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Environmental Technologies Area

December, 2013

Acknowledgements

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, [Building Technologies Program] or [Federal Energy Management Program], of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Solar Energy Materials & Solar Cells 123 (2014) 65–80,
accepted for publication December 9, 2013.

Examination of the technical potential of near-infrared switching thermochromic windows for commercial building applications

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Abstract

Current thermochromic windows modulate solar transmission primarily within the visible range, resulting in reduced space-conditioning energy use but also reduced daylight, thereby increasing lighting energy use compared to conventional static, near-infrared selective, low-emittance windows. To better understand the energy savings potential of improved thermochromic devices, a hypothetical near-infrared switching thermochromic glazing was defined based on guidelines provided by the material science community. EnergyPlus simulations were conducted on a prototypical large office building and a detailed analysis was performed showing the progression from switching characteristics to net window heat flow and perimeter zone loads and then to perimeter zone heating, ventilation, and air-conditioning (HVAC) and lighting energy use for a mixed hot/cold climate and a hot, humid climate in the US. When a relatively high daylight transmission is maintained when switched (Tsol = 0.10-0.50, Tvis = 0.30-0.60) and if coupled with a low-e inboard glazing layer (e = 0.04), the hypothetical thermochromic window with a low critical switching temperature range (14-20°C) achieved reductions in total site annual energy use of 14.0-21.1 kWh/m^2-floor-yr or 12-14%[2] for moderate- to large-area windows (WWR≥0.30) in Chicago and 9.8-18.6 kWh/m^2-floor-yr or 10-17%[3] for WWR≥0.45 in Houston compared to an unshaded spectrally-selective, low-e window (window E1) in south-, east-, and west-facing perimeter zones. If this hypothetical thermochromic window can be offered at costs that are competitive to conventional low-e windows and meet aesthetic requirements defined by the building industry and end users, then the technology is likely to be a viable energy-efficiency option for internal load dominated commercial buildings.

Keywords: Thermochromic; Windows; Solar control; Daylighting; Building energy efficiency

1. Introduction

Thermochromic (TC) windows consist of a thin polymer film or inorganic coating on glass that passively switches in response to variable thermal conditions. The thermochromic is typically applied to the outer glass layer of an insulating glass unit and when it reaches a certain critical temperature (or range of temperatures) due to high incident solar radiation and/or high outdoor temperatures, the thermochromic

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[2] Percentage values refer to the site annual energy use for the perimeter zone of a specific orientation, highest relative savings were usually reached for south or west orientation
[3] See above

changes or switches from a clear to a tinted transparent state, reducing the solar and visible transmittance of the window. The process of switching from the clear to tinted state is reversible and for some thermochromic materials, hysteresis can be observed (i.e., switching from tinted to clear occurs at a lower temperature than switching from clear to tinted) [1-3]. As a passive system, thermochromic performance is highly dependent on the interaction between the material and the climatic conditions to which it is subjected. The current understanding is that if the material properties of the thermochromic can be properly tuned, then the technology has the potential to significantly improve building energy efficiency.

A wide variety of materials have been found to have thermochromic properties, including polymers, organic and inorganic compounds [4]. Most of them offer good modulation of the visible transmission. However, they generally do not offer proper switching in the near-infrared (IR) portion of the solar spectrum. Several transition metal oxides and related compounds such as a Fe_3O_4, $FeSi_2$, NbO_2, NiS, Ti_2O_3, Ti_4O_7, Ti_5O_9, V_2O_3, and VO_2 offer interesting thermochromic properties. Among them, vanadium dioxide (VO_2) is the only metal oxide that exhibits a sharp thermochromic transition close to room temperature (68°C). The switching takes place due to a semiconductor to metal (MIT) transition that is accompanied by a first order structural phase transition from monoclinic to rutile. As a consequence, a drop in the resistance of around four orders of magnitude is observed [5], along with a remarkable decrease of the IR transmittance [6]. The origin of the MIT transition still remains controversial. It is unclear whether the insulating behavior in the low temperature phase is due to a Peierls distortion inducing the insulator energy gap, or to a Mott transition due to electron localization and increase in electron-electron repulsion [7-9]. Typical values for the modulation of solar transmission (ΔTsol) are not usually larger than 0.1 for VO_2 thin films, while visible transmittances (Tvis) do not exceed 0.4 [10].

The material science community has defined performance objectives to guide development of the next generation of thermochromic materials, namely: a) lower the critical temperature at which the TC material switches to the tinted state from 68°C to 25°C for VO_2-based materials, b) broaden the modulation of solar transmission (ΔTsol), and c) achieve a high visible transmittance (Tvis) in the unswitched state [10]. Several solutions have been proposed to overcome these difficulties. The critical temperature can be widely tuned by doping VO_2 with different transition metals [10-12], giving rise to significant changes in the electronic structure and thus the thermochromic transition. For example, VO_2 doping with W leads to a drop of the transition temperature at a rate between 5 and 24 K/at.%W, depending on the deposition conditions [10, 13]. Tvis can be enhanced by the addition of W, but the effect is not large [14]. Li *et al.* [15,16] proposed the use of VO_2 nanoparticles embedded in a dielectric host to increase ΔTsol. When in their metallic phase, the VO_2 nanoparticles undergo localized surface plasmon resonance (LSPR), leading to an increased absorption in the visible and near-IR ranges. Values of ΔTsol around 0.167 and Tvis as high as 0.72 and 0.62 in the semiconducting and metallic states respectively can be achieved. Furthermore, the use of core-shell nanostructures, where VO_2 comprises the shell, will allow reaching ΔTsol values in excess of 0.20 at the expense of a lower Tvis around 0.59 in the semiconducting state [15]. Also, tuning of the transition temperature and Tvis can be easily achieved by doping VO_2 with different transition metals. Due to its particular electronic structure, VO_2 exhibits a *2p-3d* interband transition around the visible range, leading to strong optical absorption and thus low Tvis values. Doping with Mg has been shown to broaden the bandgap of VO_2 leading to an increase Tvis to around 0.5 [17].

Following on the work of previous studies that have used building energy simulations to assess the potential energy efficiency benefits of thermochromic windows within simple room models [18-19], this study quantifies the benefits associated with thermochromic windows that meet the above stated performance objectives in order to provide developers with a deeper understanding of the level of impact associated with advancements in material science. The relationships between window heat gain, perimeter zone loads, and heating, cooling, and lighting energy use are complex and non-trivial. Performance is dependent on climate, building type (as defined by construction and internal load profile), window orientation, window size, and the efficiencies of the space conditioning and lighting equipment.

A hypothetical, near-infrared selective thermochromic window is modeled (Tsol=0.50-0.10, Tvis=0.6-0.3) with different ranges of switching temperature. While the properties of these emerging thermochromic coatings have shown great improvement in the last few years, we note that significant research needs to be carried out in order to achieve these optimum thermochromic characteristics. Design of coatings consisting of nanostructured dielectric materials and doped VO_2 will help to optimize the thermochromic properties of these systems.

The EnergyPlus building energy simulation tool is used to determine the incremental differences in energy performance for perimeter zones in a typical large commercial office building. Performance is evaluated for a mixed cold/hot northern climate and a hot, humid southern climate in order to identify regions in the United States where thermochromic windows are most likely to provide significant energy savings compared to static, near-infrared selective, low-emittance windows which are currently the leading-edge, commercially-available technology of today.

2. Methods

2.1. Properties of the thermochromic windows

2.1.1. Transmittance in visible and solar spectrum of the thermochromic glazing layer

In order to regulate solar transmission without negatively reducing daylight, thermochromic switching from the clear to tinted state should occur primarily in the near-infrared (NIR) spectrum (780-2500 nm). Since about half of the solar energy is emitted in the visible spectrum (380-780 nm), there is a physical limit to the ratio of visible to solar transmittance over the full solar spectrum (300-2500 nm). The best spectrally-selective glazings have a maximum luminous efficacy, Ke, or ratio of visible transmittance (Tvis) to solar heat gain coefficient (SHGC) of about 2.5.

For this study, we defined a hypothetical spectral distribution for the TC glazing layer where the transmittance of shorter wavelengths in the visible spectrum is maintained at a high level when the glazing is fully tinted while wavelengths in the near-infrared spectrum were cut down to a transmittance of 0.05 in the fully tinted state in order to minimize the overall solar transmittance. This hypothetical value of near-infrared transmittance represents a target value when integrating the spectral transmittance of a real material over the NIR spectrum. The spectral distribution was optimized for luminous efficacy based on the CIE Standard Illuminant D65 [20] and the CIE 1931 standard observer [21] (Y component) for visible transmittance, and on global radiation data from ISO 9845 [22] for solar transmittance. A value of Tvis = 0.30 and Tsol = 0.10 for the TC glazing layer in the fully tinted state leads to a luminous efficacy of Ke = 2.25 for the TC glazing system (Table 1). Color neutrality and appearance were not part of the optimization. Two intermediate states were defined by interpolation between the clear and tinted states; the spectral distributions for all four states are given in Figure 1.

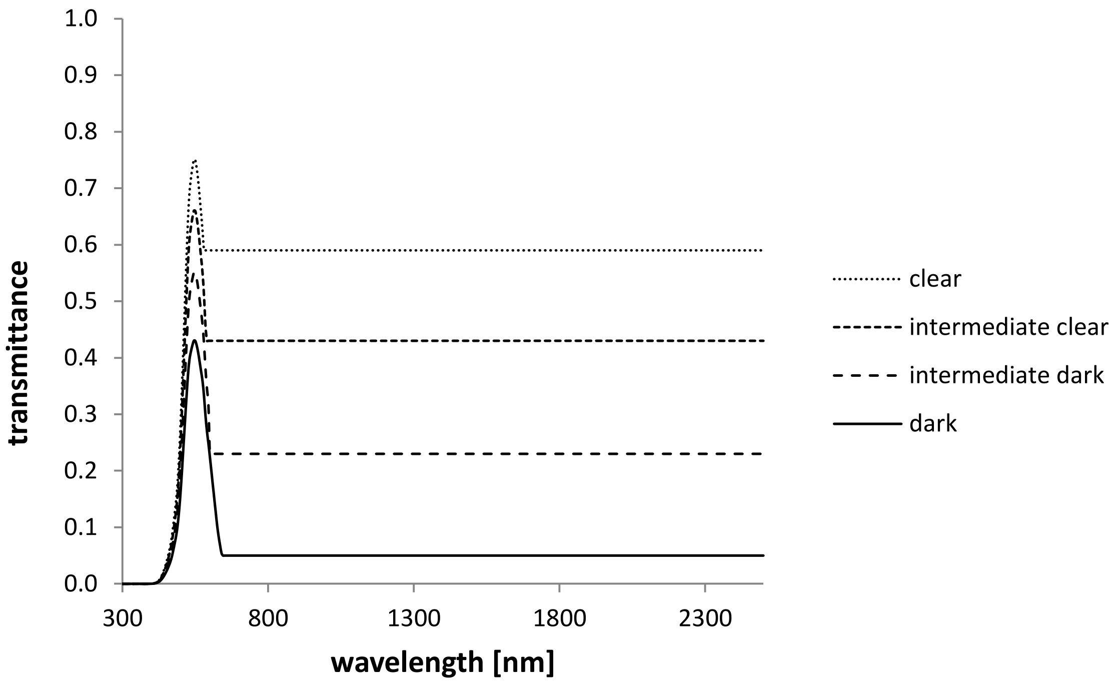

Fig. 1. Spectral data for the four different states of a hypothetical, ideal, near-infrared switching thermochromic glazing modeled in this study. These data were used to derive spectrally averaged data used in the building energy simulations (Table 1 and 2).

Table 1

Spectrally averaged properties of the glazing layers and thermochromic insulating glass unit as used in the simulation model.

	Layer 1 (outdoor) TC		Gap	Layer 2 clear low-e	Insulating glazing unit	
	clear	tinted			clear	tinted
Thickness [mm]	6		16	6	28	
Solar transmittance	0.5	0.1		0.77	0.39	0.08
Solar front reflectance	0.35	0.45		0.07	0.37	0.45
Solar back reflectance	0.35	0.45		0.07	0.37	0.45
Solar absorptance	0.15	0.45		0.16		
Visible transmittance	0.6	0.3		0.88	0.53	0.27
Front side emissivity	0.84	0.84		0.04		
Back side emissivity	0.84	0.84		0.84		
U-value (W/m^{2}K)					1.45	1.45
SHGC					0.47	0.12
Ke (=Tvis/SHGC)					1.13	2.25

Note: Solar-optical properties based on CIE Illuminant D65 (ISO/CIE 10526 Table 1), CIE 1931 standard observer Y, ISO 9845 (Table 1, column 5), U-value and SHGC from EnergyPlus. Gas fill was 90% argon, 10% air. SHGC: solar heat gain coefficient; Tvis; visible transmittance.

2.1.2. Switching temperature range of the thermochromic glazing layer

The critical switching temperature was defined with a 6°K range. Broader switching temperature ranges produced less energy savings. Thermochromics with a narrow switching range of 1-2°K can produce an uneven appearance (i.e., a mix of clear and tinted regions across the same window pane when at the critical switching temperature) due to temperature differences from the edge of the insulating glazing unit (IGU) to the center of glass and are less desirable from the architectural aesthetic perspective.

To evaluate sensitivity of performance to the critical switching temperature, the thermochromic glazing layer was defined with four possible ranges for the critical switching temperature. Switching temperature ranges varied 14-20°C for the lowest to 32-38°C for the highest. Lower switching temperatures could be beneficial but might be less acceptable to the occupants since the glazing would be in the tinted state for a significant fraction of the year, including the winter season when daylight is usually appreciated. The balance between heating, ventilation, and air-conditioning (HVAC) and lighting energy use are examined in Section 6. Table 2 summarizes the switching ranges of the four types of TC glazing layers.

Table 2

Center-of-glass transmittance and critical switching temperature (°C) for the thermochromic glazing layers.

Center-of-glass transmittance	clear state	intermediate clear	intermediate dark	dark state
Tvis	0.60	0.50	0.40	0.30
Tsol	0.50	0.37	0.23	0.10
Switching temperature (°C)				
TC 14-20	≤ 14	16	18	≥ 20
TC 20-26	≤ 20	22	24	≥ 26
TC 26-32	≤ 26	28	30	≥ 32
TC 32-38	≤ 32	34	36	≥ 38

2.1.3. Description of the thermochromic windows

Each of the four types of TC glazing layers was combined with a second glazing layer to form an insulating glass unit (IGU). Four thermochromic windows were modeled, each with the same solar-optical switching range but different ranges for the critical switching temperature.

To minimize the inward flowing fraction of absorbed radiation to the indoors, the TC glazing layer was placed as the outside lite (TC film or coating on surface #2) and a clear glazing layer with a low-emissivity coating (e = 0.04) on surface #3 was placed on the indoor side of the room to reduce heat transfer through long-wave radiation. The 24-mm thick insulating glass unit was specified with an argon gas fill. The window was modeled with a thermally-broken aluminum frame (conductance = 34.7 W/m^2-°K). Center-of-glass, solar-optical and thermal properties of the glazing layers and IGU were calculated using Window 6 [23] and are given in Table 1.

2.2. Properties of the reference windows

Three windows were defined for reference and to benchmark performance against other advanced commercially available window technologies.

For reference, a static dual-pane window was defined ("No TC") with properties of the TC window in its clear state. A dual-pane, spectrally selective, low-e window (Window "E") was defined with an outboard layer of low-iron, low-e glass (e=0.018) and an inboard layer of clear glass (system thickness: 24 mm). A three-layer, highly-insulating window (Window "F") was defined with a suspended film (e = 0.71) between two low-iron, low-e (e=0.018) glazing layers (system thickness: 37 mm). All IGUs had argon gas fill. The frame was the same as that used for the thermochromic windows. The makeup of the windows is given in Table 3. For reference, the ASHRAE 90.1-2010 prescriptive whole window values for maximum SHGC for Houston is 0.25 for window-to-exterior-wall-area ratios (WWR) between 0-0.40 and the maximum U-value is 4.26 W/m^2-°K. For Chicago, SHGCmax=0.40 and U-value = 3.12 W/m^2-°K. Windows E and F meet the required SHGC and maximum U-value for Chicago but only Window F meets the SHGC requirements for Houston (Window E just narrowly does not meet the requirements).

Table 3

Composition of the modeled windows used in the EnergyPlus simulations.

Window	Interior shade	Layer 1 (outdoor)	Gap	Layer 2	Gap	Layer 3
No TC	no	6 mm TC layer (clear state)	16 mm, 90% argon	6 mm low-e, e=0.04 on surface #3	-	-
TC 14-20*	no	6 mm TC layer (4 states)	16 mm, 90% argon	6 mm low-e, e=0.04 on surface #3	-	-
E1	no	6 mm low-e, spectrally selective coating on low-iron glass; e=0.018 on surface #2	12 mm, 90% argon	6 mm clear	-	-
E2	yes	same as E1	"	same as E1	-	-
F1	no	6 mm low-e, spectrally selective coating, on low-iron glass; e=0.018 on #2	12 mm, 90% argon	suspended film, e=0.711 on #3 & #4	12 mm, 90% argon	6 mm low-e, spectrally selective coating, on low-iron glass; e=0.018 on #5
F2	yes	same as F1	"	same as F1	"	same as F1

* Composition of the TC20-26, TC26-32, and TC32-28 windows are the same as TC14-20.

Windows E and F were modeled with and without an indoor, light gray (Rsol=0.75) fabric roller shade with an openness factor of 3% and Lambertian uniformly diffusing properties. The shade was operated according to three different control algorithms of which one represents a realistic scenario of a manually operated shade based on glare discomfort, the second represents an ideal automated shade based on glare discomfort and the third represents an automated shade based on glare and solar control. Solar optical properties for the unshaded E1 and F1 windows and shaded E2 and F2 windows are given in Table 4. Note that the unshaded reference windows had high luminous efficacies.

Table 4

Center of glass properties of thermochromic and reference windows.

	Interior shade	U-value [W/m^2-°K]	SHGC	Tvis	Ke (=Tvis/SHGC)
TC 14-20*	no	1.45	0.12-0.47	0.27-0.53	2.5 (tinted) to 1.13 (clear)
No TC	no	1.45	0.47	0.53	1.13
Window E1	no	1.35	0.30	0.64	2.13
Window E2	yes	1.18	0.17	0.09	0.53
Window F1	no	0.67	0.26	0.47	1.81
Window F2	yes	0.62	0.20	0.09	0.45

*Values for TC20-26, TC26-32, and TC32-28 are the same. Note: U-value and SHGC calculated according to NFRC 100-2004.

2.3. Description of the commercial office building prototype

EnergyPlus building energy simulations (version 7.0, [24]) were used to evaluate the performance of the various window systems in a prototypical office building. Building prototypes are often abstract, synthetic buildings, not real buildings, that have been developed for the purpose of being representative of a population of buildings of a given type; e.g., office, hospital, etc. Data are collected on real buildings and these data are used to formulate a statistical representation of building construction, systems, and operations [25]. The US Department of Energy (DOE) has invested in the development of such prototypes over the past few decades and has made the prototypes publicly available for use by the building industry in order to standardize methods for evaluating technical measures and policies and to develop energy efficiency codes [26]. The models were developed for use with EnergyPlus and are described in detail in [27] and are available at [28].

The large office prototype was defined as a 12-story, 48 m high building with a rectangular floor plate that is 73 m (north-south) by 49 m (east-west) (Figure 2). Perimeter zones were 4.57 m deep, with a 2.7 m ceiling height and a floor-to-floor height of 4 m. The perimeter zones were oriented in the four cardinal directions: due north, east, south, and west. The window-to-exterior-wall ratio was varied from 0 to 0.60 in order to quantify performance as a function of window area. Exterior walls were of mass wall construction. No exterior obstructions were modeled. Assumptions for the construction and operation of the building were compliant with the ASHRAE 90.1-2010 energy efficiency code [29].

The office prototype was defined with significant internal loads. Occupant density was 18.6 m^2 floor area per person or 5.6 W/m^2-floor. Occupancy was primarily between the hours of 9:00 to 17:00 on weekdays. Equipment loads were 13 W/m^2. Lighting loads were 9 W/m^2. When perimeter zones were modeled with daylighting controls, the ambient lighting was continuously dimmed from 20-100% light output with a corresponding power draw of 30-100% of full power. The lighting was dimmed to meet the setpoint illuminance level of 500 lux at a distance of 3 m from the window and 0.8 m above the floor.

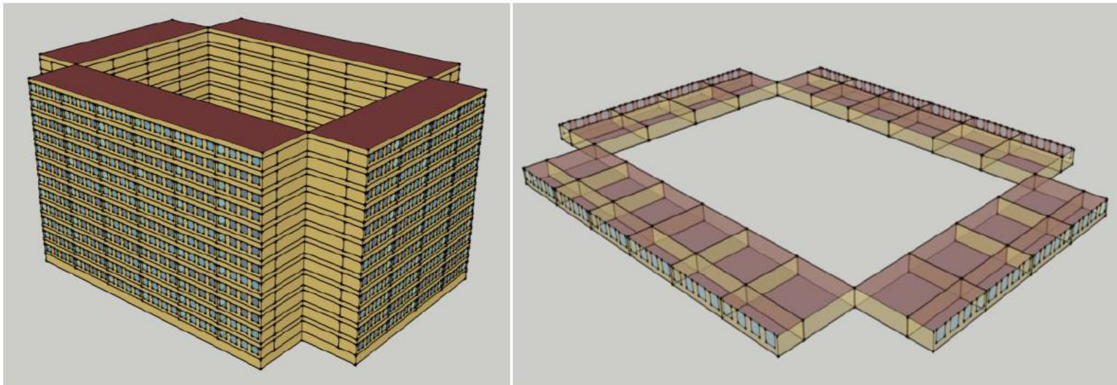

Fig. 2. Axonometric view of the large office commercial building prototype (left) and floor plan view of the perimeter zones (right).

The building was conditioned using a variable air volume (VAV) system with an air-side economizer (dry-bulb temperature controlled for Chicago and enthalpy controlled for Houston[4]). An air-side economizer uses cool outdoor air on cold, but sunny days to meet the cooling load. The main air handler units serve the different building levels (ground, mid-floors, and top floor) while the air terminal units control the air flow from the main air handler unit to the individual zones through dampers. In the original prototype model, the minimum air flow of the air terminal units was set to 30% of the maximum air flow. A few modifications were made in order to improve HVAC efficiency and make the system more responsive to changes in perimeter zone loads: the minimum air flow was reduced to 10% while the damper mode was set to reverse to guarantee sufficient air flow in the heating mode.

In order to determine cooling and heating energy use by window orientation, cooling energy use associated with the centralized HVAC system was disaggregated to the north, east, south, and west perimeter zones based on airflow of the air terminal unit to the individual zones. For heating, a decentralized system with 100% outdoor air was assumed and the disaggregation was based on reheat coil energy of the terminal units. The dead band for air temperature ranged from 21°C (setpoint temperature for heating) to 24°C (setpoint temperature for cooling) during occupied office hours.

To give the reader a sense of the relative magnitude of energy required by the various end uses for the whole building, Figures 3 and 4 show the breakdown of site and source energy for the large office prototype with the static reference window (“no TC”) and a window-to-wall ratio of 30% (no shades, no daylighting controls). The source or primary energy includes the added energy needed for transmission and distribution of energy from the utility. For natural gas, the site-to-source conversion factor is 1.1. For electricity, the conversion factor assumed for this study is 3.3. For this building type, lighting and HVAC (cooling, heating, fans and pumps) energy use are the two largest energy end uses in commercial office buildings, both of which are influenced by window and daylighting systems.

[4] The economizer will increase the outdoor air flow rate above the minimum outdoor air flow when there is a cooling load and the outdoor air temperature or enthalpy is below the zone exhaust air temperature or enthalpy.

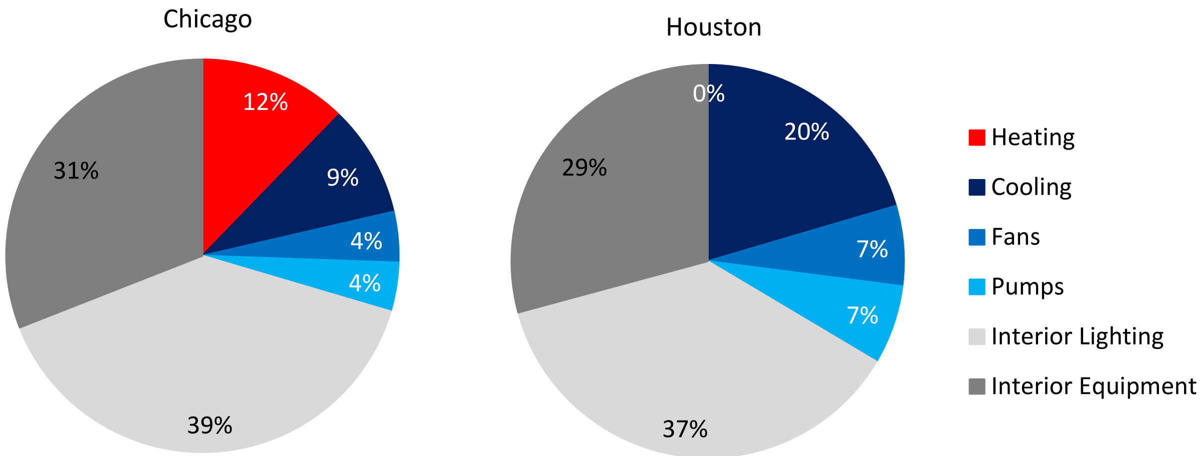

Fig. 3. Site energy for the large office building prototype with reference window ("No TC") and window-to-wall-area ratio of 0.30 (no daylighting control).

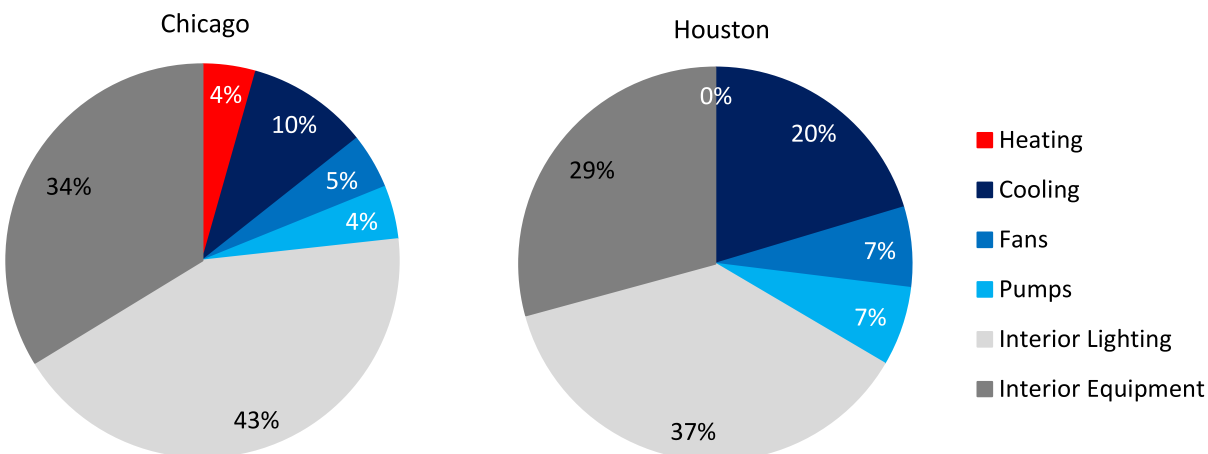

Fig. 4. Source energy for the large office building prototype with reference window ("No TC") and window-to-wall-area ratio of 0.30. Electricity site-to-source conversion factor was 3.3. Natural gas site-to-source conversion factor was 1.1 (no daylighting control).

3. Thermochromic behavior under different environmental conditions

For each time step, EnergyPlus determines the temperature of the thermochromic glazing layer using the temperature and properties of the glass from the previous time step as the initial value then solving the glazing layer heat balance given inputs of incident solar and long-wave radiation from outdoor and indoor sources, outdoor and indoor air temperature, wind speed, and convective heat transfer. The new glazing temperature is then used to determine the solar optical properties of the thermochromic layer, where values for Tsol, Tvis, etc. are selected from the four input states with the closest corresponding temperature (i.e., solar-optical data are not interpolated). These properties are then used to determine window heat gains (or losses) for the time step.

To characterize the switching behavior of the thermochromic under various weather conditions, we investigated a) which combination of outdoor environmental conditions caused the four different hypothetical thermochromic windows to switch to a partial or fully tinted state, b) what the corresponding temperature of the thermochromic glazing layer was when switched under different environmental conditions, and c) how window heat gain was affected by the different switching temperatures. This characterization enables one to understand how the inherent critical switching temperature of a prototype thermochromic material, which is typically measured under laboratory conditions in the early stages of development, is related to actual outdoor conditions to which the thermochromic glazing will be exposed.

3.1. Dry-bulb temperature and solar radiation

In a prior study [30], characterization of a polymer thermochromic window was conducted in an outdoor full-scale field test, showing strong correlation of switching response to outdoor air temperature and incident solar radiation. Similarly, for this study's hypothetical thermochromic windows, hourly temperature and radiation output data from EnergyPlus were plotted for all hours of the year when the thermochromic glazing layer was in a partial or fully tinted state, assuming a constant indoor air temperature of 21°C (Figure 5). (The temperature was kept constant throughout the year to eliminate the influence of the HVAC system and the indoor conditions.) Each datapoint represents a pair of outdoor temperature (y-axis) and incident vertical radiation (x-axis) when the temperature of the TC glazing layer was at or above the lower bound of the critical switching temperature range (e.g., TC temperature ≥14°C for window "TC 14-20"). Data for all four window orientations are given for the Chicago climate. Figure 5 shows the conditions when the TC window was partially tinted (blank squares) or fully tinted (black squares) out of a maximum number of possible annual hours for the four orientations (4 x 8760 = 35,040 hourly values maximum). For example, the window TC 14-20 was tinted 15227 hours of the year (43%), and fully tinted for 9953 hours of the year (28%). For the window TC 32-38, the window was tinted 907 hours of the year (2.6%) and fully tinted for 472 hours of the year (1.3%).

Note that for the TC window with the lowest critical switching temperature range (TC 14-20) most cases of tinting occurred when the outdoor air temperature was above the lower limit of the switching range (14°C) as to be expected. However, there were occurrences when the TC tinted with outdoor air temperatures well below the switching range because of high levels of incident solar radiation. These cases occurred on cold, sunny winter days – for example, switching occurred between 0-5°C with incident solar radiation levels between 600-900 W/m^2.

The TC window with the highest critical switching temperature range (TC 32-38) was tinted less frequently and at outdoor air temperatures that were predominantly below the lower limit of the switching range of 32°C. There were relatively few hours of the year when the outdoor air temperature exceeded 32°C so when incident solar radiation levels were sufficient to raise the glass temperature above ambient air temperature levels, the window tinted.

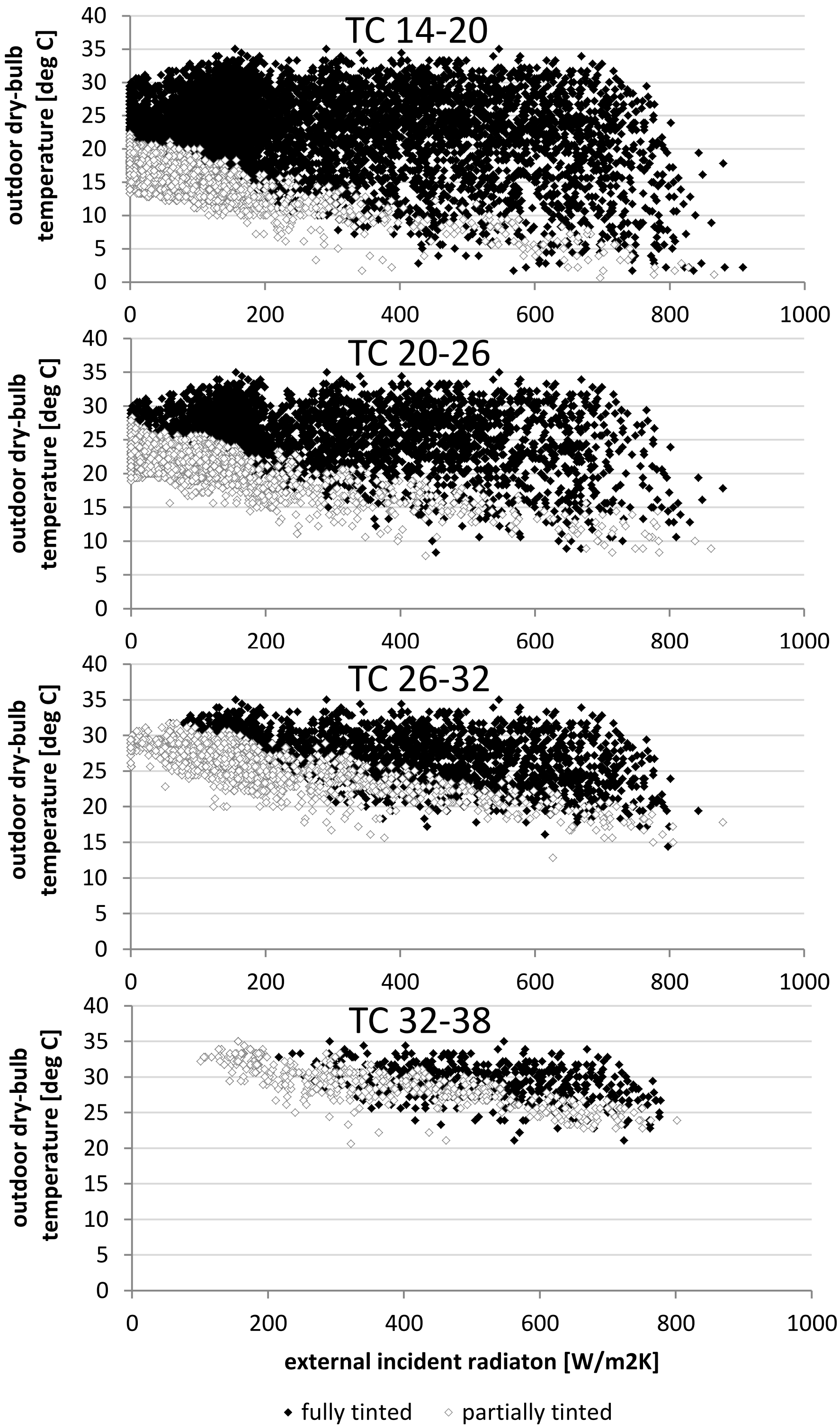

Fig. 5. Outdoor incident vertical irradiation (W/m^2) and dry-bulb temperature (°C) that resulted in partial or full tinting of the four hypothetical thermochromic window types defined by different critical switching temperature ranges. The bold squares show the hours when the window was fully tinted, and the blank squares show the hours when the window was partially tinted out of a total of 35,040 hours (annual run for four orientations). Indoor air temperature was 21°C. Data were produced by EnergyPlus simulations for the Chicago climate. All window orientations.

3.2. Temperature of the thermochromic layer and window heat gain

The same data set was used to characterize how outdoor environmental conditions determined thermochromic glass temperature, T_g, when partially or fully tinted. Associated window heat gains, Q_{window} , were in contrast correlated to the fully tinted state only because of the significant scatter of window heat gain when the TC window is only partially tinted. Linear regressions were used to correlate the data. Including wind speed in the correlation did not improve the fit. Regression coefficients and statistics for the fit are given in Tables 5 and 6. Actual and predicted values are shown in Figure 6 and Figure 7.

$$T_g\ (°C) = a + b\ I_v + c\ T_o \quad (1)$$

$$Q_{window}\ (W/m^2\text{-glass}) = d + e\ I_v + f\ T_o \quad (2)$$

where,
I_v = outdoor incident vertical radiation (W/m^2)
T_o = outdoor dry-bulb air temperature (°C)

For the plots of TC temperature T_g in Figure 6, the y-intercept was set to the lower limit of the critical switching temperature range for each of the four types of TC windows. With incident solar radiation, all of the four TC windows reached glass temperatures of up to 55°C for this Chicago climate. The correlation for the window TC 32-38 was poorer (r^2=0.52) than that for window TC 14-20 (r^2=0.97) due to the scatter below the main linear cluster of datapoints defining TC temperature when fully tinted and the lower total number of data points.

Table 5

Coefficients and statistics for the multiple linear regression predicting temperature of the TC layer, T_g (Eqn. 1).

	TC 14-20	TC 20-26	TC 26-32	TC 32-38
a [°C]	-0.106	-1.912	-6.595	-10.615
b [°C-m^2/W]	0.033	0.032	0.033	0.029
c [-]	0.963	1.028	1.160	1.265
R^2	0.97	0.94	0.84	0.52
σ_y [°C]	1.47	1.85	2.64	4.03

Table 6

Coefficients and statistics of the multiple linear regression for window heat gain with the TC window fully tinted (Eqn. 2)

	TC 14-20	TC 20-26	TC 26-32	TC 32-38
d [W/m^2]	-10.612	4.076	39.596	55.476
e [-]	0.147	0.148	0.148	0.176
f [W/m^2-°C]	0.512	0.017	-1.074	-1.691
R^2	0.91	0.84	0.69	0.38
σ_y [W/m^2]	8.69	12.73	20.36	31.48

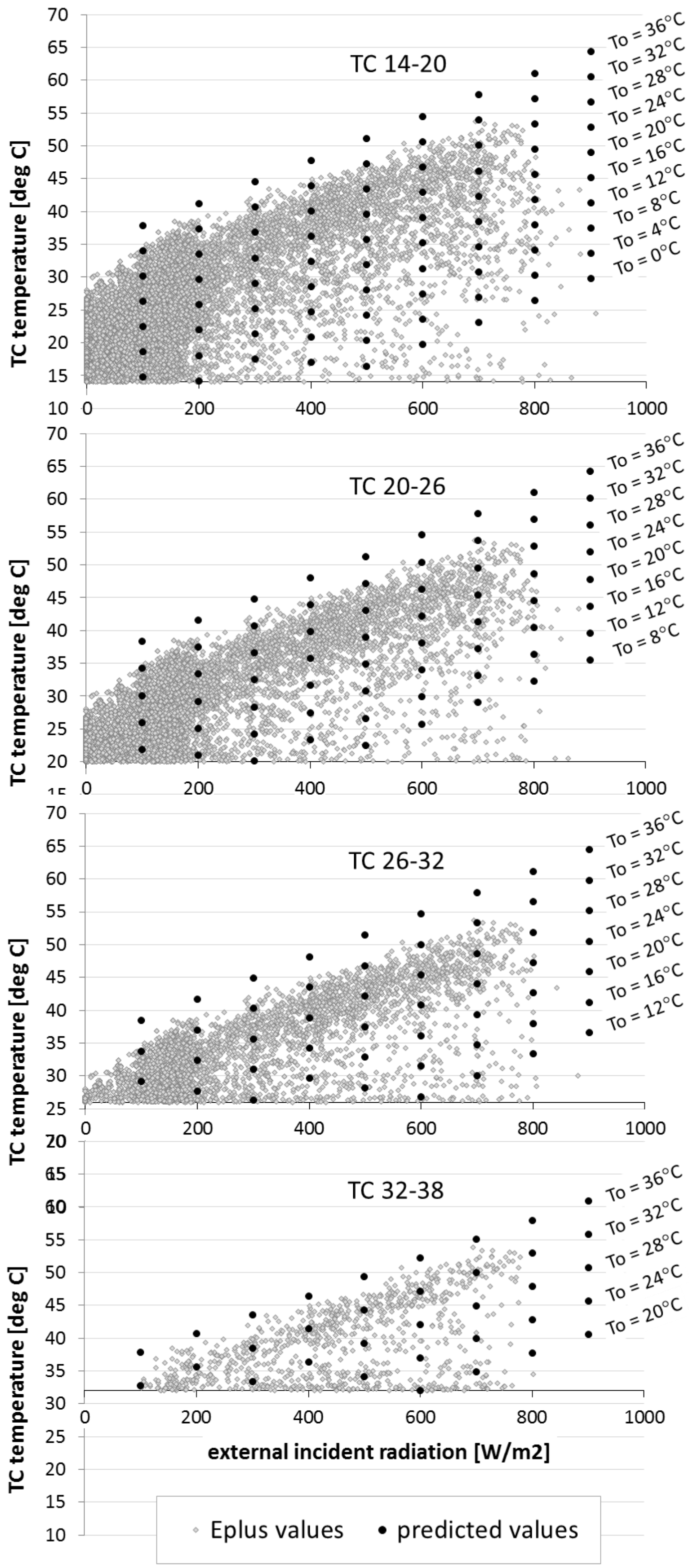

Fig. 6. Thermochromic glazing layer temperature (°C) versus incident radiation for hours when the thermochromic was in a partial or fully tinted state. Predicted TC glazing temperature values from linear regression (Equ. 1) are shown separately. EnergyPlus data are given for the four hypothetical thermochromic windows for the Chicago climate. All window orientations.

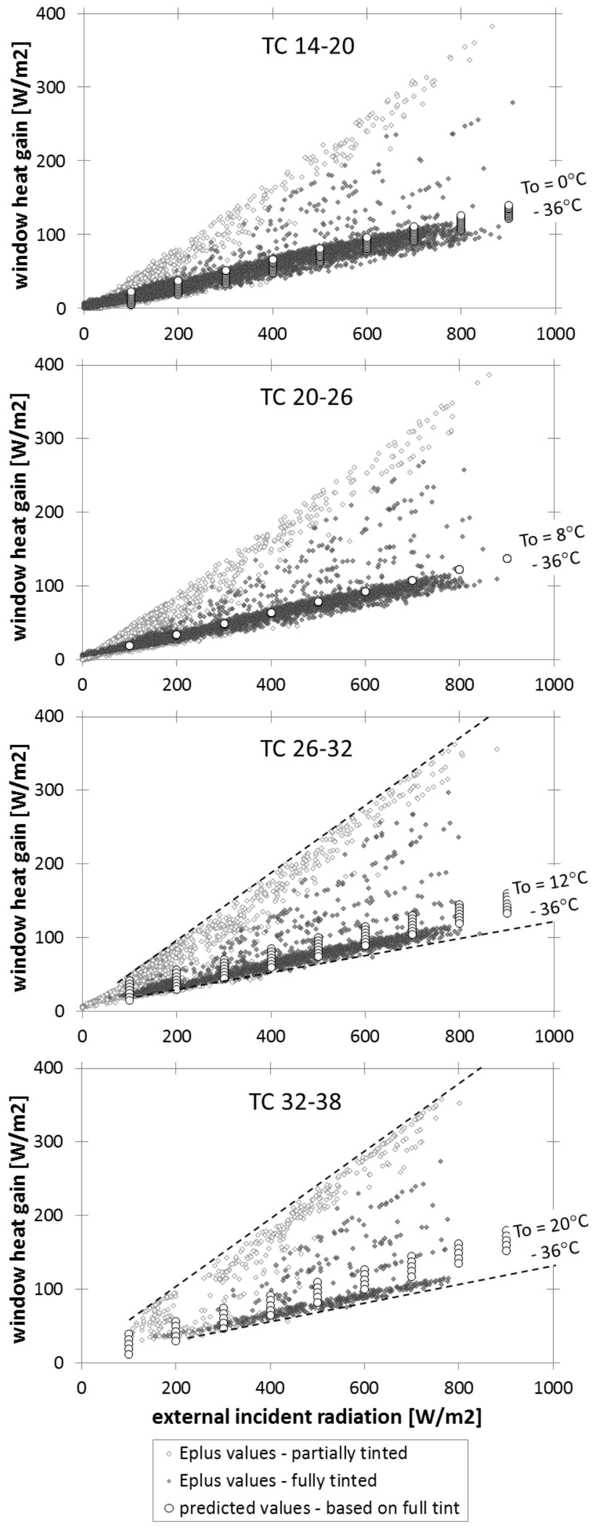

Fig. 7. Window heat gain (W/m^2) versus incident radiation for hours when the thermochromic was in the fully tinted state. Predicted values for window heat gain from linear regression (Equ. 2) are shown separately. EnergyPlus data are given for the four hypothetical thermochromic windows for the Chicago climate. All window orientations.

The window heat gain shown in Figure 7 is the heat balance of solar radiation, convective, conductive, and long-wave radiation heat transfer assuming a constant indoor air temperature. Heat gains or losses due to long-wave radiation between the indoor glass surface and room surfaces were also accounted for. Window heat gain is predominantly due to solar radiation and less to conduction which explains the low significance of outdoor temperature in the regression (with T_O not being significant for TC 20-26).

The slope of the dashed lines in Figure 7 that define the range of window heat gains for a partially or fully tinted TC window represent the minimum and maximum value of a nominal solar heat gain coefficient SHGC'. SHGC' can be obtained by dividing the value for window heat gain in W/m^2 (y-axis) by the incident radiation in W/m^2 (x-axis). For TC 14-20, the minimum value equals SHGC' = 0.11 (fully tinted state) and the maximum value equals SHGC' = 0.44 (clear state). These values increase slightly with increased switching temperature as the conductive window heat gains become a larger percentage of the total.

Note how the range of window heat gains are about the same between the four types of TC windows, but the distribution of hourly data differ amongst the types. For the TC window with the lowest critical switching temperature range (TC 14-20), most hourly data are below 100 W/m^2 since the TC window switched to a fully tinted state at the least provocation. For the TC window with higher switching temperatures (TC 32-38, e.g.), full tinting occurred much less frequently so the associated window heat gains were more broadly scattered across the 0-350 W/m^2 range.

Figure 8 shows that low switching temperatures such as TC 14-20 can reduce the window heat gain by half during the period from May to September which represents the main cooling period in Chicago. During the cold winter months when solar heat gain might be sometimes desired to offset heating requirements, and when cooling can be efficiently provided through outdoor air, the reduction of solar gain caused by thermochromic switching is less frequent. When comparing the TC 14-20 to an identical static window with the TC in its clear state ("no TC") in Figure 8, the benefit of thermochromic switching at low switching temperatures becomes even more obvious, considering that a static window would require a lower SHGC than 0.44 to minimize cooling load in summer, thus providing less solar heat gains during the heating period.

Figure 8 shows also how important a low switching temperature for peak load is; e.g., TC 26-32 can reduce window heat gain for a significant number of hours, but it does not reduce the peak load, and TC 32-38 has very little effect on the reduction of window heat gain in summer due to the small percentage of time that it is triggered to switch.

Lowering peak window heat gains during the cooling period can translate to lower capital and operating costs and greater operational efficiency if the HVAC capacity can be downsized and if peak electric demand can be curtailed during periods when the utility grid is stressed. As a benchmark for performance, low-energy cooling strategies (e.g., radiant cooling, natural ventilation) can be used if peak cooling loads within a 5-6 m deep perimeter zone are less than about 43 W/m^2-floor. Assuming a moderate-area window (WWR=0.30), peak window heat gains would need to be below 112-206 W/m^2-window to meet this target level.

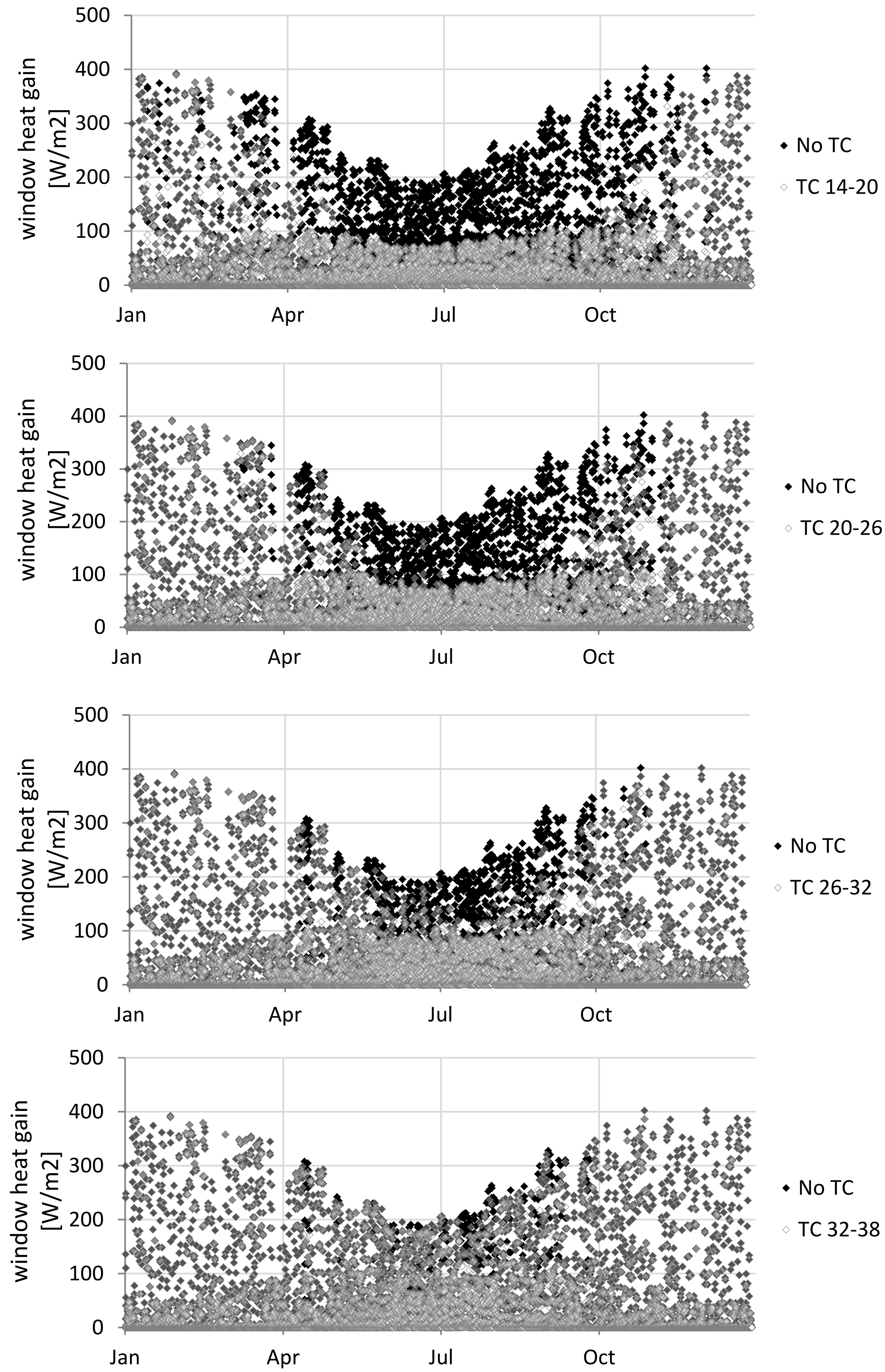

Fig. 8. Window heat gain (W/m^2) of the thermochromic window (grey squares) compared to the reference window "No TC" (black squares). Hourly values for the Chicago climate over the course of the year, all orientations, indoor air temperature of 21°C.

4. Window heat gain/loss and zone heating/cooling load

4.1. Window heat gain/ loss

Figure 9 shows total annual window heat gains and losses per unit window area for west orientation and by climate assuming a fixed indoor temperature of 21°C. (The temperature was kept constant throughout the year to eliminate the influence of the HVAC system and the indoor conditions.) The heat loss through the window is due mainly to conductive and convective effects in the absence of solar radiation and is therefore not significantly affected by the thermochromic layer. Total window heat losses are nearly constant for the reference window and four TC window types, as well as for the different orientations. Total window heat gains decrease with critical switching temperature range as the TC window switches to a tinted state more frequently.

Window heat gain and heat loss can be either beneficial or detrimental to the perimeter zone heat balance and energy consumption of the zone. The ideal thermochromic window would limit solar heat gains when the perimeter zone was in a cooling mode and admit solar heat gains when the zone was in a heating mode.

The zone heating or cooling mode is determined by the *zone net heat flow* due to heat gains or losses through the building envelope and internal loads from occupants, lighting, and equipment, in this case assuming a fixed indoor air temperature. If the zone net heat flow is zero, then heating or cooling provided by the HVAC system is not required to maintain comfort conditions in the zone, only ventilation is needed to meet the fresh air requirements. This is the overall goal of passive architectural design: optimal control of envelope loads to achieve net-zero building energy performance.

Hourly window heat gains and losses were binned according to the zone heating or cooling mode. For example, if the hourly window heat gain occurred when the perimeter zone was in a heating mode, then the window heat gain was added to the annual total. These data are summarized in Table 7 for the west perimeter zone. Note that the sum of the window heat gains or losses in this table corresponds to the totals depicted in Figure 9. (Additional results are given in Appendix A.) Note also how the different critical switching temperature ranges produce significant differences in the detrimental “window heat gains while cooling” compared to any of the other binned totals. Window heat losses again are not affected by the TC layer and so varied insignificantly across the four TC window types. Beneficial window heat gains while in the heating mode were largely offset by the detrimental heat gains while in the cooling mode. The TC system with the lowest switching temperature range produced the lowest net window heat gains given the internal load dominated profile of this west-facing perimeter zone in Chicago. Similar trends were observed for the other orientations and for the Houston climate and can be found in Appendix A.

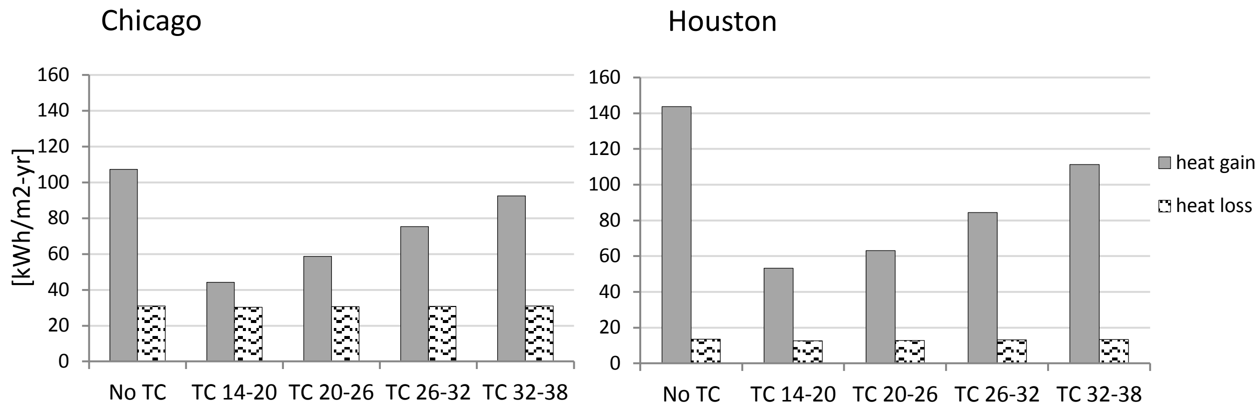

Fig. 9. Annual accumulated window heat gain and heat loss (kWh/m^2-floor-yr) of the TC windows and the reference window "No TC" for west orientation in the Chicago and Houston climates. Indoor air temperature of 21°C.

Table 7

Accumulated annual window heat gain and heat loss (kWh/m^2-window) when in zone heating or cooling mode for a west-facing perimeter zone with a large-area window (WWR=0.60) in Chicago (fixed setpoint temperature of 21°C).

	window heat gain while heating G H + kWh/m^2-yr	window heat gain while cooling G C - kWh/m^2-yr	window heat loss while heating L H - kWh/m^2-yr	window heat loss while cooling L C + kWh/m^2-yr
No TC	1.67	328.5	54.7	28.4
TC 14-20	1.68	152.1	56.4	25.8
TC 20-26	1.68	187.8	55.4	27.1
TC 26-32	1.64	233.7	54.9	27.8
TC 32-38	1.64	285.3	54.8	28.2

Note: G: window heat gain, L: window heat loss; H: heating; C: cooling; + heat gains or losses reduces energy use; - heat gains or losses increases energy use.

4.2. Impact on perimeter zone heating and cooling load

The *zone net heat flow* quantity defined in Section 4.1 is also designated as *perimeter zone sensible heating and cooling energy* in EnergyPlus. This quantity is shown in Figure 10 as the annual accumulated load per unit floor area for the 4.57-m-deep perimeter zone. The two different columns in Figure 10 are associated with two different assumptions regarding the heating and cooling setpoint: The first stacked column for each window type (e.g., "No TC") is the heating and cooling load for a constant indoor temperature of 21°C (comparable to Figure 9). The second stacked column is the heating and cooling load for a more realistic setpoint temperature schedule, where the setpoint had a deadband range of 21-24°C and reduced levels for unoccupied weekday and weekend hours (base case for HVAC energy use in Section 5).

The large reductions in window heat gains do not necessarily result in the same percentage decrease in annual load. For example, window heat gain reductions for the west-facing perimeter zone in Chicago were 70 kWh/m^2-floor or 53% (TC 14-20 versus "No TC" in Figure 9) and produced a reduction of 73 kWh/m^2-floor or 30% in total zone heating and cooling loads for a large-area window (WWR=0.60, Figure 10, first stacked column for each window type).

The second stacked column for each window type in Figure 10 shows that the heating load becomes nearly insignificant when applying a realistic heating and cooling setpoint schedule while cooling load is reduced by 20-35% on average. Most of the HVAC energy use (see Section 5) is therefore needed to offset cooling loads.

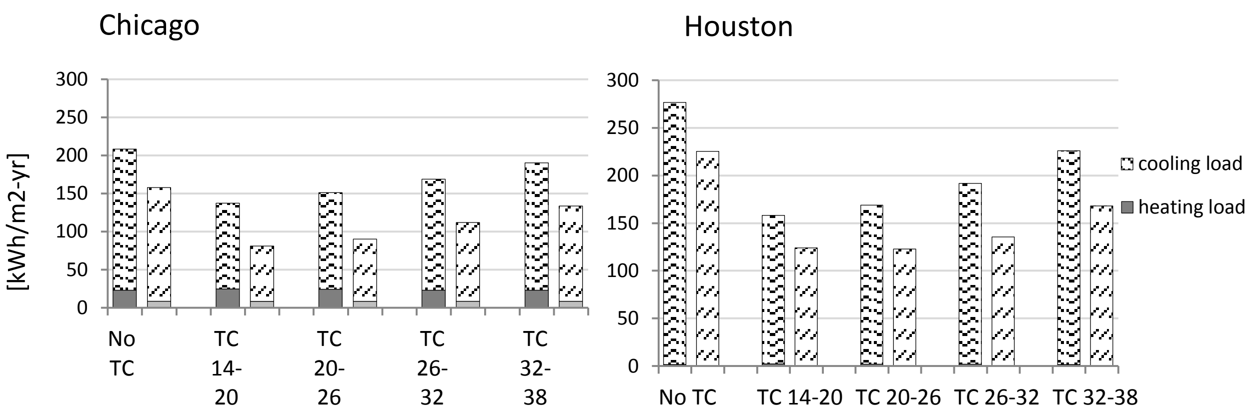

Fig. 10. Annual accumulated cooling and heating load (kWh/m^2-floor-yr) of the TC windows and the reference window "No TC" for west orientation in Chicago and Houston climate (window-to-wall ratio: 60 %). The first lefthand stacked column shown per window type are loads calculated with a constant setpoint temperature of 21°C. The second righthand stacked column are loads calculated with the HVAC setpoint temperature schedule: weekday deadband of 21-24°C; nights and weekend setback.

5. HVAC energy for perimeter zones

Heating and cooling energy use are also not necessarily proportional to the magnitude of the loads in the perimeter zones. Details of how the HVAC components are sized, how the system is operated, how outside air is handled for ventilation and to offset cooling requirements during the winter, for example, all contribute to the sensitivity of the HVAC system to the cooling and heating demands in the zone. For systems that are oversized or handle outdoor air ventilation requirements inefficiently, for example, significant differences in zone thermal loads may not result in significant differences in HVAC energy use. As distributed low-energy cooling and heating strategies start to replace centralized systems, energy use (or occupant comfort, in the minimization of space conditioning) will become more sensitive to perimeter zone loads.

Annual site cooling electricity use and natural gas use intensity data for the west orientation are given as a function of window-to-wall ratio in Figures 11-12. (Data for other orientations can be found in Appendix B.) Cooling energy includes electricity consumed by the chiller, cooling tower fan, condenser water pump, and chilled water pump. The gas heated hot water boiler serves the reheat coils, and therefore gas consumption of the boiler and electricity consumed by the hot water pump apply to actual heating as well as to reheat while in the cooling mode. Fan energy is not included since it is not separated by cooling or heating mode in EnergyPlus and so cannot be assigned to either end use. The minimum outdoor air (OAmin) requirement was set to 3.72 $m^3/(hr\text{-}m^2\text{-floor})$.

Results are intuitive for cooling (Figure 11). Energy use increases as window area increases and the relative ranking of the thermochromic windows is the same as the ranking defined in the perimeter zone loads analysis in Section 4.2. The slope of the line is an indicator of how often the thermochromic window is switched to the tinted state. The lower critical switching temperature ranges result in the greatest number of hours with the TC window being in the tinted state, and therefore the least cooling load. The absolute improvement of the thermochromic performance that can be achieved through lowering the switching temperature decreases with lower switching temperature.

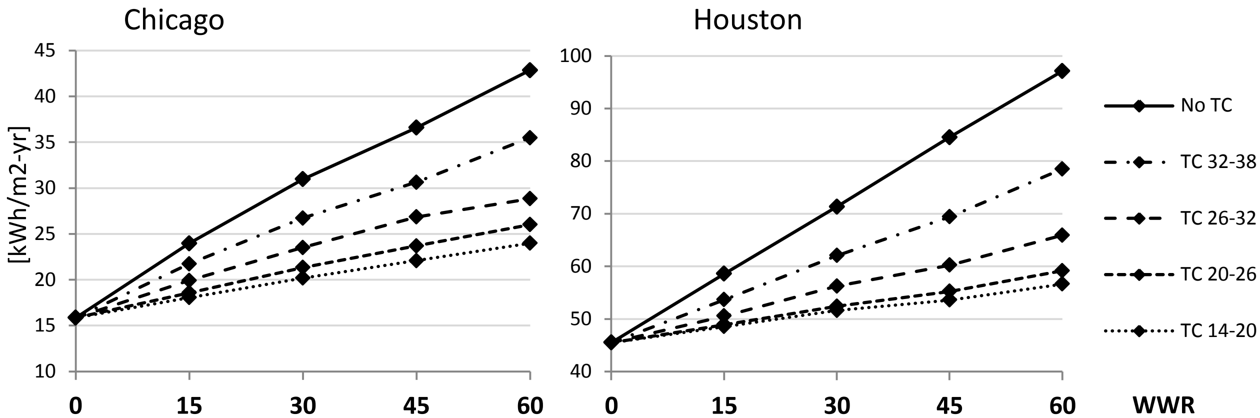

Fig. 11. Annual site cooling energy use intensity (kWh/m^2-floor-yr) for the reference window "No TC" and four thermochromic windows as a function of window-to-wall-area (WWR) ratio for the west orientation in Chicago and Houston climates.

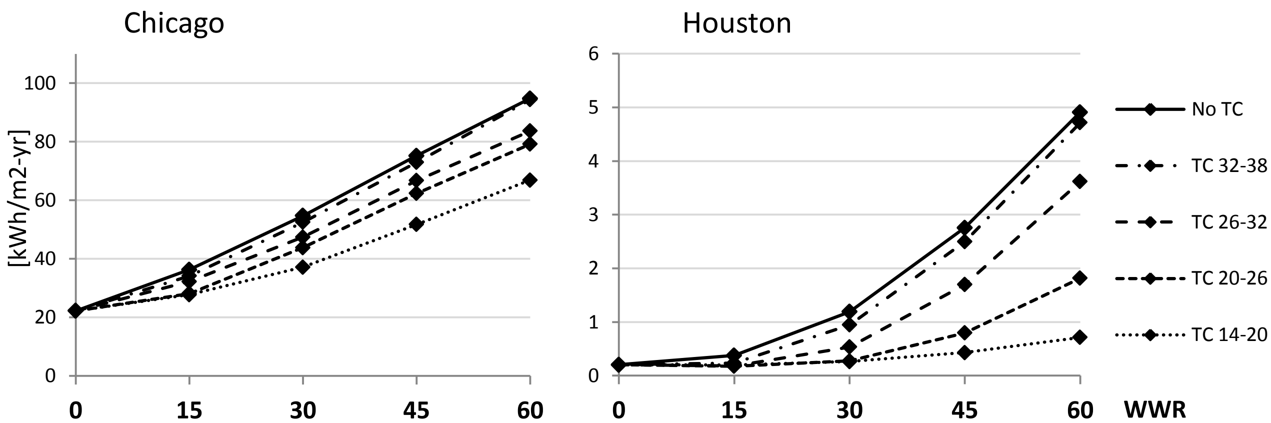

Fig. 12. Annual site natural gas use intensity (kWh/m^2-floor-yr) used for heating and reheat for the reference window "No TC" and four thermochromic windows as a function of window-to-wall-area (WWR) ratio for the west orientation in Chicago and Houston climates.

Natural gas use increases as window area increases as well (Figure 12). Natural gas use is also significantly greater than cooling energy use (per unit energy) in Chicago, although heating loads are only a small fraction of cooling loads in the perimeter zones (Figure 10).

To explain these trends, we need to give details of the sizing of the HVAC system. Peak loads determine the size of the VAV system, including the air handler units, ducts, fans, and reheat coils. Peak cooling is on average around three times greater than the peak load for heating in Chicago climate. In consequence, cooling demand determines the size of the VAV system. The greater cooling load leads to a greater maximum and minimum air flow which then requires a larger capacity reheat coil. The reheat coils in our model serve the purpose of raising the temperature of delivered air to an acceptable supply temperature in all three cases: 1) to offset heating load on cool days, 2) when cooling is required and supply air is too cold due to economizer mode (more outdoor air than OAmin is used), and 3) when the system is run at minimum air flow (OAmin + return air) because the room temperature is in the deadband between the heating setpoint (21°C) and cooling setpoint (24°C).

Therefore natural gas use for reheat/heating energy is greater on the *south* façade due to higher cooling loads than on the *north* façade which has greater heat losses but less demand for cooling. This also explains the relative ranking of TC windows even though the zone heating load is the same between the four TC window types (Figure 10). The "No TC" window with the greatest solar transmission shows the greatest reheat/heating energy use and TC 14-20 uses about two-thirds of that energy for the large-area west-facing window, WWR=0.60.

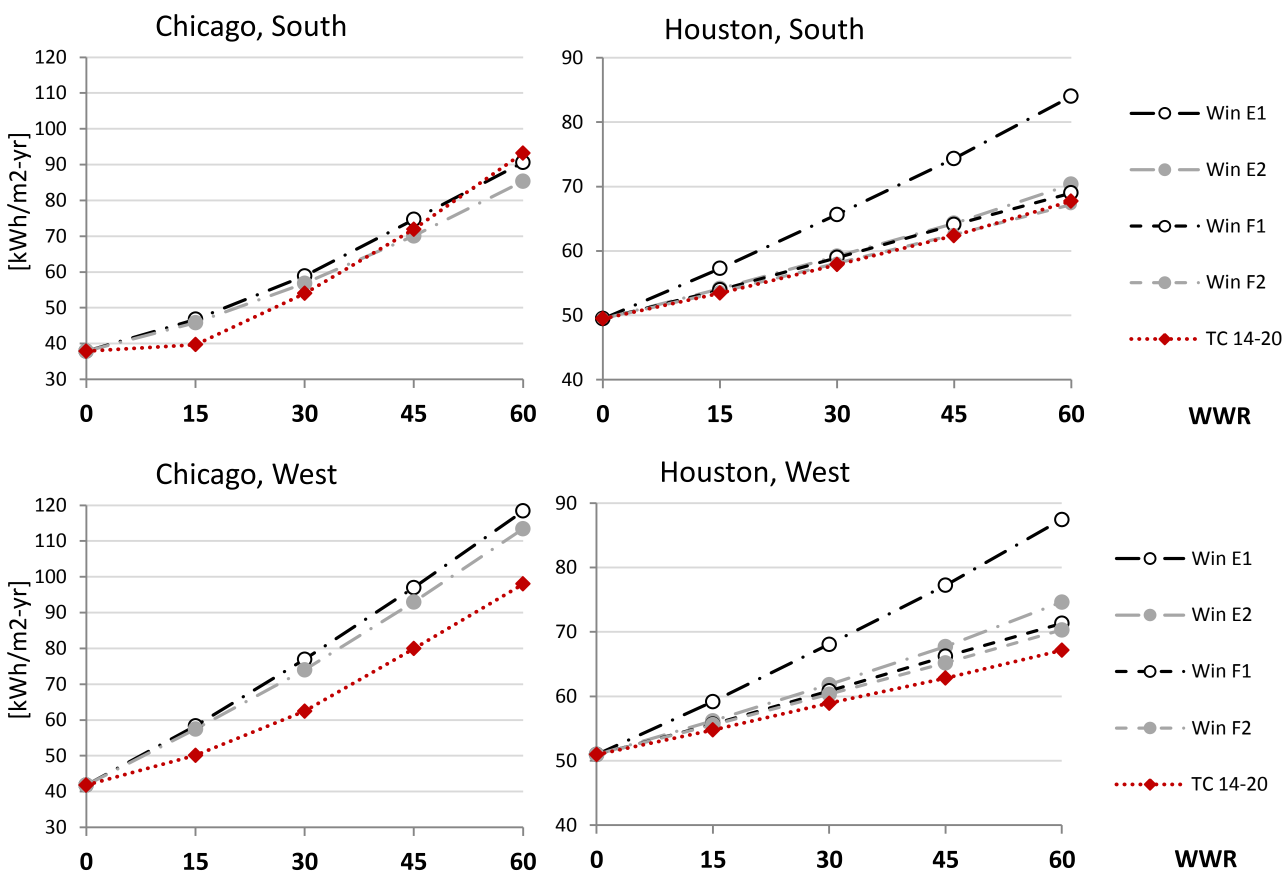

Fig. 13. Annual site energy use intensity (kWh/m^2-floor-yr) for heating, cooling, and ventilation for the hypothetical thermochromic window with a critical switching temperature range of 14-20°C (TC 14-20), the near-IR low-e window without (E1) and with (E2) an indoor gray roller shade, and a highly-insulating window without (F1) and with (F2) and indoor shade. EnergyPlus data are given as a function of window-to-wall-area (WWR) ratio for south and west facing perimeter zones in the Chicago and Houston climates.

The combined annual site heating, cooling, and fan energy use data are given in Figure 13 for window TC 14-20 for south and west orientation and benchmarked against the two static low-e and highly-insulating windows with and without interior shades. In Chicago, the highly insulating window (F1, F2) performs best for all orientations with WWR > 0.30 because of the higher thermal resistance, which is beneficial during both the hot summer and cold winter seasons. On the south façade, the TC 14-20 window achieves comparable performance to F1 and F2 when the window area is small (WWR=0.15) but for larger-area windows, its performance is comparable to the spectrally-selective low-e window (E1, E2). On the west façade with the highest solar load, the thermochromic window is preferable over the low-e window, but is outperformed by the highly insulating window.

For the hot and humid climate in Houston, the TC14-20 window reduces annual HVAC energy use significantly, outperforming even the highly insulating window with interior shade (F2) on both the west and south façades.

6. Optimizing HVAC and lighting energy use with daylighting controls

(All results shown in this chapter are based on the HVAC system providing a room temperature between heating setpoint (21°C) and cooling setpoint (24°C) during occupied office hours throughout the year.)

6.1. Comparison between thermochromic windows with different critical switching temperature ranges

Daylight can significantly reduce the lighting related energy use intensity in the perimeter zone. Without daylighting controls, the annual site lighting energy use intensity in the perimeter zones irrespective of climate, window area, or window orientation was 59 kWh/m^2-floor-yr. Reductions in lighting energy use due to varying occupancy and scheduling control strategies as required by ASHRAE 90.1-2010 are included in this value. This energy use can be further reduced by more than a third with daylight controls if the reference window ("No TC", Tvis=0.53) is used. These savings (average by area over the four main orientations with N/S:E/W = 4:3) are shown a for small and a big window-to-wall ratio as the most lefthand purple columns in Figure 14. The four thermochromic window types switch at varying degrees of frequency, depending on the critical switching temperature range, and therefore reduce availability of daylight (Tvis = 0.53-0.27) compared to the "No TC" window. This negative impact on daylight use is shown in Figure 14 as red, negative columns.

Site HVAC energy is also influenced by reduced lighting energy: less artificial lighting in summer reduces the cooling load, but electric light covers part of the heating load as a significant portion of lighting energy is transformed into heat. The savings of HVAC energy compared to the "No TC" window are shown as green, positive columns. The net total annual energy savings is the sum of the green and red columns.

With small windows (WWR=0.15) the negative impact of thermochromic switching on lighting energy use is significant but the net annual energy saving is still positive for all TC windows in Chicago and Houston.

With moderate- to large-area windows, the window TC 14-20 delivers the maximum net energy savings due to both reduced HVAC loads and adequate levels of daylight. Note that in this analysis, site energy use is used, assuming a 1:1 weighting of natural gas and electricity and ignoring the difference in energy cost and added source energy needed to transport and distribute the energy to the building site. Discomfort glare was not assessed so the lighting energy savings reflect relative differences in daylight availability.

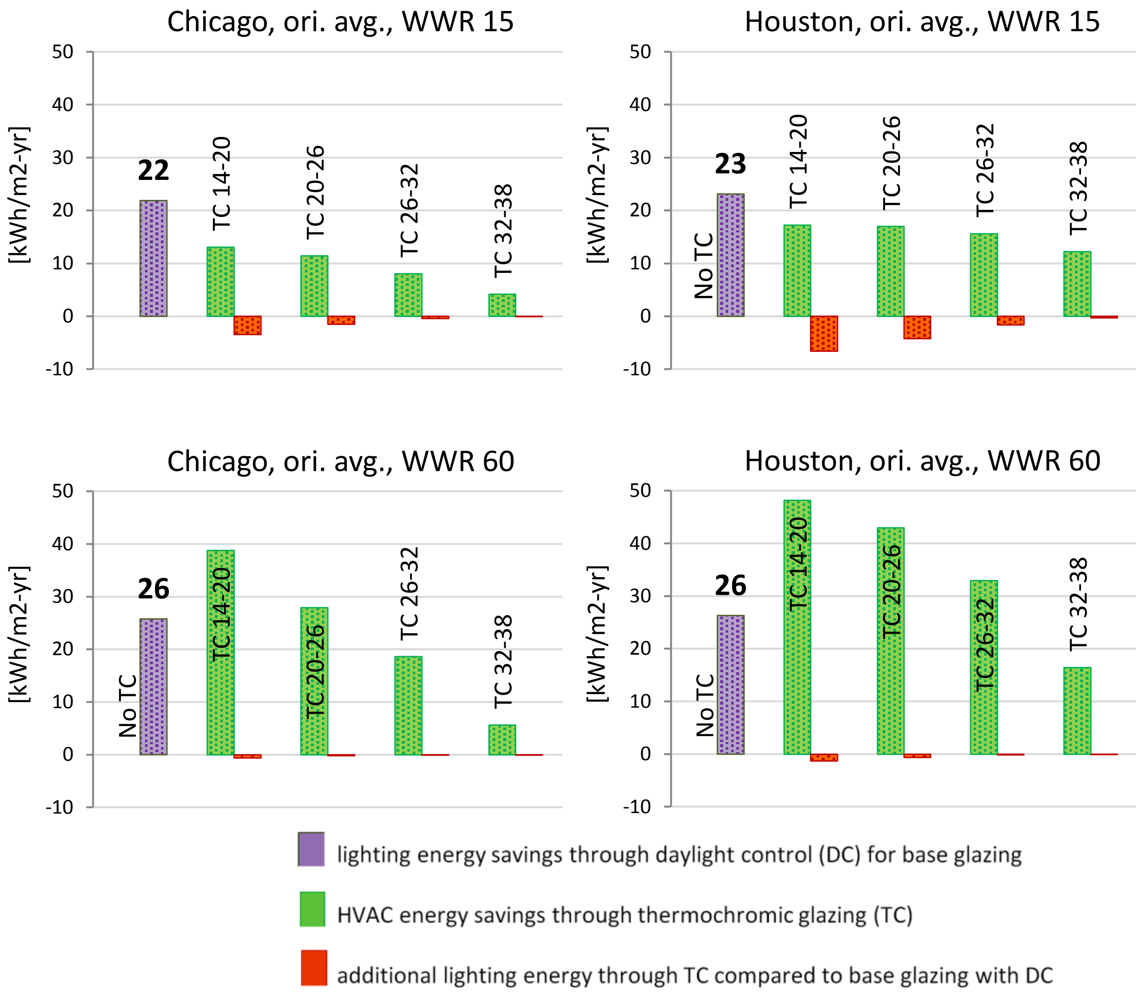

Fig. 14. Annual site lighting and HVAC energy use intensity savings (kWh/m^2-floor-yr) for the reference window "No TC" and four thermochromic windows with daylighting controls. Data for all orientations are averaged by zone floor area of the large office prototype (N/S:W/E = 4:3). Purple: Lighting energy savings of the "No TC" window with daylighting controls compared to the same window without controls. Red: Negative lighting energy savings of the four types of thermochromic windows compared to the "No TC" window. Green: Positive HVAC energy savings compared to the "No TC" window.

6.2. Comparison of thermochromic windows with static near-IR selective, low-e windows

A similar comparison is made with the static, near-IR selective, low-e windows with and without interior shades. The reference case is now the TC 14-20 window with daylighting controls, with site HVAC and lighting energy use of windows E and F shown relative to this reference case. The gray columns show the site annual HVAC energy savings relative to the TC 14-20 window, where positive values indicate that the static window performs better than the thermochromic window. The dark purple columns show annual lighting energy savings compared to the TC 14-20 window, both cases with daylighting controls. The red or green columns show the net annual energy savings of the HVAC and lighting combined compared to the TC14-20 window with daylighting controls (red is less energy savings, green is more savings than TC 14-20). The values are averaged over all orientations according to the building layout. See Appendix C for the detailed data.

One potential benefit of thermochromic glazing in addition to solar control is a reduction of the number of hours during which glare discomfort occurs in the work space. Therefore the windows E and F were modeled, in addition to the case without any interior shade, with an interior shade to reduce glare based on annual glare calculations. Radiance simulations were used to determine the Discomfort Glare Probability (DGP) as hourly values for the nine viewpoints shown in Figure 15. A DGP value greater than 0.38 for any of the viewpoints was considered to provide uncomfortable conditions which would lead to the interior shade being lowered. Table 8 shows the total number of hours (including weekends and holidays) with glare discomfort for an open office space with a transparent area of 60 % window-to-wall ratio.

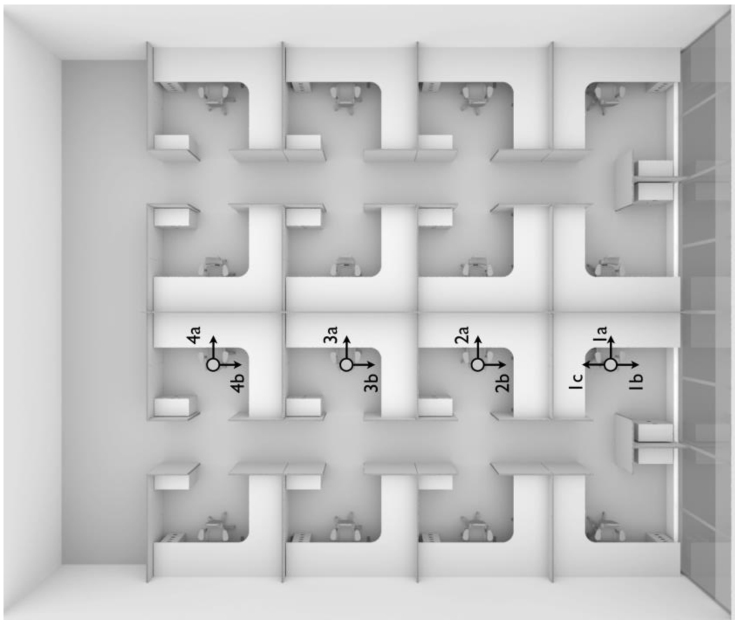

Fig. 15. Viewpoints in an open office space similar to the modeled large office prototype. For each of these viewpoints a Radiance simulation determined the Discomfort Glare Probability for every hour of the year.

Table 8

Number of hours per orientation with a Discomfort Glare Probility value > 0.38 for any of the viewpoints for the open office space (Fig. 15) with a window-to-wall ratio of 60 %.

	East	North	South	West
Window E1	3581	3234	3480	3550
Window F1	1691	286	2186	1754
TC, dark state	1049	11	1015	1158

While very useful to eliminate glare conditions, interior shades are not as efficient for solar control compared to measures that block solar radiation before it enters the room. Despite its limited efficiency to reduce cooling loads, the use of the interior shade as additional solar control was considered as well. For simulation purposes an ideal control was assumed that lowered the shade when window heat gains were greater than 35 W/m^2-floor-area during cooling conditions.

The following control algorithms were used for different scenarios of shade operation:

- “no shade”: shade always up, no control
- “manual glare control”: At the occurrence of glare discomfort, the shade is lowered and remains lowered for the rest of the day until the next morning at 5 am. This is considered a realistic scenario.
- “automated glare control”: The shade is only lowered during hours with glare discomfort and raised again as soon as there is no more glare discomfort according to the defined glare condition (DGP > 0.38). This scenario corresponds to an ideal control.
- “automated glare and solar control”: In addition to the automated glare control the shade is also lowered when the window heat gain is greater than 35 W/m^2-floor-area and there is a cooling load in the room.

In Chicago (Fig. 16A), the greatest net energy savings for all orientations and all window-to-wall ratios are obtained with window F (highly-insulating window) with no interior shade (with daylighting controls). HVAC energy savings of the highly-insulating window F without interior shade are significant while the lighting energy is similar to a window with TC 14-20, both with daylighting control. When an interior shade is used, window E leads to higher energy usage than TC14-20 in lighting energy and HVAC energy. In the case of window E without interior shade, lighting energy is only slightly less than the thermochromic window and HVAC energy is significantly greater.

If indoor roller shades are used to control glare manually, then window F still performs better than the thermochromic window for larger window areas, but for small windows the reduction of usable daylight through the shade outweighs the benefits of the better insulating value. If the interior shade is only lowered during hours with actual glare conditions and raised when there is no more glare discomfort, the negative impact of the reduced daylight availability is little compared to the case without shade at all.
There is no benefit of additional solar control for either window E or window F: solar control conditions are less frequent than glare conditions, and high window heat gains often coincide with glare.

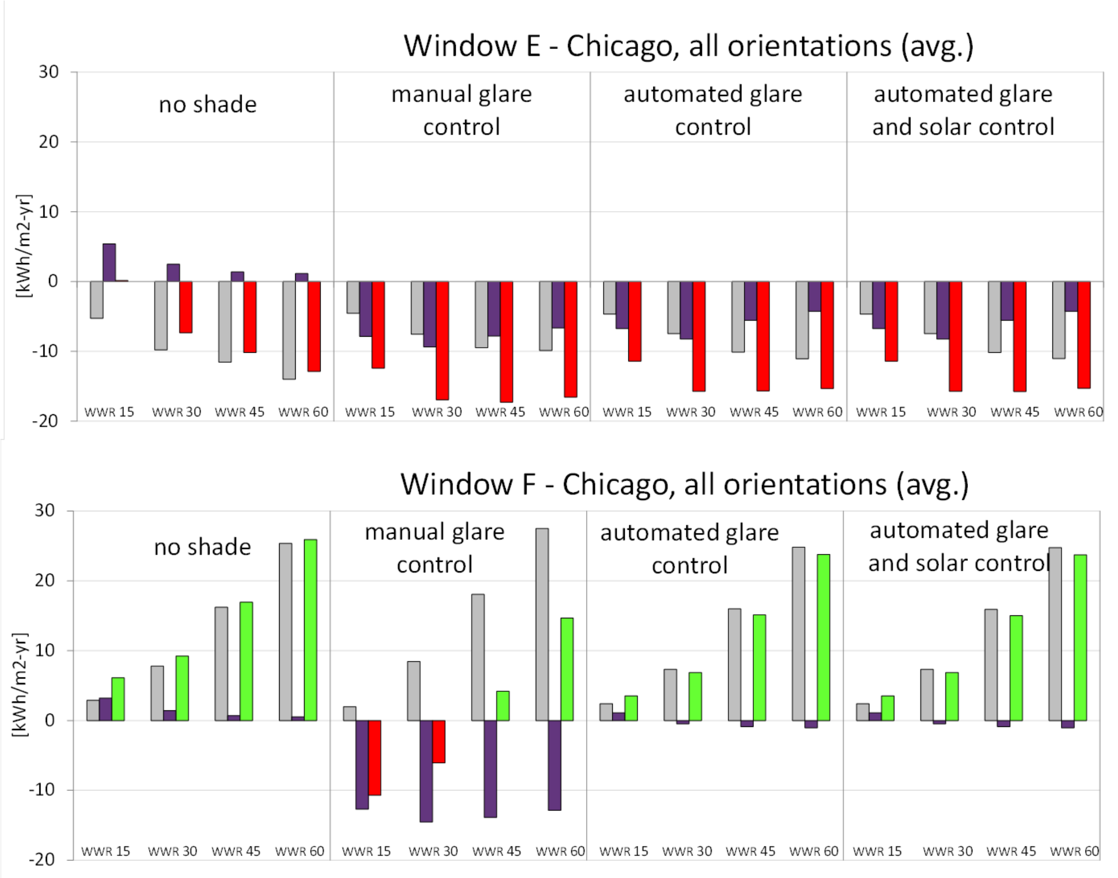

Fig. 16 A. Annual site lighting and HVAC perimeter zone energy use intensity savings (kWh/m^2-floor-yr) for the near-IR low-e window without (E1) and with (E2) an indoor gray roller shade, and a highly-insulating window without (F1) and with (F2) an indoor shade for different control algorithms compared to the TC 14-20 thermochromic window in Chicago. All cases with daylighting controls. EnergyPlus data are given as a function of window-to-wall-area (WWR) ratio. Orientations are averaged by zone floor area of the large office prototype (N/S:W/E = 4:3). Gray: HVAC energy savings. Purple: Lighting energy savings. Red or Green: Net (less or more, respectively) annual energy savings compared to the TC 14-20 window.

In Houston (Fig. 16B), if no shade is used, window E performs better than the thermochromic for small and medium sized transparent areas, but the thermochromic window requires less energy for highly glazed areas.

If an interior shade is used to reduce the significant number of hours during which glare occurs in case of window E (see Table 8), the thermochromic window shows a lower energy use intensity. A positive balance for window E can only be achieved for large window-to-wall ratios and if the use of shade is limited to the hours with glare and high window heat gains.

Window F performs better than the thermochromic window in Houston. The relatively low number of hours during which occupants would experience glare reduces the impact of the roller shade on daylight availability. Although the net energy balance is still positive in the realistic scenario of manual control where shades are left lowered after the first occurrence of a glare condition, one can see the benefit of a more refined control when comparing the manual operation with the ideal, automated shade control.

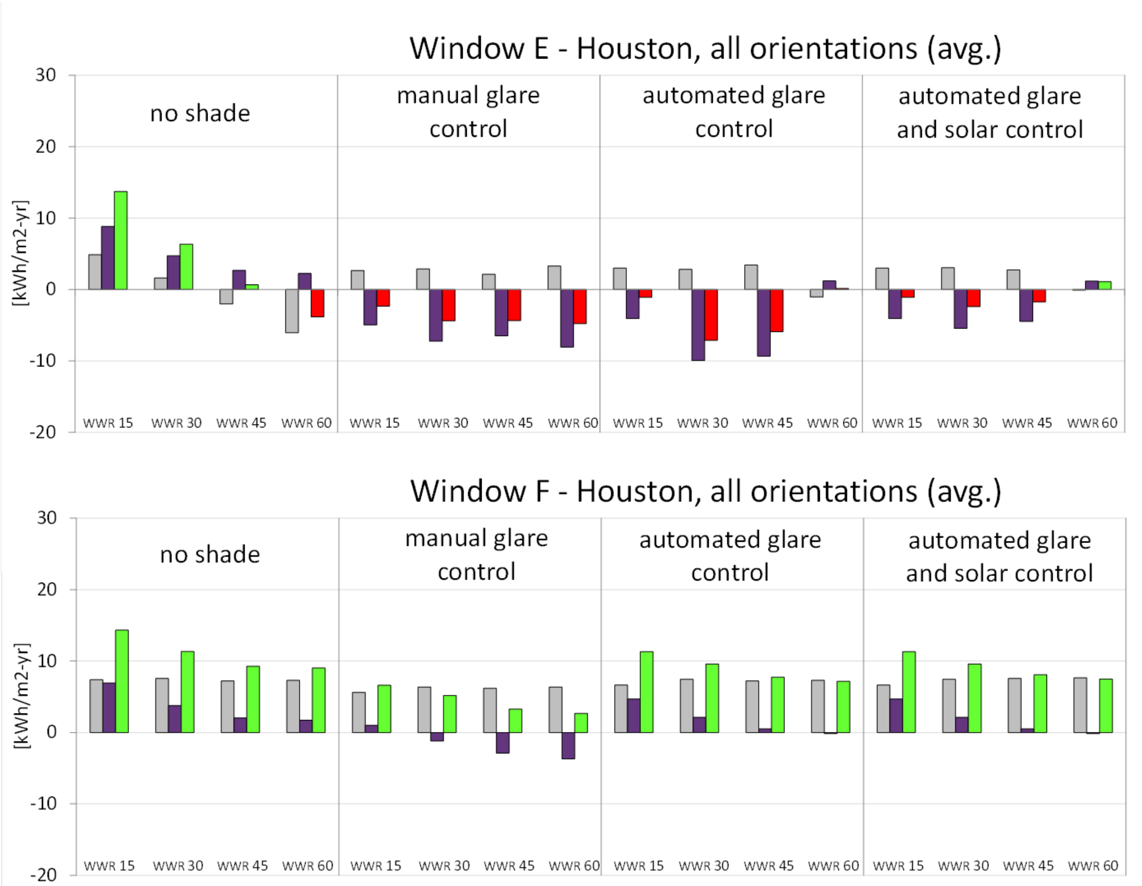

Fig. 16 B. Annual site lighting and HVAC perimeter zone energy use intensity savings (kWh/m^2-floor-yr) for the near-IR low-e window without (E1) and with (E2) an indoor gray roller shade, and a highly-insulating window without (F1) and with (F2) an indoor shade for different control algorithms compared to the TC 14-20 thermochromic window in Houston. All cases with daylighting controls. EnergyPlus data are given as a function of window-to-wall-area (WWR) ratio. Orientations are averaged by zone floor area of the large office prototype (N/S:W/E = 4:3). Gray: HVAC energy savings. Purple: Lighting energy savings. Red or Green: Net (less or more, respectively) annual energy savings compared to the TC 14-20 window.

7. Discussion

The hypothetical NIR-switching thermochromic window tinted primarily in response to outdoor air temperature and incident solar radiation. The nominal "critical switching temperature range" is defined as the glass temperature(s) at which tinting occurs. This nominal range correlates to outdoor air temperatures that are significantly lower than the nominal range if the glass is irradiated. For example, in Chicago, the thermochromic window with a nominal range of 14-20°C switched to a tinted state when outdoor air temperatures were between 0-5°C and incident irradiation was between 400-600 W/m^2. On cold winter sunny days, thermochromic windows exposed to sunlight will tint.

Logically, the thermochromic window with the lowest critical switching temperature range switches most frequently; e.g., if the switching range is 14-20°C, then partial to full tinting occurs for 43% of the year in Chicago, if frequency is averaged over the four cardinal orientations. When the thermochromic window switches and if the window can modulate transmission in the near-infrared, then the thermochromic window will produce significant reductions in window heat gain but produce no effect on window heat loss. Heat gain is reduced through absorption or reflection of solar infrared radiation and reduction of radiative heat transfer to the indoors with a low-emittance coating.

Depending on the level of internal gains within the building, this reduction in window heat gains may or may not produce a reduction in perimeter zone cooling or heating loads. For an internal load dominated commercial office building, internal heat gains from lights, occupants, and equipment cause the net heat balance in perimeter zones to be in a cooling mode for most of the time, even during the winter. For this building type, reductions in heat gains during the winter resulted in lower total annual cooling loads. Annual heating loads were not significantly affected.

The resultant impact on HVAC energy use is dependent on how the HVAC system is designed and operated. Annual cooling energy use was reduced in proportion to reductions in perimeter zone loads – the thermochromic with the lowest critical switching temperature range resulted in the lowest cooling energy in both the mixed hot/cold climate of Chicago and in the hot humid climate of Houston. Cooling energy reductions were greatest on the south, east, and west facing orientations and least on the north. Reductions in HVAC energy use were greatest for large-area windows. Gas consumption for heating and reheat followed the same trends, despite no change in perimeter zone heating loads between the thermochromics with different switching temperature ranges. The reductions were due to sizing of the HVAC system and to the fact that reheat coil energy is needed during the cooling mode because of minimum outdoor fresh air requirements.

When daylighting controls were considered, the balance between HVAC and lighting energy use was achieved with the near-IR switching thermochromic because the visible transmittance of the window was still maintained at a moderately high level when tinting occurred (Tvis = 0.53-0.27). Even though the frequency of tinting was high, the thermochromic with the lowest critical switching temperature range (TC 14-20) resulted in the greatest total annual energy savings. When benchmarked against the near-IR selective, low-e window (E1), the TC 14-20 thermochromic window resulted in less total site annual energy use in both Chicago and Houston, where savings (averaged over WWR≥0.30, all orientations) were 2.7-12.6 kWh/m^2-floor-yr (3.1-12.5%). Greater savings occurred for moderate to large-area windows with south, east, or west-facing orientations: 14.0-21.1 kWh/m^2-floor-yr or 12.5-14.4% for WWR≥0.30 in Chicago and 9.8-18.6 kWh/m^2-floor-yr or 10.0-16.7% for WWR≥0.45 in Houston). Compared to a highly-insulating window (double pane with a suspended film) with and without an indoor shade (windows F1 and F2) the thermochromic window did not do as well, particularly in Chicago for moderate- to large-area windows. Performance of thermochromic window could be improved to that of window F1 or better if the thermochromic glazing layer replaced the conventional outboard layer of window F1.

Discomfort glare was assessed for the thermochromic window, window E and window F. The number of hours during which glare occurs is highest for window E, significantly lower for window F and lowest for the thermochromic window in its tinted state. Based on the assumption that discomfort glare from the thermochromic window is low enough to not require an interior shade, its energy use was compared to those of window E and window F with and without shade. Different scenarios for shade control were assessed where an ideal (automated) shade showed significant energy savings compared to the realistic scenario of manual controlled shades.

In the development of new thermochromic materials for window applications, aesthetics will play an important role in end user adoption of the technology. It will be important to develop materials with a color neutral appearance to the extent possible given the NIR spectral selectivity of the optimum device. An assumption of a 6°C switching range was assumed in this analysis also for aesthetic reasons. Devices with a very narrow switching temperature range could appear mottled in color (regions of tinted and untinted glass across the same window pane) when non-uniformly irradiated; this appearance is unlikely to be acceptable in the market. The desire for a high visible transmittance is driven not only by the desire for lighting energy use savings but also greater indoor environmental quality. End users prefer bright daylit spaces and find spaces with tinted windows gloomy and depressing, particularly during the winter. With the broad adoption of spectrally-selective low-e windows with high luminous efficacy, end users have come to expect bright indoor spaces compared to the dark indoor environments from the 1980s where windows were typically bronze tinted glass.

8. Conclusions

Current thermochromic window technologies produce very little modulation in near infrared solar transmission, have a high critical switching temperature or temperature range, and low visible transmission range. The result is that these windows perform moderately well to control window heat gains but have a negative impact on lighting energy use and daylight quality in commercial buildings. These shortcomings could be addressed by coupling thermochromic windows with daylighting apertures in a heterogeneous façade design or by modifying the properties of the thermochromic device itself.

In order to understand the energy savings benefits of improved thermochromic devices, a hypothetical thermochromic glazing was defined with variable solar transmission in the near-infrared portion of the solar spectrum: Tsol=0.10-0.50, Tvis=0.30-0.60. The glazing layer was coupled with a low-e glazing layer (e=0.04) so that the center-of-glass window assembly had a solar heat gain coefficient range of 0.12-0.47, a visible transmittance range of 0.27-0.53, U-value of 1.45 W/m^2-°K and a luminous efficacy range of (Tvis/SHGC) of 1.13-2.25. The thermochromic was modeled with four different ranges of critical switching temperatures to determine its effect on energy use for the building type and climate. EnergyPlus simulations were conducted on a prototypical large office building that was compliant with ASHRAE 90.1-2010 energy efficiency standards.

A detailed analysis was conducted quantifying how the thermochromic windows affected solar heat gains, perimeter zone loads, then heating, cooling, and lighting energy use in different climates and for different window sizes and orientations. Performance was compared between thermochromics with different switching temperature ranges and static, near-infrared selective, low-emittance windows.

Use of the defined near-IR thermochromic window with the lowest critical switching temperature range (14-20°C) resulted in 3.1-12.5% less annual energy use in large commercial office building perimeter zones in both Chicago (hot/ cold climate) and Houston (hot climate) compared to commercially available, near-IR selective low-e windows (Tvis=0.64, SHGC=0.30, U-value=1.35, Ke=2.13). The thermochromic window delivered the most benefit – 13.7-16.7% energy savings – in the south, east, and west facing perimeter zones with large-area windows in hot climates.

The critical switching temperature, Tsol, and Tvis guidance provided by Li, Niklasson, and Granqvist [10] to the material scientist community is appropriate for commercial office buildings with high internal loads. The hypothetical thermochromic window meeting these specifications (TC 14-20) yielded significant annual HVAC and lighting perimeter zone energy savings over conventional spectrally-selective, low-e windows, particularly for facades with large-area windows with significant solar exposure in hot climates. Significant research will need to be carried out in order to achieve the characteristics proposed in this work. If the hypothetical thermochromic window can be offered at costs that are competitive to conventional low-e windows and meet aesthetic requirements defined by the building industry and end users, then the technology is likely to be a viable energy-efficiency option for internal load dominated commercial buildings.

Acknowledgments

The authors would like to acknowledge the contributions of our LBNL colleagues: Xiufeng Pang, Kaustubh Phalak, Fred Buhl, Andrew McNeil, and Stephen Selkowitz.

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State and Community Programs, Office of Building Research and Standards of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231 and by the California Energy Commission through its Public Interest Energy Research (PIER) Program on behalf of the citizens of California.

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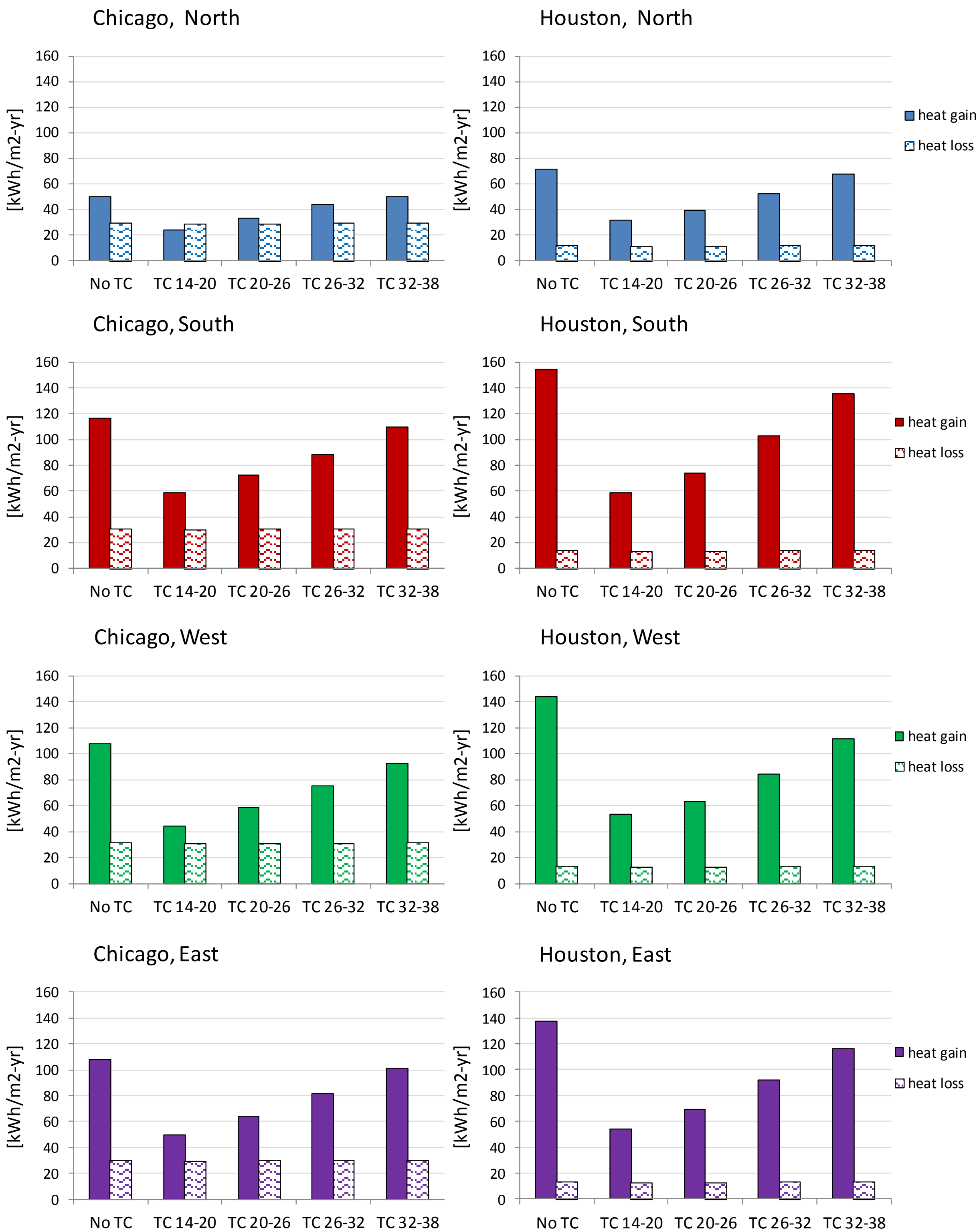
Appendix A Annual window heat gains or losses

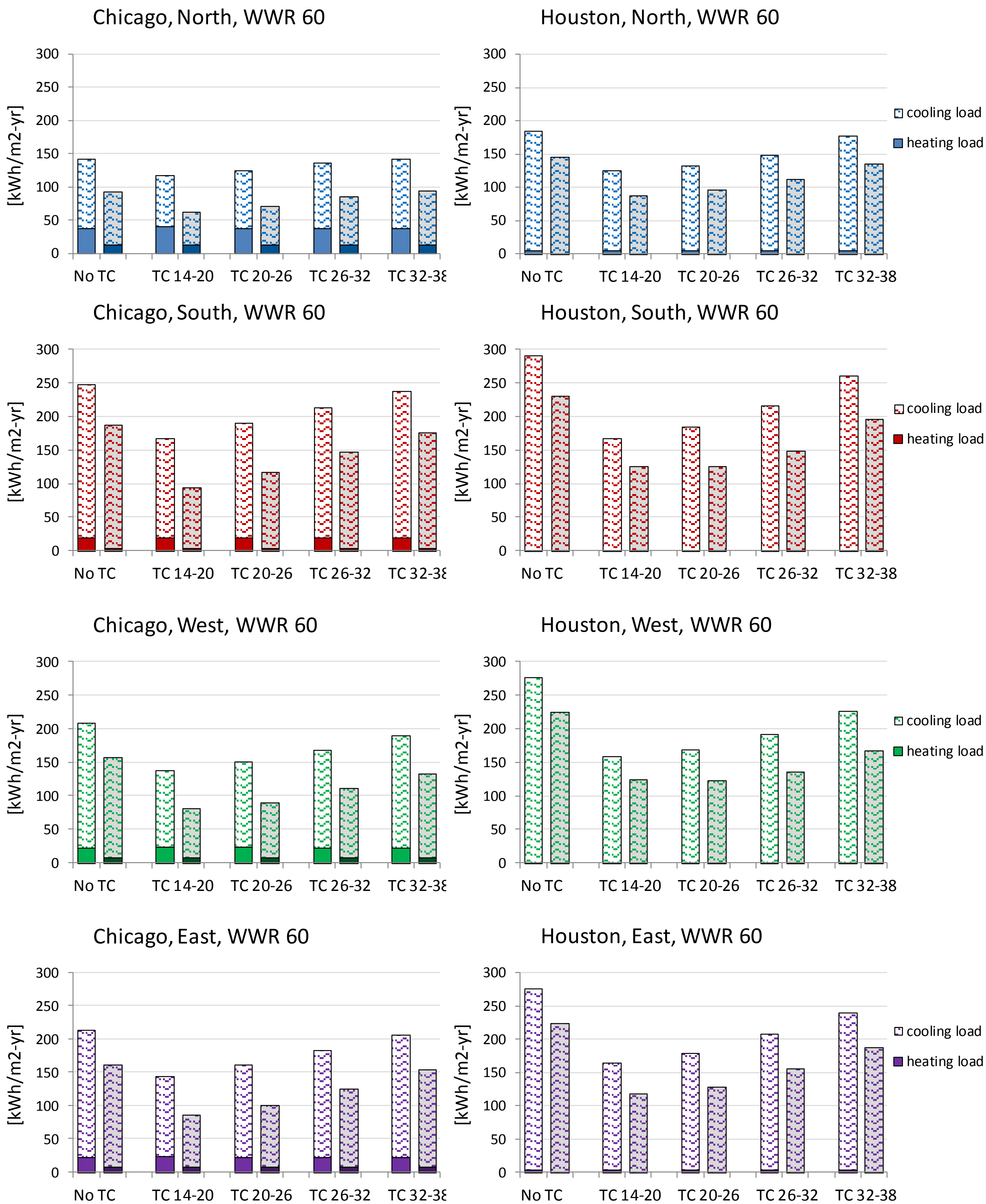
Annual window heat gains or losses (kWh/m^2-glazing-yr) when in heating or cooling mode, ASHRAE 90.1-2010 large office prototype, WWR=60, indoor temperature= 21°C, Chicago and Houston.

kWh/m2-yr		window heat gain while heating G H +	window heat gain while cooling G C -	window heat loss while heating L H -	window heat loss while cooling L C +
CHICAGO					
NORTH	No TC	1.77	150.9	62.4	17.8
	TC 14-20	1.85	77.6	63.1	16.5
	TC 20-26	1.80	102.8	62.4	17.4
	TC 26-32	1.77	134.9	62.3	17.7
	TC 32-38	1.77	150.5	62.4	17.8
SOUTH	No TC	1.62	432.1	49.1	31.4
	TC 14-20	1.68	236.2	51.2	28.5
	TC 20-26	1.66	294.0	49.9	30.1
	TC 26-32	1.62	351.7	49.2	31.0
	TC 32-38	1.62	409.5	49.1	31.3
WEST	No TC	1.67	328.5	54.7	28.4
	TC 14-20	1.68	152.1	56.4	25.8
	TC 20-26	1.68	187.8	55.4	27.1
	TC 26-32	1.64	233.7	54.9	27.8
	TC 32-38	1.64	285.3	54.8	28.2
EAST	No TC	2.70	336.5	55.3	25.0
	TC 14-20	2.94	166.6	56.4	23.5
	TC 20-26	2.71	211.1	55.6	24.5
	TC 26-32	2.70	264.4	55.3	24.9
	TC 32-38	2.70	320.1	55.3	25.0
HOUSTON					
NORTH	No TC	0.21	212.3	12.2	14.3
	TC 14-20	0.21	97.9	12.8	13.4
	TC 20-26	0.21	119.5	12.3	14.0
	TC 26-32	0.21	158.3	12.2	14.2
	TC 32-38	0.21	202.9	12.2	14.3
SOUTH	No TC	0.10	458.6	6.6	22.2
	TC 14-20	0.10	182.4	8.7	19.1
	TC 20-26	0.10	222.5	8.2	19.8
	TC 26-32	0.10	297.7	7.0	21.3
	TC 32-38	0.10	399.2	6.6	22.0
WEST	No TC	0.11	413.4	7.9	21.5
	TC 14-20	0.16	159.6	10.1	18.2
	TC 20-26	0.14	187.3	9.4	19.1
	TC 26-32	0.11	240.7	8.5	20.3
	TC 32-38	0.11	316.4	7.9	21.2
EAST	No TC	0.07	409.9	9.5	18.5
	TC 14-20	0.07	170.4	10.4	17.1
	TC 20-26	0.07	208.4	9.9	17.8
	TC 26-32	0.07	273.1	9.5	18.3
	TC 32-38	0.07	345.6	9.5	18.4

Annual accumulated window heat gain and heat loss (kWh/m^2-window-yr) of the TC windows and the reference window "No TC" for four window orientations and the Chicago and Houston climates.



Annual accumulated cooling and heating load (kWh/m^2-floor-yr) of the TC windows and the reference window "No TC" for four window orientations and the Chicago and Houston climates. The first stacked column shown per window type are loads calculated with a constant setpoint temperature of 21°C. The second stacked column are loads calculated with the HVAC setpoint temperature schedule: weekday deadband of 21-24°C; nights and weekend setback.



Appendix B Annual site HVAC energy use (no daylighting controls)

Annual site HVAC energy use intensity (kWh/m2-floor-yr) including heating, cooling and fan energy (no daylighting control) for the reference window “No TC” and four thermochromic windows and spectrally selective high-performance windows (see Table 3) as a function of window-to-wall-area (WWR) ratio for four window orientations and the Chicago climate.

	No TC*, no DC**	TC 32-38 no DC**		TC 26-32 no DC**		TC 20-26 no DC**		TC 14-20 no DC**		Win E1 no DC**		Win E2 no DC**		Win F1 no DC**		Win F2 no DC**	
CHICAGO	HVAC (site) total [kWh/m^2-yr]	HVAC (site) total [kWh/m^2-yr]	Savings compared to No TC*, no DC**	HVAC (site) total [kWh/m^2-yr]	Savings compared to No TC*, no DC**	HVAC (site) total [kWh/m^2-yr]	Savings compared to No TC*, no DC**	HVAC (site) total [kWh/m^2-yr]	Savings compared to No TC*, no DC**	HVAC (site) total [kWh/m^2-yr]	Savings compared to No TC*, no DC**	HVAC (site) total [kWh/m^2-yr]	Savings compared to No TC*, no DC**	HVAC (site) total [kWh/m^2-yr]	Savings compared to No TC*, no DC**	HVAC (site) total [kWh/m^2-yr]	Savings compared to No TC*, no DC**
NORTH																	
WWR 15	55.2	54.5	1%	53.0	4%	50.5	9%	49.8	10%	52.5	5%	52.3	5%	45.6	17%	45.6	18%
WWR 30	69.4	68.3	2%	64.8	7%	60.0	14%	58.2	16%	64.3	7%	65.3	6%	49.4	29%	49.2	29%
WWR 45	83.7	82.1	2%	78.7	6%	71.8	14%	68.2	19%	77.6	7%	78.7	6%	53.4	36%	53.1	37%
WWR 60	98.2	97.0	1%	91.1	7%	83.6	15%	77.5	21%	90.3	8%	93.6	5%	57.7	41%	57.1	42%
SOUTH																	
WWR 15	52.2	49.8	5%	45.2	13%	42.5	19%	39.7	24%	46.7	10%	45.8	12%	41.1	21%	41.0	21%
WWR 30	74.4	70.9	5%	63.1	15%	57.9	22%	54.0	27%	58.9	21%	56.8	24%	45.2	39%	45.7	39%
WWR 45	99.2	95.2	4%	83.8	16%	78.3	21%	71.9	27%	74.7	25%	70.0	29%	51.0	49%	50.9	49%
WWR 60	130.7	124.2	5%	107.0	18%	100.7	23%	93.2	29%	90.6	31%	85.3	35%	58.3	55%	58.5	55%
WEST																	
WWR 15	66.2	61.4	7%	57.2	14%	51.2	23%	50.1	24%	58.3	12%	57.4	13%	49.3	26%	49.6	25%
WWR 30	94.3	86.9	8%	77.6	18%	70.9	25%	62.4	34%	76.9	18%	74.0	22%	56.8	40%	57.9	39%
WWR 45	123.5	113.6	8%	101.9	17%	93.2	25%	79.9	35%	97.0	21%	93.0	25%	64.8	48%	66.2	46%
WWR 60	152.9	142.8	7%	122.7	20%	113.6	26%	98.0	36%	118.4	23%	113.4	26%	73.0	52%	75.8	50%
EAST																	
WWR 15	66.0	62.1	6%	57.3	13%	52.9	20%	49.0	26%	58.8	11%	56.7	14%	50.0	24%	49.9	24%
WWR 30	92.2	85.7	7%	77.4	16%	69.9	24%	60.1	35%	75.8	18%	72.7	21%	57.1	38%	57.3	38%
WWR 45	119.7	112.1	6%	102.8	14%	89.4	25%	76.2	36%	93.5	22%	89.7	25%	65.0	46%	64.9	46%
WWR 60	150.7	141.2	6%	126.5	16%	110.0	27%	94.3	37%	112.0	26%	106.9	29%	73.1	51%	73.7	51%
AVERAGE																	
WWR 15	58.7	56.0	5%	52.4	11%	48.7	17%	46.7	20%	53.2	9%	52.3	11%	45.9	22%	45.9	22%
WWR 30	80.4	76.3	5%	69.4	14%	63.5	21%	58.2	28%	67.5	16%	66.0	18%	51.2	36%	51.5	36%
WWR 45	103.5	98.4	5%	89.7	13%	81.5	21%	73.2	29%	83.8	19%	81.1	22%	57.3	45%	57.4	45%
WWR 60	129.4	123.1	5%	109.3	16%	100.0	23%	89.6	31%	100.3	22%	97.7	24%	64.0	51%	64.6	50%

* no TC: base glazing without thermochromic layer (see Table 3)

** no DC: no daylighting control

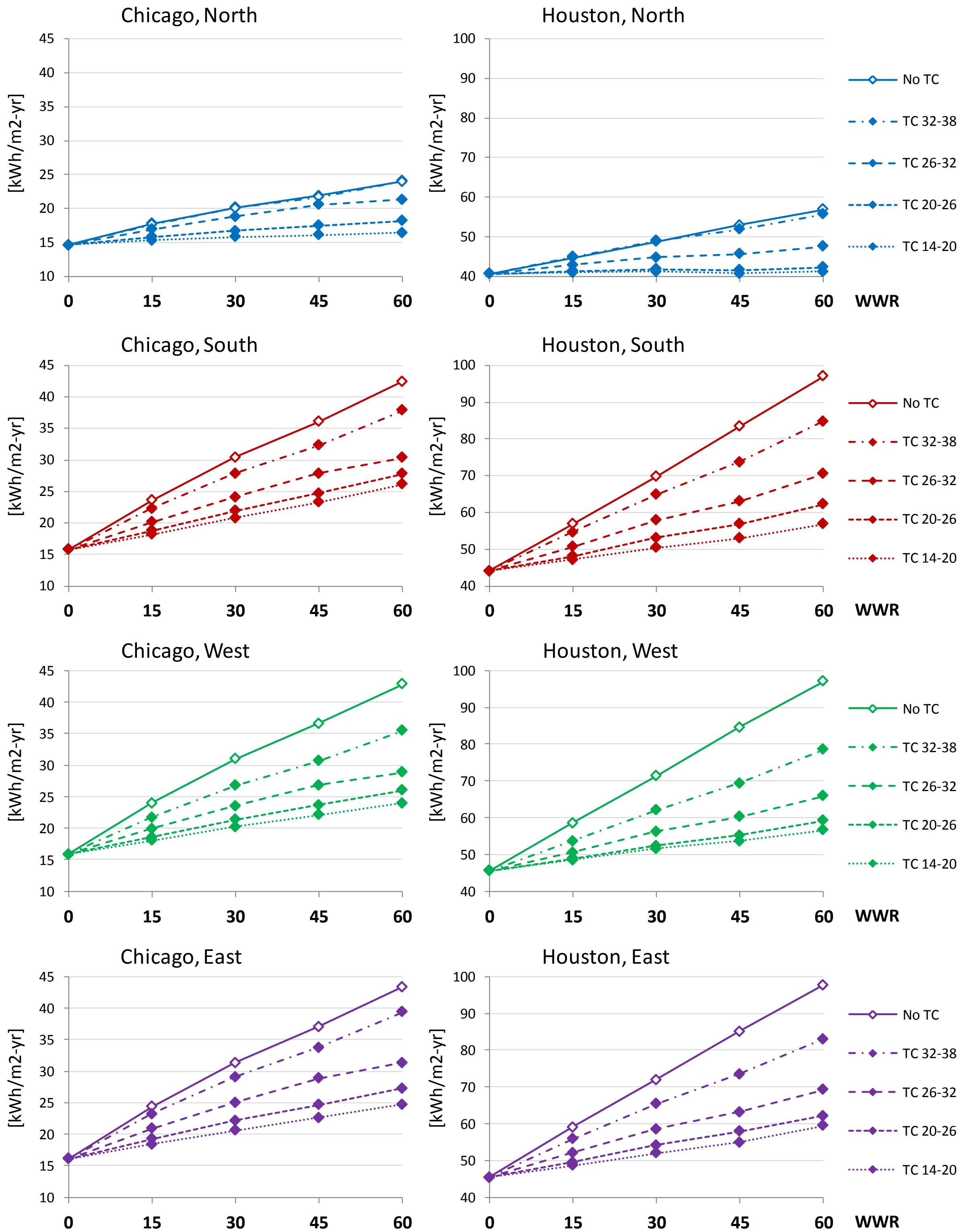
Annual site HVAC energy use intensity (kWh/m2-floor-yr) including heating, cooling and fan energy (no daylighting control) for the reference window “No TC” and four thermochromic windows and spectrally selective high-performance windows (see Table 3) as a function of window-to-wall-area (WWR) ratio for four window orientations and the Houston climate.

	No TC*, no DC**	TC 32-38 no DC**		TC 26-32 no DC**		TC 20-26 no DC**		TC 14-20 no DC**		Win E1 no DC**		Win E2 no DC**		Win F1 no DC**		Win F2 no DC**	
HOUSTON	HVAC (site) total [kWh/m^2-yr]	HVAC (site) total [kWh/m^2-yr]	Savings compared to No TC*, no DC**	HVAC (site) total [kWh/m^2-yr]	Savings compared to No TC*, no DC**	HVAC (site) total [kWh/m^2-yr]	Savings compared to No TC*, no DC**	HVAC (site) total [kWh/m^2-yr]	Savings compared to No TC*, no DC**	HVAC (site) total [kWh/m^2-yr]	Savings compared to No TC*, no DC**	HVAC (site) total [kWh/m^2-yr]	Savings compared to No TC*, no DC**	HVAC (site) total [kWh/m^2-yr]	Savings compared to No TC*, no DC**	HVAC (site) total [kWh/m^2-yr]	Savings compared to No TC*, no DC**
NORTH																	
WWR 15	52.2	51.5	1%	48.7	7%	46.9	10%	46.4	11%	48.0	8%	46.3	11%	46.6	11%	46.3	11%
WWR 30	58.8	57.7	2%	51.7	12%	47.9	18%	47.2	20%	50.9	13%	47.3	20%	47.8	19%	46.9	20%
WWR 45	65.7	63.0	4%	54.7	17%	49.1	25%	48.0	27%	53.6	18%	48.4	26%	49.2	25%	48.0	27%
WWR 60	72.6	69.1	5%	57.8	20%	50.5	31%	49.0	32%	56.9	22%	50.1	31%	50.3	31%	49.0	32%
SOUTH																	
WWR 15	66.5	62.7	6%	57.7	13%	54.6	18%	53.4	20%	57.3	14%	54.1	19%	54.0	19%	53.6	19%
WWR 30	84.5	77.0	9%	67.4	20%	61.2	28%	57.9	32%	65.7	22%	59.2	30%	59.0	30%	58.1	31%
WWR 45	104.9	91.1	13%	77.0	27%	67.7	35%	62.4	41%	74.4	29%	64.3	39%	64.1	39%	62.5	40%
WWR 60	126.4	108.3	14%	88.7	30%	76.0	40%	67.7	46%	84.0	34%	70.3	44%	69.0	45%	67.2	47%
WEST																	
WWR 15	68.1	61.3	10%	57.3	16%	55.2	19%	54.8	20%	59.2	13%	56.2	18%	55.7	18%	55.6	18%
WWR 30	86.3	73.4	15%	65.0	25%	60.0	30%	58.9	32%	68.1	21%	61.8	28%	60.8	29%	60.3	30%
WWR 45	106.5	85.9	19%	73.0	32%	65.3	39%	62.8	41%	77.2	28%	67.7	36%	66.2	38%	65.2	39%
WWR 60	127.6	100.9	21%	82.5	35%	71.4	44%	67.2	47%	87.4	31%	74.6	41%	71.3	44%	70.3	45%
EAST																	
WWR 15	68.8	63.8	7%	59.2	14%	56.0	19%	54.9	20%	59.4	14%	56.0	19%	55.8	19%	55.4	19%
WWR 30	87.2	77.4	11%	67.8	22%	62.3	29%	59.4	32%	68.8	21%	61.7	29%	61.2	30%	60.1	31%
WWR 45	107.3	90.4	16%	76.7	29%	68.9	36%	64.7	40%	78.1	27%	67.4	37%	66.8	38%	65.1	39%
WWR 60	127.7	105.1	18%	86.4	32%	75.5	41%	71.0	44%	88.2	31%	74.0	42%	71.9	44%	70.0	45%
AVERAGE																	
WWR 15	63.0	59.3	6%	55.2	12%	52.7	16%	51.9	18%	55.3	12%	52.6	17%	52.5	17%	52.2	17%
WWR 30	77.7	70.6	9%	62.3	20%	57.2	26%	55.2	29%	62.3	20%	56.6	27%	56.4	27%	55.6	28%
WWR 45	93.9	81.5	13%	69.4	26%	61.9	34%	58.6	38%	69.5	26%	60.8	35%	60.6	36%	59.2	37%
WWR 60	110.8	94.4	15%	77.7	30%	67.3	39%	62.7	43%	77.4	30%	65.8	41%	64.4	42%	62.9	43%

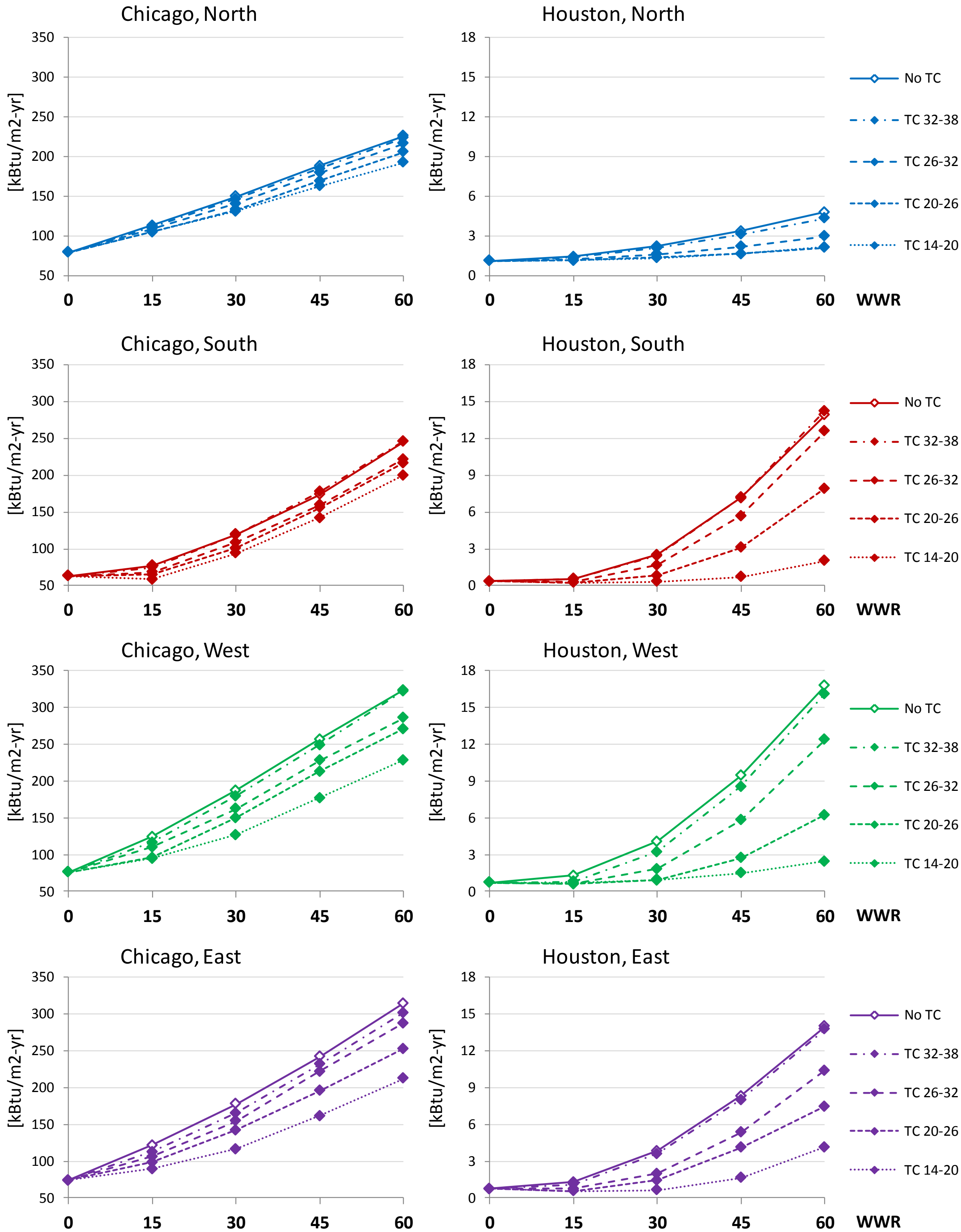
* no TC: base glazing without thermochromic layer (see Table 3)

** no DC: no daylighting control

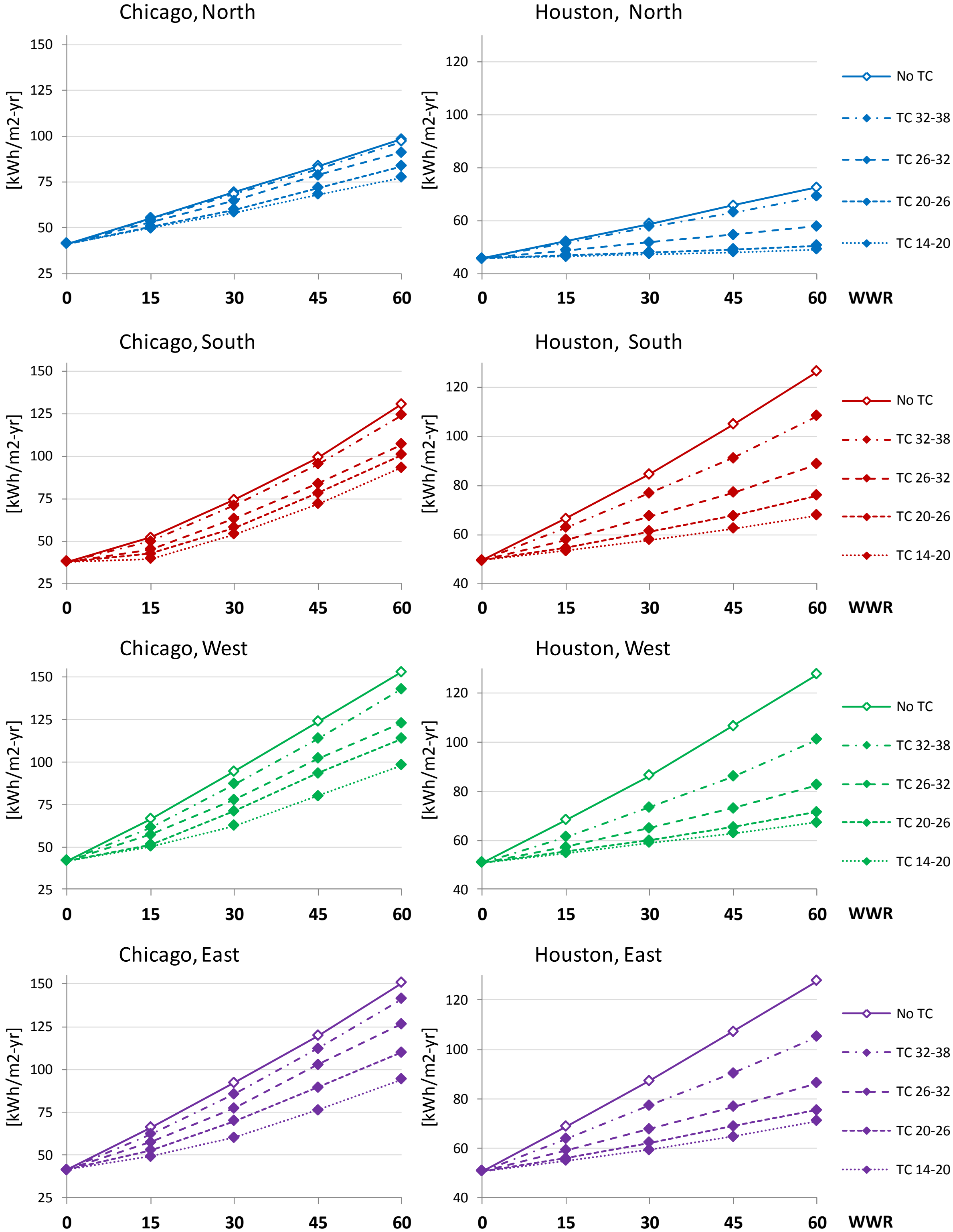
Annual site cooling energy use intensity (kWh/m^2-floor-yr) for the reference window "No TC" and four thermochromic windows as a function of window-to-wall-area (WWR) ratio for four window orientations and the Chicago and Houston climates.



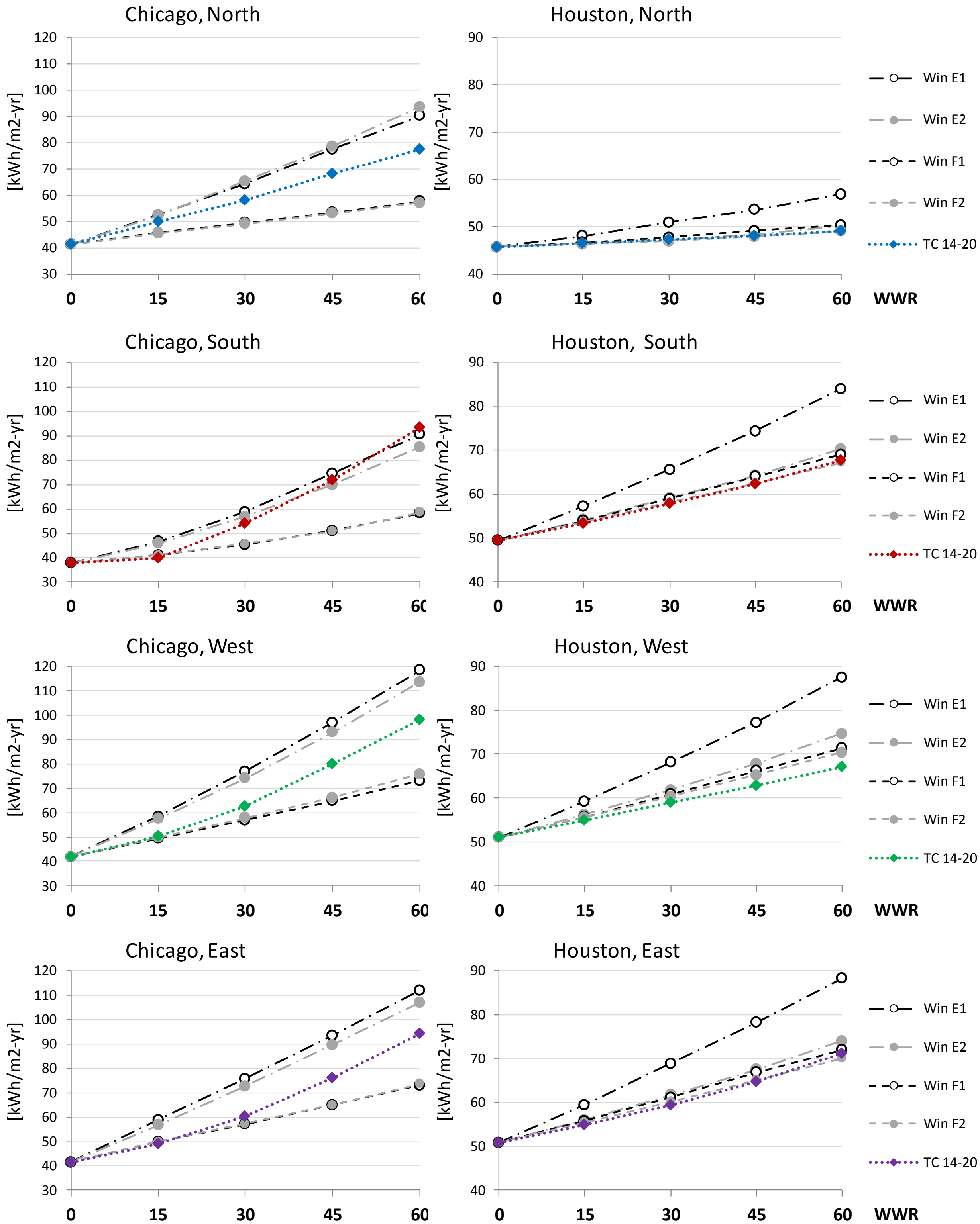
Annual natural gas use intensity (kBtu/m^2-floor-yr) used for heating and reheat for the reference window “No TC” and four thermochromic windows as a function of window-to-wall-area (WWR) ratio for four window orientations and the Chicago and Houston climates.



Annual site energy use intensity (kWh/m^2-floor-yr) for heating, cooling, and ventilation for the reference window “No TC” and four thermochromic windows as a function of window-to-wall-area (WWR) ratio for four window orientations and the Chicago and Houston climates.



Annual site energy use intensity (kWh/m2-floor-yr) for heating, cooling, and ventilation for the reference window “No TC” base window and four thermochromic windows as a function of window-to-wall-area (WWR) ratio.   for four window orientations and forthe Chicago and Houston climates.



Appendix C Annual total site and source energy use with daylighting controls

Annual total site energy use intensity (kWh/m2-floor-yr) including heating, cooling, fan and lighting energy with daylighting control for the reference window "No TC", four thermochromic windows and spectrally selective high-performance windows (see Table 3) as a function of window-to-wall-area (WWR) ratio for four window orientations and the Chicago climate.

	No TC*, no DC**	No TC*, DC**		TC 32-38 DC**		TC 26-32 DC**		TC 20-26 DC**		TC 14-20 DC**		Win E1 DC**		Win E2 DC**		Win F1 DC**		Win F2 DC**	
CHICAGO	Site total [kWh/m2-yr]	Site total [kWh/m2-yr]	Savings compared to No TC, no DC	Site total [kWh/m2-yr]	Savings compared to No TC, DC	Site total [kWh/m2-yr]	Savings compared to No TC, DC	Site total [kWh/m2-yr]	Savings compared to No TC, DC	Site total [kWh/m2-yr]	Savings compared to No TC, DC	Site total [kWh/m2-yr]	Savings compared to No TC, DC	Site total [kWh/m2-yr]	Savings compared to No TC, DC	Site total [kWh/m2-yr]	Savings compared to No TC, DC	Site total [kWh/m2-yr]	Savings compared to No TC, DC
NORTH																			
WWR 15	114.3	91.3	20%	90.9	0%	90.2	1%	90.8	0%	93.8	-3%	88.1	3%	107.9	-18%	82.8	9%	101.9	-12%
WWR 30	128.5	104.0	19%	102.9	1%	100.1	4%	96.2	7%	96.0	8%	100.7	3%	117.0	-13%	83.9	19%	103.2	1%
WWR 45	142.7	117.8	17%	117.0	1%	114.0	3%	107.3	9%	104.0	12%	114.2	3%	127.5	-8%	87.6	26%	104.2	12%
WWR 60	157.3	133.3	15%	132.2	1%	126.0	5%	119.0	11%	112.9	15%	127.2	5%	139.1	-4%	91.5	31%	106.3	20%
SOUTH																			
WWR 15	111.3	86.5	22%	84.1	3%	79.3	8%	76.7	11%	75.4	13%	80.3	7%	95.2	-10%	75.5	13%	93.2	-8%
WWR 30	133.4	107.7	19%	104.7	3%	95.8	11%	92.2	14%	88.5	18%	91.4	15%	100.5	7%	78.0	28%	92.2	14%
WWR 45	158.3	131.5	17%	127.9	3%	115.8	12%	110.7	16%	105.1	20%	107.6	18%	110.5	16%	83.2	37%	94.1	28%
WWR 60	189.7	162.8	14%	157.0	4%	140.1	14%	134.4	17%	127.0	22%	125.8	23%	124.8	23%	90.8	44%	99.0	39%
WEST																			
WWR 15	125.3	101.5	19%	96.6	5%	92.5	9%	87.6	14%	89.0	12%	93.3	8%	107.3	-6%	84.7	17%	102.2	-1%
WWR 30	153.5	128.7	16%	121.5	6%	113.9	11%	105.2	18%	97.6	24%	111.6	13%	120.2	7%	91.1	29%	105.7	18%
WWR 45	182.7	157.9	14%	149.0	6%	136.5	14%	127.7	19%	114.4	28%	132.5	16%	136.2	14%	98.9	37%	111.3	30%
WWR 60	212.1	187.8	11%	176.6	6%	160.0	15%	150.4	20%	133.5	29%	154.6	18%	155.2	17%	107.7	43%	118.9	37%
EAST																			
WWR 15	125.0	102.4	18%	99.4	3%	94.2	8%	90.6	11%	88.2	14%	93.7	8%	106.5	-4%	86.0	16%	102.3	0%
WWR 30	151.3	126.7	16%	120.4	5%	112.7	11%	105.2	17%	95.7	24%	111.9	12%	118.7	6%	92.4	27%	106.5	16%
WWR 45	178.8	154.0	14%	145.5	6%	135.3	12%	123.1	20%	111.7	28%	130.2	15%	134.0	13%	99.6	35%	110.9	28%
WWR 60	209.8	184.6	12%	175.1	5%	161.6	12%	144.8	22%	129.5	30%	149.2	19%	150.9	18%	108.0	41%	117.4	36%
AVERAGE																			
WWR 15	117.7	94.1	20%	91.7	3%	88.2	6%	85.9	9%	86.2	8%	87.9	7%	103.7	-10%	81.6	13%	99.4	-6%
WWR 30	139.5	114.6	18%	110.6	3%	104.1	9%	98.6	14%	94.0	18%	102.3	11%	113.1	1%	85.3	26%	101.1	12%
WWR 45	162.6	137.2	16%	132.4	4%	123.3	10%	115.6	16%	107.9	21%	119.1	13%	125.4	9%	90.9	34%	103.9	24%
WWR 60	188.5	163.3	13%	157.1	4%	144.1	12%	135.1	17%	124.6	24%	136.7	16%	140.4	14%	97.8	40%	108.8	33%

* no TC: base glazing without thermochromic layer (see Table 3)

** no DC/DC: with/without daylighting control

Annual total source energy use intensity (kWh/m2-floor-yr) including heating, cooling, fan and lighting energy with daylighting control for the reference window "No TC", four thermochromic windows and spectrally selective high-performance windows (see Table 3) as a function of window-to-wall-area (WWR) ratio for four window orientations and the Chicago climate.

	No TC*, no DC**	No TC*, DC**		TC 32-38 DC**		TC 26-32 DC**		TC 20-26 DC**		TC 14-20 DC**		Win E1 DC**		Win E2 DC**		Win F1 DC**		Win F2 DC**	
CHICAGO	Source total [kWh/m2-yr]	Source total [kWh/m2-yr]	Savings compared to No TC, no DC	Source total [kWh/m2-yr]	Savings compared to No TC, DC	Source total [kWh/m2-yr]	Savings compared to No TC, DC	Source total [kWh/m2-yr]	Savings compared to No TC, DC	Source total [kWh/m2-yr]	Savings compared to No TC, DC	Source total [kWh/m2-yr]	Savings compared to No TC, DC	Source total [kWh/m2-yr]	Savings compared to No TC, DC	Source total [kWh/m2-yr]	Savings compared to No TC, DC	Source total [kWh/m2-yr]	Savings compared to No TC, DC
NORTH																			
WWR 15	304.4	224.4	26%	223.6	0%	222.5	1%	225.6	-1%	235.2	-5%	212.2	5%	281.6	-25%	212.0	6%	277.7	-24%
WWR 30	327.8	237.9	27%	236.0	1%	229.2	4%	220.2	7%	220.3	7%	224.0	6%	285.6	-20%	204.4	14%	275.2	-16%
WWR 45	349.7	256.9	27%	254.9	1%	248.0	3%	232.3	10%	226.0	12%	240.3	6%	290.6	-13%	208.0	19%	272.2	-6%
WWR 60	373.5	281.2	25%	278.8	1%	264.1	6%	247.4	12%	236.1	16%	257.6	8%	298.5	-6%	213.2	24%	271.2	4%
SOUTH																			
WWR 15	317.4	230.1	27%	224.1	3%	213.7	7%	208.6	9%	208.8	9%	209.8	9%	262.0	-14%	204.1	11%	265.8	-16%
WWR 30	363.1	270.4	26%	260.7	4%	240.3	11%	230.7	15%	224.8	17%	229.0	15%	261.7	3%	208.3	23%	259.0	4%
WWR 45	410.6	314.7	23%	300.3	5%	273.3	13%	259.0	18%	249.1	21%	255.7	19%	271.0	14%	218.4	31%	258.3	18%
WWR 60	467.4	371.8	20%	350.9	6%	311.0	16%	296.1	20%	283.0	24%	286.0	23%	289.2	22%	233.3	37%	264.5	29%
WEST																			
WWR 15	333.6	249.3	25%	238.2	4%	229.4	8%	222.5	11%	227.7	9%	226.4	9%	281.2	-13%	217.7	13%	280.0	-12%
WWR 30	386.0	294.6	24%	275.2	7%	258.1	12%	242.2	18%	232.3	21%	253.4	14%	292.1	1%	224.6	24%	280.7	5%
WWR 45	437.2	344.0	21%	317.7	8%	292.0	15%	273.1	21%	253.6	26%	285.8	17%	309.6	10%	237.9	31%	286.4	17%
WWR 60	491.4	398.2	19%	364.5	8%	326.5	18%	305.8	23%	280.6	30%	320.9	19%	332.5	16%	254.1	36%	296.6	26%
EAST																			
WWR 15	334.6	251.8	25%	245.7	2%	235.5	6%	230.2	9%	228.8	9%	228.4	9%	280.1	-11%	220.2	13%	279.9	-11%
WWR 30	384.8	294.2	24%	280.8	5%	261.5	11%	246.4	16%	232.9	21%	255.6	13%	290.9	1%	227.5	23%	281.9	4%
WWR 45	434.3	341.7	21%	322.4	6%	296.8	13%	271.8	20%	253.5	26%	285.1	17%	307.3	10%	240.4	30%	286.3	16%
WWR 60	489.9	396.0	19%	373.0	6%	336.1	15%	304.1	23%	279.8	29%	316.5	20%	327.6	17%	256.2	35%	294.7	26%
AVERAGE																			
WWR 15	320.2	236.6	26%	231.1	2%	223.9	5%	220.8	7%	224.5	5%	217.5	8%	275.3	-16%	212.4	10%	275.1	-16%
WWR 30	361.4	270.3	25%	260.2	4%	244.8	9%	233.0	14%	226.6	16%	237.7	12%	280.8	-4%	214.2	21%	272.8	-1%
WWR 45	402.4	308.7	23%	294.6	5%	274.1	11%	256.3	17%	243.9	21%	263.0	15%	291.9	5%	223.6	28%	273.7	11%
WWR 60	448.5	354.7	21%	336.4	5%	305.1	14%	285.0	20%	267.8	25%	290.5	18%	308.4	13%	236.0	33%	279.0	21%

* no TC: base glazing without thermochromic layer (see Table 3)

** no DC/DC: with/without daylighting control

Annual total site energy use intensity (kWh/m2-floor-yr) including heating, cooling, fan and lighting energy with daylighting control for the reference window "No TC", four thermochromic windows and spectrally selective high-performance windows (see Table 3) as a function of window-to-wall-area (WWR) ratio for four window orientations and the Houston climate.

HOUSTON	No TC*, no DC**	No TC*, DC**		TC 32-38 DC**		TC 26-32 DC**		TC 20-26 DC**		TC 14-20 DC**		Win E1 DC**		Win E2 DC**		Win F1 DC**		Win F2 DC**	
	Site total [kWh/m2-yr]	Site total [kWh/m2-yr]	Savings compared to No TC, no DC	Site total [kWh/m2-yr]	Savings compared to No TC, DC	Site total [kWh/m2-yr]	Savings compared to No TC, DC	Site total [kWh/m2-yr]	Savings compared to No TC, DC	Site total [kWh/m2-yr]	Savings compared to No TC, DC	Site total [kWh/m2-yr]	Savings compared to No TC, DC	Site total [kWh/m2-yr]	Savings compared to No TC, DC	Site total [kWh/m2-yr]	Savings compared to No TC, DC	Site total [kWh/m2-yr]	Savings compared to No TC, DC
NORTH																			
WWR 15	111.4	80.5	28%	80.2	0%	80.0	1%	83.6	-4%	87.1	-8%	75.2	7%	100.1	-24%	76.6	5%	101.7	-26%
WWR 30	117.9	83.9	29%	82.7	2%	77.0	8%	75.1	10%	77.3	8%	75.5	10%	96.4	-15%	73.4	13%	98.8	-18%
WWR 45	124.9	90.3	28%	87.4	3%	78.9	13%	74.5	18%	74.6	17%	77.7	14%	92.5	-2%	73.6	19%	96.3	-7%
WWR 60	131.6	97.2	26%	93.4	4%	81.8	16%	75.4	22%	75.1	23%	80.7	17%	89.9	8%	74.1	24%	94.4	3%
SOUTH																			
WWR 15	125.5	92.9	26%	89.6	4%	85.9	8%	85.2	8%	86.6	7%	83.1	11%	101.9	-10%	81.0	13%	104.3	-12%
WWR 30	143.6	109.4	24%	101.6	7%	93.0	15%	88.1	19%	85.4	22%	89.8	18%	100.1	8%	83.7	23%	102.8	6%
WWR 45	164.0	129.2	21%	115.5	11%	102.5	21%	93.2	28%	88.2	32%	98.1	24%	100.0	23%	87.9	32%	102.7	20%
WWR 60	185.5	151.1	19%	133.3	12%	114.7	24%	102.4	32%	93.4	38%	107.6	29%	102.8	32%	92.8	39%	104.1	31%
WEST																			
WWR 15	127.3	95.4	25%	88.5	7%	86.1	10%	88.1	8%	90.3	5%	85.4	10%	104.5	-10%	83.8	12%	107.0	-12%
WWR 30	145.4	111.1	24%	98.0	12%	90.0	19%	86.6	22%	87.2	21%	92.4	17%	104.1	6%	85.6	23%	106.0	5%
WWR 45	165.5	130.8	21%	110.1	16%	97.6	25%	90.1	31%	88.7	32%	100.8	23%	105.9	19%	90.0	31%	106.9	18%
WWR 60	186.7	152.2	19%	125.2	18%	107.2	30%	96.3	37%	92.4	39%	111.0	27%	109.5	28%	94.9	38%	109.0	28%
EAST																			
WWR 15	127.9	96.6	24%	92.1	5%	89.8	7%	89.7	7%	90.7	6%	86.0	11%	104.8	-8%	84.5	13%	106.9	-11%
WWR 30	146.2	112.4	23%	102.1	9%	93.7	17%	90.1	20%	88.8	21%	93.1	17%	104.4	7%	86.5	23%	106.0	6%
WWR 45	166.5	131.8	21%	114.7	13%	102.0	23%	95.1	28%	91.6	31%	101.9	23%	105.5	20%	90.7	31%	107.0	19%
WWR 60	186.9	152.4	18%	129.7	15%	111.2	27%	102.4	33%	97.4	36%	112.3	26%	109.6	28%	95.6	37%	109.4	28%
AVERAGE																			
WWR 15	122.1	90.4	26%	87.0	4%	85.0	6%	86.2	5%	88.3	2%	81.8	10%	102.5	-13%	80.9	11%	104.6	-16%
WWR 30	136.8	102.7	25%	95.3	7%	87.7	15%	84.3	18%	84.0	18%	86.7	16%	100.7	2%	81.6	21%	102.9	0%
WWR 45	153.1	118.4	23%	105.8	11%	94.4	20%	87.4	26%	84.9	28%	93.3	21%	100.1	15%	84.6	29%	102.5	13%
WWR 60	169.9	135.4	20%	119.0	12%	102.6	24%	93.1	31%	88.5	35%	101.1	25%	101.6	25%	88.2	35%	103.2	24%

* no TC: base glazing without thermochromic layer (see Table 3)

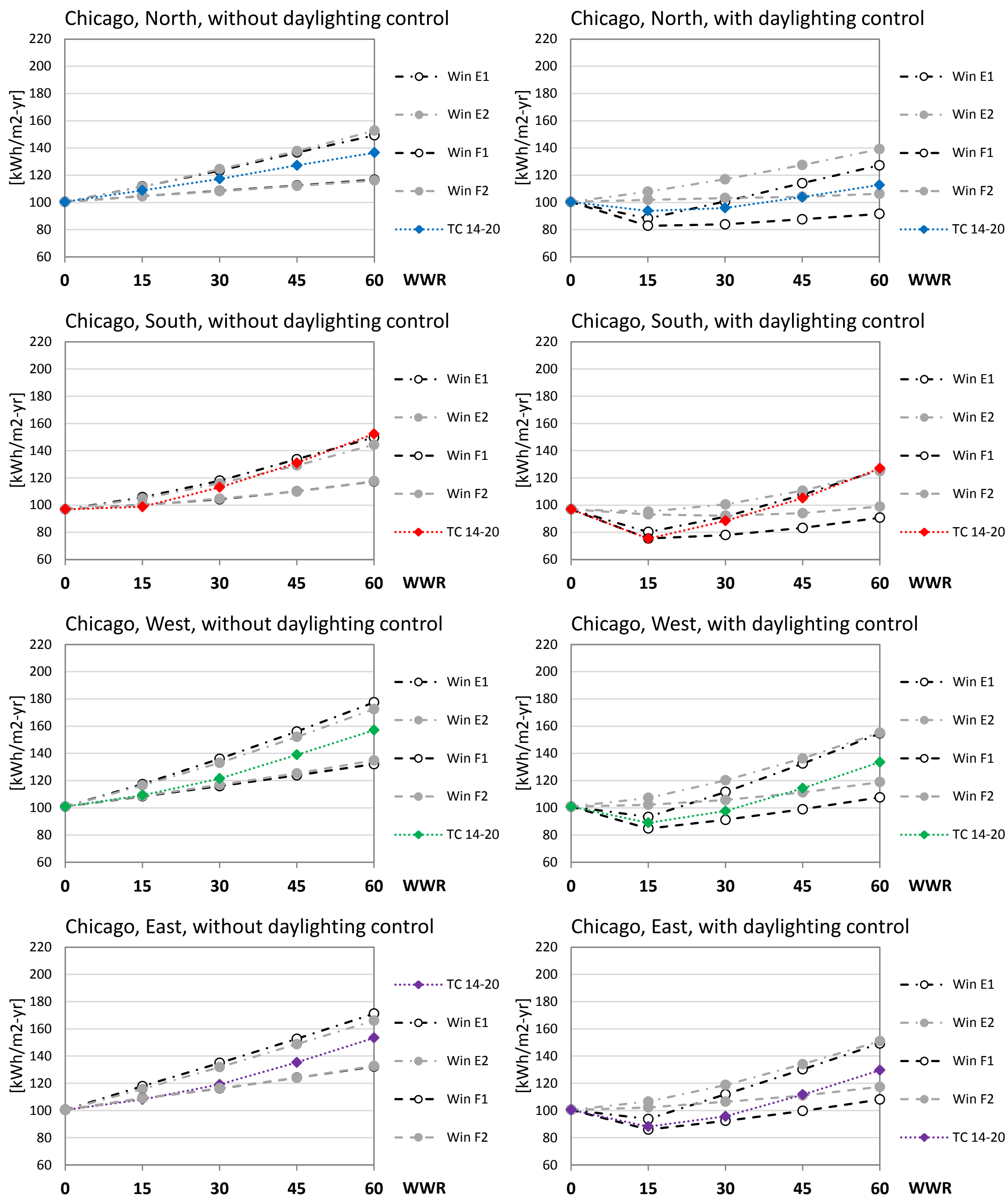
** no DC/DC: with/without daylighting control

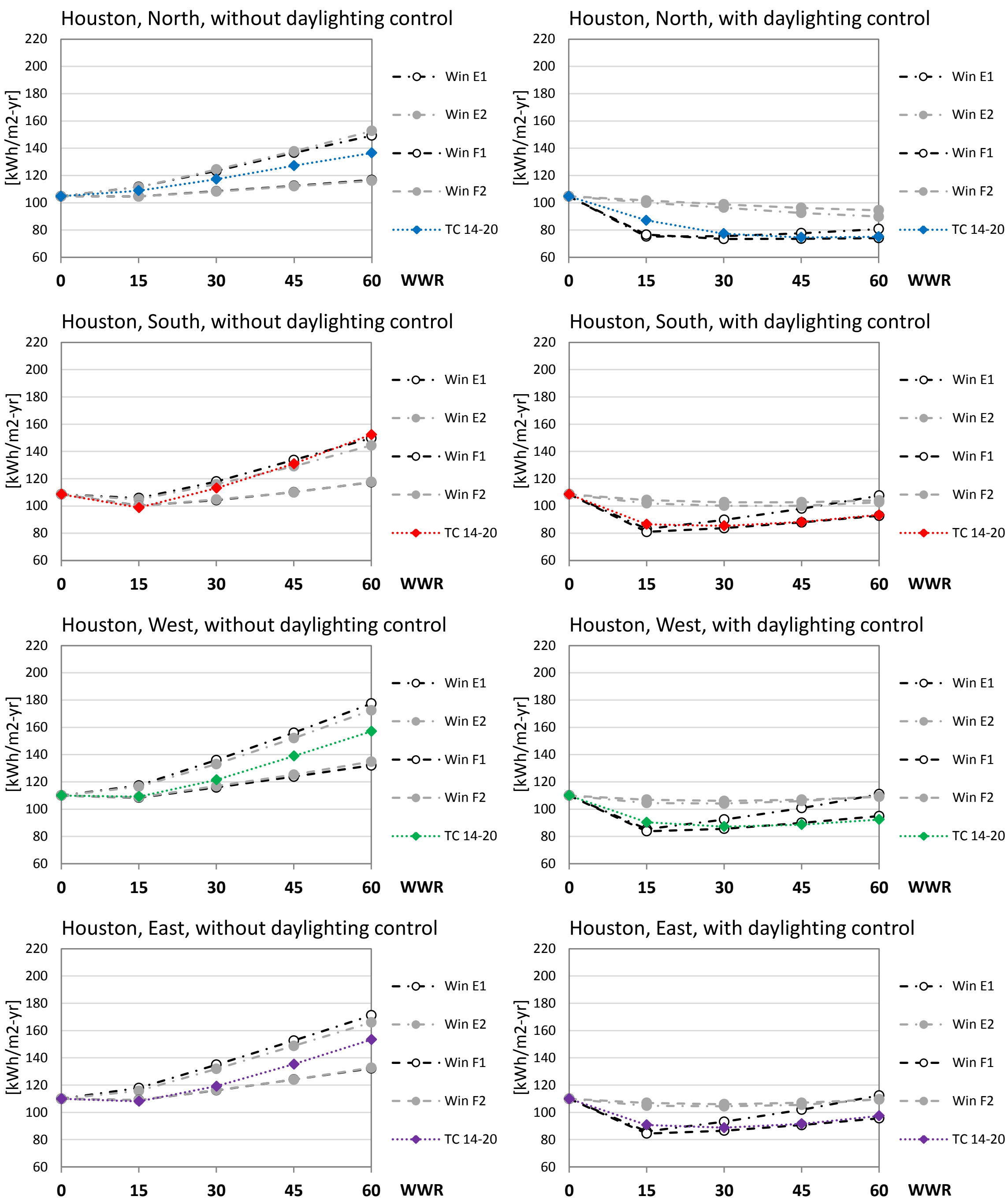
Annual total source energy use intensity (kWh/m2-floor-yr) including heating, cooling, fan and lighting energy with daylighting control for the reference window "No TC", four thermochromic windows and spectrally selective high-performance windows (see Table 3) as a function of window-to-wall-area (WWR) ratio for four window orientations and the Houston climate.

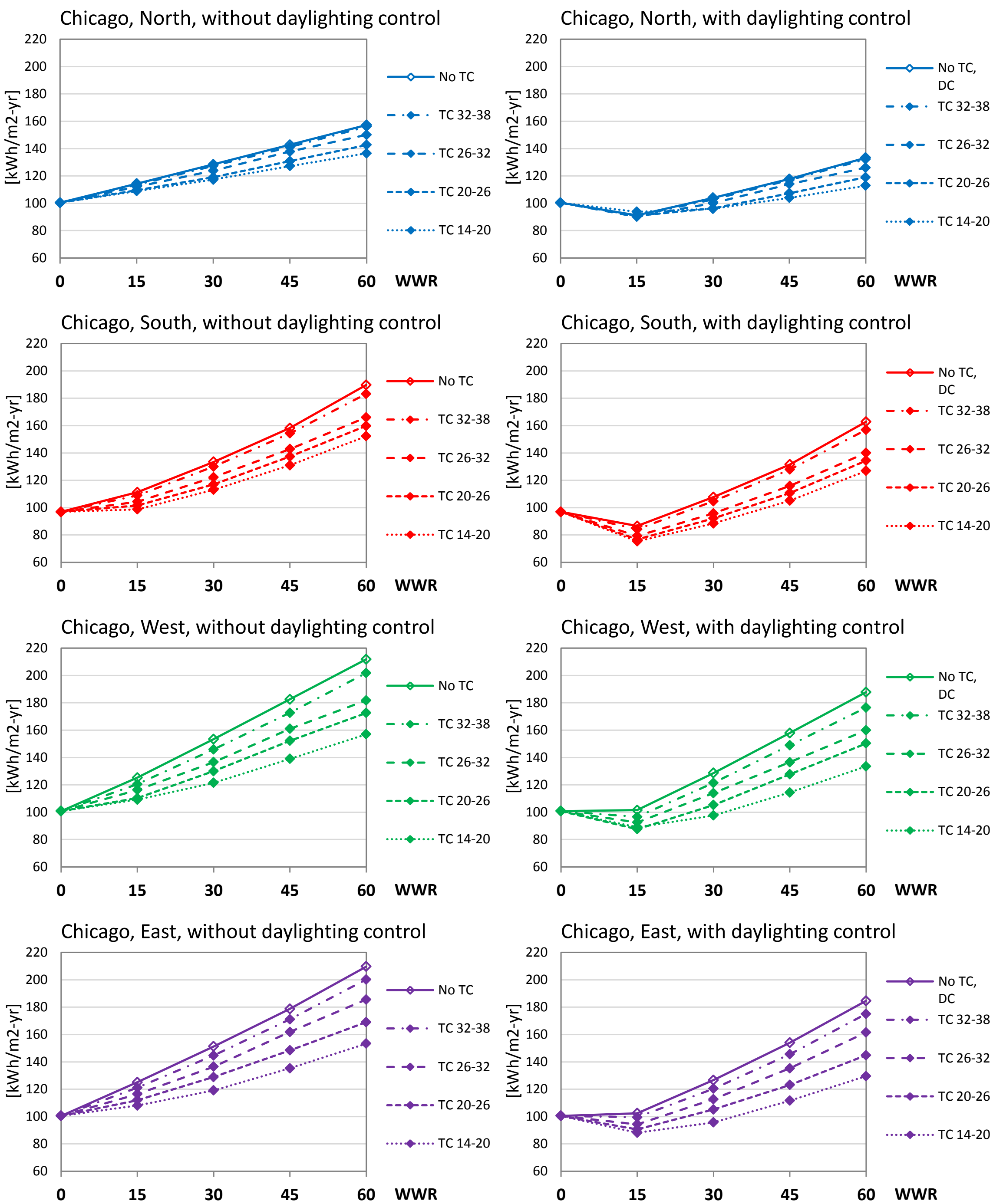
HOUSTON	No TC*, no DC**	No TC*, DC**		TC 32-38 DC**		TC 26-32 DC**		TC 20-26 DC**		TC 14-20 DC**		Win E1 DC**		Win E2 DC**		Win F1 DC**		Win F2 DC**	
	Source total [kWh/m2-yr]	Source total [kWh/m2-yr]	Savings compared to No TC, no DC	Source total [kWh/m2-yr]	Savings compared to No TC, DC	Source total [kWh/m2-yr]	Savings compared to No TC, DC	Source total [kWh/m2-yr]	Savings compared to No TC, DC	Source total [kWh/m2-yr]	Savings compared to No TC, DC	Source total [kWh/m2-yr]	Savings compared to No TC, DC	Source total [kWh/m2-yr]	Savings compared to No TC, DC	Source total [kWh/m2-yr]	Savings compared to No TC, DC	Source total [kWh/m2-yr]	Savings compared to No TC, DC
NORTH																			
WWR 15	366.6	264.7	28%	263.5	0%	263.0	1%	275.0	-4%	286.6	-8%	246.9	7%	329.2	-24%	251.8	5%	334.9	-27%
WWR 30	387.7	275.2	29%	271.1	1%	252.9	8%	246.8	10%	254.1	8%	247.2	10%	316.6	-15%	241.4	12%	325.3	-18%
WWR 45	409.9	295.4	28%	286.1	3%	258.8	12%	244.5	17%	244.7	17%	253.5	14%	303.2	-3%	241.8	18%	317.0	-7%
WWR 60	431.2	317.1	26%	304.8	4%	267.6	16%	247.3	22%	246.0	22%	262.5	17%	293.4	7%	243.5	23%	310.8	2%
SOUTH																			
WWR 15	413.7	306.3	26%	295.2	4%	283.3	7%	281.1	8%	285.4	7%	273.8	11%	336.0	-10%	267.0	13%	344.1	-12%
WWR 30	472.2	359.0	24%	333.5	7%	305.5	15%	290.1	19%	281.7	22%	295.5	18%	329.8	8%	276.0	23%	338.8	6%
WWR 45	536.6	421.1	22%	376.0	11%	334.3	21%	305.5	27%	290.6	31%	321.4	24%	328.7	22%	289.7	31%	338.6	20%
WWR 60	603.1	488.5	19%	429.6	12%	369.6	24%	332.2	32%	306.9	37%	350.6	28%	336.1	31%	305.4	37%	342.9	30%
WEST																			
WWR 15	419.3	313.7	25%	291.3	7%	283.6	10%	290.2	7%	297.5	5%	280.8	10%	344.1	-10%	276.0	12%	352.5	-12%
WWR 30	477.2	363.4	24%	320.8	12%	295.6	19%	284.9	22%	287.1	21%	302.9	17%	341.9	6%	281.6	23%	349.2	4%
WWR 45	540.2	424.6	21%	357.0	16%	317.8	25%	295.3	30%	291.4	31%	328.7	23%	346.5	18%	295.9	30%	352.1	17%
WWR 60	605.4	489.7	19%	401.2	18%	344.9	30%	313.3	36%	303.1	38%	359.5	27%	355.8	27%	311.7	36%	358.4	27%
EAST																			
WWR 15	421.4	317.8	25%	302.9	5%	295.7	7%	295.6	7%	299.0	6%	282.9	11%	345.3	-9%	278.2	12%	352.5	-11%
WWR 30	479.9	367.7	23%	334.0	9%	307.6	16%	296.2	19%	292.4	20%	305.3	17%	343.4	7%	284.9	23%	349.3	5%
WWR 45	544.0	428.7	21%	372.3	13%	332.5	22%	310.7	28%	300.9	30%	332.6	22%	345.4	19%	298.4	30%	352.5	18%
WWR 60	607.9	492.4	19%	417.9	15%	359.4	27%	331.8	33%	318.4	35%	364.7	26%	356.9	28%	314.1	36%	360.0	27%
AVERAGE																			
WWR 15	402.2	297.6	26%	286.4	4%	279.7	6%	284.0	5%	290.9	2%	268.9	10%	337.4	-13%	266.5	10%	344.7	-16%
WWR 30	449.4	336.5	25%	312.3	7%	288.1	14%	277.3	18%	276.6	18%	284.4	15%	331.0	2%	268.5	20%	339.0	-1%
WWR 45	500.8	385.6	23%	344.5	11%	308.0	20%	286.2	26%	279.1	28%	304.7	21%	328.0	15%	278.3	28%	337.6	12%
WWR 60	552.9	438.1	21%	384.1	12%	332.0	24%	302.9	31%	290.2	34%	328.8	25%	331.4	24%	289.8	34%	339.8	22%

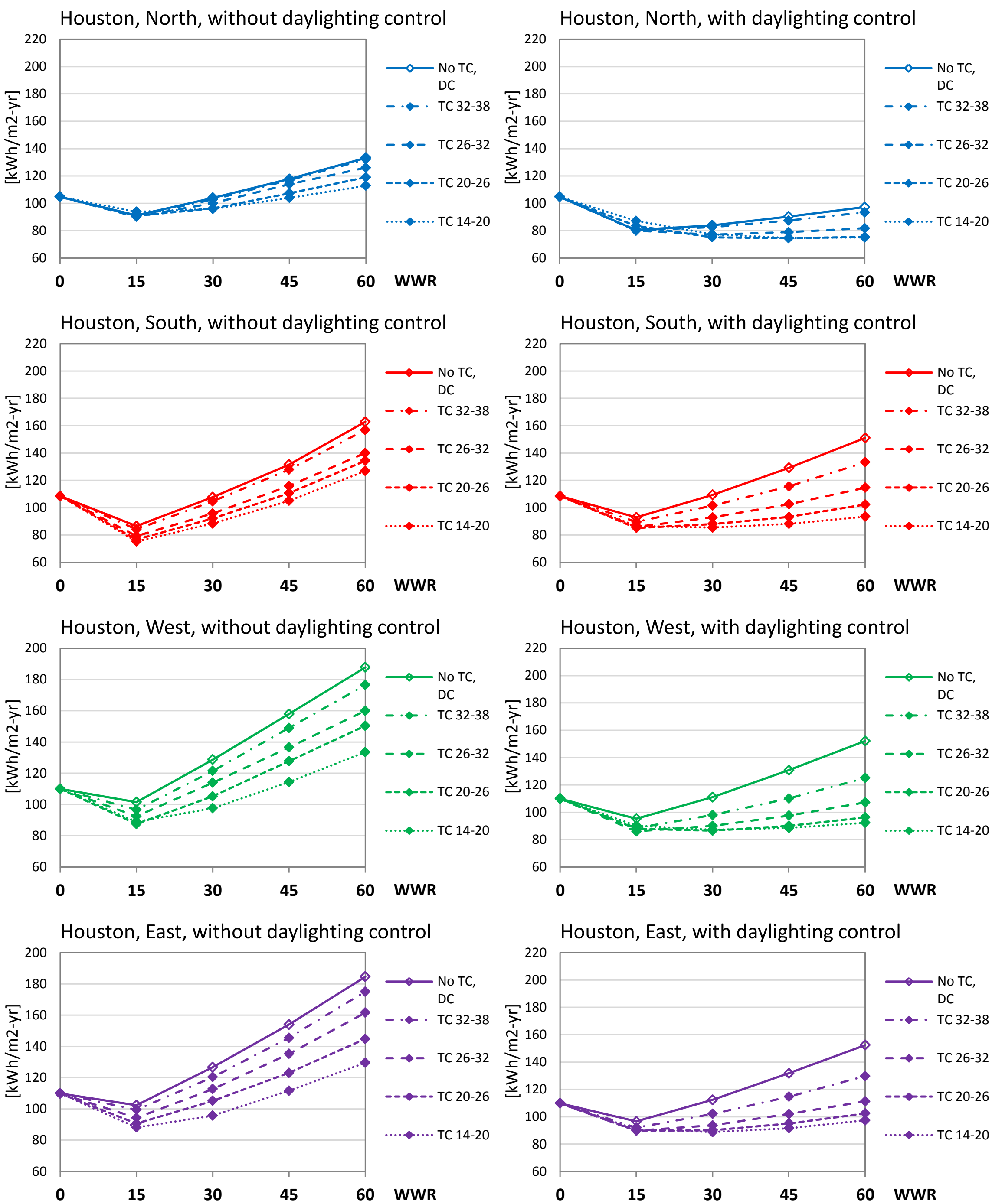
* no TC: base glazing without thermochromic layer (see Table 3)

** no DC/DC: with/without daylighting control


Chicago, North, without daylighting control
Chicago, North, with daylighting control
Chicago, South, without daylighting control
Chicago, South, with daylighting control
Chicago, West, without daylighting control
Chicago, West, with daylighting control
Chicago, East, without daylighting control
Chicago, East, with daylighting control
[kWh/m2-yr]
WWR
Win E1
Win E2
Win F1
Win F2
TC 14-20
0
15
30
45
60
60
80
100
120
140
160
180
200
220


Houston, North, without daylighting control
Houston, North, with daylighting control
Houston, South, without daylighting control
Houston, South, with daylighting control
Houston, West, without daylighting control
Houston, West, with daylighting control
Houston, East, without daylighting control
Houston, East, with daylighting control
[kWh/m2-yr]
220
200
180
160
140
120
100
80
60
0
15
30
45
60
WWR
Win E1
Win E2
Win F1
Win F2
TC 14-20


Chicago, North, without daylighting control
Chicago, North, with daylighting control
Chicago, South, without daylighting control
Chicago, South, with daylighting control
Chicago, West, without daylighting control
Chicago, West, with daylighting control
Chicago, East, without daylighting control
Chicago, East, with daylighting control
[kWh/m2-yr]
220
200
180
160
140
120
100
80
60
0
15
30
45
60
WWR
No TC
No TC, DC
TC 32-38
TC 26-32
TC 20-26
TC 14-20


Houston, North, without daylighting control
Houston, North, with daylighting control
Houston, South, without daylighting control
Houston, South, with daylighting control
Houston, West, without daylighting control
Houston, West, with daylighting control
Houston, East, without daylighting control
Houston, East, with daylighting control
[kWh/m2-yr]
220
200
180
160
140
120
100
80
60
0
15
30
45
60
WWR
No TC, DC
TC 32-38
TC 26-32
TC 20-26
TC 14-20