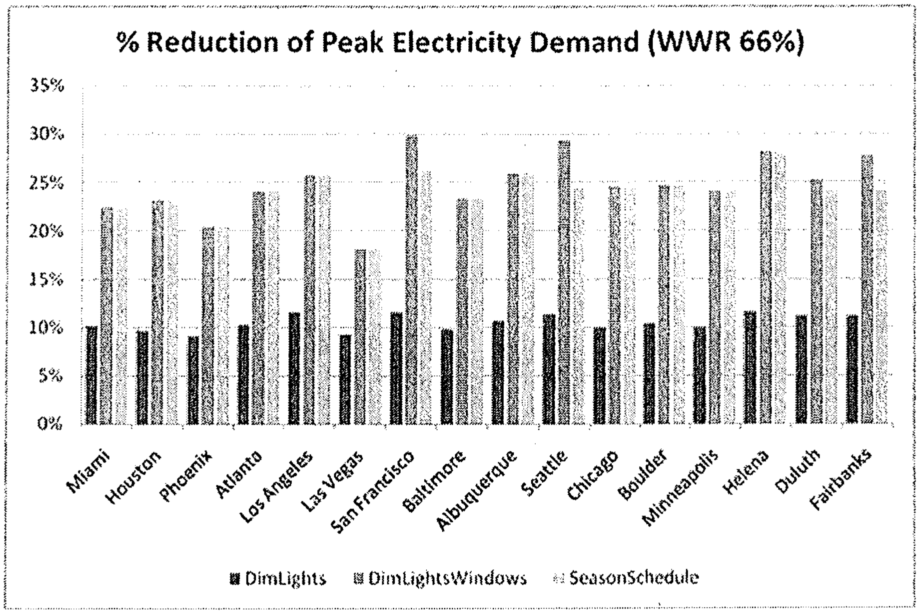

Figure 13. Percent reduction of peak electricity demand relative to Reference for WWR 66%.

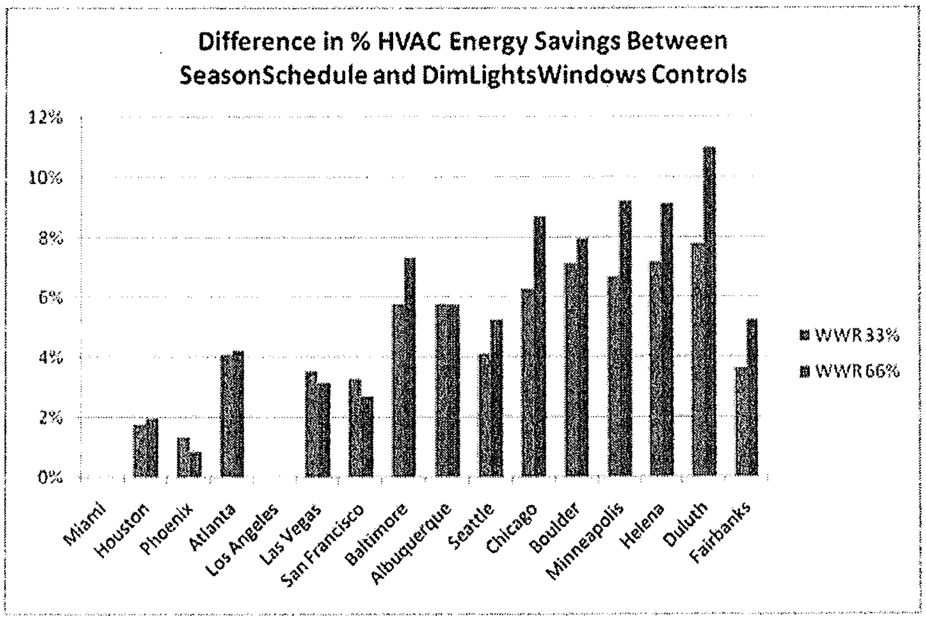

Figure 14. Difference in HVAC energy savings between the SeasonSchedule and DimLightsWindows control strategies.