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THE IMPACT OF OVERHANG DESIGN ON THE PERFORMANCE OF THE ELECTROCHROMIC WINDOWS

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ABSTRACT

In this study, various facade designs with overhangs combined with electrochromic window control strategies were modeled with a prototypical commercial office building in a hot and cold climate using the DOE 2.1E building energy simulation program. Annual total energy use (ATE), peak electric demand (PED), average daylight illuminance (DI), and daylight glare index (DGI) were computed and compared to determine which combinations of façade design and control strategies yielded the greatest energy efficiency, daylight amenity, and visual comfort.

Keywords: Electrochromic windows, overhangs, building energy simulations, visual comfort

1. INTRODUCTION

Smart, switchable electrochromic (EC) windows promise to be the next major advance in emerging, energy-efficient window technologies because of their capability to change state from a clear to a colored tint without loss of view. This technology provides an opportunity to improve and optimize both the energy-efficiency and comfort aspects of a building through dynamic control and integration with automated lighting controls designed to respond to daylight. Although EC windows can provide considerable energy savings and relatively stable daylight levels, they cannot block direct sun, which may result in unacceptable glare and reduced computer display visibility in office environments [1]. It should be noted that when EC windows are fully colored in order to control direct sun and glare, there are adverse effects on daylight levels, lighting energy savings, and room brightness [2]. To satisfy visual comfort requirements, EC windows may require interior or exterior shading devices to block direct sun. Fenestration elements such as overhangs combined with EC control strategies may enable one to achieve greater energy-efficiency and visual comfort. The objective of this study is to determine the effect of various shading solutions of different overhang placements and depths on moderate and large area EC windows having various control algorithms in a cold (Chicago) and hot climate (Houston).

2. METHODOLOGY

2.1. Simulation Software

A parametric study was conducted using the DOE-2.1E building energy simulation program [3] to generate relative performance data. DOE 2.1E is a comprehensive and general purpose thermal analysis program designed to explore the energy behavior of buildings and their associated HVAC systems. The program performs hourly thermal load and daylighting calculations based on the physical description of the building and ambient weather conditions.

2.2. Description of the Prototype Office Building

A commercial office-building prototype originally developed by LBNL [4] was simulated. The prototype is a synthetic, hypothetical building, not a physically real building, with size, envelope construction, HVAC system type, operating schedules, etc. based on the mean prevailing condition among statistical samples and engineering judgment. The three-story prototype consists of a ground, intermediate and rooftop floor. Each perimeter zone consisted of ten 3.04-m wide, 4.6-m deep, 2.74 m high private offices and faced the four cardinal directions. Since the energy performance of EC windows is improved with the integration of daylighting control strategies that operate the dimming of electric lights, daylight controls were specified for the perimeter zones. The perimeter zone electric lights are dimmed linearly so as to provide 538 lux at 3.05 m from the window wall, centered on the window and at a work plane height of 75 cm for the evaluations.

2.3. Window System and Overhang Design

Prototype EC windows were modeled for all perimeter zones. An EC glazing layer was combined with a 6-mm interior clear glazing layer. Thermal and solar-optical properties of glazing are given in Table 1. The exterior and interior glazing surface emittances were 0.84 and 0.15, respectively. All windows were modeled with a 12.7-mm aluminum spacer, air gas fill, and thermally-broken aluminum frame (U_{frame}=5.67 W/m^{2}K). Moderate- and large-area windows were modeled with a window-to-exterior wall area ratio (WWR) of 0.30 and 0.60. The head height of the window was set at 2.74 m for both window sizes. The EC façade was split into an upper and lower aperture, each controlled independently. The height of the upper aperture was kept constant at 61 cm for both window sizes. Window dimensions are given in Table 2 and shown in Fig. 1.

TABLE 1 PROPERTIES OF EC WINDOWS

	U ov.	U COG	SHGC ov	SHGC COG	Tv ov	Tv COG
Clear EC	2.87	1.87	0.37	0.42	0.45	0.56
Colored EC	2.87	1.87	0.10	0.09	0.02	0.02

COG: Center-of-glass; SHGC: Solar heat gain coefficient; Tv: Visible transmittance; EC: Electrochromic glazing; ov: overall window.
U values are given for ASHRAE winter conditions in W/m^{2}K. Overall U-values are given for a window whose overall dimensions including frame are 1.2x1.8 m (7.5 cm frame). SHGC is computed for ASHRAE summer conditions. All properties were determined using WINDOW 4.1.

TABLE 2. WINDOW DIMENSIONS (m)

WWR	EC1 width	EC1 height	EC2 width	EC2 height
0.3	1.83	1.22	1.83	0.61
0.6	3.05	1.58	3.05	0.61

EC1=Lower portion of the window, EC2=Upper portion of the window
WWR=Window-to-wall ratio (includes frame)

Control algorithms for the upper and lower apertures are given in Table 3. The switching control strategies of EC windows were based on daylight or solar control. For the daylight control strategy, the EC window was modulated linearly between the clear and colored states so as to provide a daylight illuminance of 538 lux at a reference point located 3.05 m from the window wall, centered on the window and at a work plane height of 75 cm every hour during daylight hours. For the solar control strategy, the EC window was modulated linearly between the clear and colored state as a function of the incident total solar radiation. The clear state was assumed for incident total solar radiation levels less than or equal to 63 W/m^2. The fully switched state was assumed for incident total solar radiation levels greater than or equal to 315 or 95 W/m^2.

TABLE 3. EC CONTROL STRATEGIES

	EC1 - Lower aperture Control Strategy	EC2 - Upper aperture Control Strategy
A	DayL (538 lux)	None: always clear
B	ISolR (63-315 W/m^2)	None: always clear
C	DayL (538 lux)	DayL (538 lux)
D	ISolR (63-315 W/m^2)	ISolR(63-315 W/m^2)
E	ISolR (63-315 W/m^2)	DayL (538 lux)
F	ISolR (63-95 W/m^2)	DayL (538 lux)

DayL: Daylight, ISolR: Incident total solar radiation

An opaque, non-reflective exterior overhang was placed perpendicular to the EC window. The overhang was placed either at the top of the upper aperture or in between the upper and lower apertures of the window at all zones. The overhang was 3.05 m wide and 85, 100, 130, or 150 cm deep (Fig. 1). These obstructions blocked diffuse light from the sky and direct sun but reflected no light from the ground.

3. PARAMETRIC STUDY ON OVERHANG DESIGN

A parametric study was conducted that compares the performance of various combinations of EC façade designs and control algorithms in a hot climate (Houston, Texas) and a cold climate (Chicago, Illinois). The base case is identical to the test case except it has no overhang. The percentage of savings in annual total energy use (ATE) and peak electric demand (PED) for the south zone of three-story commercial building was computed. Annual total energy use is given where electricity and natural gas (for heating) end uses were combined using an electricity-to-gas fuel ratio of 3:1. The average annual daylight illuminance (DI) for the south zone is given at 3.05 m from the window wall, centered on the window and at a workplane height of 75 cm. The average annual daylight glare index (DGI) is given at 1.5 m from the window wall, centered on the window, looking at the east side wall, at a height of 1.21 m above the floor. Optimum solutions are identified by analyzing these performance data as a function of window size, EC control algorithm, and overhang placement and depth for heating- and cooling-dominated climates.

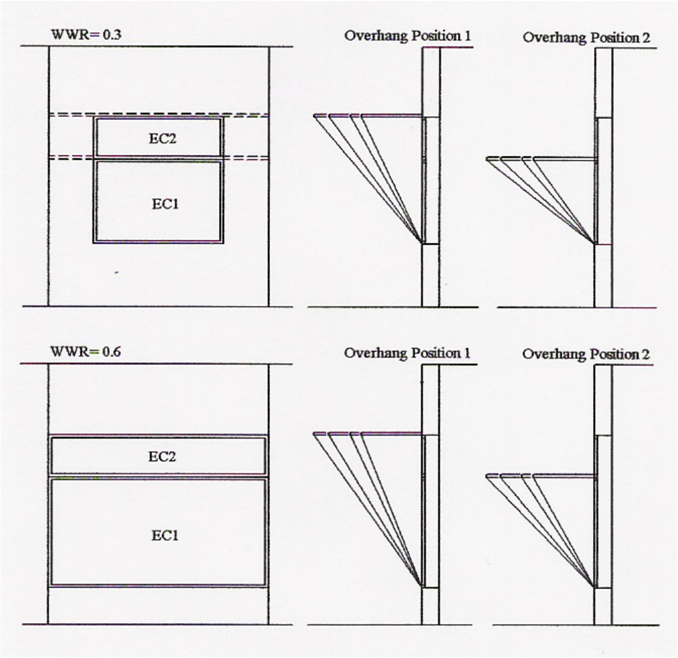

Fig. 1: Window system configurations.

3.1. Annual Total Energy Use (ATE)

The percentage reductions in ATE for large and moderate area EC windows with overhangs of various depths versus the no-overhang case are given for Houston and Chicago in Fig. 2-a, b, c, d. When an overhang is combined with an EC window, annual cooling energy is decreased for all overhang configurations while annual lighting energy use varies depending on the overhang design and switching control algorithms for both window sizes. The simulation results indicate that several EC switching control strategies provide greater energy-efficiency than the EC window alone, depending on the placement of the overhang, particularly for large-area windows. Up to 14% and 10% savings can be achieved depending on the overhang depth and control algorithm in Chicago and Houston, respectively, if the window area is large.

The placement of the overhang affects the effectiveness of the control algorithm. The percentage of savings is greater for some control algorithms if the overhang is placed between the windows because the upper aperture admits daylight, which can then decrease lighting energy use. Maximum savings for all overhang designs were attained by controlling the upper and lower EC windows based on incident total solar radiation (D) for large and moderate area windows in both climates. Savings were 9% and 13% for large-area EC windows in Houston and Chicago, respectively, while the savings were approximately 7% for moderate-area EC windows in both climates.

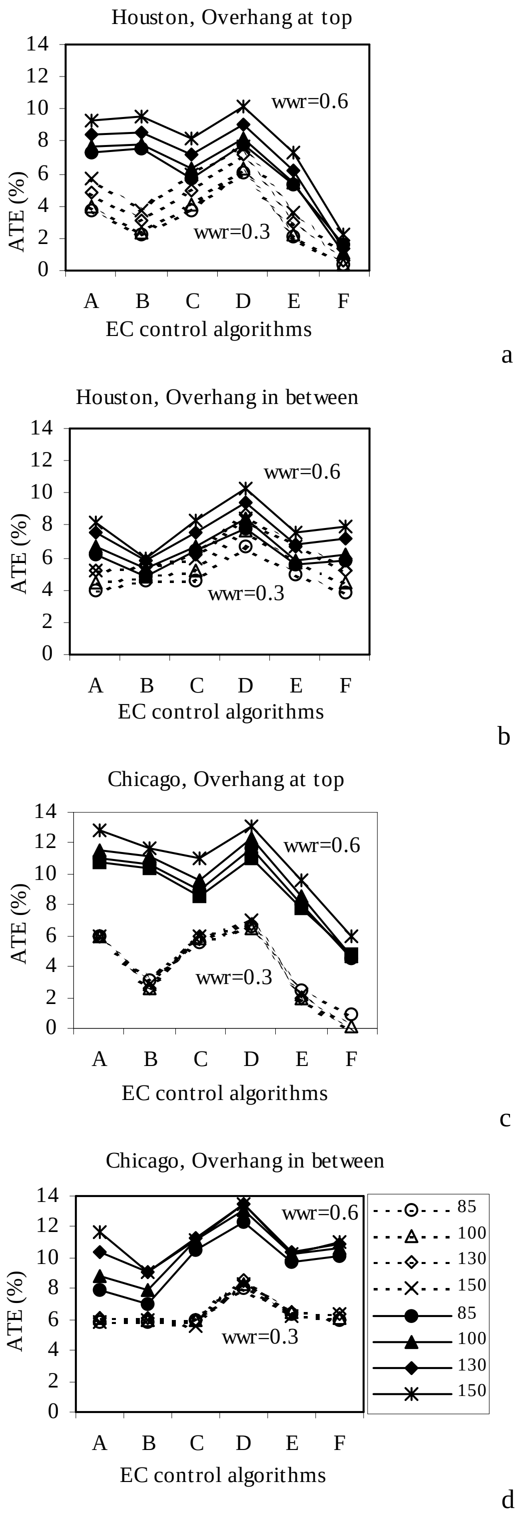

Fig. 2: Percentage reduction in ATE when various depths of overhangs are combined with large- (WWR=0.6) and moderate-area (WWR=0.3) EC windows having various control algorithms versus the same configuration without an overhang.

In Chicago, control algorithms D, E and F yielded better performance when the overhang was in between the two apertures. In Houston, algorithms C, D, and E yielded almost the same performance for either overhang locations while algorithm F, which was designed to minimize glare in the lower aperture and bring daylight into through the upper aperture, yielded better performance with the in-between overhang position. With this case, algorithm F maintained the lower aperture at or near the fully colored state for most hours in the year while the upper aperture, which was modulated for daylight, provided daylight to offset lighting energy use requirements. Further studies can be conducted to optimize the area of the upper aperture for algorithm F: This aperture may be too small to provide the required daylight illuminance (see Section 3.3), which may increase lighting energy use.

Deeper overhangs located either at the top or in between the EC apertures provided virtually no savings for a moderate-area window and small savings (~4% maximum) for a large-area window in Chicago. The same can be said for Houston, where a change in depth from 85 cm to 150 cm produced a maximum reduction in energy use of only ~3%.

3.2. Peak Electric Demand (PED)

The percentage reductions in PED provided by EC windows combined with overhangs of various depths and locations versus no-overhang options is presented in Fig. 3-a, b, c, d.

Use of an overhang significantly decreases PED by reducing incident solar radiation on the façade, thus lowering the cooling load. This is particularly true for large-area windows in hotter geographic locations. Greater savings can be achieved by placing the overhang at the top of the window for the most EC configurations. Greater savings are achieved with increased overhang depth, particularly for large-area windows. The greatest PED reductions are achieved again with control algorithm D for all window designs, with algorithm B being a close contender in Houston with the overhang at the top of the window.

3.3. Annual Daylight Illuminance (DI) and Daylight Glare Index (DGI)

From the energy-efficiency perspective, daylight offsets the need for electric lighting by providing adequate levels of illuminance in a space. More daylight does not necessarily equate to better lighting conditions. It is a matter of balancing daylight admission with glare control. Average annual work plane illuminance (DI) is given as a function of various EC control algorithms and window designs in Fig.4-a, b, c, d. All data are given as an average of the year, where the year is defined by all hours when the sun is up.

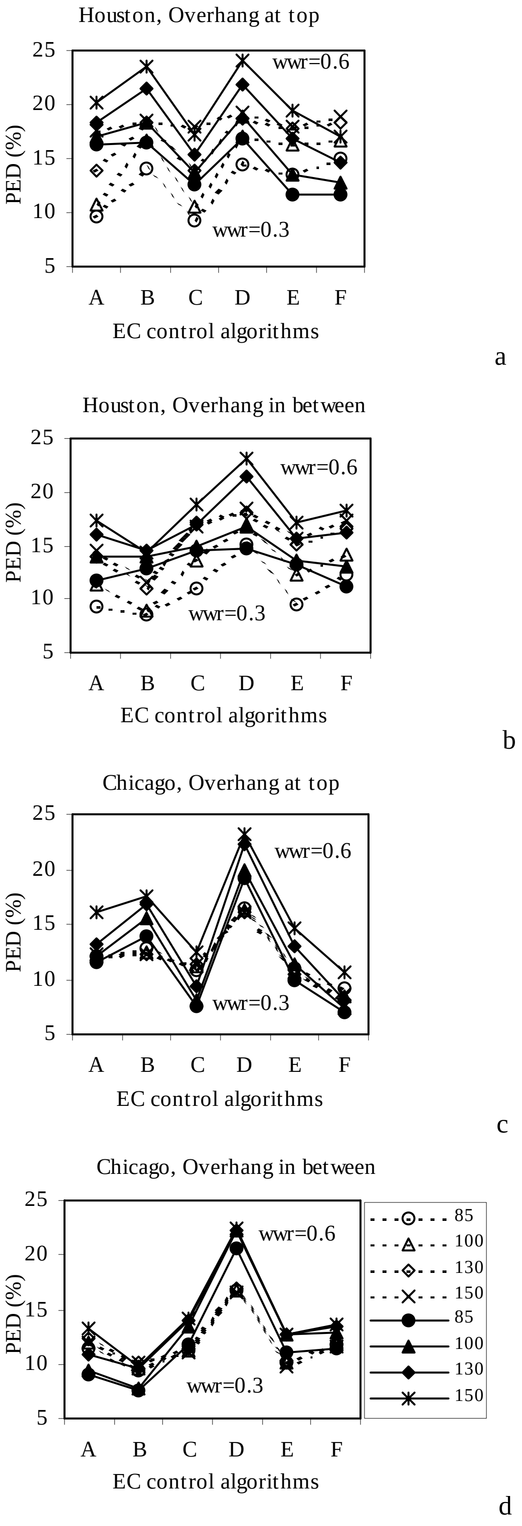

Fig. 3: The rate of reduction in PED when various depths of overhangs are combined with large- (WWR=0.6) and moderate-area (WWR=0.3) EC windows having various control algorithms versus the same configuration without an overhang.

For most of these window designs and EC control algorithms, DI levels did not exceed the design level of 538 lux for most configurations in either climate. One cannot conclude that this metric is an indicator of gloom; alternate performance metrics would need to be calculated to assess interior brightness. There were several exceptions. With no overhang and WWR=0.6, DI levels were between 1300-1600 lux for this south-facing window in Chicago (latitude=42°). With the in-between overhang, DI levels were also between 1300-1600 lux for control algorithms A and B for all overhang depths. Direct sun from low winter sun angles was admitted through the fully-bleached EC upper aperture and increased average DI levels in south facing room in higher latitudes. In Houston, DI levels were increased for control algorithms B, E, and F if the overhang was placed in between the EC apertures. For example, DI values for control algorithm F was 89-122 lux with the overhang at the top of the window and 260-263 lux with the in-between overhang given a moderate-area window. As mentioned earlier, the lower EC was controlled to near or at the fully colored state, so the upper aperture was controlled to at or near the clear state for most of the year in order to reach the daylight illuminance design level.

The average annual DGI for different EC window configurations is given in Fig. 5-a, b, c, d. This DGI is an approximate measure of visual discomfort one feels from a large-area daylight source within one's peripheral view. A DGI value of 10 is the threshold between "just imperceptible" and "just acceptable" discomfort glare. In conventional designs, glare control often conflicts with the control objectives for energy efficiency since daylight illuminance levels are often diminished significantly in order to achieve a glare-free environment. With the proper façade design and control algorithm, it is possible to achieve both objectives. For example, control strategy F yields the lowest annual DGI for all cases because the lower EC aperture is most often in a dark tinted state throughout the year thus reducing the luminance of the large-area glare source. If the in-between overhang case is selected, the ATE performance is nearly comparable to the optimal ATE EC control: algorithm D. Algorithm D has a less stringent control of the lower aperture and therefore has a significantly greater DGI value than algorithm F with only a 2% increase in percentage ATE reduction.

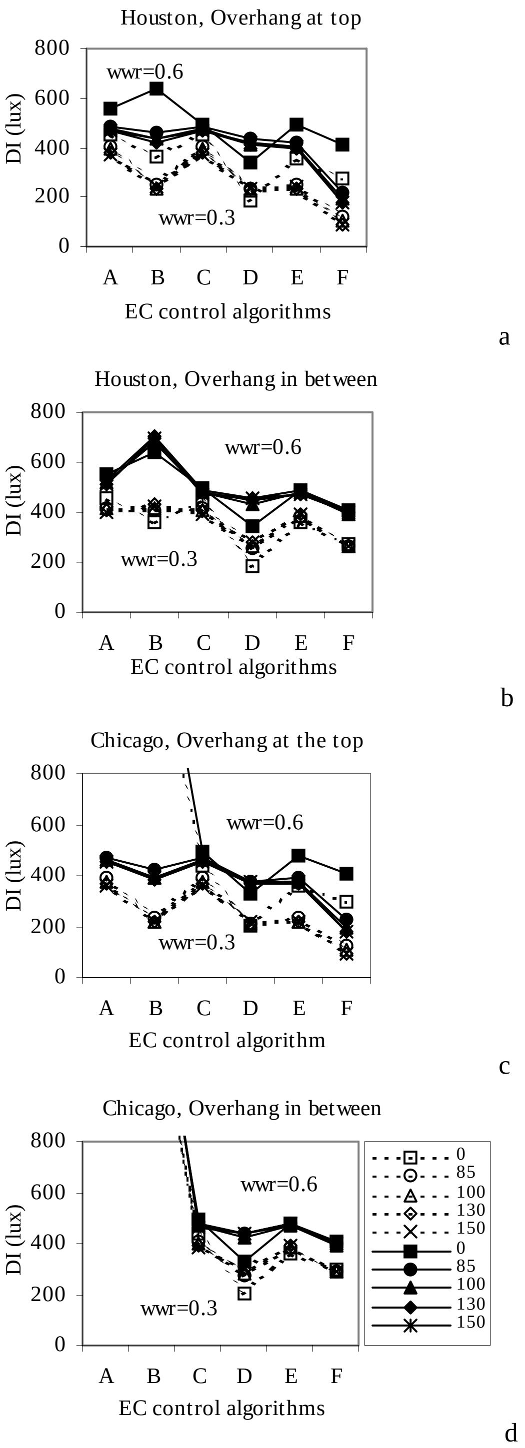

Fig. 4: Average annual daylight illuminance levels (DI) at 3.05 m from the window, centered on the window, and at a work plane height of 75 cm.

4. CONCLUSION

Field studies, lighting studies using ray-tracing simulation tools, and human subjects studies conducted with EC windows indicate that EC windows must be combined with either interior or exterior shading to control direct sun. Even if the EC were to achieve a visible transmittance of 0.001 in the colored state, the orb of the sun at over a billion cd/m^2 as it approaches the meridian is still a decisive glare source. Therefore, performance indices such as DGI and other visual comfort indicators must be considered with equal weight when evaluating the energy-savings and market potential of emerging technologies such as electrochromic windows. If the criteria is to maximize energy use savings while minimizing discomfort glare, then:

1) For cold climates like Chicago with EC window designs of moderate area, the in-between overhang position with control algorithm D best meets this criteria, but strategies E and F yield almost equitable ATE reductions with slightly lower glare. Overhang depth was of no consequence. ATE reductions were 6-9% with DGI levels of 1-3. PED reductions were 10-17%. DI levels were 200-400 lux.

2) For cold climates with large-area EC windows, the in-between overhang position with control algorithm F meets the criteria. Glare was controlled through the lower aperture and the upper aperture provided sufficient daylight to offset lighting energy use requirements. The overhang provided additional protection from direct solar heat gains. Overhang depth was of no consequence. ATE reductions were 10-11% with DGI levels of 4. PED reductions were 11-14%. DI levels were 400 lux.

3) For hot climates like Houston with moderate-area EC windows, control algorithm D best meets the criteria with either overhang position. Overhang depth has some minor on ATE but larger impact on PED. ATE reductions were 6-9% with DGI levels of 2-4. PED reductions were 15-19%. DI levels were 200-300 lux.

4) For hot climates with large-area EC windows, differences in DGI drive the selection of the best case. The in-between overhang with control algorithm F best meets the criteria. Increasing overhang depth has some impact on ATE but a larger impact on PED. ATE reductions were 6-8% with DGI levels of 5. PED reductions were 11-18%. DI levels were 400 lux.

Further work is required to gain a better understanding of how best to optimize the energy and comfort potential of EC windows. Combining EC windows with light-redirecting, sun-control systems hold even greater potential for achieving energy-efficiency and market acceptance.

5. REFERENCES

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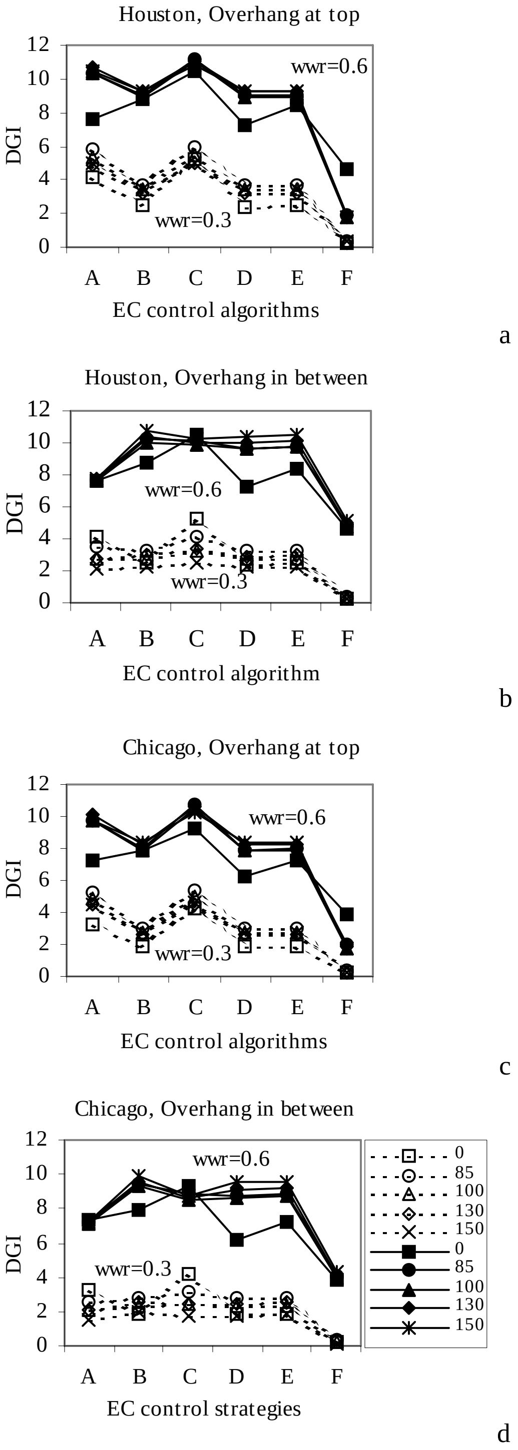

Fig. 5: Average annual daylight glare index (DGI) for a view 1.5 m from the window looking at the side wall.