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Abstract

A DOE-2.1E energy simulation analysis of a switchable electrochromic (EC) glazing with daylighting controls has been conducted for prototypical office buildings in New York (NY). The modeling included four types of office buildings: "old" and "new" vintages and large (10,405 m^2, 112,000 ft^2) and small (502 m^2, 5400 ft^2) buildings. Five commercially-available, base case windows with and without interior shades were modeled. Window area varied from 0 to 60% of the exterior floor-to-floor wall area. The electric lighting had either no controls or continuous daylighting controls. The prototypes were modeled in New York City or Buffalo.

Energy performance data are given for each of the four perimeter zones. Data are presented as a function of window-to-wall ratio in order to better understand the interactions between 1) electric lighting energy use and daylight admission and 2) solar heat gains and space-conditioning energy use. Maximum and minimum reductions in energy use between the EC glazing and all other base case conditions are also presented. Projected energy use reductions relative to typical specified NY office buildings are presented as an indication of the potential impacts EC glazings might have in retrofit and new construction.

The energy and demand reductions provided by EC glazings with daylighting controls relative to what is typically specified in office buildings in NY are quite substantial. EC glazings will also dampen fluctuations in interior daylight levels and window brightness, potentially increasing visual comfort.

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1. Introduction

Electrochromic glazings promise to be the next major advance in energy-efficient window technology, helping to transform windows and skylights from an energy liability to an energy source for the nation's building stock. Electrochromic glazing can be reversibly switched from a clear to a transparent, colored state by means of a small applied voltage, resulting in thermal

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and optical properties that can be dynamically controlled. "Smart windows" incorporating electrochromic glazings could reduce peak electric loads by 20 to 30% in many commercial buildings and provide added daylighting benefits throughout the US, as well as improve comfort and enhance productivity in our homes and offices. These technologies will provide maximum flexibility in aggressively managing energy use in buildings in the emerging deregulated utility environment and will move the building community toward the goal of producing advanced buildings that have minimal impact on the nation's energy resources. Customer choice will be further enhanced by the flexibility to dynamically control envelope-driven cooling and lighting loads.

Building simulations have been performed to predict the energy performance of electrochromic windows in commercial buildings [Sullivan et al. 1997]. Lighting energy performance data have also been measured in limited full-scale tests using large-area electrochromic windows [Lee et al. 2000]. Additional studies to better understand the performance of such windows in real-world applications are planned. No simulation study has been conducted to quantify the potential impacts of electrochromic windows on commercial buildings situated in New York. Hence, this study examines the energy-efficiency impacts of EC glazings for several generic building characteristics and climates of New York State. Such data may serve to help stakeholders, such as utilities, building owners, and consumers, improve their understanding of the potential performance benefits of this emerging technology.

2. Method

Building energy simulations of standard and advanced electrochromic glazings were performed using the DOE-2.1E building energy simulation program (version 112) [Winkelmann et al. 1993]. The DOE-2 program is the building industry standard that requires as input a geometrical description of the building and a physical description of the building construction, heating, ventilating, air-conditioning (HVAC) equipment, end use load schedules, utility rates, and hourly weather data to determine the energy consumption of the building.

2.1. Building Module

Four commercial office prototypes were defined in order to determine energy impacts relative to typical new and vintage commercial office building stock of New York:

- Large office, old vintage
- Large office, new vintage
- Small office, old vintage
- Small office, new vintage

The basic framework of the prototypical buildings, including geometry, operating schedules, and thermal zoning was based on the existing Pacific Northwest National Laboratory (PNNL) three-story office prototype [Friedrich and Messinger 1995]. However, to more closely model the characteristics of commercial buildings in New York, several modifications to the PNL prototype were made. These modifications were based on a separate study by Huang and Franconi [1998], where prototypes ("HF") were developed based on a statistical analysis of the

Table 1
Characteristics of Modeled Office Prototypes

	Large Office Old	Large Office New	Small Office Old	Small Office New
Building area (ft^2)	112,000	112,000	5,400	5,400
Floors	7	7	2	2
Shell				
Percent glass	0.45	0.45	0.15	0.15
Glass Type (see Table 2)	Clear IGU	Bronze IGU	Clear IGU	Bronze IGU
Window U-value (Btu/h-ft^2-°F)	0.56	0.57	0.56	0.49
Window SHGC	0.69	0.62	0.69	0.62
Window Tv	0.78	0.62	0.78	0.62
Wall R-value (Btu/h-ft^2-°F)	2.5	4.6	4.9	6.3
Roof R-value (Btu/h-ft^2-°F)	9.1	9.1	11.9	13.3
Wall material	masonry	masonry	masonry	masonry
Roof material	built-up	built-up	built-up	built-up
Equipment power density (W/ft^2)	0.75	0.75	0.5	0.5
Electric lighting				
Lighting power density (W/ft^2)	1.8	1.3	2.2	1.7
Minimum dimming power	20%	33%	20%	33%
System and plant characteristics				
System type	SZRH	VAV	PSZ	PSZ with econ
Heating plant	Gas boiler	Gas boiler	None	None
Cooling plant	Open Centrifugal chiller	Hermetic Centrifugal chiller	None	None
Service hot water	Gas boiler	Gas boiler	Gas boiler	Gas boiler

1989 Commercial Building Energy Consumption Survey (CBECS) [EIA 1992] to determine the average building conditions (size, levels of insulation, window type and area, etc.) within that building population. The CBECS database of building characteristics for the North and South regions of the US is based on survey data collected at building sites throughout the nation. The HF prototypes were not used directly because they consist of hypothetical geometries that reflect typical conditions and because daylighting requires modeling of actual physical spaces.

The number of floors, opaque shell conditions, and lighting and equipment end-use intensities of the PNNL prototype were modified to match the values of the HF prototypes. Building floor areas were matched as closely as possible, given the constraints of actual physical geometries. Window area and glass type were also closely matched; parametrics runs were used to derive data for the exact matching conditions. If daylighting control systems were modeled, old vintage buildings were assumed to use the older ballasts with a minimum power fraction of 33%, while new buildings were modeled with new ballast products that have a minimum power fraction of 20%. For the HVAC system, we matched the category defined in the Huang and Franconi study, using input from the PNNL prototype to define the variable-air volume (VAV), single-zone constant volume reheat (SZRH), and packaged single-zone (PSZ) systems.

Table 1 lists prototypical building conditions. The large office building prototype consists of seven floors with four perimeter zones, oriented to face the four cardinal directions, and one

Table 2
Glazing Properties

	Match*	Percent window area	U-value Btu/h-ft²-°F	U-value W/m²-°C	SHGC	Tv	Graph code
HF Prototype:							
Large Office - Old	a	40%	0.69	3.91	0.69	NA	
Large Office - New	b	50%	0.58	3.29	0.59	NA	
Small Office - Old	c	20%	0.57	3.23	0.68	NA	
Small Office - New	d	15%	0.50	2.84	0.61	NA	
Modeled base case glazings:							
Clear single-pane			1.09	6.18	0.82	0.88	1001
Clear IGU	a&c		0.56	3.18	0.69	0.78	2003
Bronze IGU	b&d		0.49	2.78	0.62	0.62	2201
Selective tint IGU			0.29	1.65	0.28	0.41	2667
Selective clear IGU			0.29	1.65	0.42	0.68	2664
Modeled electrochromic glazing:							
Bleached			0.33	1.90	0.46	0.59	2980
Colored			0.33	1.90	0.09	0.02	2981

* Match: The modeled glazing that best matches the characteristics defined by the HF prototype.
SHGC: center-of-glass solar heat gain coefficient; Tv: center-of-glass visible transmittance; IGU: Insulating glass unit; HF: Huang and Franconi study [1998].

central 30.5x30.5 m (100x100 ft) core zone per floor. Each perimeter zone consists of ten 3.0x4.7x2.7 m (10x15x9 ft) offices. The small office building prototype consists of two floors with four perimeter zones, oriented to face the four cardinal directions, and one central 9.1x9.1 m (30x30 ft) core zone. Each perimeter zone consists of three 3.0x4.7x2.7 m (10x15x9 ft) office spaces. All spaces for both the large and small office prototypes have 0.9 m (3 ft) high unconditioned plenums.

2.2. Windows

Discrete, punched windows were modeled in the exterior wall of each perimeter zone. Glazing area was varied from 0% to 60% window-to-wall ratio (WWR); where the wall area is defined as the floor-to-floor exterior wall area, and the floor-to-floor height is 3.66 m (12 ft). The size and position of the windows were identical between the base case and electrochromic glazing simulations.

Several types of base case glazing were selected, based on a) matching the HF prototype glazing properties (variants of double-pane bronze glazing or single-pane clear glazing) and b) modeling alternate advanced commercially-available glazing options for retrofit and new construction (Table 2).

A 3 mm (0.12 in) prototype electrochromic (EC) glazing was modeled. Measured solar-optical data taken at LBNL for the bleached and colored states (Figure 1). Data for a 6 mm (0.24 in) EC, typical of commercial construction, was not available. The EC glazing was modeled to switch linearly between these two states. The EC glazing was assumed to have an emissivity of 0.84 on the exterior surface and 0.15 on the interior. The EC glazing was com-

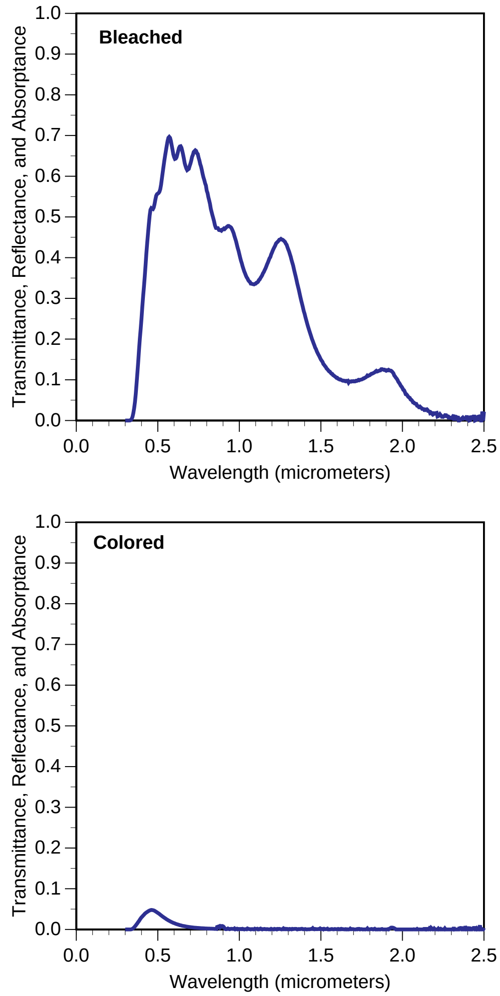

Figure 1. Measured total solar transmittance (T) data for the bleached and colored states of the 3 mm electrochromic glazing layer as a function of wavelength.

bined with a 3 mm (0.12 in) interior clear glazing layer with a 12.7 mm (0.5 in) wide air gap.

The electrochromic window was switched so as to provide 510 lux (50 fc) at 3.0 m (10 ft) from the window wall, centered on the window, and at a work plane height of 0.76 m (2.5 ft) every hour during daylight hours. If there was insufficient daylight, the window was switched to fully bleached. If there was too much daylight, the window was switched to fully colored. This strategy is called "daylight control" and is best used to minimize cooling loads and lighting energy use.

The base case windows were modeled with and without an interior diffusing shade. The electrochromic window was modeled without a shade. The shade was modeled as manually operated where the shade was drawn down completely by the occupant for daylight hours if direct sun or glare was present. The shade is triggered if the transmitted direct solar radiation exceeded 94.5 W/m^2 (30 Btu/h-ft^2) or if the daylighting glare index computed using the Hopkinson Cornell-BRS formula exceeded 22 ("just uncomfortable"). With the shade drawn, the visible transmittance of the glazing is reduced by 65% and the solar heat gain coefficient (SHGC) by 40%. No other exterior or interior obstructions were modeled.

2.3. *Lighting System*

Recessed fluorescent lighting systems were modeled for all prototypes. The lighting power density varied between prototypes and vintages (Table 1). Heat from the lighting system was apportioned to the interior space (60%) and to the unconditioned plenum (40%). Ballasts were modeled with a minimum power consumption of 33% (old vintage) and 20% (new vintage). The lights were dimmed linearly (continuous dimming) according to the daylight available at the work plane reference point given above for EC switching so as to top up the daylight to 510 lux (50 fc) at 3.0 m (10 ft) from the window wall, centered on the window, and at a work plane height of 0.76 m (2.5 ft) every hour during daylight hours. If no daylighting controls were specified, the lighting was assumed to be at 100% power, but governed, as in the daylighting case, by the occupancy schedule.

2.4. *HVAC System*

Five separate HVAC systems were employed: one for each perimeter zone facing a particular orientation and one for the core zone. Such zoning allowed us to isolate heating and cooling energy use to a particular window orientation. A variable-air-volume system was used for the new vintage large office prototype. A single-zone reheat system was used for the old vintage large office prototype. Packaged single-zone systems with and without economizer were defined for the new and old vintage small office prototypes, respectively. Plenums were unconditioned.

Perimeter zone cooling electric use data were determined using system-level extraction loads converted to plant-level electric use with a fixed coefficient of performance (COP) of 3.0. Perimeter zone heating energy use data were determined using system-level extraction loads converted to plant-level energy use with a fixed heating efficiency factor (HEF) of 0.8. The COP and HEF efficiency factors represent system-to-plant efficiency, not component-level equipment efficiencies such as those given in ASHRAE 90.1. Such a procedure was necessary since the DOE-2.1E program does not separate zonal energy at the plant level. Peak electric demand data are also given for the peak condition that occurs in each perimeter zone and are non-coincident with the whole building's peak condition. These perimeter zone data enable equitable comparisons to be made across the entire dataset.

The HVAC capacity of the heating and cooling systems were also determined. For the large office prototypes, DOE-2 was allowed to automatically size the plant equipment for each parametric run to ensure realistic part-load-ratio operations. The central plant consisted of an open-centrifugal chiller, cooling tower, and hot-water boiler. For the small office prototypes, sizing of the packaged single-zone system capacity was also automatically determined by DOE-2. HVAC capacities are given here for the whole building and are therefore not consistent with the perimeter zone data presented throughout this report. However, DOE-2 does not allow PLANT-level capacities to be assigned to specific building zones, therefore we present these data as an indication of potential HVAC capacity reductions that may result from the use of EC glazings.

2.5. *Energy Cost*

Two different electricity-to-natural-gas fuel-cost ratios (FR) of 1:1 and 5:1 were assumed for this analysis. This range allows one to gauge the effect of potentially different pricing forecast scenarios that may occur in New York.[1]

2.6. Parametrics

The following parametrics were performed for each of the building prototypes:

Climates:	New York City, Buffalo
Glazing area:	0, 0.15, 0.30, 0.45, 0.60 window-to-wall ratio (WWR)
Glazings:	single-pane clear, clear insulating glass unit (IGU), bronze IGU, spectrally-selective tinted IGU, spectrally-selective clear IGU, "457" electrochromic with daylight control
Daylighting controls:	Base case glazings with and without controls, electrochromic glazings with controls
Interior shade:	Base case glazings with and without shade, electrochromic glazings without shade

3. Results

Annual energy and peak demand data are presented as a function of window-to-wall ratio (WWR) for all cases (four building prototypes, perimeter zone orientation, interior shades, daylighting controls, and glazing types) in Figures 2-9. For each building prototype and climate, we show the following sub-figures (a-f):

- Figure 2. Large Office, Old Vintage, NYC
  - a) Annual Lighting Energy Use
  - b) Annual Cooling Energy Use
  - c) Total Annual Electricity Use
  - d) Total Peak Electricity Demand
  - e) Annual Heating Energy Use
  - f) Energy Cost, Fuel Ratio 1:1
  - g) Energy Cost, Fuel Ratio 5:1
- Figure 3a-3g. Large Office, New Vintage, NYC
- Figure 4a-4g. Small Office, Old Vintage, NYC
- Figure 5a-5g. Small Office, New Vintage, NYC
- Figure 6a-6g. Large Office, Old Vintage, Buffalo
- Figure 7a-7g. Large Office, New Vintage, Buffalo
- Figure 8a-7g. Small Office, Old Vintage, Buffalo
- Figure 9a-9g. Small Office, New Vintage, Buffalo

All parts of Figure 2 are shown in the following pages, as well as part (c) of Figures 3-9. The complete Figures 3-9 are given in the Appendix. Each line on these graphs represents a single glazing type, as noted in the legend. Refer to the glass code in Table 2 for glass types. The EC glazing is noted as "sage457n2-p3". All data have been normalized to the perimeter zone floor area. All EC data are given for the same case: daylight control of the EC glazing and daylighting controls (no interior shades). Data for this EC case are shown side-by-side with all base case conditions.

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[1] The fuel-cost ratio of 5:1 was suggested as indicative of New York state-wide averages [Carver 2001].

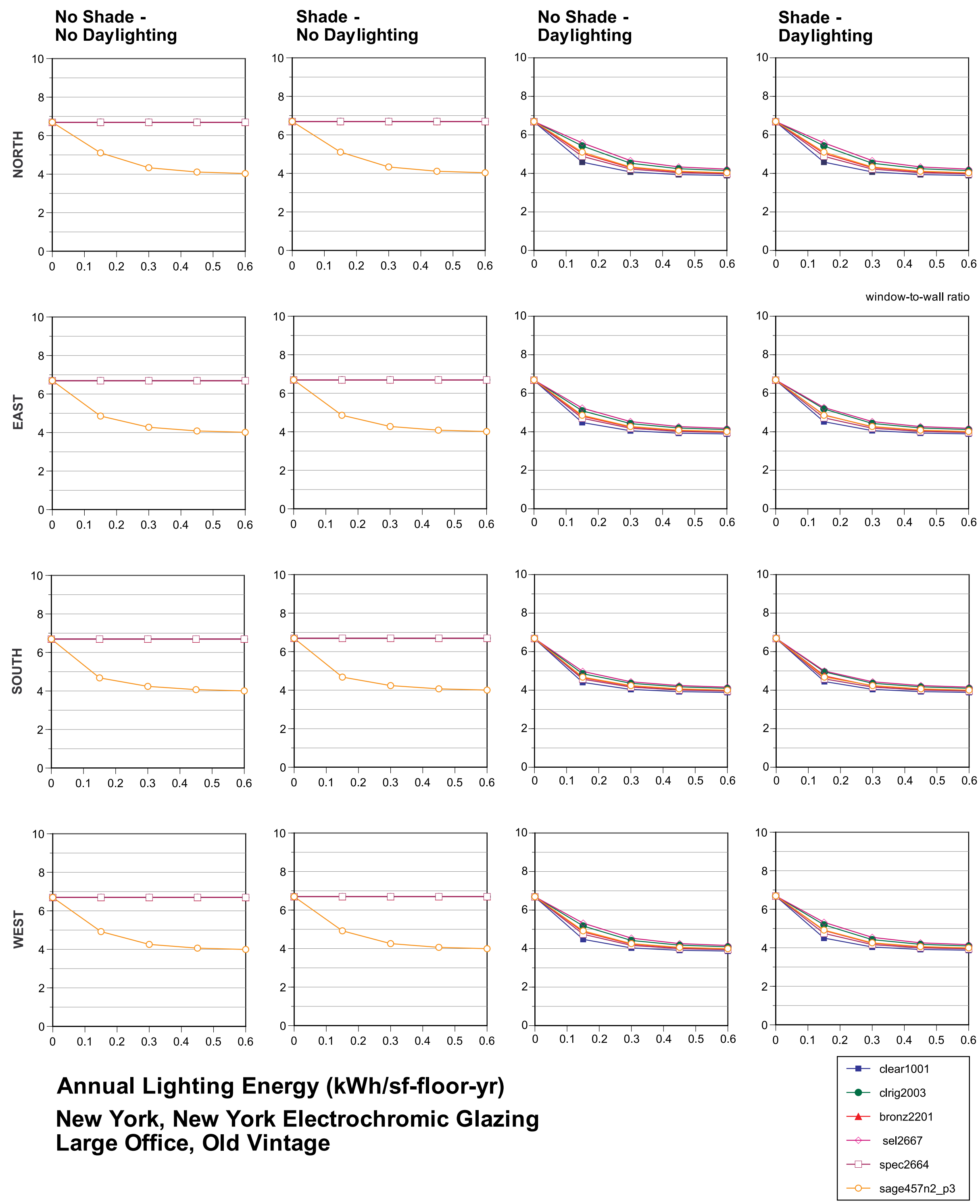


Figure 2a. Annual lighting energy use for an old large office in New York, New York.

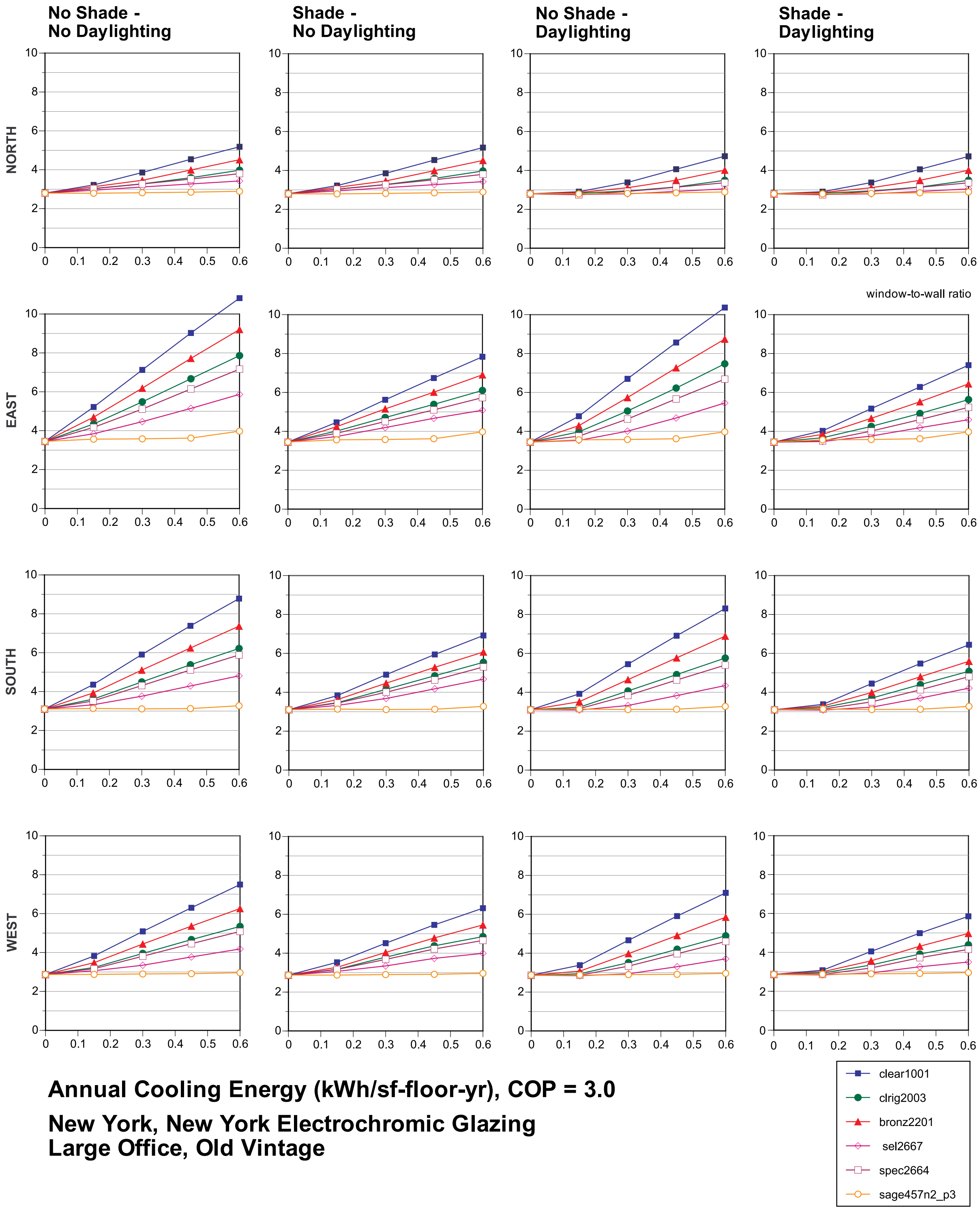


Figure 2b. Annual cooling energy use for an old large office in New York, New York.

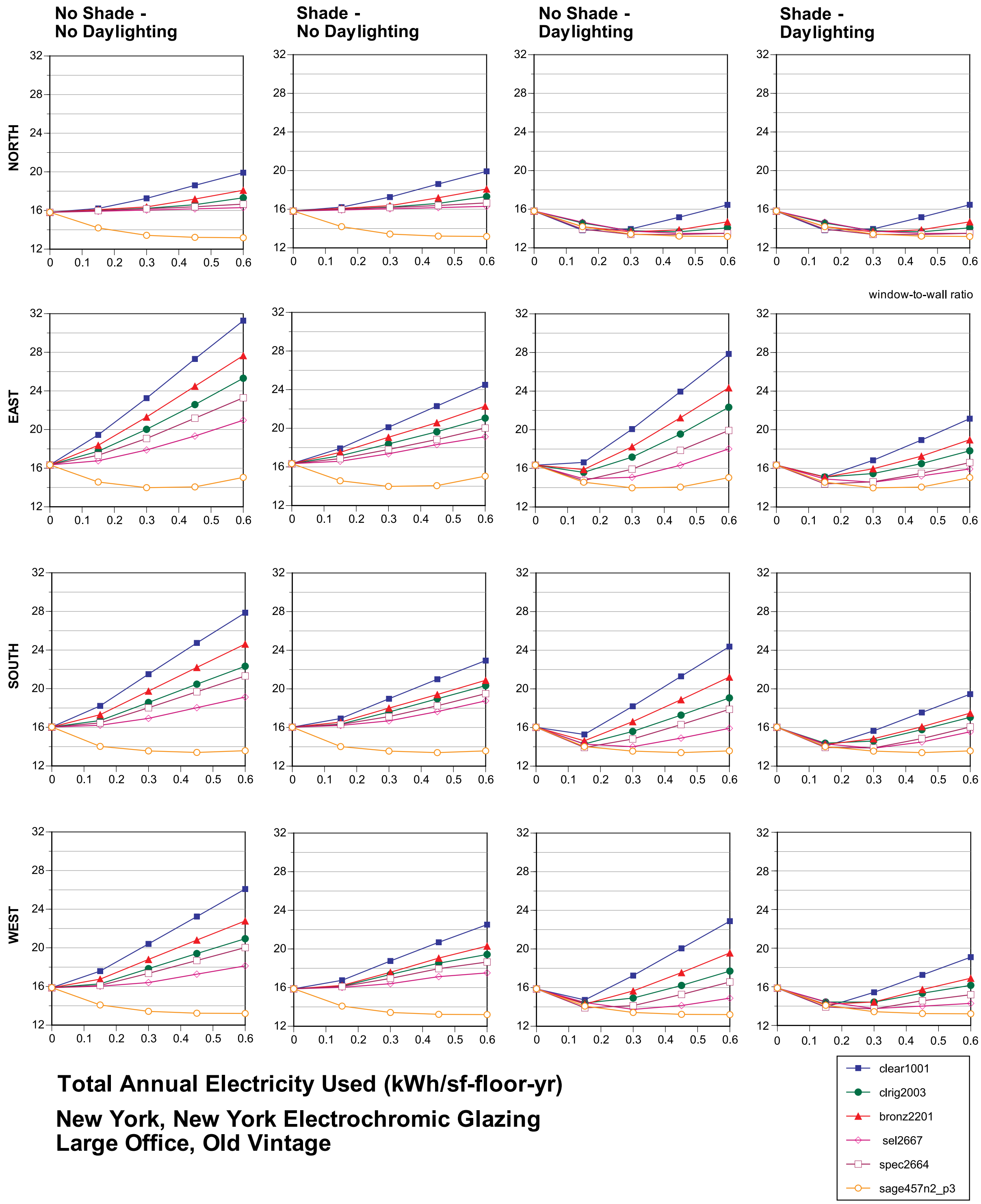


Figure 2c. Annual total electricity use for an old large office in New York, New York.

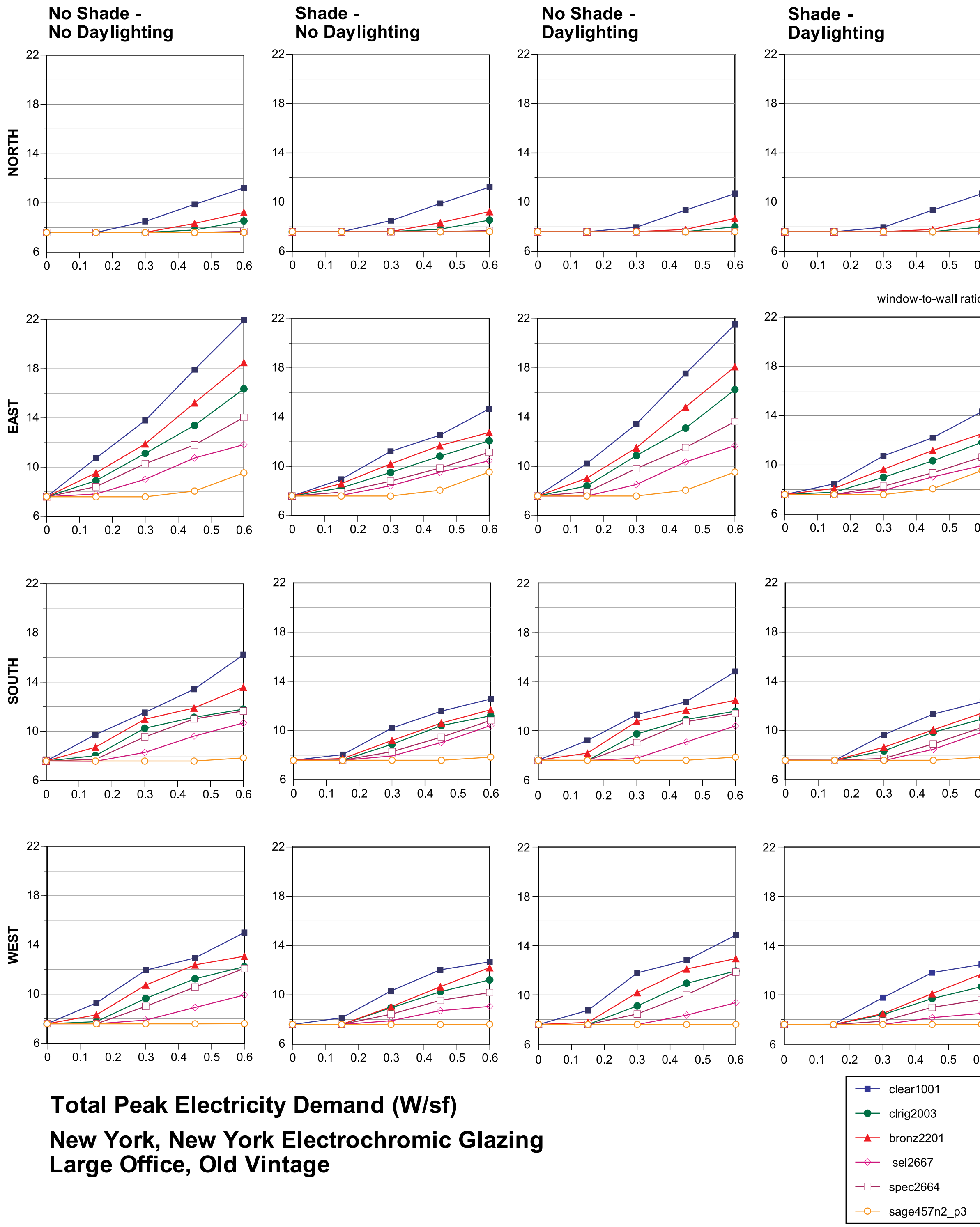


Figure 2d. Total peak electricity use for an old large office in New York, New York.

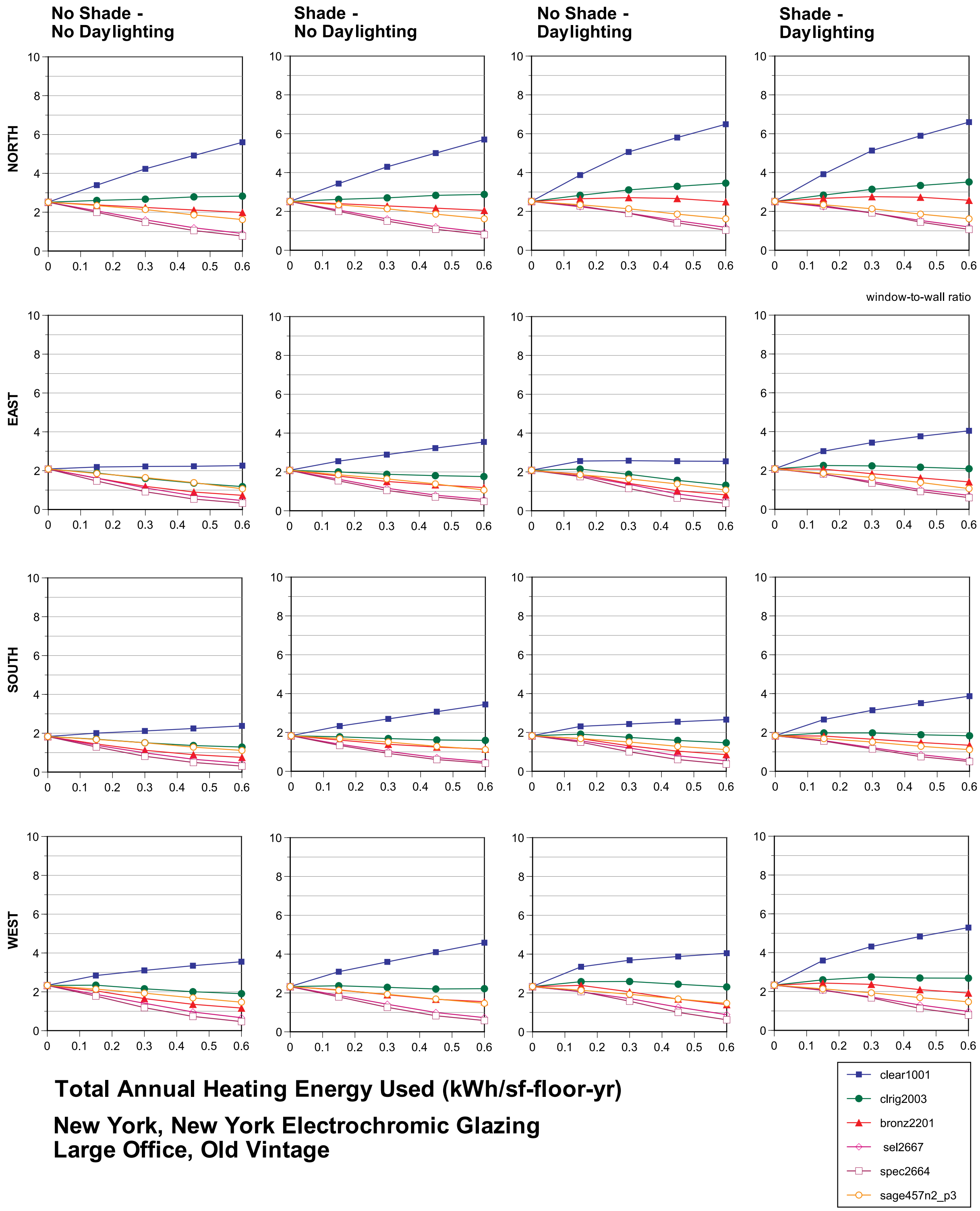


Figure 2e. Annual total heating energy use for an old large office in New York, New York.

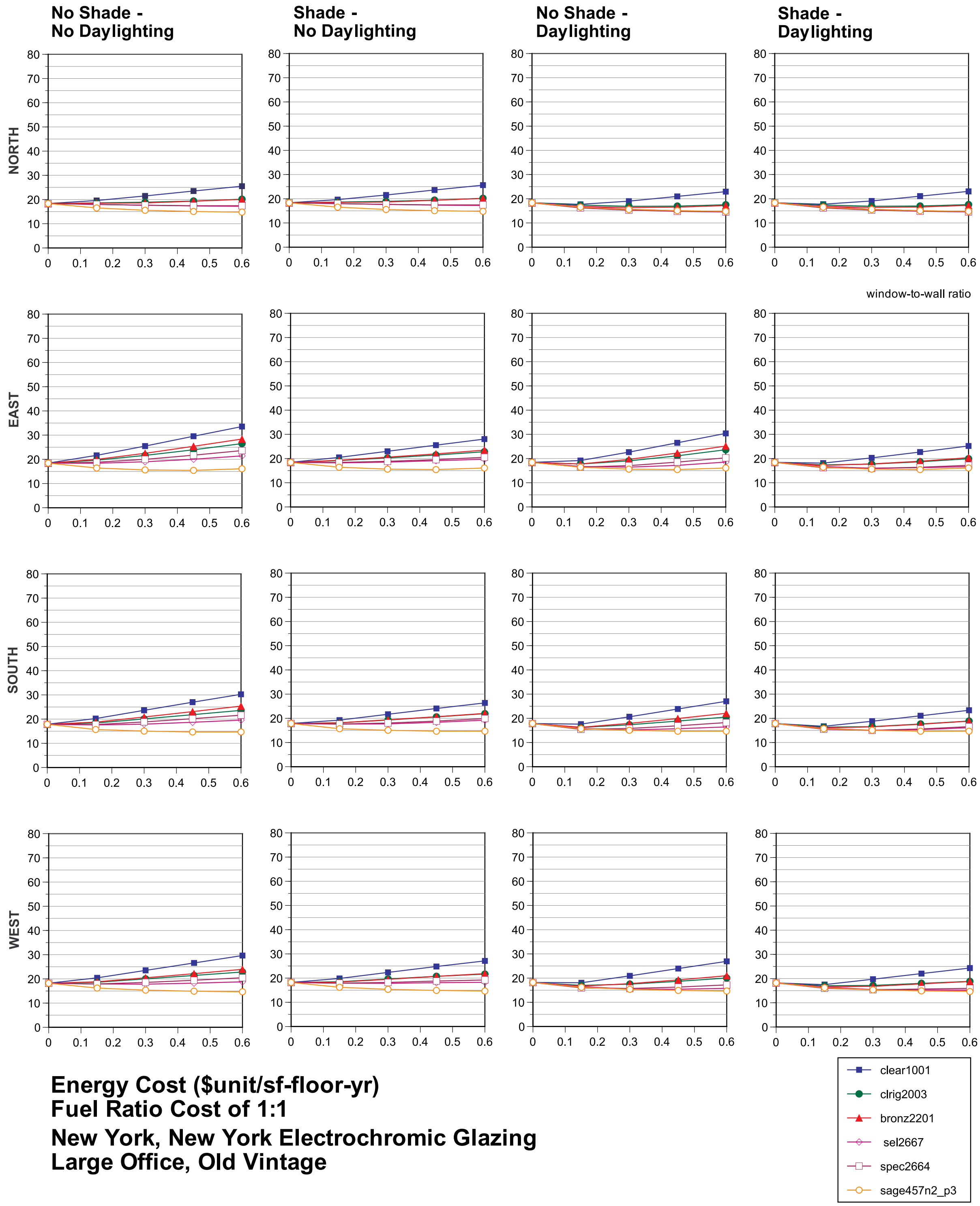


Figure 2f. Annual total energy cost (fuel ratio 1:1) for an old large office in New York, New York.

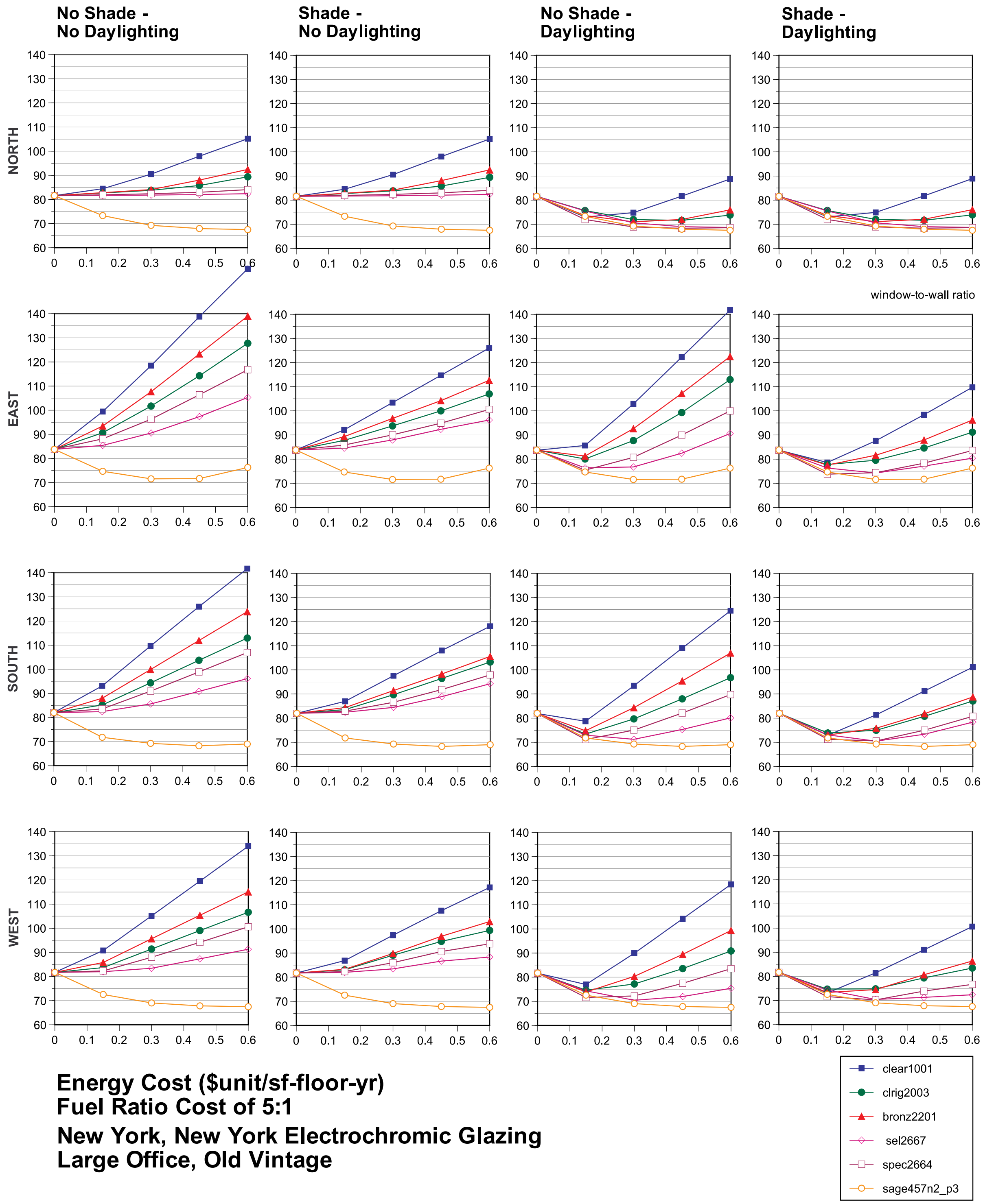


Figure 2g. Annual total energy cost (fuel ratio 5:1) for an old large office in New York, New York.

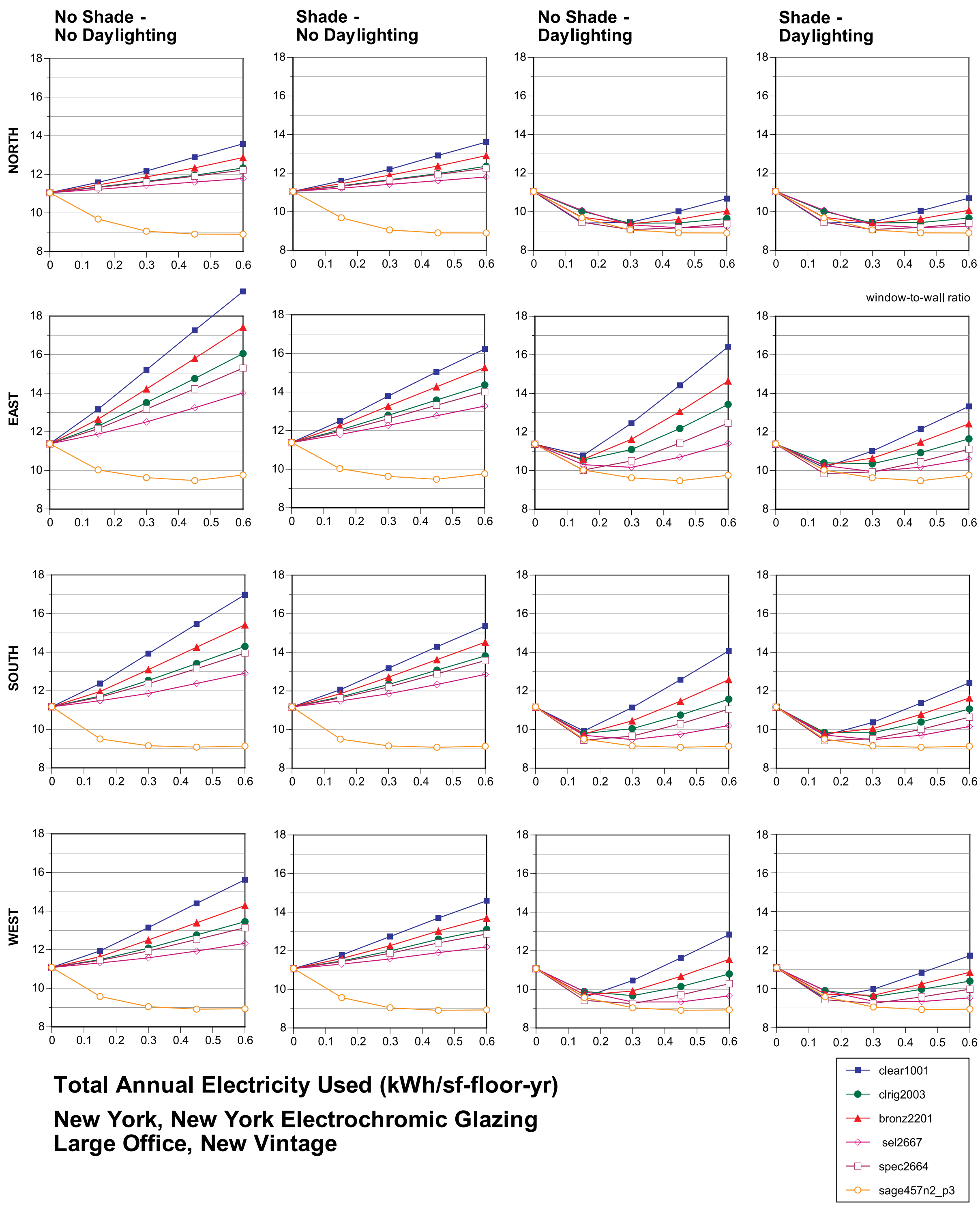


Figure 3c. Annual total electricity use for a new large office in New York, New York.
(Complete set of Figures are given in the Appendix.)

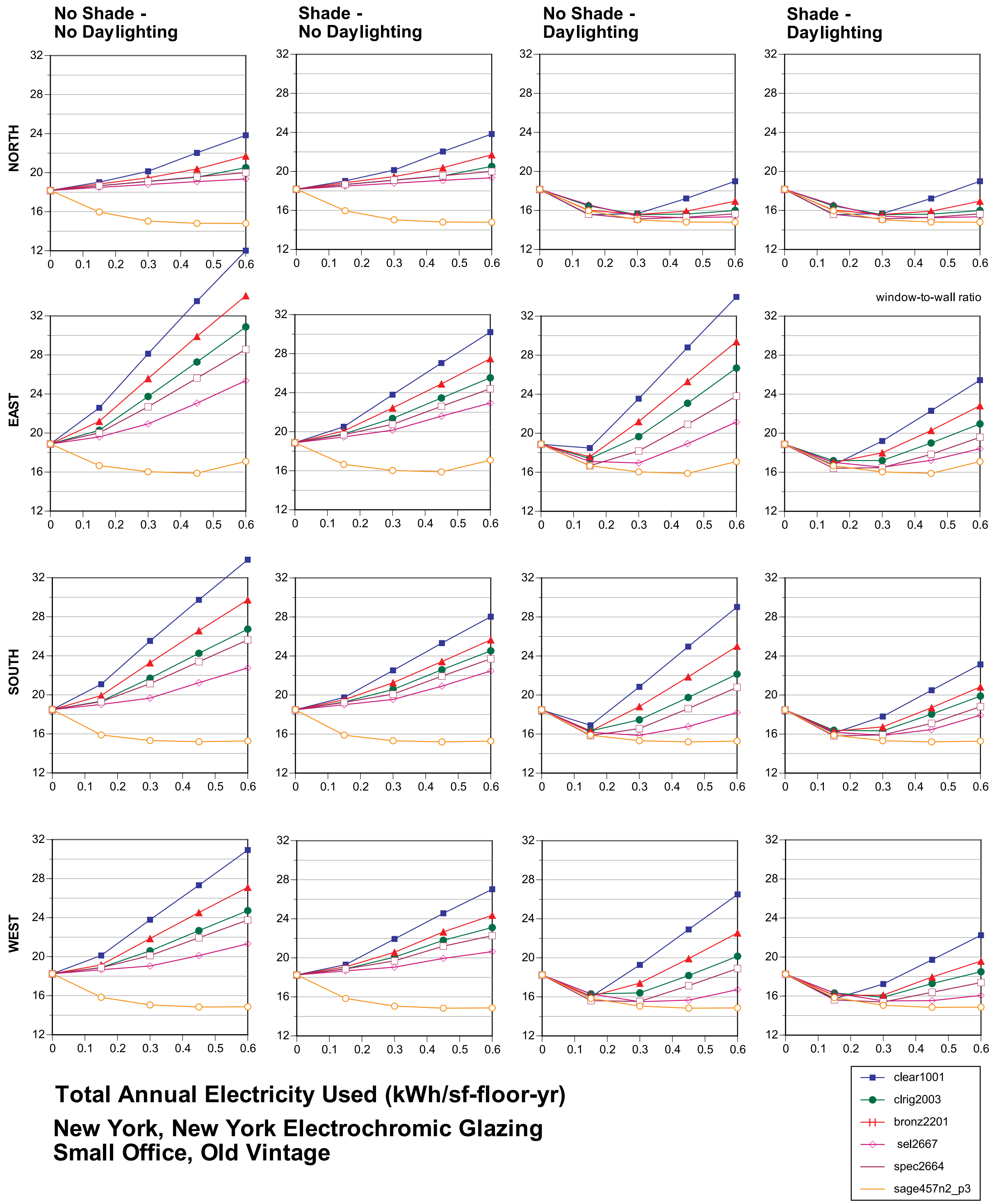


Figure 4c. Annual total electricity use for an old small office in New York, New York. (Complete set of Figures are given in the Appendix.)

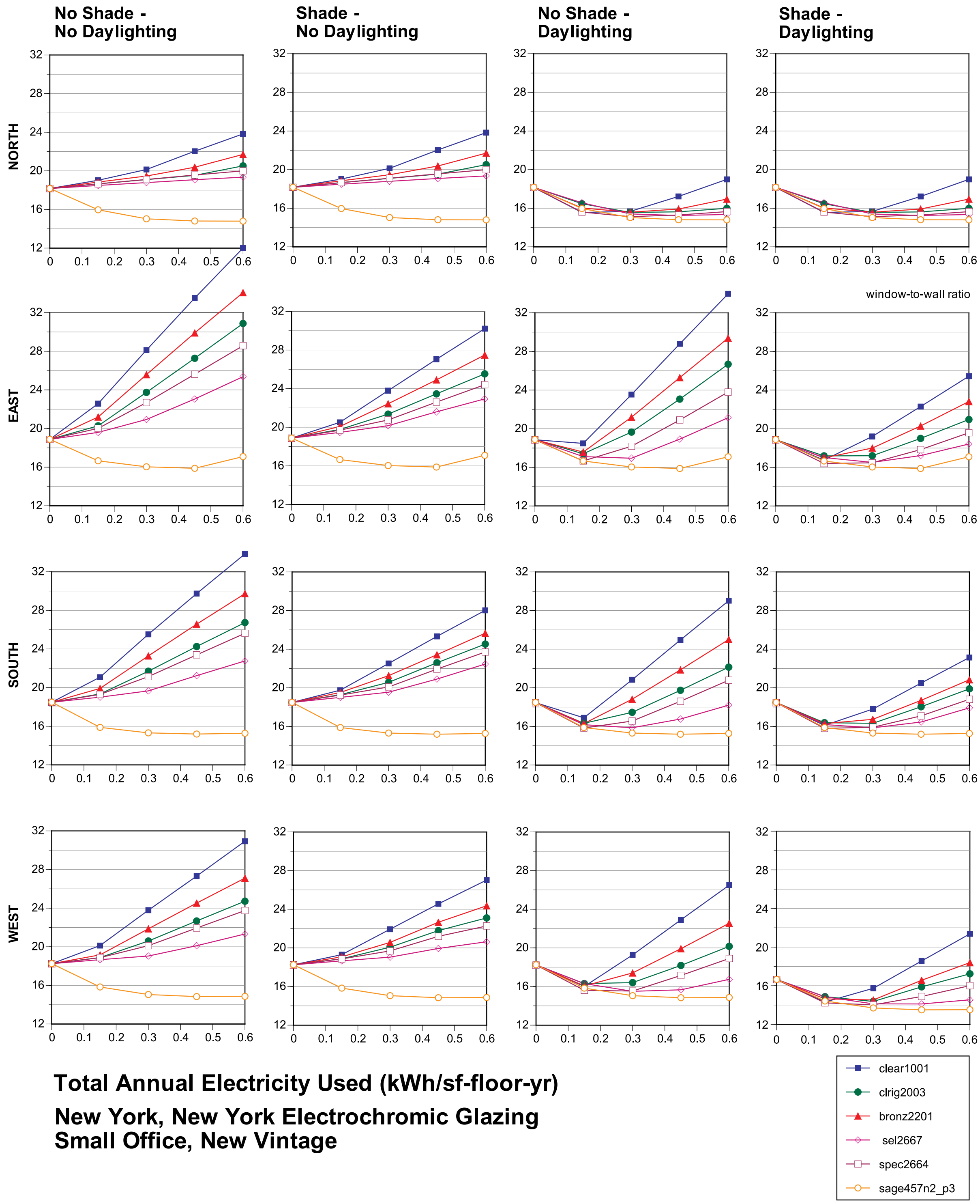


Figure 5c. Annual total electricity use for a new small office in New York, New York. (Complete set of Figures are given in the Appendix.)

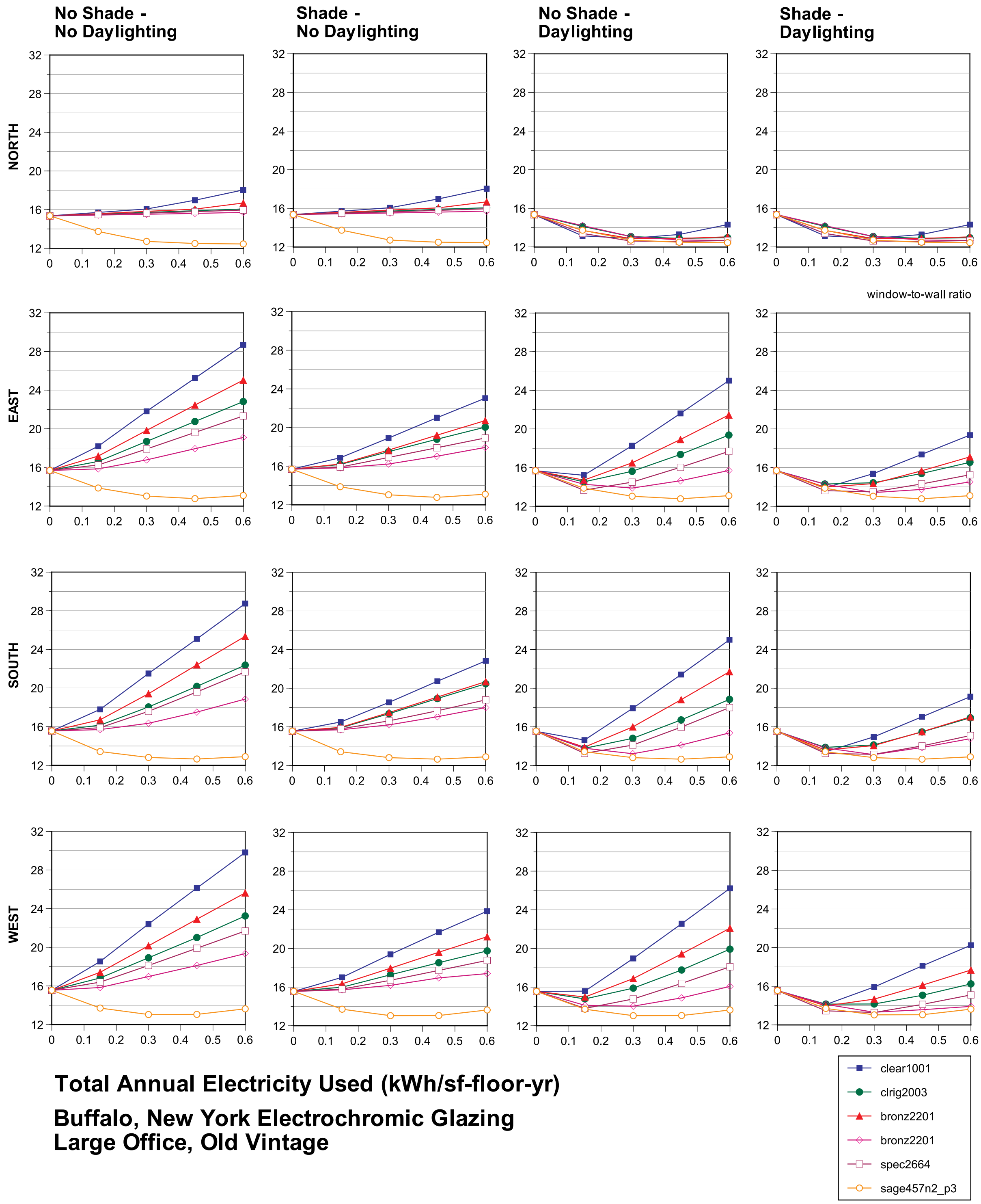


Figure 6c. Annual total electricity use for an old large office in Buffalo, New York.
(Complete set of Figures are given in the Appendix.)

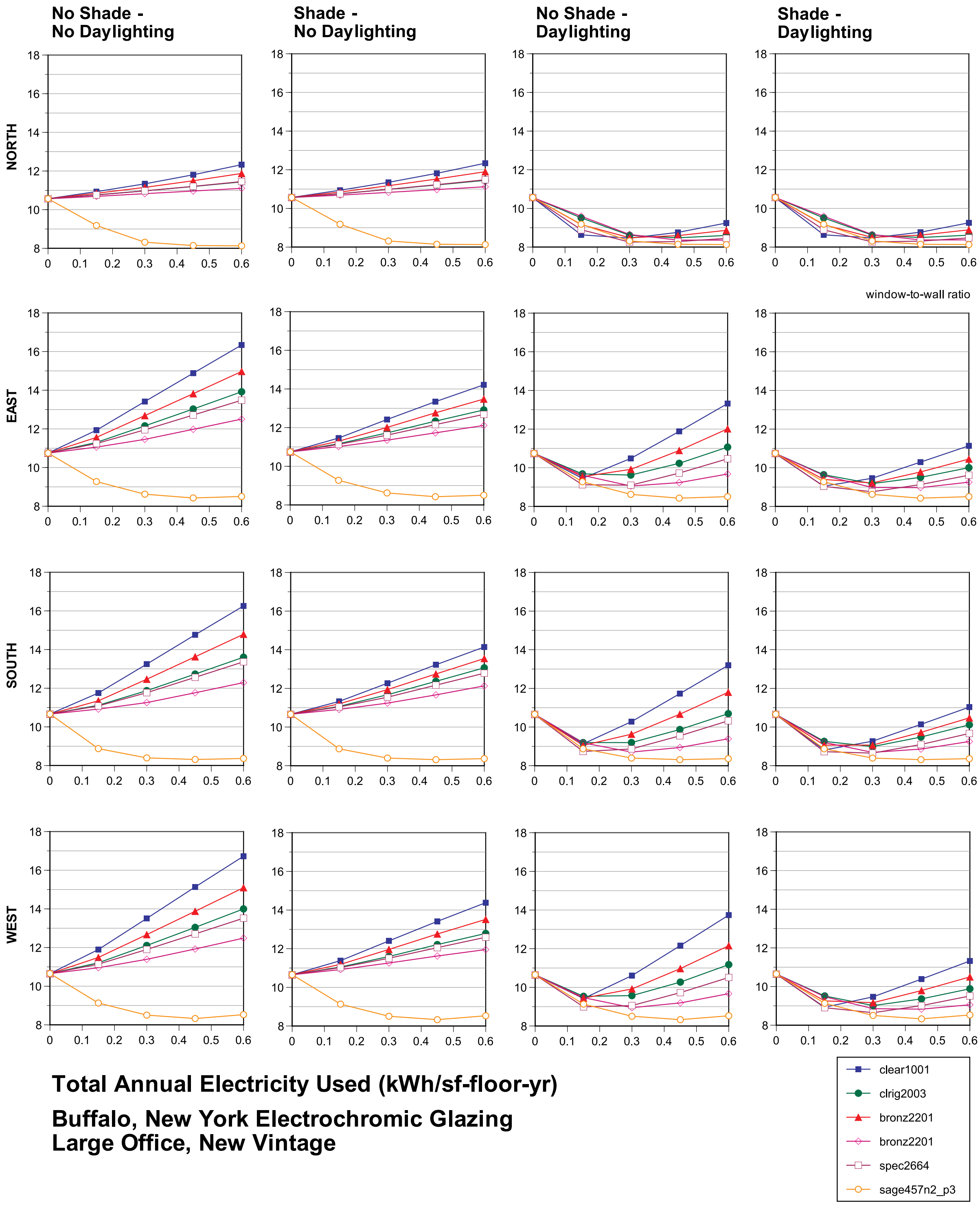


Figure 7c. Annual total electricity use for a new large office in Buffalo, New York. (Complete set of Figures are given in the Appendix.)

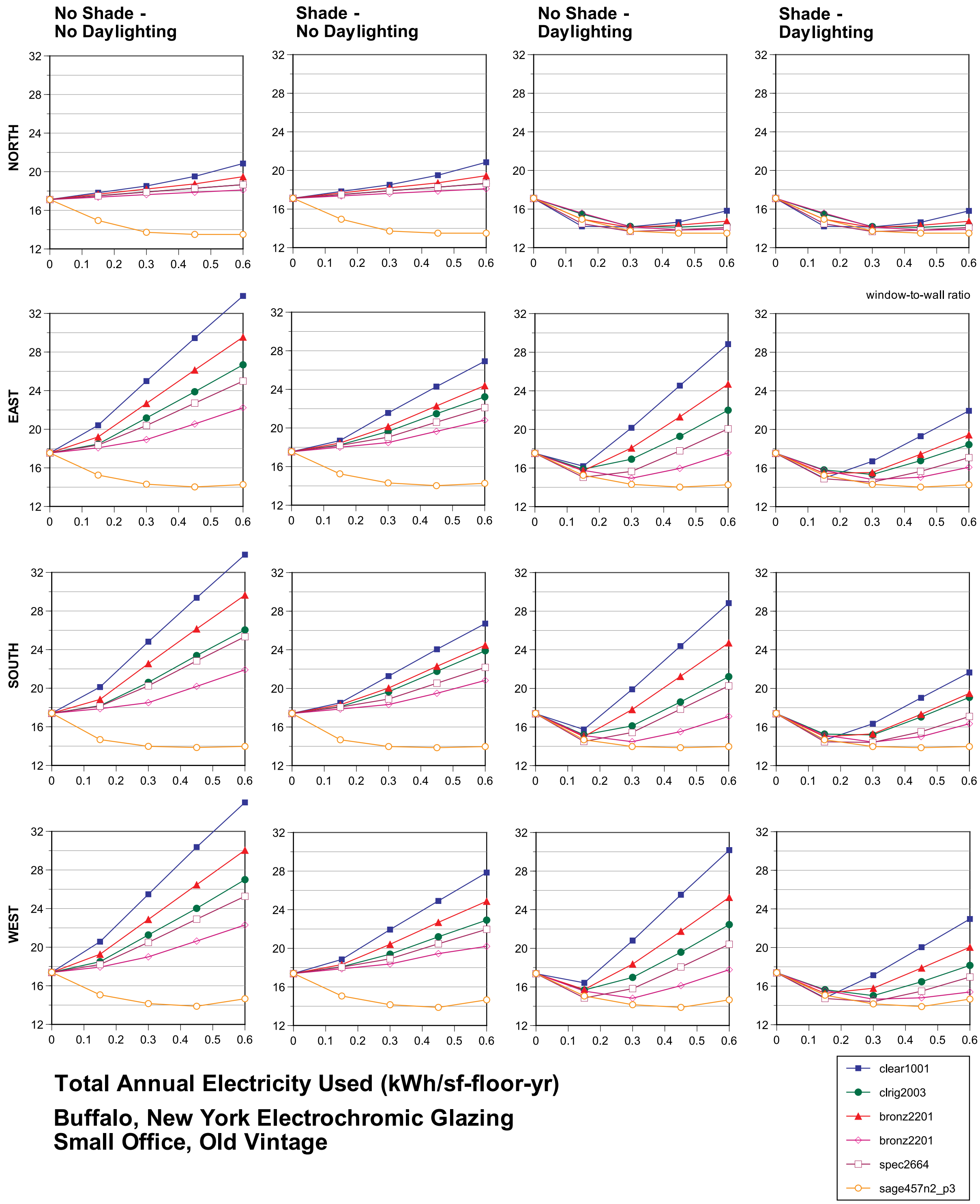


Figure 8c. Annual total electricity use for an old small office in Buffalo, New York. (Complete set of Figures are given in the Appendix.)

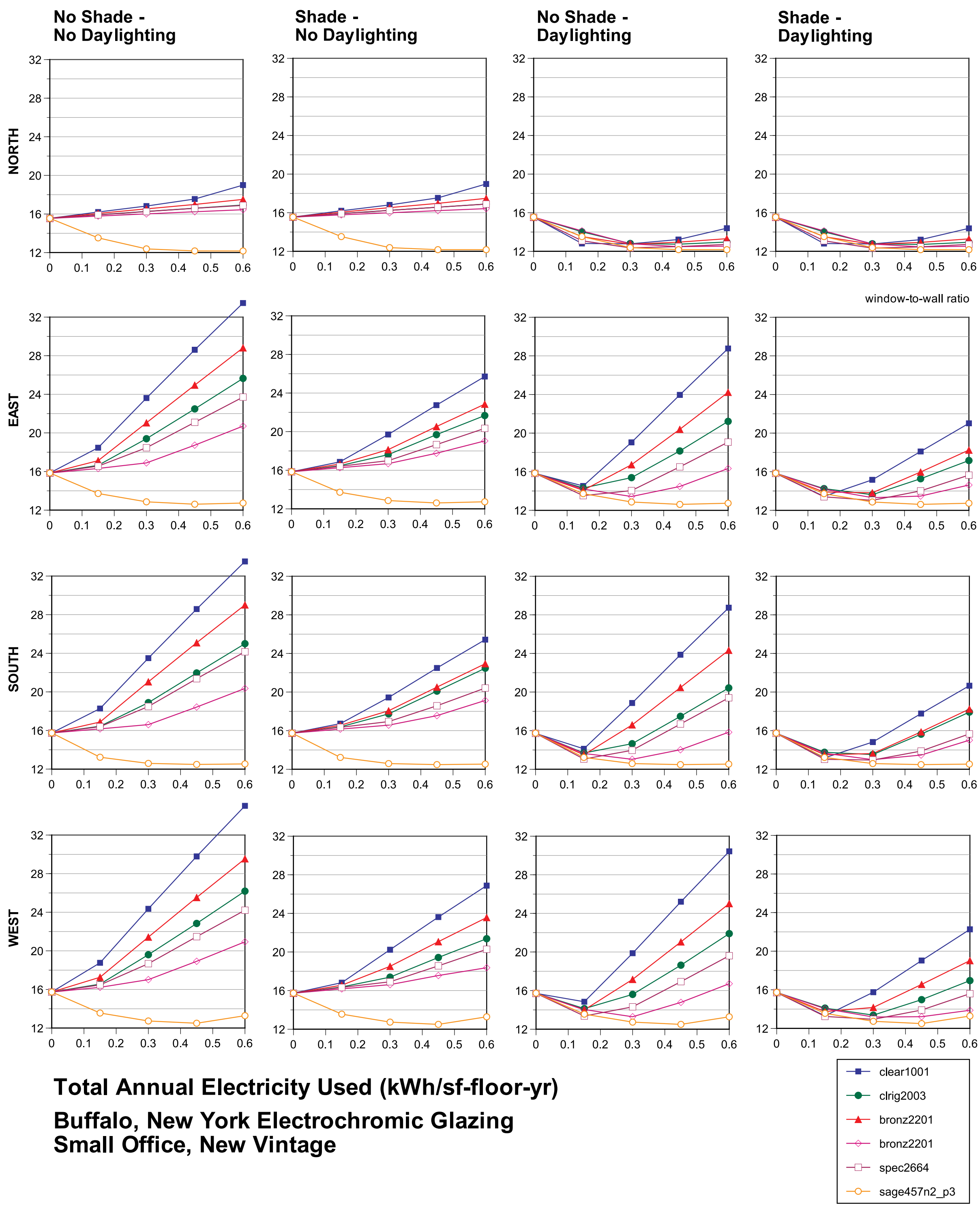


Figure 9c. Annual total electricity use for a new small office in Buffalo, New York. (Complete set of Figures are given in the Appendix.)

Table 3.1
Maximum Perimeter Zone Savings or Percentage Reductions by Electrochromic Glazings – Large Office Prototypes, New York, New York

Base case has daylighting?		Lighting Energy	Cooling Energy	Electric Total	Peak Demand	Heating Energy	Energy Cost 1:1	Energy Cost 1:5
		Large Office, Old Vintage, NYC						
yes	max	9%	62%	46%	56%	75%	47%	46%
yes	min	0%	0%	0%	0%	0%	0%	0%
yes	avg	4%	27%	16%	21%	43%	21%	17%
yes	max wwr>0.45	5%	62%	46%	56%	75%	47%	46%
yes	min wwr>0.45	4%	30%	13%	19%	46%	28%	17%
yes	max wwr<0.30	9%	47%	30%	44%	58%	31%	30%
yes	min wwr<0.30	4%	4%	2%	0%	27%	6%	3%
no	max	40%	63%	52%	57%	72%	52%	52%
no	min	0%	0%	0%	0%	0%	0%	0%
no	avg	28%	32%	26%	24%	37%	28%	26%
no	max wwr>0.45	40%	63%	52%	57%	72%	52%	52%
no	min wwr>0.45	39%	37%	29%	23%	38%	36%	31%
no	max wwr<0.30	37%	50%	40%	45%	50%	39%	40%
no	min wwr<0.30	24%	13%	12%	0%	15%	16%	13%
		Large Office, New Vintage, NYC						
yes	max	11%	68%	41%	60%	74%	59%	48%
yes	min	0%	0%	0%	0%	0%	0%	0%
yes	avg	6%	31%	13%	21%	39%	26%	17%
yes	max wwr>0.45	7%	68%	41%	60%	74%	59%	48%
yes	min wwr>0.45	5%	37%	11%	16%	47%	30%	18%
yes	max wwr<0.30	11%	51%	23%	46%	62%	43%	29%
yes	min wwr<0.30	6%	8%	3%	2%	19%	8%	4%
no	max	48%	69%	49%	64%	72%	61%	53%
no	min	0%	0%	0%	0%	0%	0%	0%
no	avg	34%	37%	26%	29%	36%	31%	27%
no	max wwr>0.45	48%	69%	49%	64%	72%	61%	53%
no	min wwr>0.45	46%	45%	31%	32%	45%	38%	33%
no	max wwr<0.30	44%	55%	37%	52%	60%	47%	40%
no	min wwr<0.30	28%	21%	16%	11%	10%	16%	16%

This is defined as the range of maximum percentage savings that can be realized by the EC glazing compared to the base case glazings. The range is determined by the parametric cases, which include 5 base case glazings, 4 WWR, shades (yes/no), daylighting controls (yes/no), and four perimeter zone orientations.

Table 3.2

Minimum Perimeter Zone Savings or Percentage Reductions by Electrochromic Glazings – Large Office Prototype, New York, New York

Base case has daylighting?		Lighting Energy	Cooling Energy	Electric Total	Peak Demand	Heating Energy	Energy Cost 1:1	Energy Cost 1:5
		Large Office, Old Vintage, NYC						
yes	max	0%	27%	16%	24%	0%	13%	16%
yes	min	-11%	-3%	-3%	0%	-203%	-2%	-2%
yes	avg	-4%	6%	3%	5%	-42%	2%	3%
yes	max wwr>0.45	-3%	27%	16%	24%	-28%	13%	16%
yes	min wwr>0.45	-4%	2%	1%	0%	-203%	-2%	1%
yes	max wwr<0.30	-5%	11%	7%	11%	-3%	5%	7%
yes	min wwr<0.30	-11%	-3%	-3%	0%	-50%	-2%	-2%
no	max	40%	32%	29%	27%	0%	25%	28%
no	min	0%	0%	0%	0%	-263%	0%	0%
no	avg	28%	13%	16%	7%	-73%	12%	15%
no	max wwr>0.45	40%	32%	29%	27%	-72%	25%	28%
no	min wwr>0.45	39%	13%	18%	0%	-263%	13%	17%
no	max wwr<0.30	37%	20%	22%	16%	-17%	18%	21%
no	min wwr<0.30	24%	4%	11%	0%	-86%	8%	10%
		Large Office, Old Vintage, NYC						
yes	max	0%	32%	14%	30%	20%	17%	15%
yes	min	-15%	-5%	-3%	-1%	-28%	-5%	-2%
yes	avg	-6%	7%	3%	3%	-5%	0%	2%
yes	max wwr>0.45	-4%	32%	14%	30%	20%	17%	15%
yes	min wwr>0.45	-6%	3%	3%	1%	-23%	-5%	1%
yes	max wwr<0.30	-7%	10%	5%	4%	0%	3%	5%
yes	min wwr<0.30	-15%	-5%	-3%	-1%	-28%	-5%	-2%
no	max	48%	38%	30%	39%	12%	24%	28%
no	min	0%	0%	0%	0%	-51%	0%	0%
no	avg	34%	16%	18%	13%	-16%	9%	16%
no	max wwr>0.45	48%	38%	30%	39%	12%	24%	28%
no	min wwr>0.45	46%	18%	23%	12%	-47%	8%	19%
no	max wwr<0.30	44%	22%	23%	21%	-8%	15%	21%
no	min wwr<0.30	28%	7%	14%	5%	-51%	6%	12%

This is defined as the range of maximum percentage savings that can be realized by the EC glazing compared to the base case glazings. The range is determined by the parametric cases, which include 5 base case glazings, 4 WWR, shades (yes/no), daylighting controls (yes/no), and four perimeter zone orientations.

(Tables 3.3, 3.4, and Tables 4.1-4.4 are given in the Appendix)

Maximum and minimum percentage reductions[2] in energy use across all base case glazing conditions are also given in Tables 3 and 4, respectively. Partial data for the large office prototypes in New York, New York (Tables 3.1 and 3.2) are given in the previous pages. The complete set of data for all prototypes and climates (Tables 3 and 4) are given in the Appendix.

3.1. Annual Lighting Energy Use

For all cases with daylighting controls, annual lighting energy use decreases exponentially as glazing area is increased (Figure 2a). Glazing types with the greatest visible transmittance (Tv) and therefore greatest daylight admission yielded the least annual lighting energy use: e.g., single-pane clear glass (Tv=0.88) and double-pane clear glass (Tv=0.78).

For all cases with daylighting controls, the maximum reduction in annual lighting energy use between the EC glazing and all other static glazings varied from 3-8% for large glazing areas (WWR≥0.45) and 4-13% for small to moderate glazing areas (WWR≤0.30). For most cases, these maximum reductions were realized against the selective tinted glazing (Tv=0.41).

For all cases with daylighting controls, the minimum reduction in annual lighting energy use between the EC glazing and all other static glazings varied from –(3-6)% for large glazing areas (WWR≥0.45) and –(5-22)% for small to moderate glazing areas (WWR≤0.30). Lighting energy use of the EC glazing was greater than some static glazings, therefore the negative percentage differences. For most cases, these minimum reductions (rather maximum increases) were realized against the clear single-pane glazing (Tv=0.88).

Use of older ballasts with a minimum power range of 33% (versus 20% for the new dimming ballasts) caused annual lighting energy use differences between glazings to increase slightly.

There were insignificant differences in both the magnitude and trends of lighting energy use between the New York City (NYC) and Buffalo climates.

3.2. Annual Cooling Energy Use

For all cases, annual cooling energy use increases with glazing area (Figure 2b). The rate of increase is less if daylighting controls are used due to decreased lighting loads. The rate of increase is also less if interior shades are used due to decreased solar heat gains. If EC glazings are used, the rate of increase is minimal compared to conventional static glazings.

Electrochromic glazings with daylighting controls clearly yield the least annual cooling energy use for all cases, except for some cases with small glazing areas (WWR≤0.15) and some conditions in the north perimeter zone.

For all cases, the maximum reduction in annual cooling energy use between the EC glazing and all other static glazings is 16-72% for large glazing areas (WWR≥0.45) and 2-57% for small to moderate glazing areas (WWR≤0.30). These maximum reductions were realized for almost all cases against the single-pane clear glazing, with the largest reductions occurring at

[2] To arrive at these values, we first determined per case the maximum energy use between all base case glazings, then we determined the percentage difference between this glazing and the EC glazing. We then determined the range of "maximum reduction in energy use" values across all cases (climates, prototypes, perimeter zone orientations, shades, daylighting controls, glazing area, base case glazing types), unless stipulated in the text. The "minimum reduction in energy use" values were determined similarly. This allowed us to bound the potential range of energy use savings derived through the use of EC glazings for the cases modeled in this study.

very large glazing areas (WWR=0.60). See Tables 3-4 and Figure 2(b) to better understand the origin of this large range in percentage energy reductions.

For all cases, the minimum reduction in annual cooling energy use between the EC glazing and all other static glazings is 1-41% for large glazing areas (WWR≥0.45) and –5% to 23% for small to moderate glazing areas (WWR≤0.30). These minimum reductions were realized for almost all cases against the double-pane, spectrally-selective, tinted glazing ("spec2667").

Static glazing types with the least combined solar heat gain coefficient (SHGC) and U-value yield the least annual cooling energy use. EC glazings controlled to minimize both lighting and solar heat gain loads yield even lower annual cooling energy use.

Buffalo had less cooling energy use requirements than NYC, but the trends with glazing area and between glazing types and the percentage reductions were approximately the same between the two climates.

3.3. Annual Total Electricity Use

For all base case conditions, annual total electricity use increases with glazing area if no daylighting controls are used (Figure 2c). If daylighting controls are used, annual total electricity use decreases to a minimum value at small to moderate glazing areas (WWR≤0.30), then increases as glazing area increases. With the EC glazing, annual total electricity use decreases asymptotically with glazing area for most cases (there is an increase at WWR=0.60 for some cases).

Electrochromic glazings with daylighting controls again yield the least annual total electricity energy use for all cases, except for small glazing areas (WWR≤0.15) and some conditions in the north perimeter zone.

Maximum reductions in annual total electricity use between the EC glazing and all other static glazings ranged from 6-63% for large glazing areas (WWR≥0.45) and 2-48% for small to moderate glazing areas (WWR≤0.30). For most cases, these maximum reductions were realized against the single-pane clear glazing.

For all cases, the minimum reduction in annual total electricity energy use between the EC glazing and all other static glazings is 1-39% for large glazing areas (WWR≥0.45) and –6% to 25% for small to moderate glazing areas (WWR≤0.30). These minimum reductions were realized for almost all cases against again the double-pane, spectrally-selective, tinted glazing ("spec2667").

These reductions in energy can be explained by the combined reductions of lighting and cooling energy use, given above.

3.4. Peak Electricity Use

Peak electric demand data are given for the peak condition that occurs in each perimeter zone and are non-coincident with the whole building's peak condition. These data allowed us to compare relative demand impacts as a function of window orientation (Figure 2d).

For all cases, the total peak electricity demand increases with glazing area. The rate of increase is small to almost flat for the EC glazing with daylighting controls. Data are given for the peak demand condition over the course of the year and may not be concurrent (occurring at the same time of the year) between cases.

Electrochromic glazings with daylighting controls yield the least peak electricity demand for all cases, except for small glazing areas (WWR≤0.15) and some conditions in the north perimeter zone.

Maximum reductions in peak electricity demand between the EC glazing and all other static glazings ranged from 8-72% for large glazing areas (WWR≥0.45) and 0-60% for small to moderate glazing areas (WWR≤0.30) and were generally achieved against the single-pane clear glazing.

For all cases, the minimum reduction in peak electricity demand between the EC glazing and all other static glazings is 0-45% for large glazing areas (WWR≥0.45) and –5% to 30% for small to moderate glazing areas (WWR≤0.30). These minimum reductions were realized for almost all cases against the double-pane, spectrally-selective, tinted glazing ("spec2667").

Peak electric demand is less in Buffalo for all prototypes due to lower cooling demand requirements.

3.5. Annual Heating Energy Use

The trends of annual heating energy use versus glazing area differed between the four prototypes due to differences between the HVAC system types. Generally, the EC glazing yielded greater heating energy use compared to the base case conditions except for some conditions (Figure 2e).

Generally, the EC glazing with daylighting controls reduced annual heating energy use compared to the clear glazings and increased annual heating energy use compared to spectrally-selective glazings. Exceptions can be found in the figures.

Maximum reductions in annual heating energy use between the EC glazing and all other static glazings ranged from 9-75% for large glazing areas (WWR≥0.45) and 7-62% for small to moderate glazing areas (WWR≤0.30) and were generally achieved against the single-pane clear glazing due to improved U-value from double-pane glass.

For all cases, the minimum reduction in annual heating energy use between the EC glazing and all other static glazings was –273% (increased) to 23% (decreased) for large glazing areas (WWR≥0.45) and –126% to 0% for small to moderate glazing areas (WWR≤0.30). These minimum reductions (or increases) were realized for almost all cases against the two selective glazings ("spec2667" and "spec2664").

Heating energy in Buffalo was significantly greater than NYC due to more severe winters.

3.6. Annual Energy Cost

Total annual energy cost reflects both natural gas and electricity consumption costs so the summed impact of EC glazings on cooling, heating, and lighting energy usage can be determined. For all non-daylighting base case glazings, total energy cost increases with glazing area (Figures 2f and 2g). For all cases with a fuel ratio of 1:1, total energy cost increases with glazing area. For all orientations except the north, a fuel ratio of 1:5, and with daylighting controls, total energy cost decreases then increases with glazing area starting from WWR≈0.15-0.30 and thereafter.

Electrochromic glazings with daylighting controls yield the least energy cost for most cases, particularly if the fuel cost ratio is 5:1 and if compared to base case conditions with no daylighting controls. Exceptions include small glazing areas (WWR≤0.15) and some conditions in the north perimeter zone.

Between all cases, maximum reductions in energy cost between the EC glazing and all other static glazings ranged from 13-63% for large glazing areas (WWR≥0.45) and 3-49% for small to moderate glazing areas (WWR≤0.30) and were generally achieved against the single-pane clear glazing.

Minimum reductions in energy cost between the EC glazing and all other static glazings was –7% to 36% for large glazing areas (WWR≥0.45) and –6% to 24% for small to moderate glazing areas (WWR≤0.30). These minimum reductions were realized for almost all cases against the double-pane, spectrally-selective, tinted glazing ("spec2667").

3.7 Visual Comfort

Data for the average annual work plane illuminance (Figure 10a), percentage of the year that the design work plane illuminance of 510 lux (50 fc) was exceeded (Figure 10b), and average annual glare index (Figure 10c) are shown as a function of window-to-wall ratio and glazing type. Note that since the geometry of the small and large offices were the same, interior daylight levels and glare indices were the same between all four prototypes for the same window and glazing configuration. In addition, data shown in Figure 10 are given for daylight only, not including electric lighting, so interior illuminance levels and glare indices do not change between the daylighting and no-daylighting control cases. All data are given as an average or percentage of the year, where year is defined by all hours that the sun is up.

For all cases, the average annual interior daylight illuminance level at a workplane positioned 3.0 m (10 ft) from the window wall was controlled to within 510 lux (50 fc) by the electrochromic glazing. All other static glazings yielded greater average annual interior illuminance levels, even with an interior shade, for moderate to very large glazing areas.

It's interesting to note that the percentage of the year that interior daylight illuminance levels exceed 510 lux (50 fc) is larger for the EC glazing than for the selective tint and clear double-pane glazings in Figure 10b. This does not imply that the EC glazing is unable to control interior illuminance levels as well as the other two static glazings. The static glazings result in a broader fluctuation in interior daylight levels (note average annual interior daylight illuminance levels) as sunlight levels vary throughout the day, while the EC glazing dampens this variation. For example, interior illuminance levels at 3.0 m (10 ft) from the window wall never exceed 753 lux (70 fc) over the year with a south-facing EC window (WWR=0.45 in Buffalo), while illuminance levels exceed 753 lux (70 fc) for 58% of the year with selective tinted glass and 43% with clear double-pane glass, both with interior shades.

For paper-based reading and writing tasks, greater interior illuminance levels do not necessarily translate into greater visual discomfort. In fact, for some tasks requiring high visual acuity such as sewing or some manufacturing, greater illuminance levels may be preferred. However, for many office tasks, where computer use is now prevalent, controlled interior illuminance levels can be an indicator of visibility performance. Computer displays require close control of surrounding interior surface luminances and a uniform distribution of luminance to avoid screen wash-out or veiling reflections.

With a view of the sidewall 1.52 m and 3.05 m (5 ft and 10 ft) from the window wall, the average annual daylight glare index of all glazings is within the range of "just perceptible" (DGI=10) to "just acceptable" (DGI=16) for all cases. EC glazings probably again control

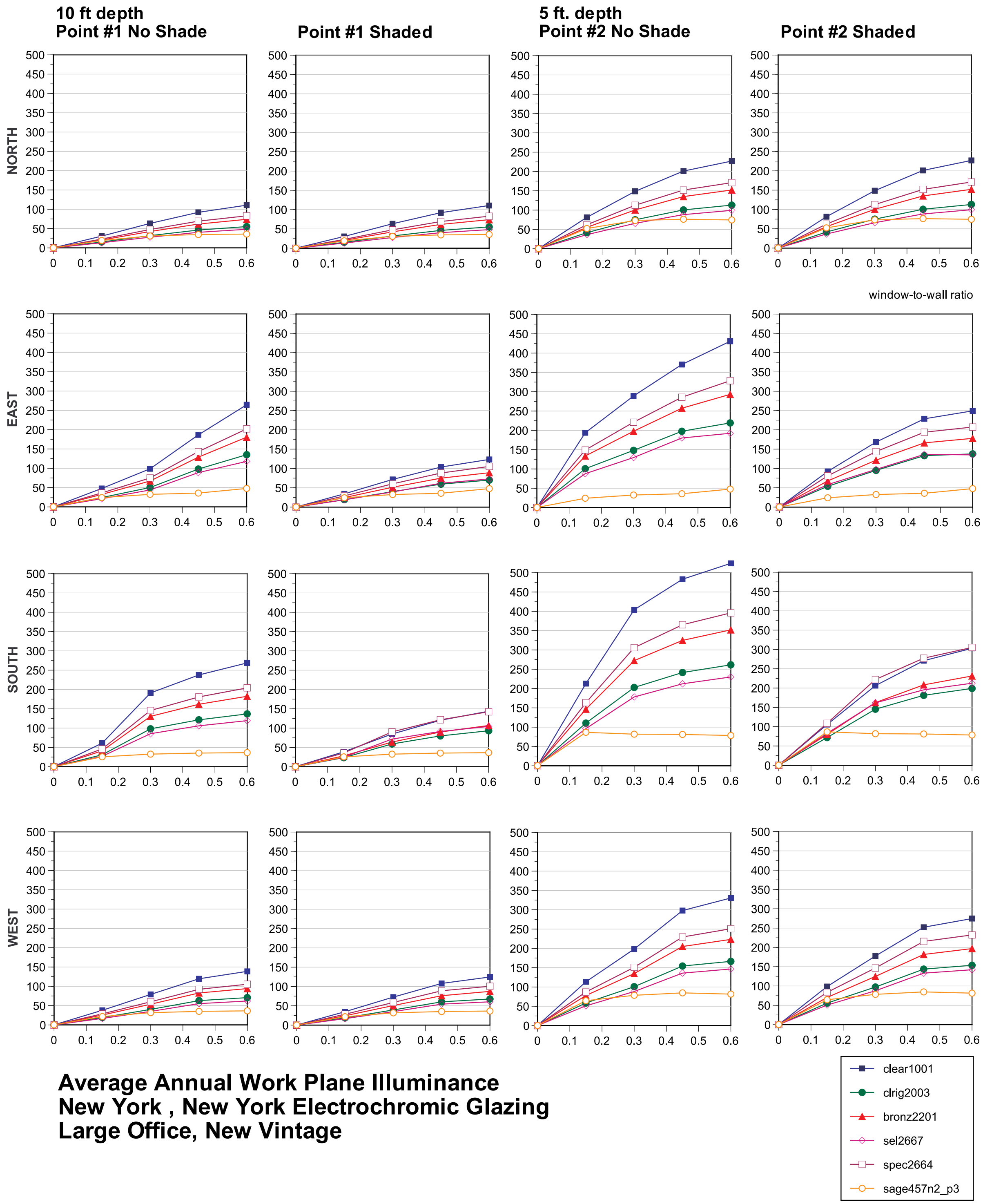
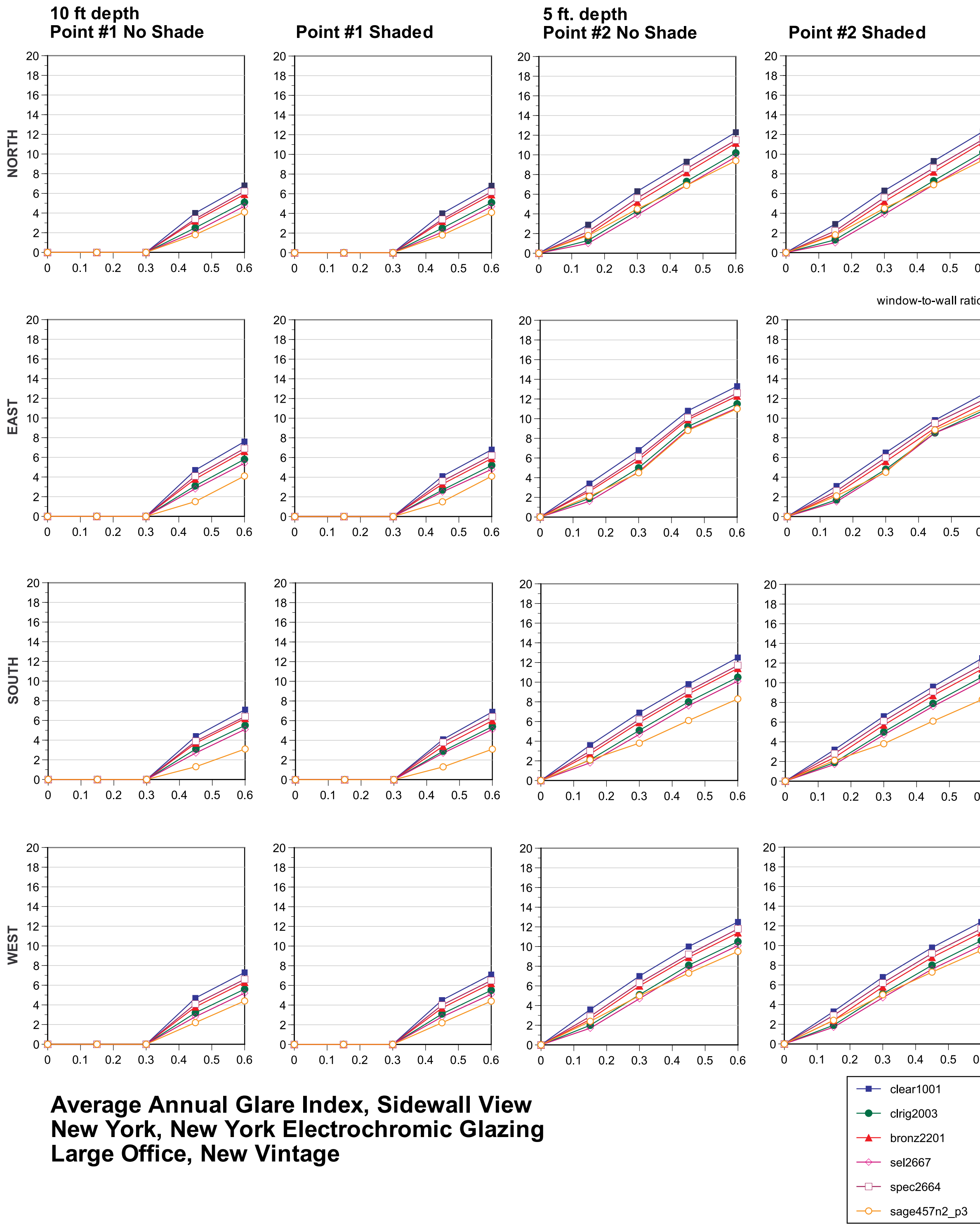


Figure 10a. Average annual work plane illuminance as a function of window-to-wall ratio and glazing type for all building prototypes, New York, New York.



Average Annual Glare Index, Sidewall View
New York, New York Electrochromic Glazing
Large Office, New Vintage

Figure 10b. Percentage of year design work plane illuminance of 510 lux (50 fc) is exceeded as a function of window-to-wall ratio and glazing type for all building prototypes, New York, New York.

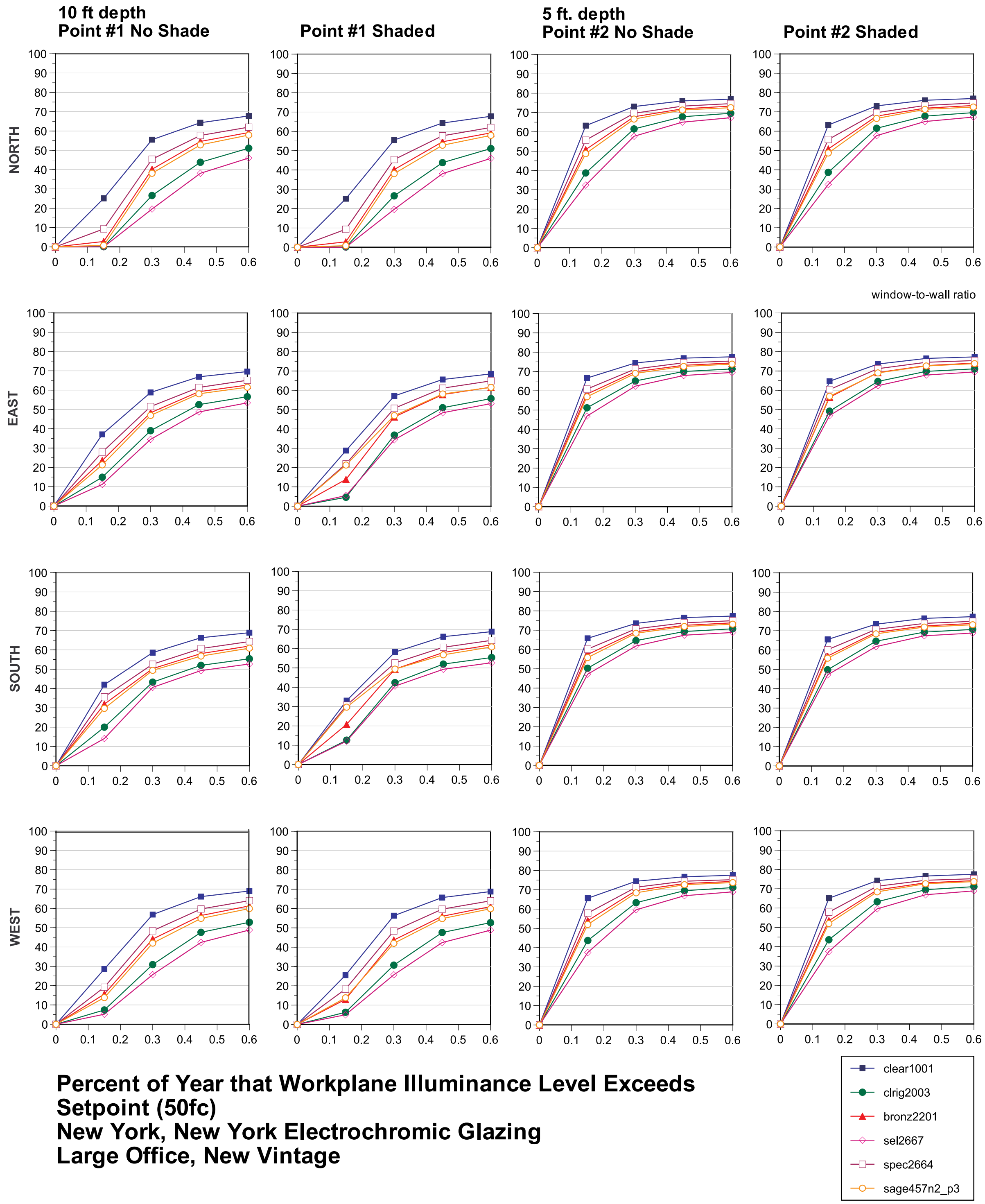


Figure 10c. Average annual glare index as a function of window-to-wall ratio and glazing type for all building prototypes, New York, New York.

fluctuations in window brightness over the course of a day more tightly than static glazings, however we present no data here to substantiate this argument.

3.8. HVAC Capacity and Whole Building Peak Demand

HVAC capacity can be reduced with decreased peak cooling and heating requirements. Capacity reductions for the whole building are given in Tables 5-6. Table 5.1 is given for the large office with no daylighting controls and Table 5.2 is given for the large office with daylighting controls. The same are given for Tables 6.1 and 6.2 for the small office, respectively. Capacity is proportional the building's peak electric demand. Building peak electric demand follows similar trends to those discussed above in Section 3.4 for perimeter zones. These relationships are shown in Figure 11 for each prototype and climate.

a) Large Offices

For the large office prototypes, maximum reductions in heating capacity between the EC glazing and all other static glazings ranged from 19-56% for large glazing areas (WWR≥0.45) and 7-42% for small to moderate glazing areas (WWR≤0.30). Logically, the largest percentage reductions occurred against the clear single-pane clear glazing with no shades and no daylighting controls.

For the large office prototypes, minimum reductions in heating capacity between the EC glazing and all other static glazings was –79% to 12% for large glazing areas (WWR≥0.45) and –(1-25)% for small to moderate glazing areas (WWR≤0.30).

For the large office prototypes, maximum reductions in both chiller and cooling tower capacities between the EC glazing and all other static glazings ranged from 18-32% for large glazing areas (WWR≥0.45) and 3-23% for small to moderate glazing areas (WWR≤0.30). Minimum reductions in heating capacity between the EC glazing and all other static glazings was 5-16% for large glazing areas (WWR≥0.45) and –3% to 9% for small to moderate glazing areas (WWR≤0.30).

b) Small Offices

For the small office prototypes, maximum reductions in cooling capacity between the EC glazing and all other static glazings ranged from 34-66% for large glazing areas (WWR≥0.45) and 0-46% for small to moderate glazing areas (WWR≤0.30). Logically, the largest percentage reductions occurred against the clear single-pane clear glazing with no shades and no daylighting controls

For the small office prototypes, minimum reductions in whole-building cooling capacity between the EC glazing and all other static glazings was –3% to 32% for large glazing areas (WWR≥0.45) and –11% to 9% for small to moderate glazing areas (WWR≤0.30).

For the small office prototypes, maximum reductions in heating capacity between the EC glazing and all other static glazings ranged from 36-65% for large glazing areas (WWR≥0.45) and 0-46% for small to moderate glazing areas (WWR≤0.30). Minimum reductions in whole-building heating capacity between the EC glazing and all other static glazings was 3-30% for large glazing areas (WWR≥0.45) and 0-5% for small to moderate glazing areas (WWR≤0.30). Note that even though annual heating energy use of EC glazings was greater than some base case glazings, heating capacity was less than all base case conditions. This is because heating capacity is based on peak heating requirements.

Table 5.1

Percentage HVAC Capacity Reductions for Large Offices – No daylighting controls

	New York, New York				Buffalo, New York			
Office:	Old	Old	New	New	Old	Old	New	New
Reduction:	Max	Min	Max	Min	Max	Min	Max	Min
WWR	Heater Capacity – No shades							
0.15	22%	-7%	20%	-4%	7%	-1%	17%	-3%
0.30	35%	-23%	42%	-3%	11%	-5%	33%	-2%
0.45	47%	-58%	51%	1%	21%	-11%	43%	6%
0.60	55%	-79%	54%	2%	29%	-23%	49%	12%
	Chiller Capacity – No shades							
0.15	14%	0%	10%	0%	13%	2%	10%	0%
0.30	23%	5%	19%	4%	20%	9%	18%	5%
0.45	27%	12%	27%	8%	31%	14%	24%	12%
0.60	28%	14%	32%	10%	30%	16%	27%	15%
	Cooling Tower – No shades							
0.15	14%	0%	10%	0%	13%	2%	10%	0%
0.30	23%	5%	19%	4%	20%	9%	18%	5%
0.45	27%	12%	27%	8%	31%	14%	24%	12%
0.60	28%	14%	32%	10%	30%	16%	27%	15%
WWR	Heater Capacity – With shades							
0.15	23%	-6%	15%	-2%	8%	-1%	8%	-1%
0.30	36%	-25%	34%	-4%	13%	-4%	22%	-4%
0.45	47%	-42%	41%	0%	19%	-7%	30%	0%
0.60	56%	-59%	44%	0%	23%	-14%	35%	2%
	Chiller Capacity – With shades							
0.15	6%	0%	6%	0%	9%	1%	6%	0%
0.30	19%	4%	16%	3%	20%	8%	13%	5%
0.45	26%	9%	22%	8%	24%	12%	21%	11%
0.60	27%	11%	28%	10%	27%	13%	25%	14%
	Cooling Tower – With shades							
0.15	6%	0%	6%	0%	9%	1%	6%	0%
0.30	19%	4%	16%	3%	20%	8%	13%	5%
0.45	26%	9%	22%	8%	24%	12%	21%	11%
0.60	27%	11%	28%	10%	26%	13%	25%	14%

Table 5.2
Percentage HVAC Capacity Reductions for Large Offices – With daylighitng controls

	New York, New York				Buffalo, New York			
Office:	Old	Old	New	New	Old	Old	New	New
Reduction:	Max	Min	Max	Min	Max	Min	Max	Min
WWR	Heater Capacity – No shades							
0.15	23%	-3%	19%	-3%	7%	-1%	15%	-2%
0.30	36%	-16%	42%	-3%	12%	-4%	32%	-2%
0.45	47%	-43%	51%	1%	20%	-9%	43%	5%
0.60	54%	-74%	53%	2%	29%	-20%	49%	10%
	Chiller Capacity – No shades							
0.15	11%	-1%	8%	-2%	9%	-1%	7%	-2%
0.30	22%	2%	16%	1%	17%	4%	15%	1%
0.45	26%	9%	25%	5%	22%	10%	22%	8%
0.60	27%	12%	31%	8%	20%	9%	25%	12%
	Cooling Tower – No shades							
0.15	11%	-1%	8%	-2%	9%	-1%	7%	-2%
0.30	22%	2%	16%	1%	17%	4%	15%	1%
0.45	26%	9%	25%	5%	22%	10%	22%	8%
0.60	27%	12%	31%	8%	20%	9%	25%	12%
WWR	Heater Capacity – With shades							
0.15	24%	-4%	16%	-1%	8%	-1%	8%	-1%
0.30	37%	-16%	33%	-4%	13%	-3%	20%	-4%
0.45	47%	-34%	40%	-2%	19%	-5%	29%	-1%
0.60	56%	-60%	43%	-1%	24%	-11%	34%	1%
	Chiller Capacity – With shades							
0.15	3%	-1%	4%	-2%	4%	-1%	3%	-3%
0.30	16%	1%	14%	1%	13%	2%	10%	1%
0.45	24%	6%	20%	5%	18%	6%	18%	7%
0.60	26%	8%	26%	7%	18%	8%	22%	10%
	Cooling Tower – With shades							
0.15	3%	-1%	4%	-2%	4%	-1%	3%	-3%
0.30	16%	1%	14%	1%	13%	2%	10%	1%
0.45	24%	6%	20%	5%	18%	6%	18%	7%
0.60	26%	8%	26%	7%	18%	8%	22%	10%

Table 6.1
Percentage HVAC Capacity Reductions for Small Offices – No daylighting controls

	New York, New York				Buffalo, New York			
Office:	Old	Old	New	New	Old	Old	New	New
Reduction:	Max	Min	Max	Min	Max	Min	Max	Min
WWR	Cool Capacity – No shades							
0.15	19%	5%	16%	5%	22%	5%	19%	4%
0.30	44%	9%	42%	8%	46%	8%	46%	5%
0.45	56%	22%	56%	18%	60%	25%	60%	23%
0.60	62%	27%	62%	26%	66%	32%	66%	32%
	Heat Capacity – No shades							
0.15	16%	0%	12%	0%	20%	0%	17%	0%
0.30	43%	4%	42%	2%	46%	5%	45%	2%
0.45	57%	18%	57%	16%	59%	21%	58%	19%
0.60	63%	26%	63%	24%	65%	30%	65%	30%
WWR	Cool Capacity – With shades							
0.15	6%	5%	5%	5%	6%	5%	5%	4%
0.30	28%	6%	25%	6%	29%	-3%	27%	-3%
0.45	42%	16%	40%	13%	44%	11%	43%	8%
0.6	48%	19%	47%	17%	51%	15%	51%	13%
	Heat Capacity – With shades							
0.15	1%	0%	0%	0%	2%	0%	0%	0%
0.30	25%	0%	22%	0%	26%	0%	24%	0%
0.45	41%	11%	40%	9%	42%	11%	40%	8%
0.60	48%	16%	47%	14%	49%	16%	49%	15%

4. Discussion

4.1. Provisos

The above DOE-2 simulation results describe a wide range of possible outcomes when comparing EC glazings to conventional glazings. The following provisos are given to bracket these outcomes with real-world commercial building operations and to assist the reader to better understand the impacts of the modeling assumptions underlying these simulations.

First, deployment of the simulated interior shade is probably more regular than what one may expect in the real world. Therefore, data for the conventional glazings with an interior shade may be more optimal than that can be expected in the real world. For example, on the peak day, if an occupant is not present in the room to draw the shade when direct transmitted radiation exceeds 94.5 W/m^2 (30 Btu/h-ft^2), then peak demand reductions may be comparable to the no-shade case.

Table 6.2

Percentage HVAC Capacity Reductions for Small Offices – With daylighting controls

	New York, New York				Buffalo, New York			
Office:	Old	Old	New	New	Old	Old	New	New
Reduction:	Max	Min	Max	Min	Max	Min	Max	Min
WWR	Cool Capacity – No shades							
0.15	8%	0%	6%	0%	13%	-1%	10%	-1%
0.30	39%	2%	38%	2%	43%	1%	42%	0%
0.45	54%	13%	53%	11%	58%	18%	57%	17%
0.60	60%	20%	60%	20%	64%	26%	65%	26%
	Heat Capacity – No shades							
0.15	9%	0%	6%	0%	15%	0%	12%	0%
0.30	40%	1%	39%	0%	44%	0%	43%	0%
0.45	56%	13%	55%	12%	58%	16%	57%	14%
0.60	62%	22%	62%	21%	64%	27%	64%	27%
WWR	Cool Capacity – With shades							
0.15	0%	0%	0%	0%	1%	-1%	1%	-1%
0.30	19%	0%	16%	1%	21%	-11%	19%	-11%
0.45	36%	6%	34%	3%	39%	-1%	38%	-3%
0.60	43%	9%	43%	8%	47%	5%	47%	5%
	Heat Capacity – With shades							
0.15	0%	0%	0%	0%	0%	0%	0%	0%
0.30	19%	0%	17%	0%	22%	0%	19%	0%
0.45	38%	5%	36%	3%	38%	5%	37%	3%
0.60	46%	10%	45%	8%	47%	11%	47%	11%

Second, the DOE-2 daylighting control algorithms will yield greater lighting energy use savings than that conventionally realized for continuous dimming systems in the real world. Poor control systems, lack of proper commissioning, and occupant intervention typically reduces the effectiveness of conventional daylighting controls. If stepped manual switching is available and the occupant uses this option with some frequency (~50% of the time), however, these lighting energy use savings can be comparable.

Therefore, we can argue that the EC glazings will:

1) yield greater energy savings than the results with interior shades given here, since real-world interior shades are often operated sub-optimally, and
2) yield less energy savings than the given results with daylighting controls, since real-world daylighting controls often operate sub-optimally.

Other considerations that should be noted are occupant preferences and comfort. The EC glazings were modeled without an interior shade, so the following ramifications should be noted:

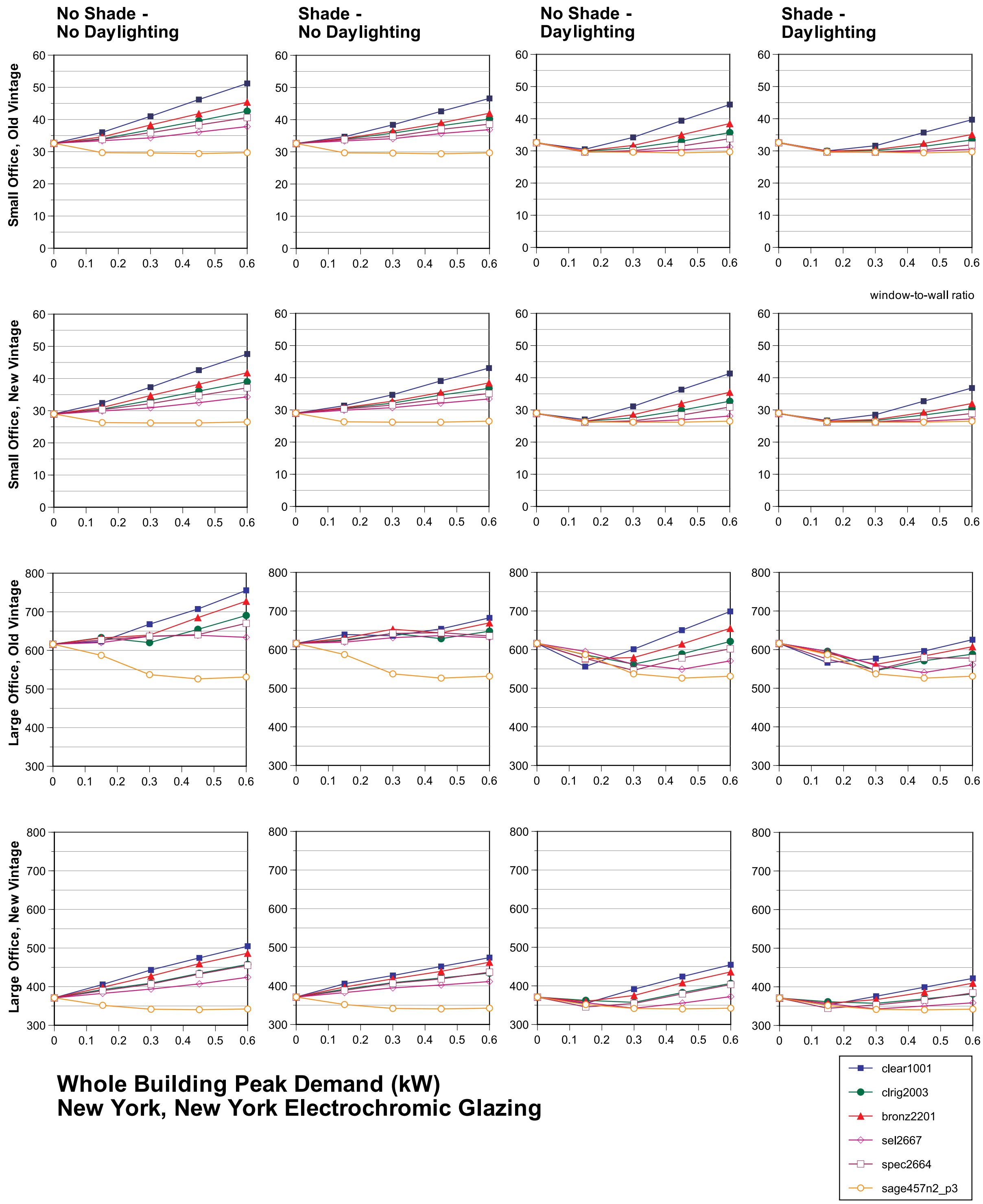


Figure 11a. Whole building peak demand as a function of window-to-wall ratio and glazing type, New York, New York.

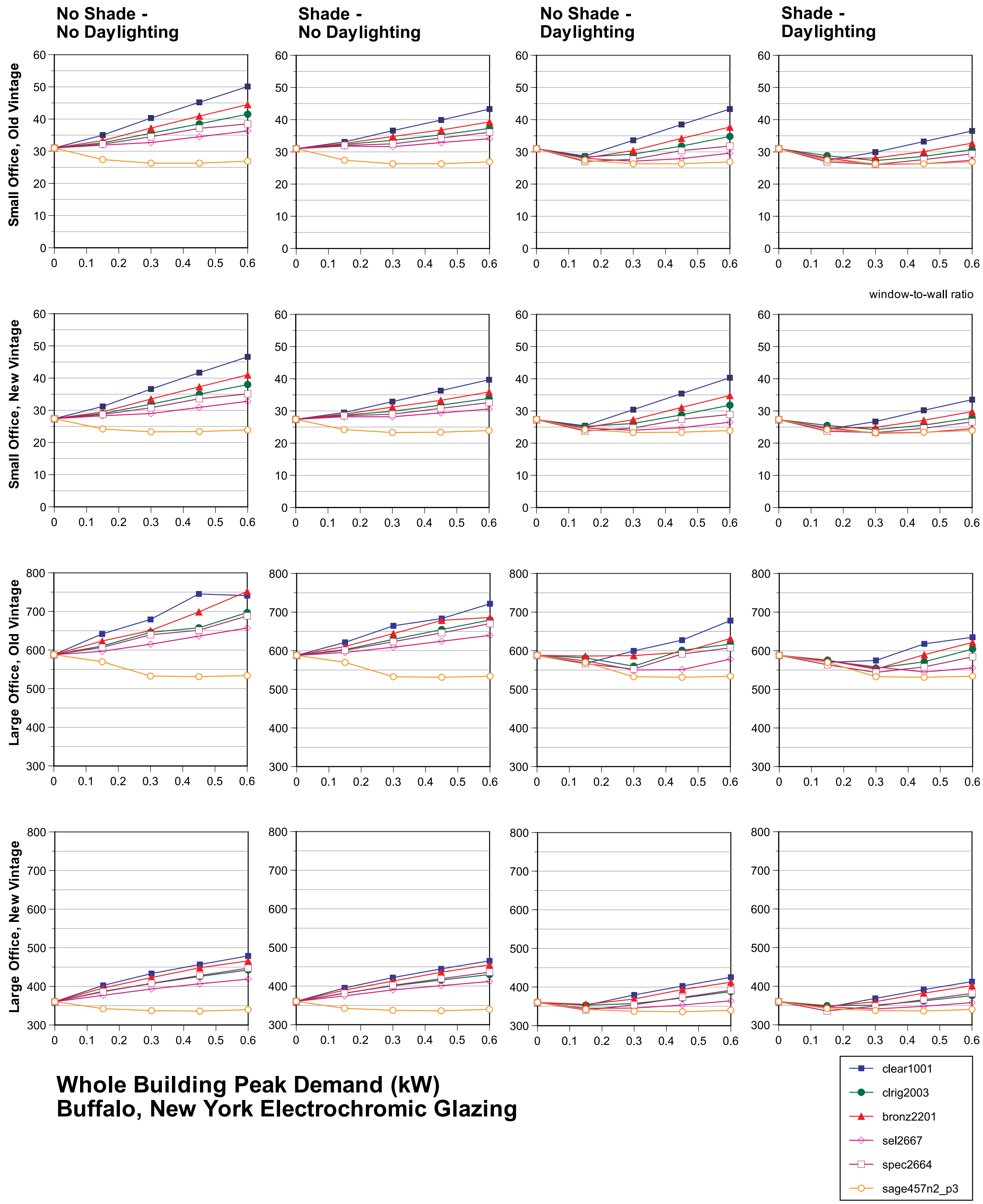


Figure 11b. Whole building peak demand as a function of window-to-wall ratio and glazing type, Buffalo, New York.

1) it is unknown whether the EC glazing will provide sufficient control of interior brightness and glare under direct sun conditions with the daylight control algorithm. Certainly, for some tasks and view positions, an interior shade may be required to provide visual comfort. On the other hand, occupants may be more willing to accept non-uniform luminance distributions in order to obtain the benefits of an unobstructed view. If an interior shade is deployed manually or if the EC is colored further to control glare, one can assume that lighting energy use will increase for those hours. Architectural strategies (switching over a portion of the window wall or use of a light shelf) can be used to improve daylighting.
2) It is unknown whether the occupant would prefer to have the EC glazing adjusted differently than that given under the daylight control algorithm. User-provisions should be accommodated to increase acceptance and satisfaction with this technology and the impact of providing such user control on energy use is unknown.

4.2. Comparison to "Typical" New York Building Stock

In Tables 7.1-7.3, the net savings in energy and demand are given relative to "typical" glazing and window area conditions of NY state commercial office buildings, as defined in Table 1. Base case conditions are defined with and without daylighting controls and with and without an interior shade to indicate possible range in values given retrofit or operational differences in the existing stock.

Based on the assumption that the impacts on NY state commercial office buildings are based not on what is commercially available (e.g., spectrally selective glass), but what is typically specified, for the cases shown in this Table, the most significant reductions in total annual electricity use are realized in old vintage, large office buildings which have large glazing areas (WWR=0.45), clear double-pane glass, no daylighting controls, and conventional interior shades. South-, east-, and west-facing perimeter zones realize the most significant savings: on the order of 56.9-67.5 kWh/m2-yr (5.29-6.27 kWh/ft^2-yr) saved, if the shade, no daylighting controls case is assumed as typical for the old large office base condition. If the four base case building prototypes already use daylighting controls, then the net benefit of EC glazings would be on the order of 22.6-30.4 kWh/m^2-yr (2.10-2.82 kWh/ft^2-yr). If spectrally-selective glazing with an interior shade and daylighting controls were specified for any of the four prototypes, then this system's performance would closely rival or even equal the performance of EC glazings for all orientations for WWR=0.45.

Small offices realize significant reductions as well, but the magnitude of savings are less since the glazing areas are small (WWR=0.15-0.20).

The impact of EC glazings on heating energy is mixed across the four prototypes. Annual heating energy is decreased (0.75-24.3 kWh/m^2-yr, 0.07-2.26 kWh/ft^2-yr) for most large office and old vintage, small office perimeter zones and increased slightly (0.11-3.66 kWh/m^2-yr, 0.01-0.34 kWh/ft^2-yr) for new vintage, small office perimeter zones.

Reductions in the perimeter zone peak demand can be significant – on the order of 22.9-34.4 W/m^2 (2.13-3.20 W/ft^2) in the east-, west-, or south-facing perimeter zones of old large offices – compared to glazings that are typically specified in these buildings. If spectrally selective glass and daylighting controls are specified, then reductions would be less. For example, for a new large office east-facing perimeter zone, EC glazings would save 34.4 W/m^2 (3.2 W/ft^2) compared to conventional practice (bronze without daylighting controls) and 4.3 W/

Table 7.1
Reduction in Annual Heating Energy Use (ΔkWh/ft²-floor-yr) Compared to Typical New York Conditions

Location	Building Type	Daylighting	Shades	Small Office North	East	South	West	Large Office North	East	South	West
NYC	old	none	no shade	0.24	0.12	-0.05	0.17	0.93	-0.02	0.08	0.32
NYC	old	none	shade	0.25	0.16	0.02	0.20	0.97	0.42	0.33	0.52
NYC	old	yes	no shade	0.53	0.41	0.22	0.49	1.43	0.18	0.30	0.76
NYC	old	yes	shade	0.54	0.45	0.31	0.51	1.47	0.78	0.59	1.01
Buffalo	old	none	no shade	0.28	0.12	-0.16	0.18	1.11	-0.14	-0.08	-0.05
Buffalo	old	none	shade	0.30	0.17	-0.04	0.22	1.16	0.38	0.23	0.56
Buffalo	old	yes	no shade	0.71	0.59	0.30	0.64	1.89	0.42	0.28	0.53
Buffalo	old	yes	shade	0.72	0.64	0.44	0.68	1.94	1.08	0.67	1.31
NYC	new	none	no shade	0.01	-0.14	-0.25	-0.05	0.04	6.44	3.70	4.06
NYC	new	none	shade	0.03	-0.03	-0.15	-0.01	0.07	2.26	0.88	1.87
NYC	new	yes	no shade	0.37	0.20	-0.02	0.30	0.63	7.06	4.05	4.83
NYC	new	yes	shade	0.39	0.30	0.12	0.35	0.67	2.76	1.16	2.33
Buffalo	new	none	no shade	-0.02	-0.21	-0.47	-0.20	-0.35	6.60	5.68	7.51
Buffalo	new	none	shade	0.00	-0.11	-0.34	-0.08	-0.33	2.44	1.39	3.07
Buffalo	new	yes	no shade	0.50	0.32	-0.06	0.39	0.68	7.48	6.36	8.59
Buffalo	new	yes	shade	0.52	0.42	0.14	0.45	0.71	3.12	1.89	3.92

Typical New York conditions defined in Table 1. Old small office: clear IGU with WWR=0.15; old large office: clear IGU with WWR=0.45; new small office: bronze IGU with WWR=0.15; new large office: bronze IGU with WWR=0.45.

m² (0.4 W/ft²) compared to what is commercially-available (selective tinted glass with daylighting controls). Both cases are given with interior shades.

5. Conclusion

A DOE-2.1E energy simulation analysis of an electrochromic (EC) glazing with daylighting controls has been conducted for prototypical office buildings in New York. The modeling included four types of office buildings: "old" and "new" vintages and large (10,405 m², 112,000 ft²) and small (502 m², 5400 ft²) buildings. Five commercially-available, base case windows with and without interior shades were modeled. Window area varied from 0 to 60% of the exterior floor-to-floor wall area. The electric lighting had either no controls or continuous daylighting controls. The prototypes were modeled in New York City or Buffalo.

The best opportunities for EC window-daylighting systems to reduce total energy use in commercial office buildings in New York are for any of the following specified base case conditions (any combination of the following):

Table 7.2
Reduction in Annual Electrical Energy Use ($\Delta kWh/ft^2$-floor-yr) and Peak Demand ($\Delta W/ft^2$-floor) Compared to Typical New York Conditions – Large Office

				Total Annual Electricity Use				Total Peak Demand			
Location	Building Type	Daylighting	Shades	North	East	South	West	North	East	South	West
Newyork	large/old	none	noshade	3.38	8.52	7.07	6.18	0.21	5.34	3.55	3.66
Newyork	large/old	none	shade	3.38	5.58	5.57	5.29	0.21	2.76	2.82	2.66
Newyork	large/old	Continuous	noshade	0.45	5.49	3.88	2.99	0.01	5.04	3.31	3.35
Newyork	large/old	Continuous	shade	0.45	2.43	2.38	2.10	0.01	2.27	2.27	2.11
Buffalo	large/old	none	noshade	3.39	7.98	7.52	7.95	0.50	4.46	3.01	4.31
Buffalo	large/old	none	shade	3.40	6.02	6.27	5.47	0.52	2.90	2.88	2.22
Buffalo	large/old	Continuous	noshade	0.40	4.59	4.06	4.71	0.02	4.15	2.45	4.01
Buffalo	large/old	Continuous	shade	0.40	2.62	2.82	2.02	0.02	2.40	1.42	1.27
Newyork	large/new	none	noshade	3.43	6.33	5.18	4.48	1.15	6.29	4.07	3.53
Newyork	large/new	none	shade	3.47	4.79	4.54	4.11	1.14	3.20	2.13	2.29
Newyork	large/new	Continuous	noshade	0.69	3.59	2.39	1.76	0.24	5.12	2.67	2.08
Newyork	large/new	Continuous	shade	0.73	2.00	1.71	1.32	0.25	1.96	0.83	0.97
Buffalo	large/new	none	noshade	3.35	5.40	5.31	5.55	1.29	5.45	4.45	5.55
Buffalo	large/new	none	shade	3.38	4.34	4.43	4.43	1.27	2.90	2.96	3.14
Buffalo	large/new	Continuous	noshade	0.45	2.46	2.35	2.64	0.39	4.14	3.04	4.19
Buffalo	large/new	Continuous	shade	0.47	1.36	1.41	1.46	0.38	1.58	1.59	1.77

Typical New York conditions defined in Table 1. Old large office: clear IGU with WWR=0.45; new large office: bronze IGU with WWR=0.45.

- Large office buildings (10,405 m^2, 112,000 ft^2)
- Large glazing areas (WWR≥0.45)
- South, east, and west orientations
- Flush facades with no exterior shading
- Conventional clear or tinted glazings
- No daylighting controls
- Buildings where interior shade use is expected to be sub-optimal (with respect to energy-efficiency) due to shared or open plan office space or a strong desire for view.

6. Acknowledgments

This work was supported by Sage Electrochromics, Inc. through the New York State Energy and Research Development Authority. Additional support was provided 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 US Department of Energy under Contract No. DE-AC03-76SF00098.

Table 7.3

Reduction in Annual Electrical Energy Use (ΔkWh/ft^2-floor-yr) and Peak Demand (ΔW/ft^2-floor) Compared to Typical New York Conditions – Small Office

Location	Building Type	Daylighting	Shades	Total Annual Electricity Use North	East	South	West	Total Peak Demand North	East	South	West
Newyork	small/old	none	noshade	2.69	3.62	3.46	3.05	0.89	1.54	1.15	1.21
Newyork	small/old	none	shade	2.69	3.11	3.40	3.04	0.89	1.33	1.14	1.20
Newyork	small/old	Continuous	noshade	0.50	0.75	0.44	0.47	0.05	0.28	0.12	0.17
Newyork	small/old	Continuous	shade	0.49	0.53	0.50	0.48	0.05	0.19	0.10	0.13
Buffalo	small/old	none	noshade	2.57	3.22	3.51	3.44	1.05	1.54	1.38	2.02
Buffalo	small/old	none	shade	2.57	3.00	3.44	3.03	1.04	1.34	1.35	1.39
Buffalo	small/old	Continuous	noshade	0.53	0.65	0.51	0.62	0.22	0.40	0.15	0.26
Buffalo	small/old	Continuous	shade	0.53	0.56	0.59	0.57	0.21	0.21	0.11	0.17
Newyork	small/new	none	noshade	2.66	3.95	3.48	3.04	0.84	1.98	1.31	1.32
Newyork	small/new	none	shade	2.65	3.11	3.35	3.00	0.83	1.37	1.09	1.14
Newyork	small/new	Continuous	noshade	0.05	0.67	0.37	0.22	0.05	0.27	0.17	0.12
Newyork	small/new	Continuous	shade	0.04	0.31	0.38	0.21	0.05	0.09	0.11	0.10
Buffalo	small/new	none	noshade	2.53	3.40	3.65	3.71	1.19	1.92	1.67	2.33
Buffalo	small/new	none	shade	2.53	2.92	3.33	3.00	1.18	1.48	1.32	1.42
Buffalo	small/new	Continuous	noshade	0.00	0.35	0.27	0.44	0.11	0.34	0.22	0.31
Buffalo	small/new	Continuous	shade	-0.01	0.17	0.28	0.18	0.08	0.11	0.11	0.03

Typical New York conditions defined in Table 1. Old small office: clear IGU with WWR=0.15; new small office: bronze IGU with WWR=0.15.

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7. Appendices

Tables

Table 3.1 Maximum Percentage Energy Reductions for Large Offices, NYC, New York, see p.22
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Figure 4a-4g. Small Office, Old Vintage, NYC
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Table 3.3

Maximum Perimeter Zone Savings or Percentage Reductions by Electrochromic Glazings, Small Office Prototypes, New York, New York

Base case has daylighting?		Lighting Energy	Cooling Energy	Electric Total	Peak Demand	Heating Energy	Energy Cost 1:1	Energy Cost 1:5
		Small Office, Old Vintage, NYC						
yes	max	9%	63%	50%	63%	64%	48%	49%
yes	min	0%	0%	0%	0%	0%	0%	0%
yes	avg	4%	27%	17%	22%	39%	21%	18%
yes	max wwr>0.45	5%	63%	50%	63%	64%	48%	49%
yes	min wwr>0.45	4%	28%	14%	15%	31%	28%	18%
yes	max wwr<0.30	9%	47%	32%	45%	58%	32%	32%
yes	min wwr<0.30	4%	3%	3%	1%	33%	7%	3%
no	max	40%	65%	56%	66%	57%	54%	55%
no	min	0%	0%	0%	0%	0%	0%	0%
no	avg	29%	33%	28%	32%	30%	29%	29%
no	max wwr>0.45	40%	65%	56%	66%	57%	54%	55%
no	min wwr>0.45	39%	39%	33%	33%	17%	37%	34%
no	max wwr<0.30	37%	52%	43%	53%	49%	41%	43%
no	min wwr<0.30	24%	17%	16%	16%	18%	19%	17%
		Small Office, New Vintage, NYC						
yes	max	11%	65%	54%	65%	62%	52%	53%
yes	min	0%	0%	0%	0%	0%	0%	0%
yes	avg	6%	27%	18%	23%	39%	23%	19%
yes	max wwr>0.45	7%	65%	54%	65%	62%	52%	53%
yes	min wwr>0.45	5%	25%	14%	16%	29%	30%	19%
yes	max wwr<0.30	11%	50%	36%	48%	60%	36%	36%
yes	min wwr<0.30	6%	2%	3%	1%	34%	8%	3%
no	max	48%	68%	59%	68%	56%	56%	59%
no	min	0%	0%	0%	0%	0%	0%	0%
no	avg	34%	32%	30%	33%	31%	30%	30%
no	max wwr>0.45	48%	68%	59%	68%	56%	56%	59%
no	min wwr>0.45	46%	35%	33%	34%	16%	38%	35%
no	max wwr<0.30	44%	54%	46%	55%	51%	44%	46%
no	min wwr<0.30	29%	13%	16%	15%	20%	20%	17%

This is defined as the range of maximum percentage savings that can be realized by the EC glazing compared to the base case glazings. The range is determined by the parametric cases, which include 5 base case glazings, 4 WWR, shades (yes/no), daylighting controls (yes/no), and four perimeter zone orientations.

Table 3.4
Minimum Perimeter Zone Savings or Percentage Reductions by Electrochromic Glazings, Small Office Prototypes, New York, New York

Base case has daylighting?		Lighting Energy	Cooling Energy	Electric Total	Peak Demand	Heating Energy	Energy Cost 1:1	Energy Cost 1:5
		Small Office, Old Vintage, NYC						
yes	max	0%	29%	19%	29%	0%	13%	18%
yes	min	-11%	-3%	-3%	-1%	-179%	-2%	-2%
yes	avg	-4%	6%	4%	4%	-38%	1%	3%
yes	max wwr>0.45	-3%	29%	19%	29%	-25%	13%	18%
yes	min wwr>0.45	-4%	4%	3%	1%	-179%	-1%	2%
yes	max wwr<0.30	-5%	8%	5%	3%	-5%	3%	5%
yes	min wwr<0.30	-11%	-3%	-3%	-1%	-59%	-2%	-2%
no	max	40%	36%	33%	39%	0%	27%	31%
no	min	0%	0%	0%	0%	-262%	0%	0%
no	avg	29%	16%	18%	16%	-81%	14%	17%
no	max wwr>0.45	40%	36%	33%	39%	-81%	27%	31%
no	min wwr>0.45	39%	18%	22%	16%	-262%	15%	21%
no	max wwr<0.30	37%	22%	23%	22%	-28%	19%	22%
no	min wwr<0.30	24%	8%	14%	8%	-116%	11%	13%
		Small Office, New Vintage, NYC						
yes	max	0%	30%	21%	31%	0%	15%	20%
yes	min	-15%	-2%	-3%	-1%	-185%	-2%	-2%
yes	avg	-6%	6%	4%	4%	-40%	1%	3%
yes	max wwr>0.45	-4%	30%	21%	31%	-26%	15%	20%
yes	min wwr>0.45	-6%	3%	3%	1%	-185%	-1%	2%
yes	max wwr<0.30	-7%	6%	5%	2%	-5%	3%	4%
yes	min wwr<0.30	-15%	-2%	-3%	-1%	-63%	-2%	-2%
no	max	48%	36%	35%	41%	0%	27%	33%
no	min	0%	0%	0%	0%	-273%	0%	0%
no	avg	34%	14%	18%	16%	-85%	14%	17%
no	max wwr>0.45	48%	36%	35%	41%	-83%	27%	33%
no	min wwr>0.45	46%	14%	23%	15%	-273%	14%	21%
no	max wwr<0.30	44%	18%	23%	22%	-31%	18%	22%
no	min wwr<0.30	29%	6%	14%	8%	-126%	11%	13%

This is defined as the range of maximum percentage savings that can be realized by the EC glazing compared to the base case glazings. The range is determined by the parametric cases, which include 5 base case glazings, 4 WWR, shades (yes/no), daylighting controls (yes/no), and four perimeter zone orientations.

Table 4.1
Maximum Perimeter Zone Savings or Percentage Reductions by Electrochromic Glazings, Large Office Prototypes, Buffalo, New York

Base case has daylighting?		Lighting Energy	Cooling Energy	Electric Total	Peak Demand	Heating Energy	Energy Cost 1:1	Energy Cost 1:5
		Large Office, Old Vintage, Buffalo						
yes	max	10%	64%	48%	59%	69%	48%	48%
yes	min	0%	0%	0%	0%	0%	0%	0%
yes	avg	5%	28%	17%	21%	35%	22%	18%
yes	max wwr>0.45	6%	64%	48%	59%	69%	48%	48%
yes	min wwr>0.45	4%	25%	6%	11%	36%	28%	13%
yes	max wwr<0.30	10%	47%	31%	42%	49%	31%	31%
yes	min wwr<0.30	6%	3%	3%	0%	21%	7%	3%
no	max	45%	66%	55%	60%	65%	53%	55%
no	min	0%	0%	0%	0%	0%	0%	0%
no	avg	31%	34%	27%	25%	28%	28%	28%
no	max wwr>0.45	45%	66%	55%	60%	65%	53%	55%
no	min wwr>0.45	43%	35%	26%	19%	27%	36%	29%
no	max wwr<0.30	41%	51%	42%	44%	42%	38%	41%
no	min wwr<0.30	24%	14%	13%	0%	8%	16%	13%
		Large Office, New Vintage, Buffalo						
yes	max	13%	70%	38%	68%	74%	62%	49%
yes	min	0%	0%	0%	0%	0%	0%	0%
yes	avg	7%	32%	12%	23%	38%	27%	18%
yes	max wwr>0.45	8%	70%	38%	68%	74%	62%	49%
yes	min wwr>0.45	5%	32%	7%	8%	34%	23%	13%
yes	max wwr<0.30	13%	53%	20%	46%	61%	46%	30%
yes	min wwr<0.30	8%	5%	4%	2%	19%	8%	4%
no	max	53%	71%	49%	71%	73%	63%	55%
no	min	0%	0%	0%	0%	0%	0%	0%
no	avg	37%	38%	27%	33%	35%	32%	28%
no	max wwr>0.45	53%	71%	49%	71%	73%	63%	55%
no	min wwr>0.45	51%	43%	31%	26%	32%	32%	31%
no	max wwr<0.30	49%	57%	37%	53%	59%	49%	41%
no	min wwr<0.30	29%	20%	16%	14%	8%	15%	16%

This is defined as the range of maximum percentage savings that can be realized by the EC glazing compared to the base case glazings. The range is determined by the parametric cases, which include 5 base case glazings, 4 WWR, shades (yes/no), daylighting controls (yes/no), and four perimeter zone orientations.

Table 4.2
Minimum Perimeter Zone Savings or Percentage Reductions by Electrochromic Glazings, Large Office Prototypes, Buffalo, New York

Base case has daylighting?		Lighting Energy	Cooling Energy	Electric Total	Peak Demand	Heating Energy	Energy Cost 1:1	Energy Cost 1:5
		Large Office, Old Vintage, Buffalo						
yes	max	0%	27%	17%	26%	0%	9%	15%
yes	min	-17%	-3%	-4%	-1%	-149%	-4%	-2%
yes	avg	-5%	6%	3%	4%	-32%	1%	3%
yes	max wwr>0.45	-3%	27%	17%	26%	-20%	9%	15%
yes	min wwr>0.45	-4%	1%	1%	0%	-149%	-4%	0%
yes	max wwr<0.30	-5%	8%	7%	10%	-2%	3%	6%
yes	min wwr<0.30	-17%	-3%	-4%	-1%	-40%	-3%	-2%
no	max	45%	35%	32%	28%	0%	24%	30%
no	min	0%	0%	0%	0%	-192%	0%	0%
no	avg	31%	14%	17%	8%	-58%	11%	16%
no	max wwr>0.45	45%	35%	32%	28%	-55%	24%	30%
no	min wwr>0.45	43%	13%	20%	1%	-192%	11%	18%
no	max wwr<0.30	41%	19%	23%	15%	-14%	15%	21%
no	min wwr<0.30	24%	4%	11%	0%	-73%	6%	10%
		Large Office, New Vintage, Buffalo						
yes	max	0%	31%	12%	28%	23%	17%	14%
yes	min	-22%	-4%	-6%	-1%	-22%	-7%	-3%
yes	avg	-7%	7%	3%	5%	-3%	1%	2%
yes	max wwr>0.45	-4%	31%	12%	28%	23%	17%	14%
yes	min wwr>0.45	-6%	1%	2%	3%	-21%	-7%	-1%
yes	max wwr<0.30	-7%	7%	5%	3%	0%	2%	4%
yes	min wwr<0.30	-22%	-4%	-6%	-1%	-22%	-6%	-3%
no	max	53%	39%	32%	41%	16%	25%	30%
no	min	0%	0%	0%	0%	-46%	0%	0%
no	avg	37%	18%	20%	17%	-14%	9%	17%
no	max wwr>0.45	53%	39%	32%	41%	16%	25%	30%
no	min wwr>0.45	51%	18%	26%	16%	-44%	5%	21%
no	max wwr<0.30	49%	23%	25%	21%	-8%	13%	22%
no	min wwr<0.30	29%	7%	14%	8%	-46%	5%	12%

This is defined as the range of maximum percentage savings that can be realized by the EC glazing compared to the base case glazings. The range is determined by the parametric cases, which include 5 base case glazings, 4 WWR, shades (yes/no), daylighting controls (yes/no), and four perimeter zone orientations.

Table 4.3
Maximum Perimeter Zone Savings or Percentage Reductions by Electrochromic Glazings – Small Office Prototypes, Buffalo, New York

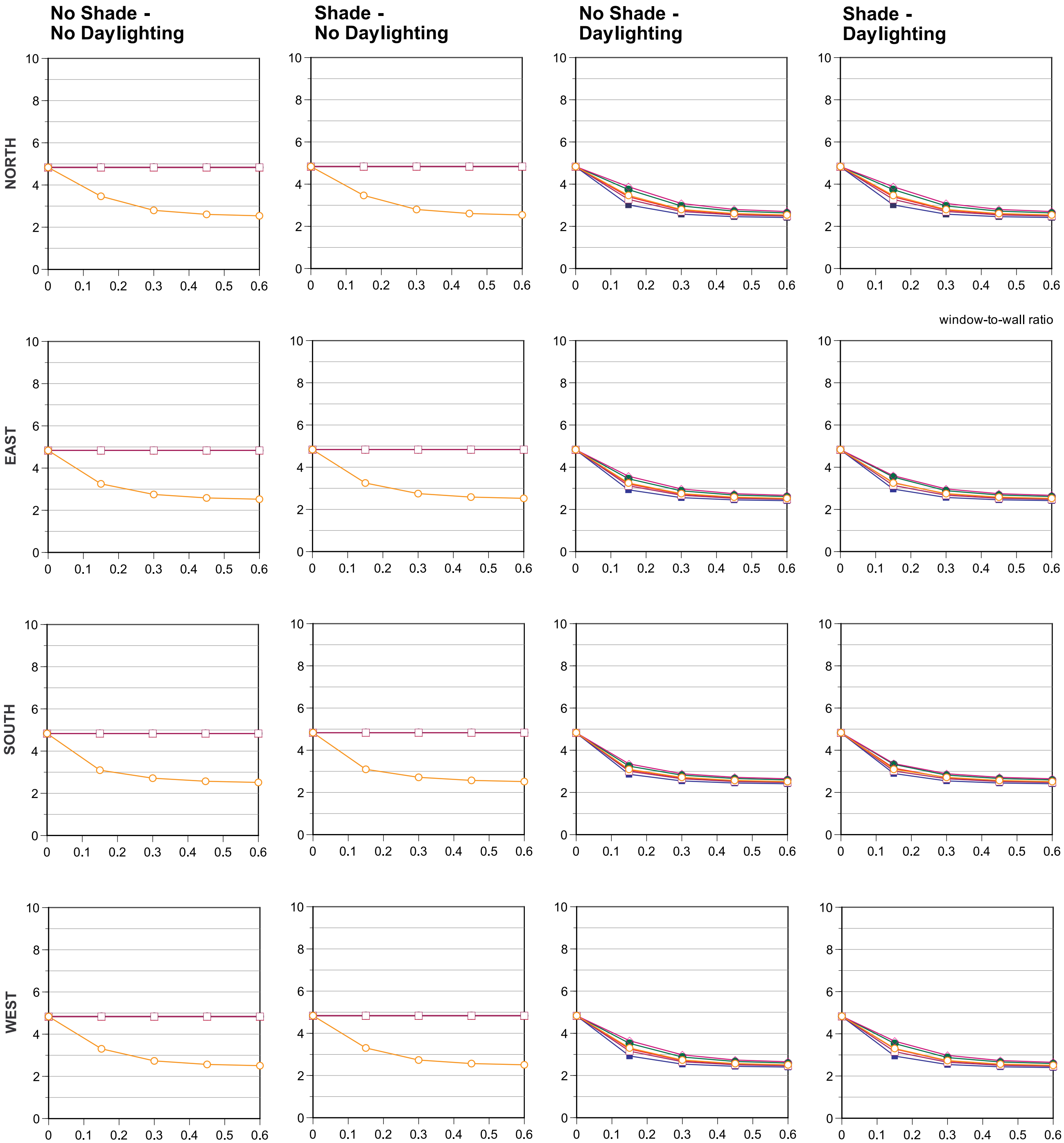
Base case has daylighting?		Lighting Energy	Cooling Energy	Electric Total	Peak Demand	Heating Energy	Energy Cost 1:1	Energy Cost 1:5
		Small Office, Old Vintage, Buffalo						
yes	max	9%	66%	52%	67%	60%	48%	51%
yes	min	0%	0%	0%	0%	0%	0%	0%
yes	avg	5%	28%	18%	26%	33%	22%	19%
yes	max wwr>0.45	5%	66%	52%	67%	60%	48%	51%
yes	min wwr>0.45	3%	23%	8%	15%	22%	29%	14%
yes	max wwr<0.30	9%	48%	32%	51%	51%	32%	32%
yes	min wwr<0.30	6%	2%	3%	2%	24%	8%	4%
no	max	45%	69%	59%	70%	54%	53%	58%
no	min	0%	0%	0%	0%	0%	0%	0%
no	avg	31%	35%	30%	36%	23%	29%	30%
no	max wwr>0.45	45%	69%	59%	70%	54%	53%	58%
no	min wwr>0.45	43%	37%	31%	35%	11%	37%	32%
no	max wwr<0.30	41%	54%	44%	58%	42%	40%	44%
no	min wwr<0.30	25%	18%	16%	16%	7%	19%	17%
		Small Office, New Vintage, Buffalo						
yes	max	12%	70%	56%	69%	59%	52%	55%
yes	min	0%	0%	0%	0%	0%	0%	0%
yes	avg	7%	28%	19%	27%	34%	24%	21%
yes	max wwr>0.45	8%	70%	56%	69%	59%	52%	55%
yes	min wwr>0.45	5%	16%	8%	17%	20%	30%	15%
yes	max wwr<0.30	12%	52%	36%	53%	53%	36%	36%
yes	min wwr<0.30	8%	2%	3%	2%	25%	9%	4%
no	max	53%	72%	63%	72%	54%	56%	61%
no	min	0%	0%	0%	0%	0%	0%	0%
no	avg	38%	34%	31%	37%	24%	31%	31%
no	max wwr>0.45	53%	72%	63%	72%	54%	56%	61%
no	min wwr>0.45	51%	28%	31%	36%	9%	38%	33%
no	max wwr<0.30	49%	56%	48%	60%	44%	43%	47%
no	min wwr<0.30	30%	13%	17%	18%	9%	20%	17%

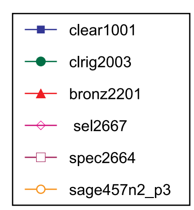
This is defined as the range of maximum percentage savings that can be realized by the EC glazing compared to the base case glazings. The range is determined by the parametric cases, which include 5 base case glazings, 4 WWR, shades (yes/no), daylighting controls (yes/no), and four perimeter zone orientations.

Table 4.4
Minimum Perimeter Zone Savings or Percentage Reductions by Electrochromic Glazings – Small Office Prototypes, Buffalo, New York

Base case has daylighting?		Lighting Energy	Cooling Energy	Electric Total	Peak Demand	Heating Energy	Energy Cost 1:1	Energy Cost 1:5
		Small Office, Old Vintage, Buffalo						
yes	max	0%	30%	19%	30%	0%	9%	17%
yes	min	-17%	-3%	-5%	-5%	-157%	-3%	-3%
yes	avg	-5%	7%	4%	6%	-31%	0%	3%
yes	max wwr>0.45	-3%	30%	19%	30%	-19%	9%	17%
yes	min wwr>0.45	-4%	2%	2%	0%	-157%	-3%	1%
yes	max wwr<0.30	-5%	6%	5%	8%	-4%	2%	4%
yes	min wwr<0.30	-17%	-3%	-5%	-5%	-48%	-3%	-3%
no	max	45%	41%	36%	43%	0%	25%	34%
no	min	0%	0%	0%	0%	-220%	0%	0%
no	avg	31%	18%	20%	21%	-68%	13%	18%
no	max wwr>0.45	45%	41%	36%	43%	-64%	25%	34%
no	min wwr>0.45	43%	20%	24%	25%	-220%	13%	22%
no	max wwr<0.30	41%	23%	25%	30%	-22%	17%	24%
no	min wwr<0.30	25%	9%	14%	13%	-102%	9%	13%
		Small Office, New Vintage, Buffalo						
yes	max	0%	33%	22%	33%	0%	10%	19%
yes	min	-22%	-2%	-6%	-3%	-163%	-4%	-3%
yes	avg	-7%	7%	4%	7%	-32%	0%	3%
yes	max wwr>0.45	-4%	33%	22%	33%	-19%	10%	19%
yes	min wwr>0.45	-6%	1%	2%	2%	-163%	-4%	1%
yes	max wwr<0.30	-7%	4%	4%	8%	-4%	1%	4%
yes	min wwr<0.30	-22%	-2%	-6%	-3%	-51%	-3%	-3%
no	max	53%	41%	39%	45%	0%	25%	36%
no	min	0%	0%	0%	0%	-228%	0%	0%
no	avg	38%	15%	20%	22%	-70%	13%	19%
no	max wwr>0.45	53%	41%	39%	45%	-63%	25%	36%
no	min wwr>0.45	51%	15%	25%	25%	-228%	12%	22%
no	max wwr<0.30	49%	18%	25%	29%	-24%	16%	23%
no	min wwr<0.30	30%	7%	14%	13%	-109%	10%	13%

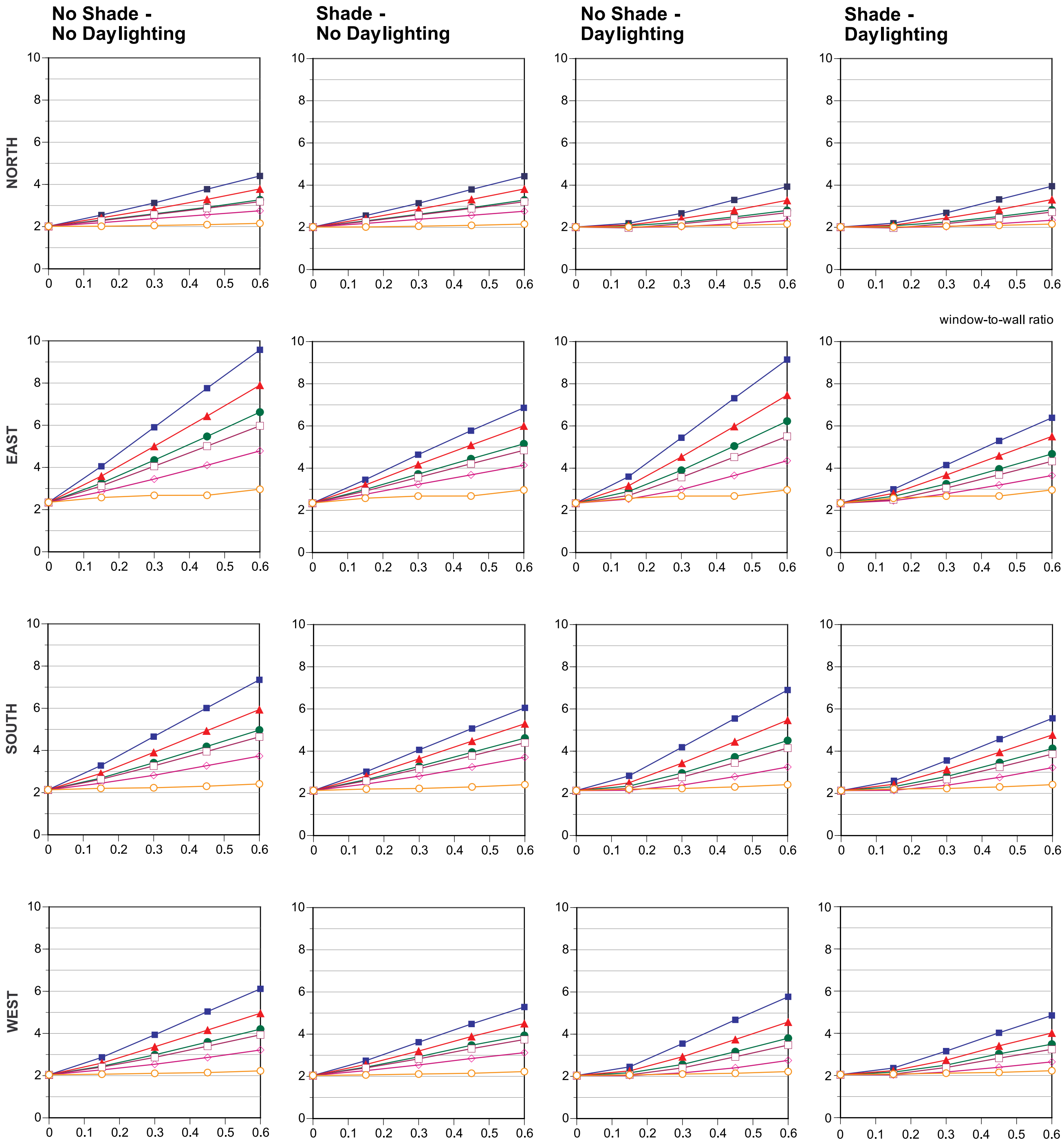
This is defined as the range of maximum percentage savings that can be realized by the EC glazing compared to the base case glazings. The range is determined by the parametric cases, which include 5 base case glazings, 4 WWR, shades (yes/no), daylighting controls (yes/no), and four perimeter zone orientations.





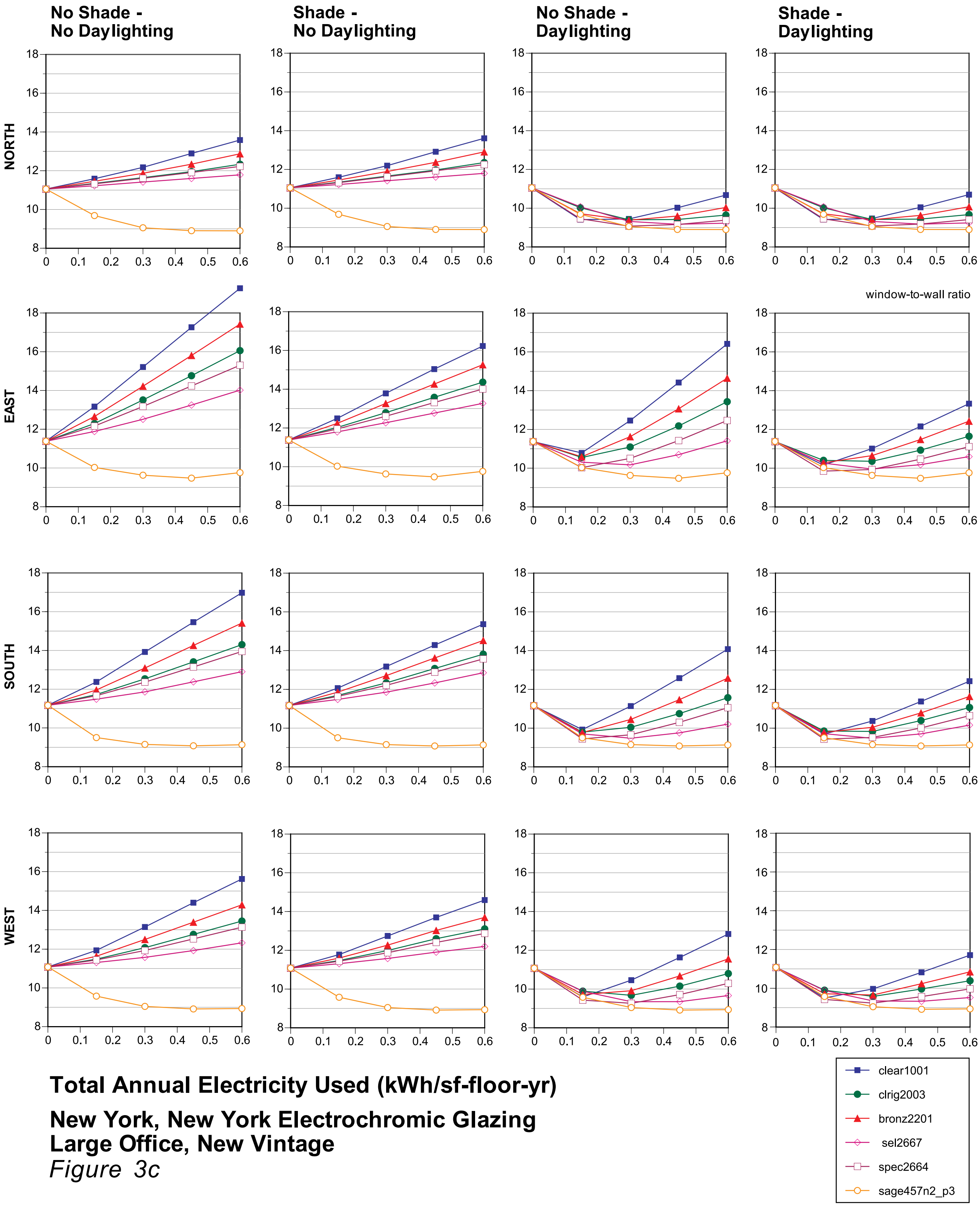
Annual Lighting Energy (kWh/sf-floor-yr)

New York, New York Electrochromic Glazing
Large Office, New Vintage
Figure 3a



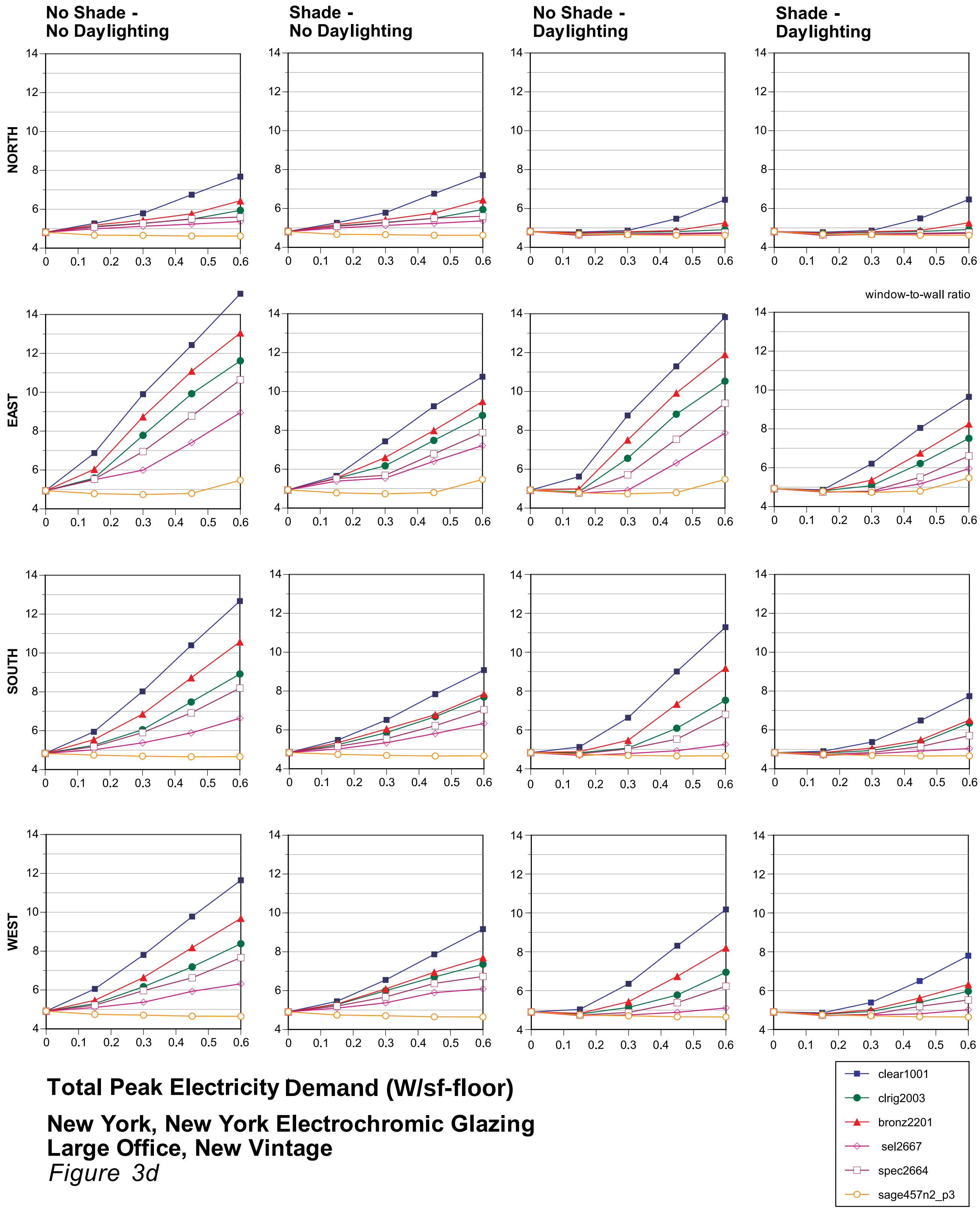
Annual Cooling Energy (kWh/sf-floor-yr), COP = 3.0

New York, New York Electrochromic Glazing
Large Office, New Vintage
Figure 3b



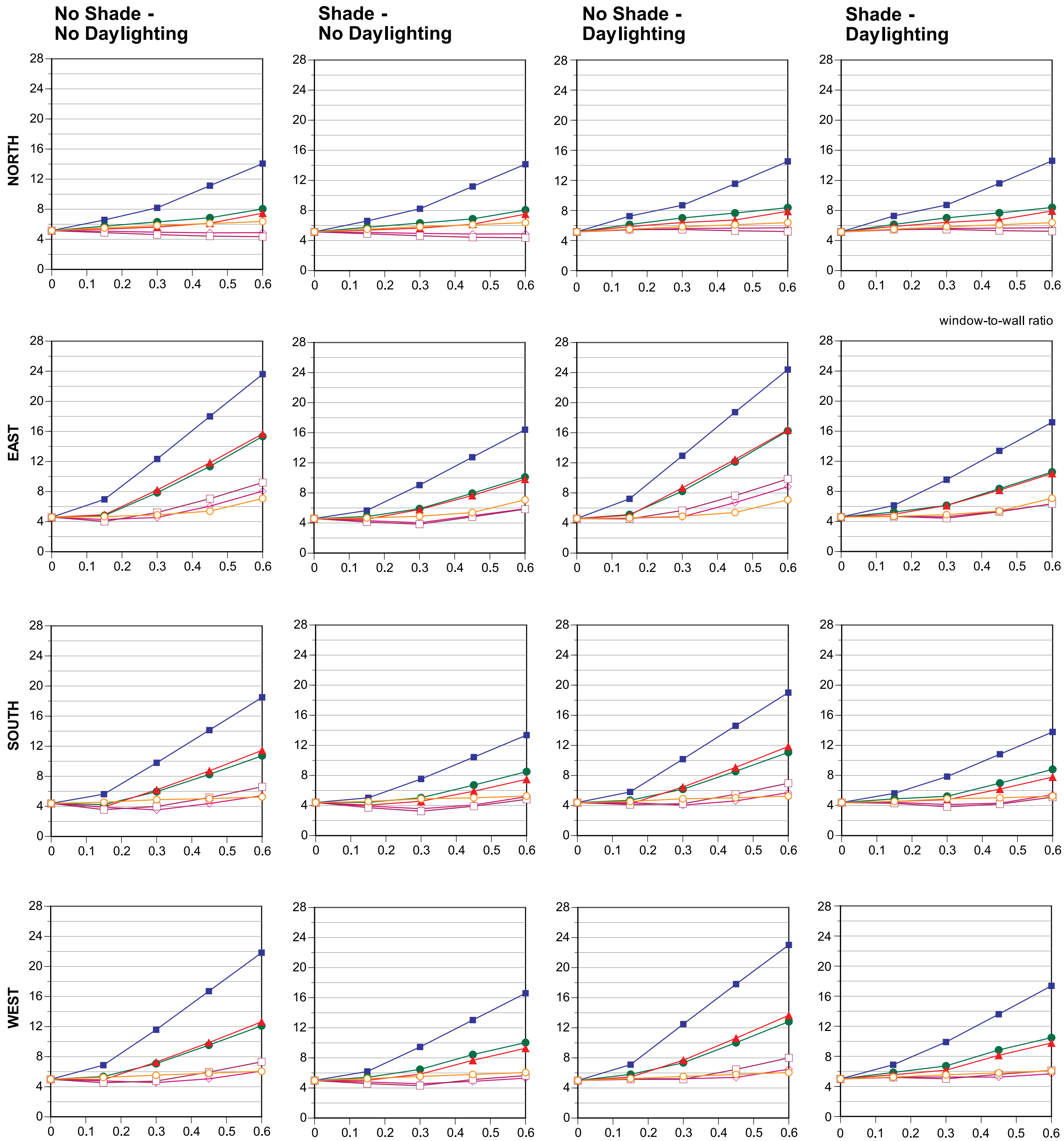
Total Annual Electricity Used (kWh/sf-floor-yr)

New York, New York Electrochromic Glazing
Large Office, New Vintage
Figure 3c

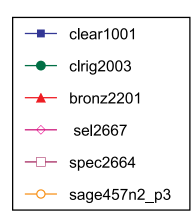


Total Peak Electricity Demand (W/sf-floor)

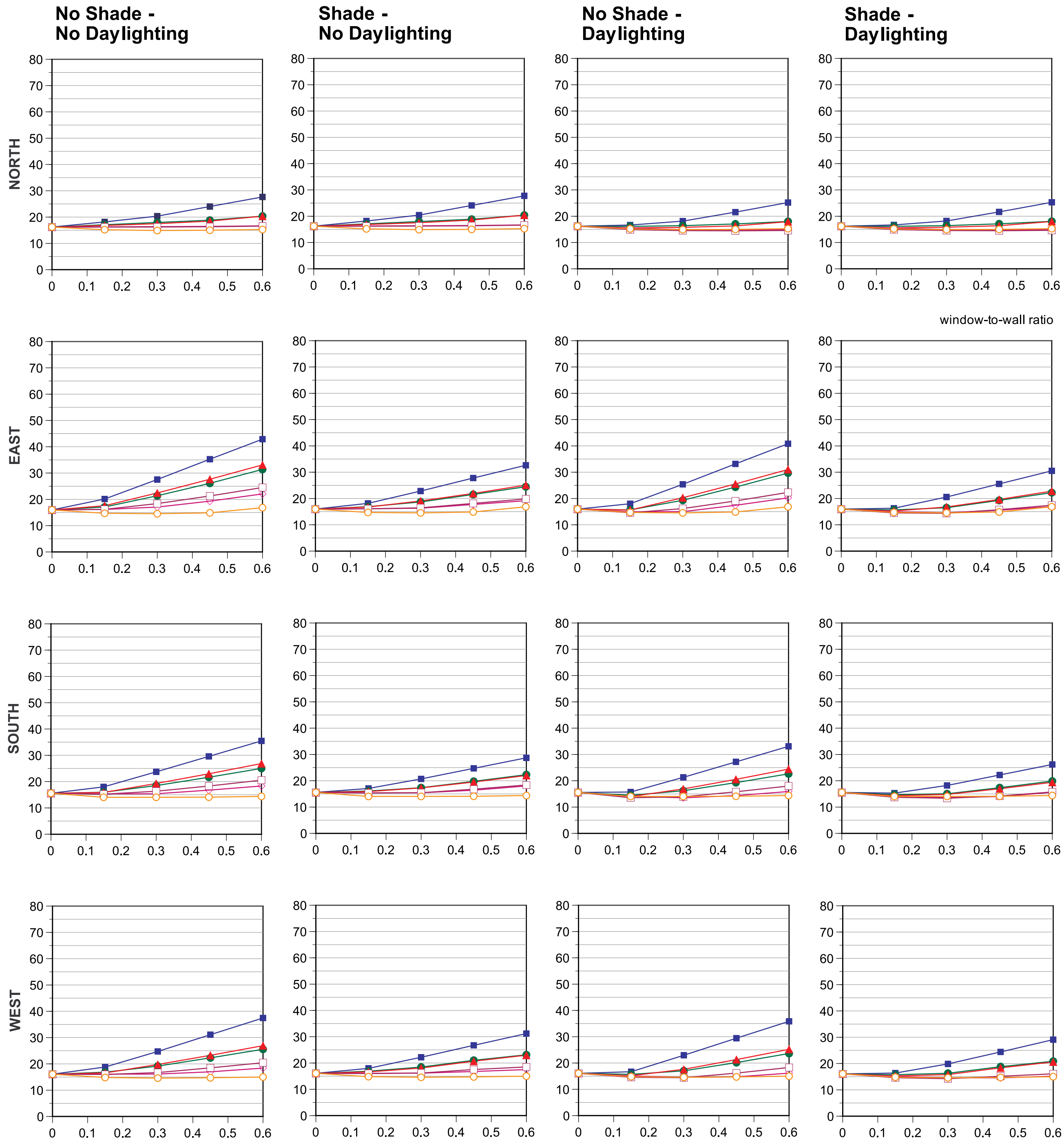
New York, New York Electrochromic Glazing
Large Office, New Vintage
Figure 3d



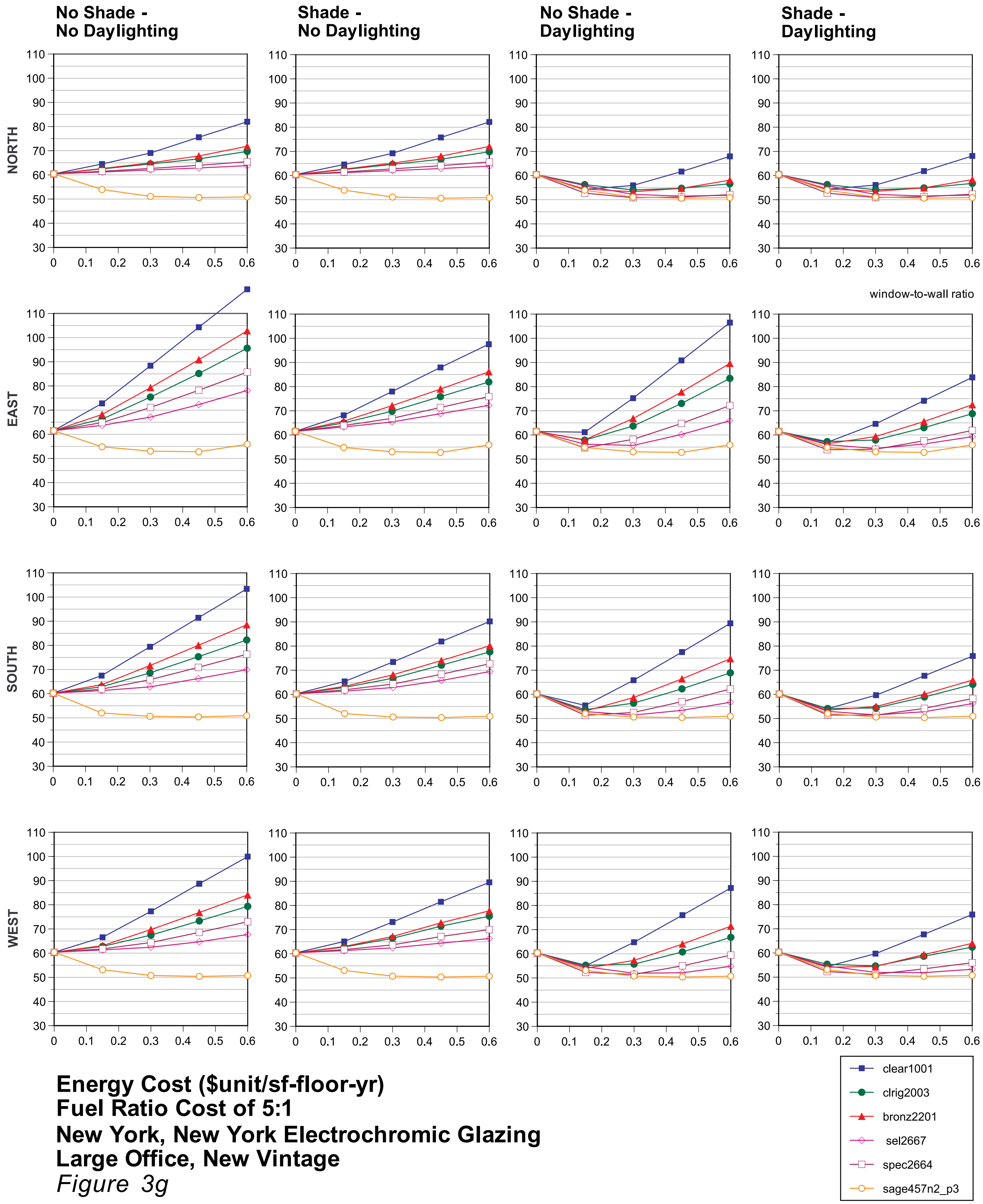
Total Annual Heating Energy Used (kWh/sf-floor-yr)



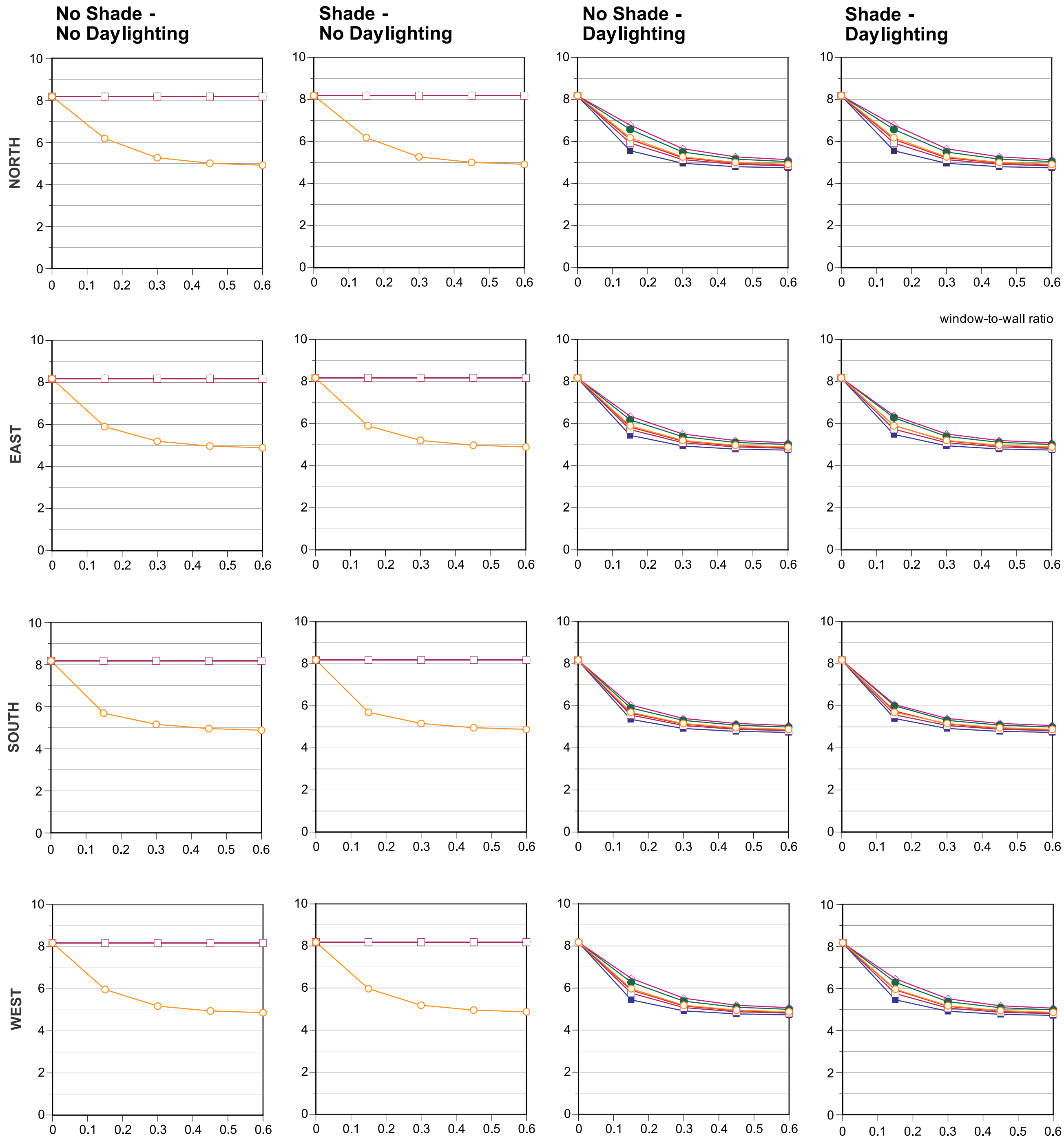
New York, New York Electrochromic Glazing
Large Office, New Vintage
Figure 3e

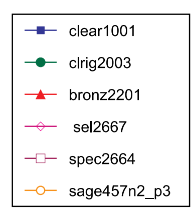


Energy Cost ($unit/sf-floor-yr)
Fuel Ratio Cost of 1:1
New York, New York Electrochromic Glazing
Large Office, New Vintage
Figure 3f



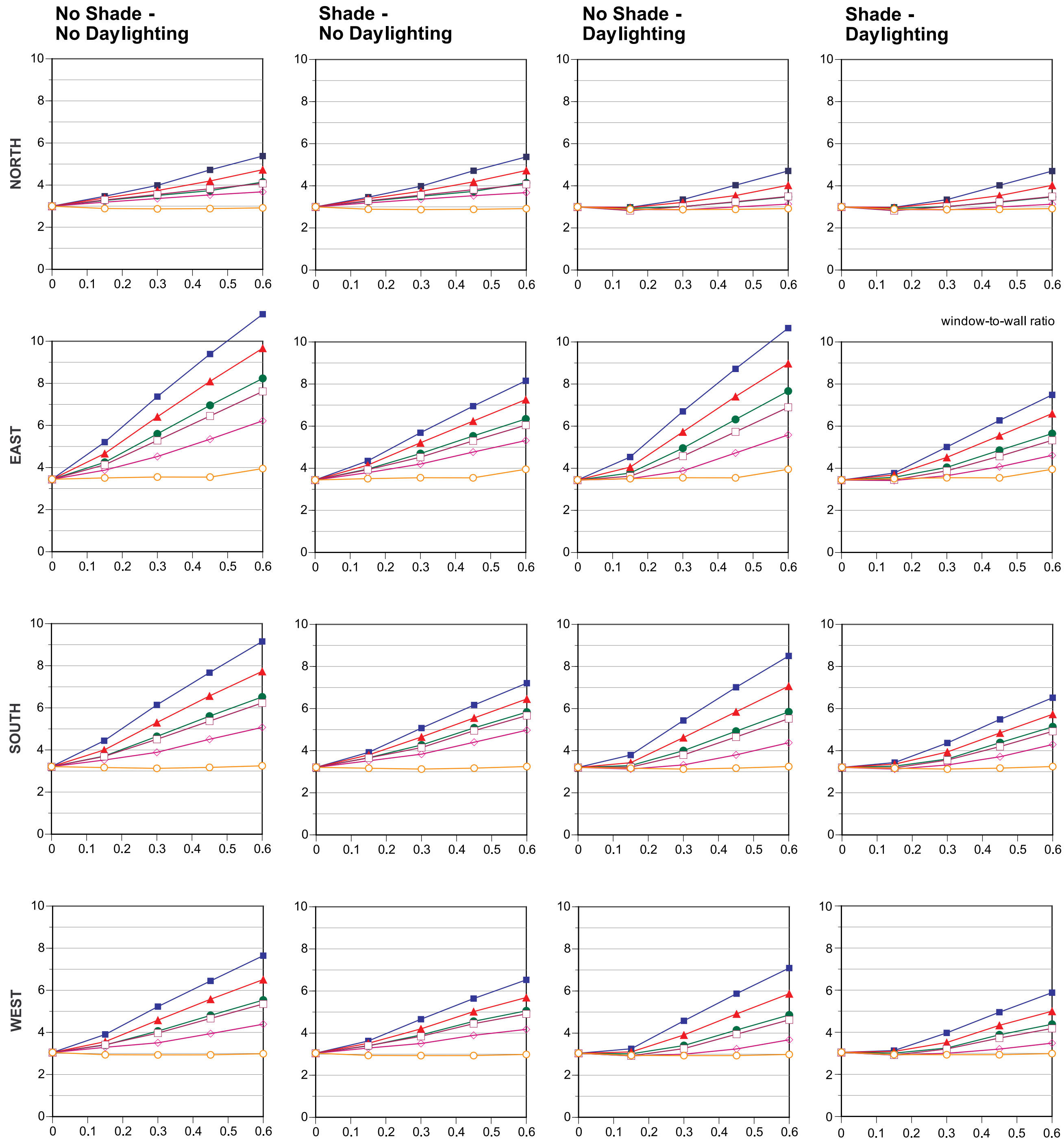
Energy Cost ($unit/sf-floor-yr)
Fuel Ratio Cost of 5:1
New York, New York Electrochromic Glazing
Large Office, New Vintage
Figure 3g

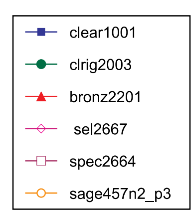




Annual Lighting Energy (kWh/sf-floor-yr)

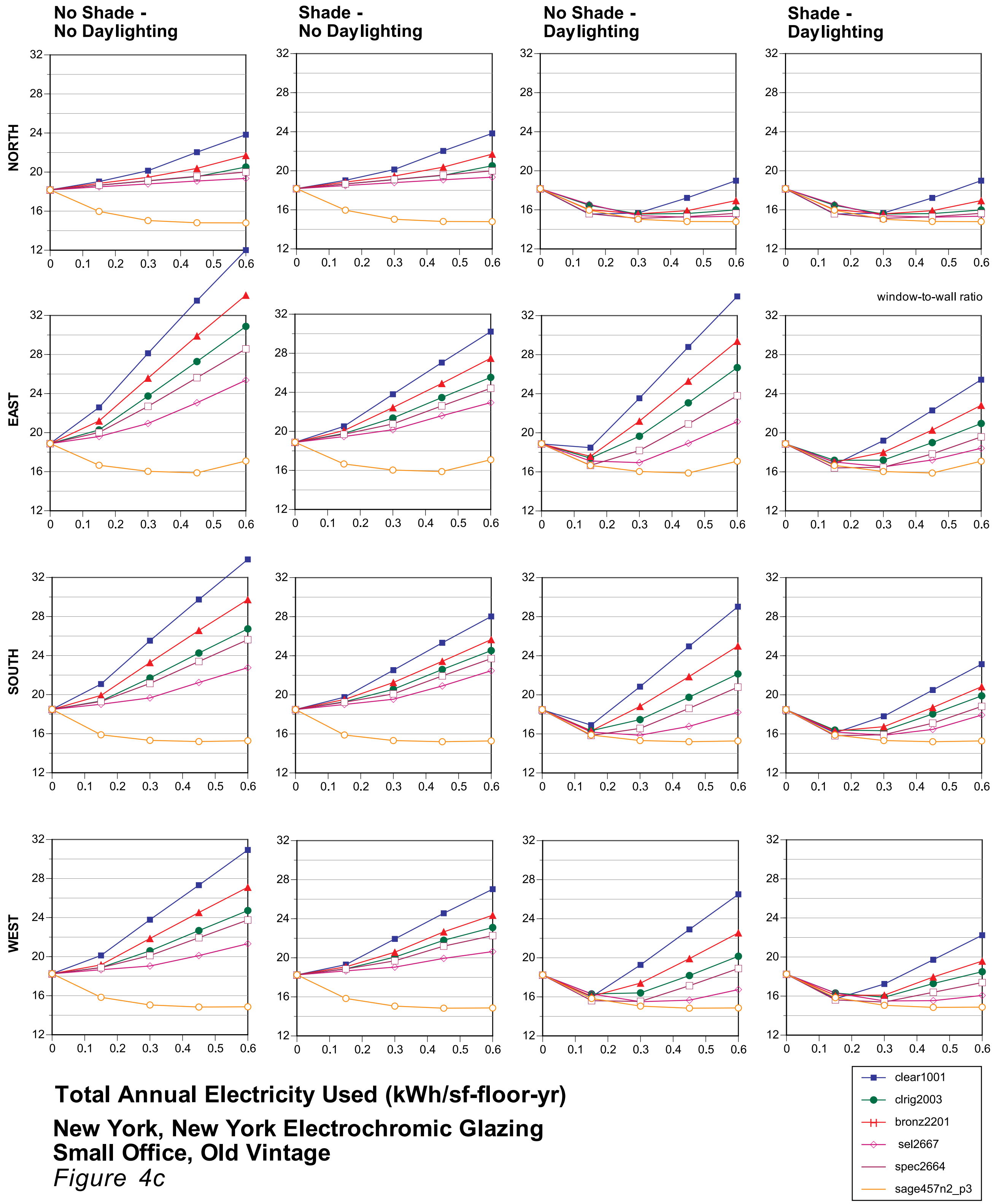
New York, New York Electrochromic Glazing
Small Office, Old Vintage
Figure 4a





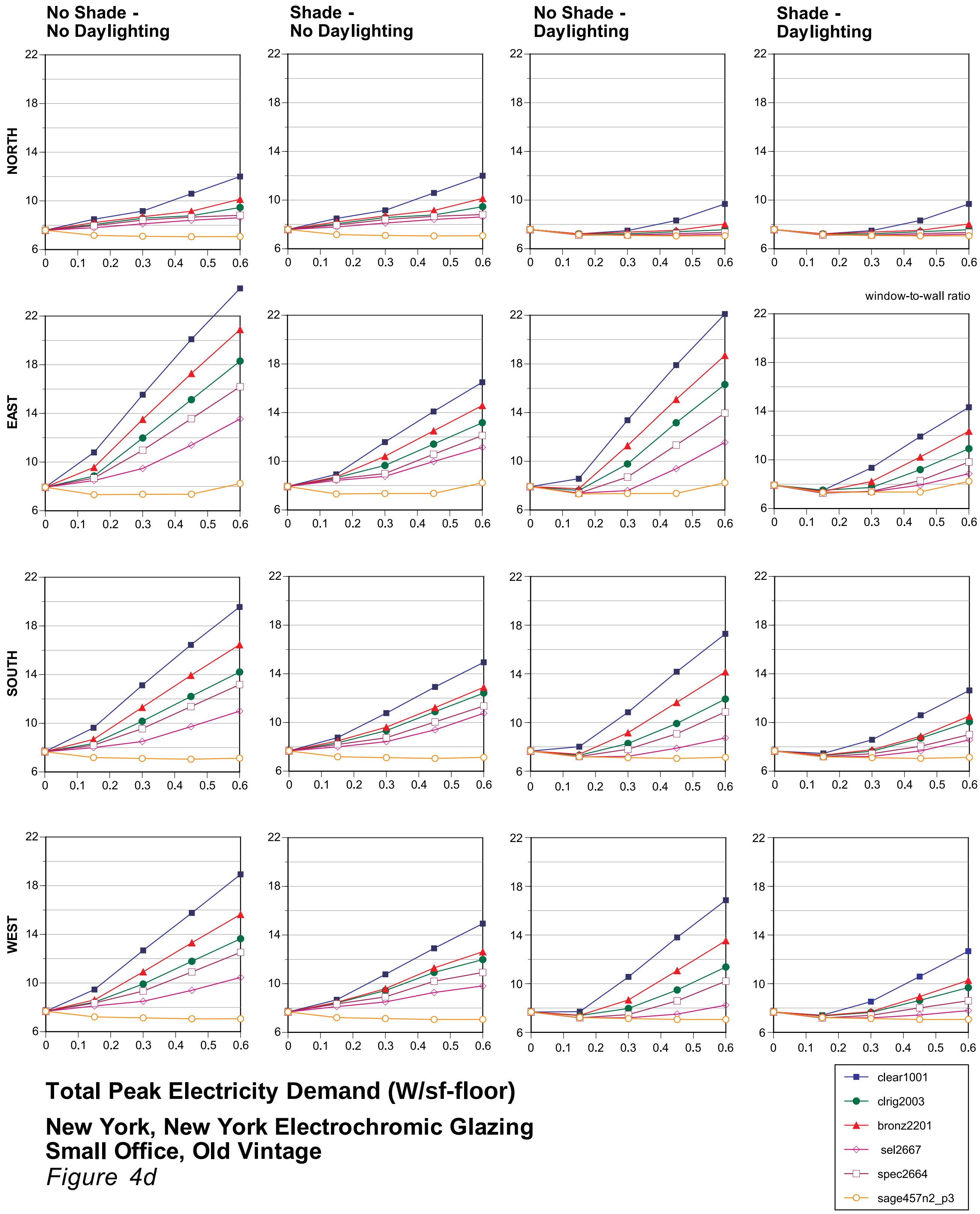
Annual Cooling Energy (kWh/sf-floor-yr), COP = 3.0

New York, New York Electrochromic Glazing
Small Office, Old Vintage
Figure 4b



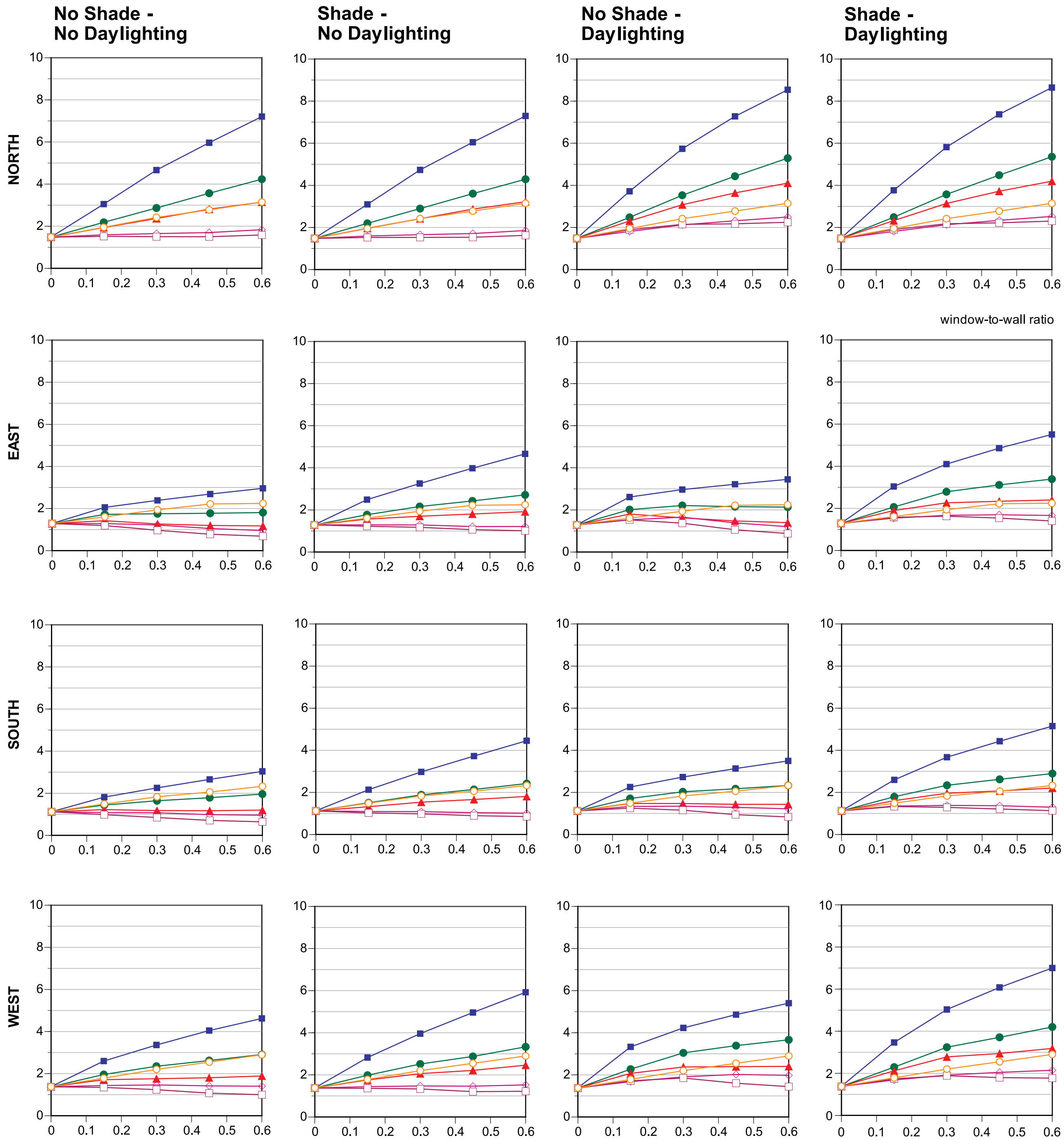
Total Annual Electricity Used (kWh/sf-floor-yr)

New York, New York Electrochromic Glazing
Small Office, Old Vintage
Figure 4c



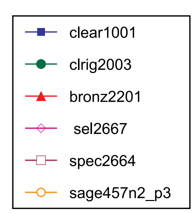
Total Peak Electricity Demand (W/sf-floor)

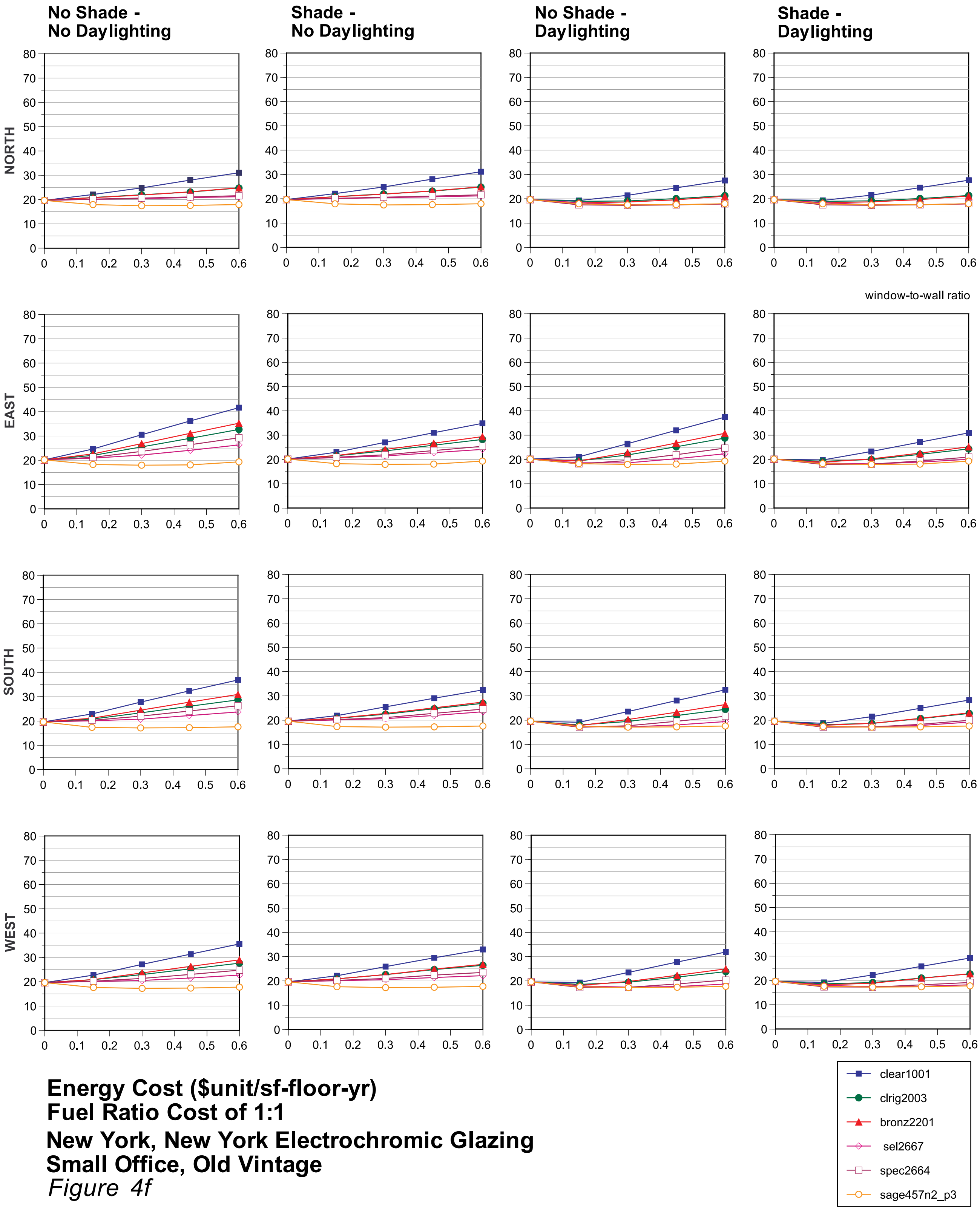
New York, New York Electrochromic Glazing
Small Office, Old Vintage
Figure 4d



Total Annual Heating Energy Used (kWh/sf-floor-yr)

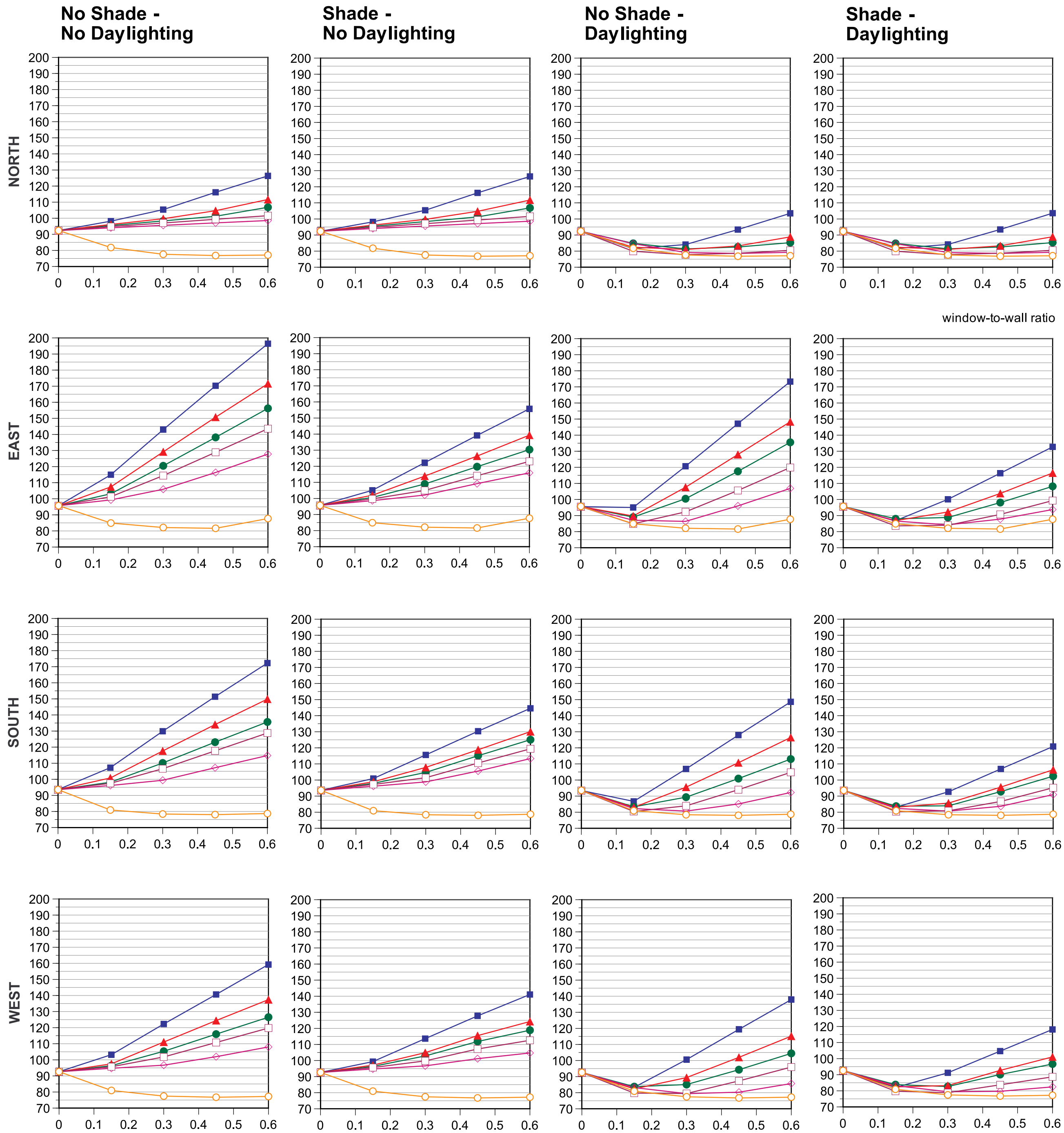
New York, New York Electrochromic Glazing
Small Office, Old Vintage
Figure 4e

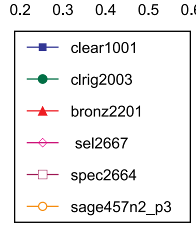




Energy Cost ($unit/sf-floor-yr)
Fuel Ratio Cost of 1:1

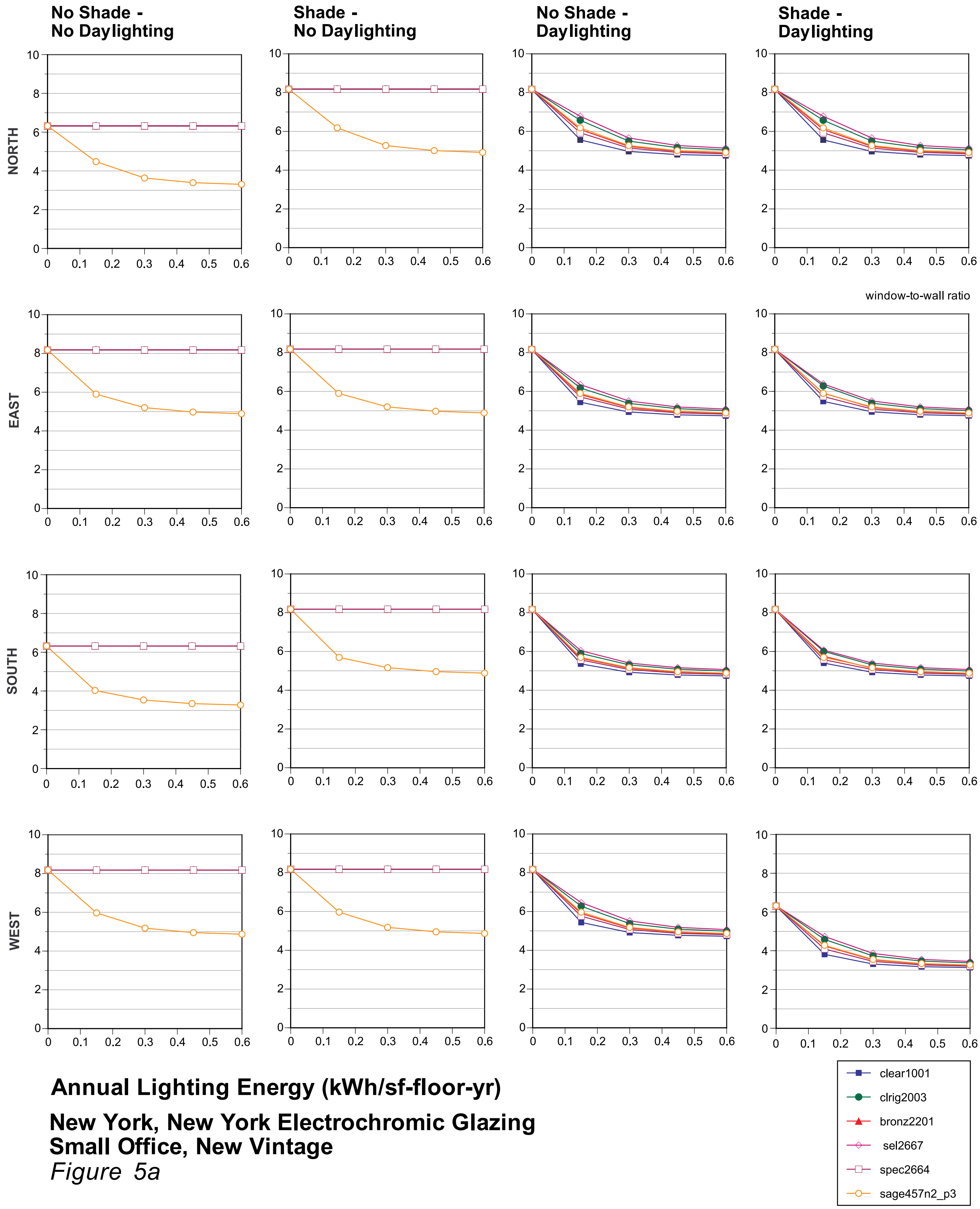
New York, New York Electrochromic Glazing
Small Office, Old Vintage
Figure 4f





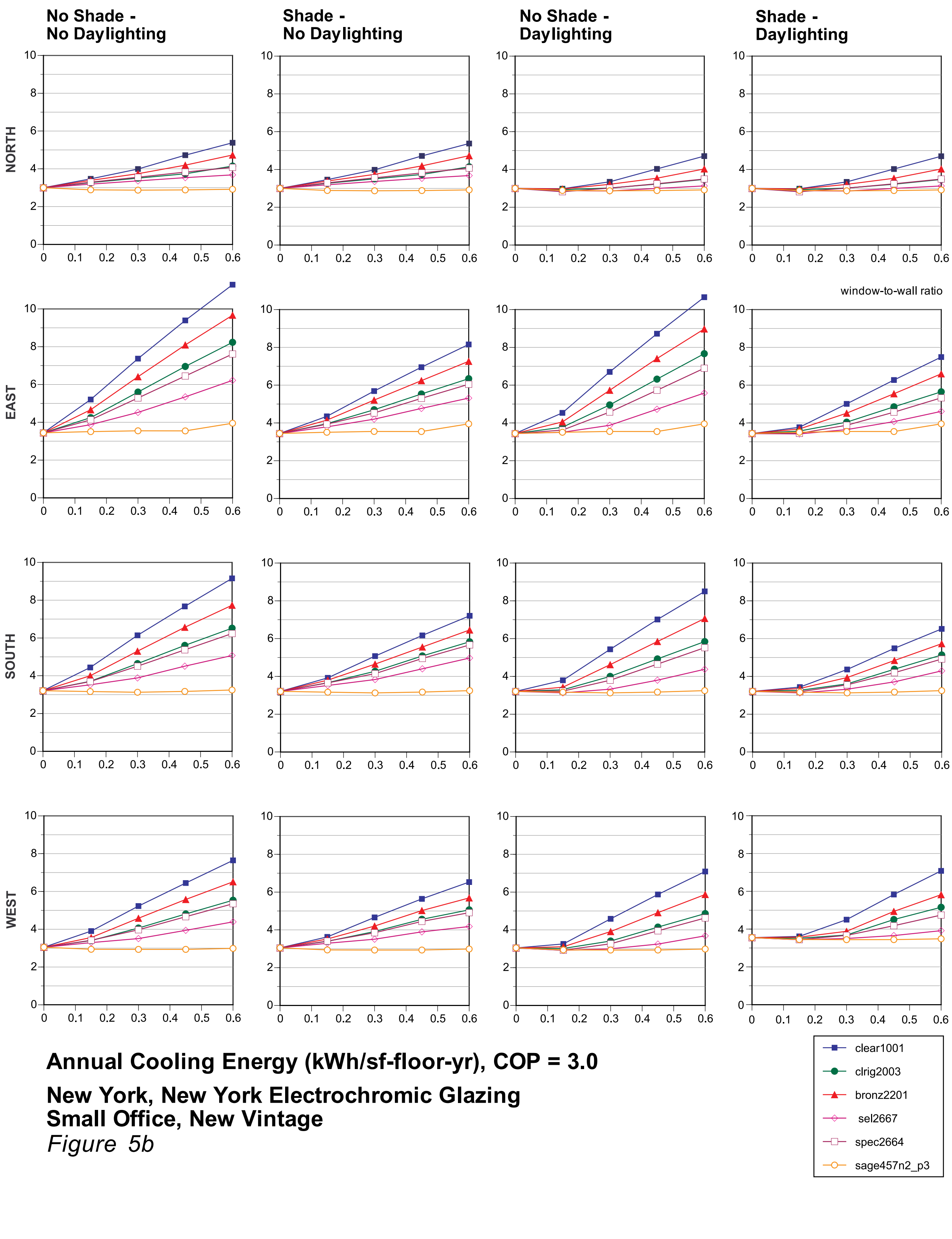
Energy Cost ($unit/sf-floor-yr)
Fuel Ratio Cost of 5:1

New York, New York Electrochromic Glazing
Small Office, Old Vintage
Figure 4g



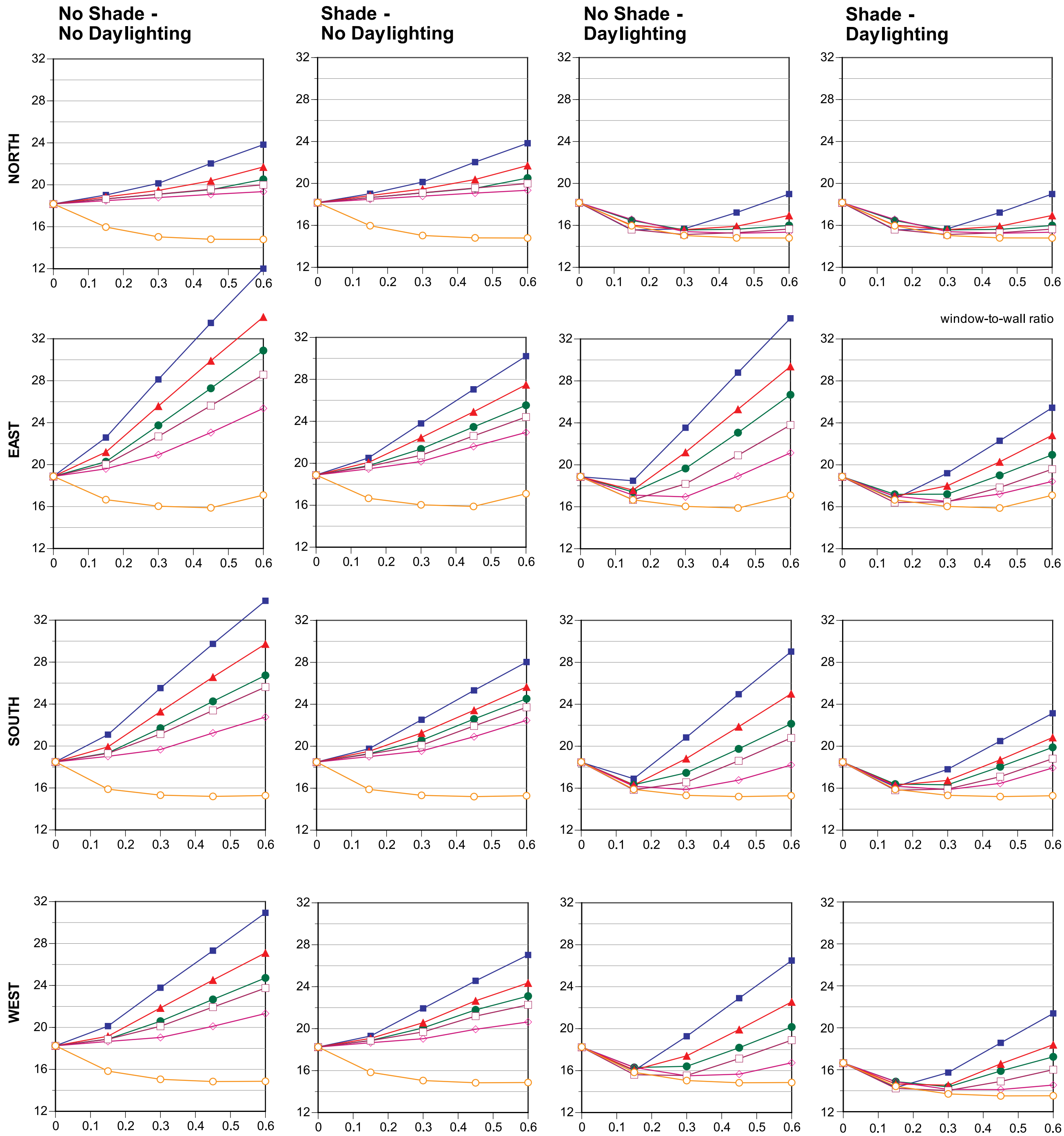
Annual Lighting Energy (kWh/sf-floor-yr)

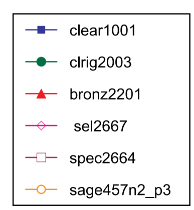
New York, New York Electrochromic Glazing
Small Office, New Vintage
Figure 5a



Annual Cooling Energy (kWh/sf-floor-yr), COP = 3.0

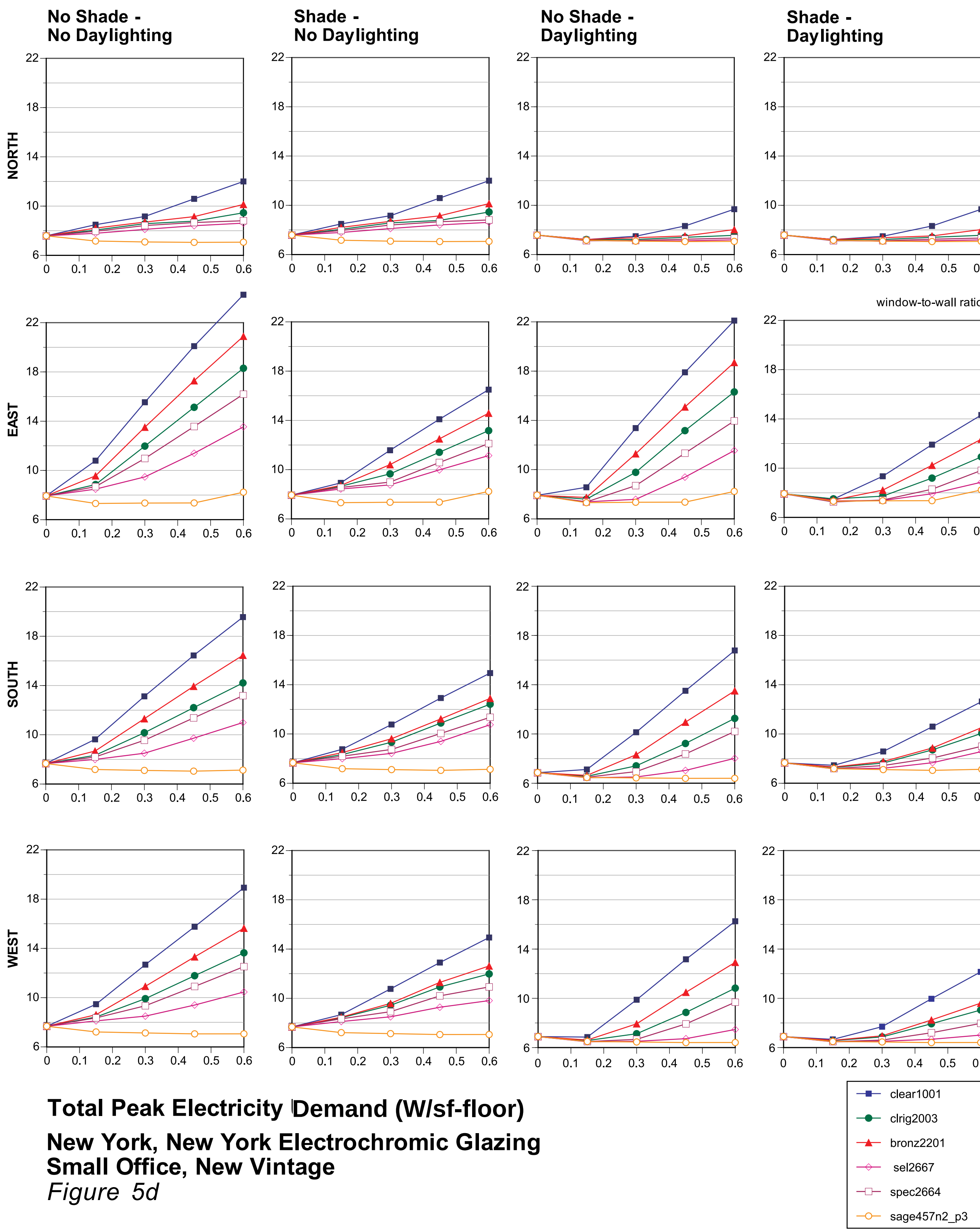
New York, New York Electrochromic Glazing
Small Office, New Vintage
Figure 5b





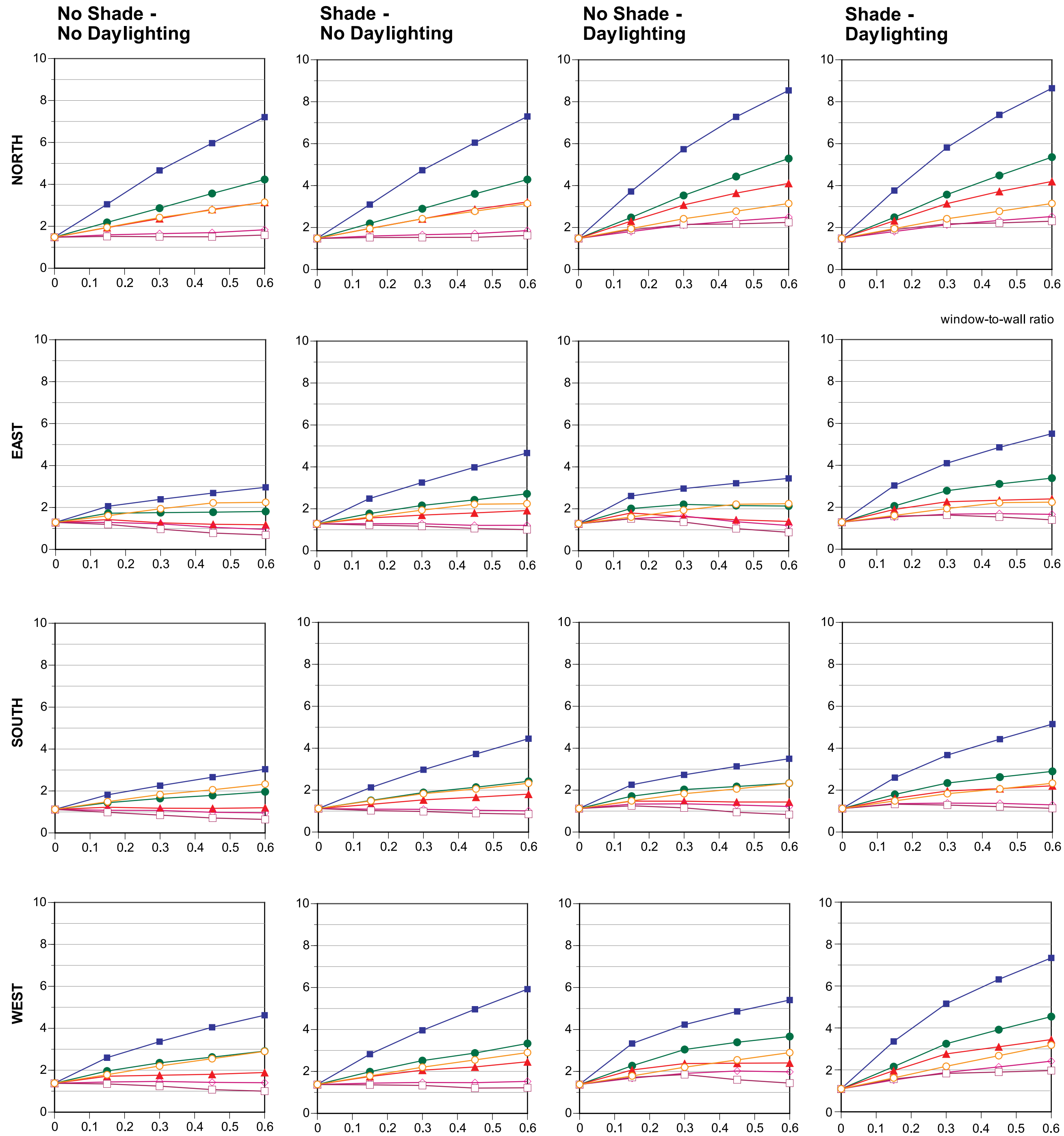
Total Annual Electricity Used (kWh/sf-floor-yr)

New York, New York Electrochromic Glazing
Small Office, New Vintage
Figure 5c

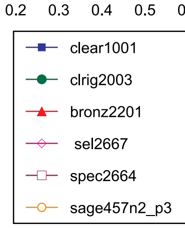


Total Peak Electricity Demand (W/sf-floor)

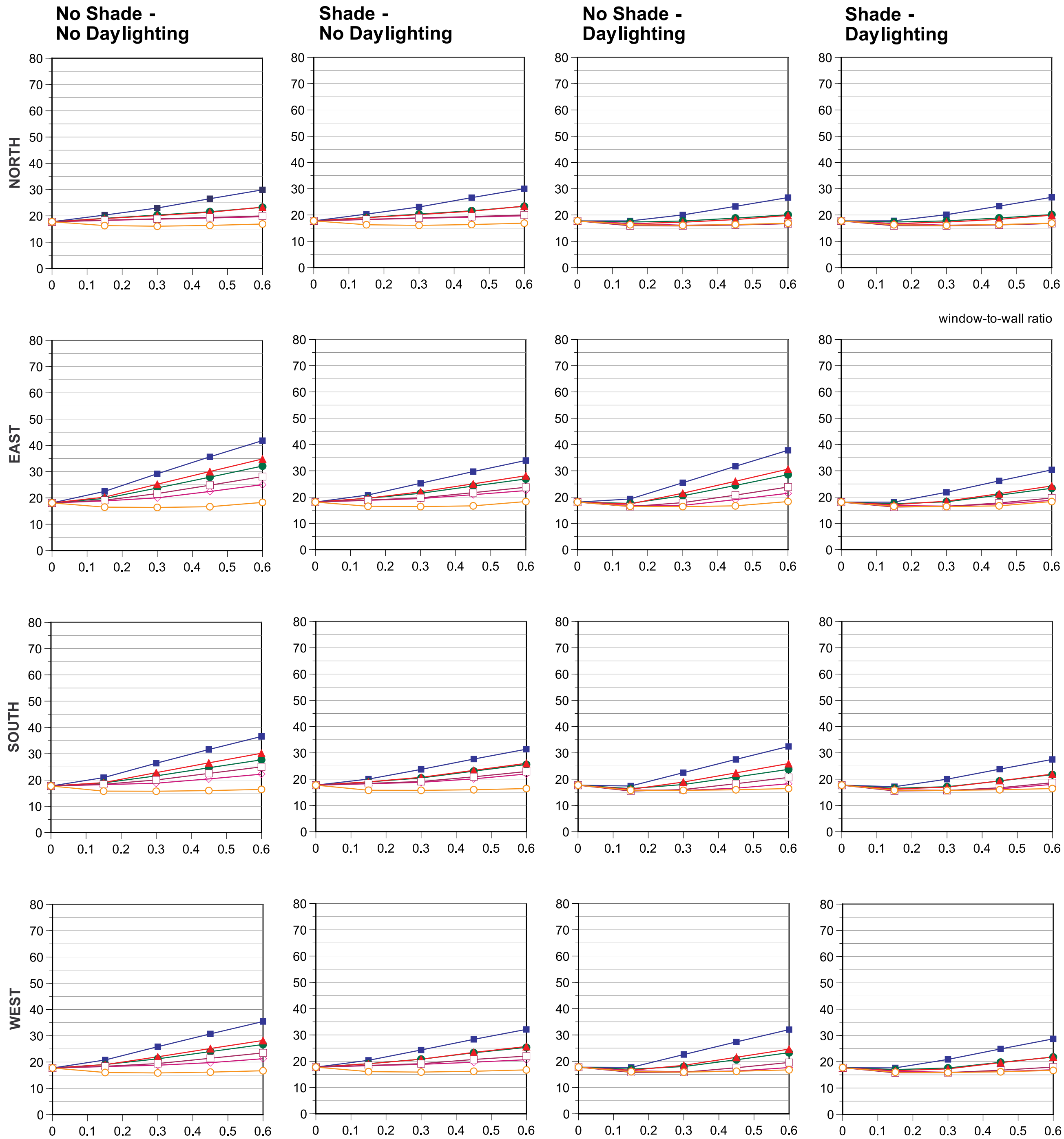
New York, New York Electrochromic Glazing
Small Office, New Vintage
Figure 5d

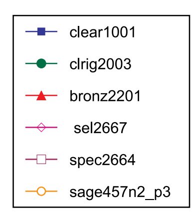


Total Annual Heating Energy Used (kWh/sf-floor-yr)



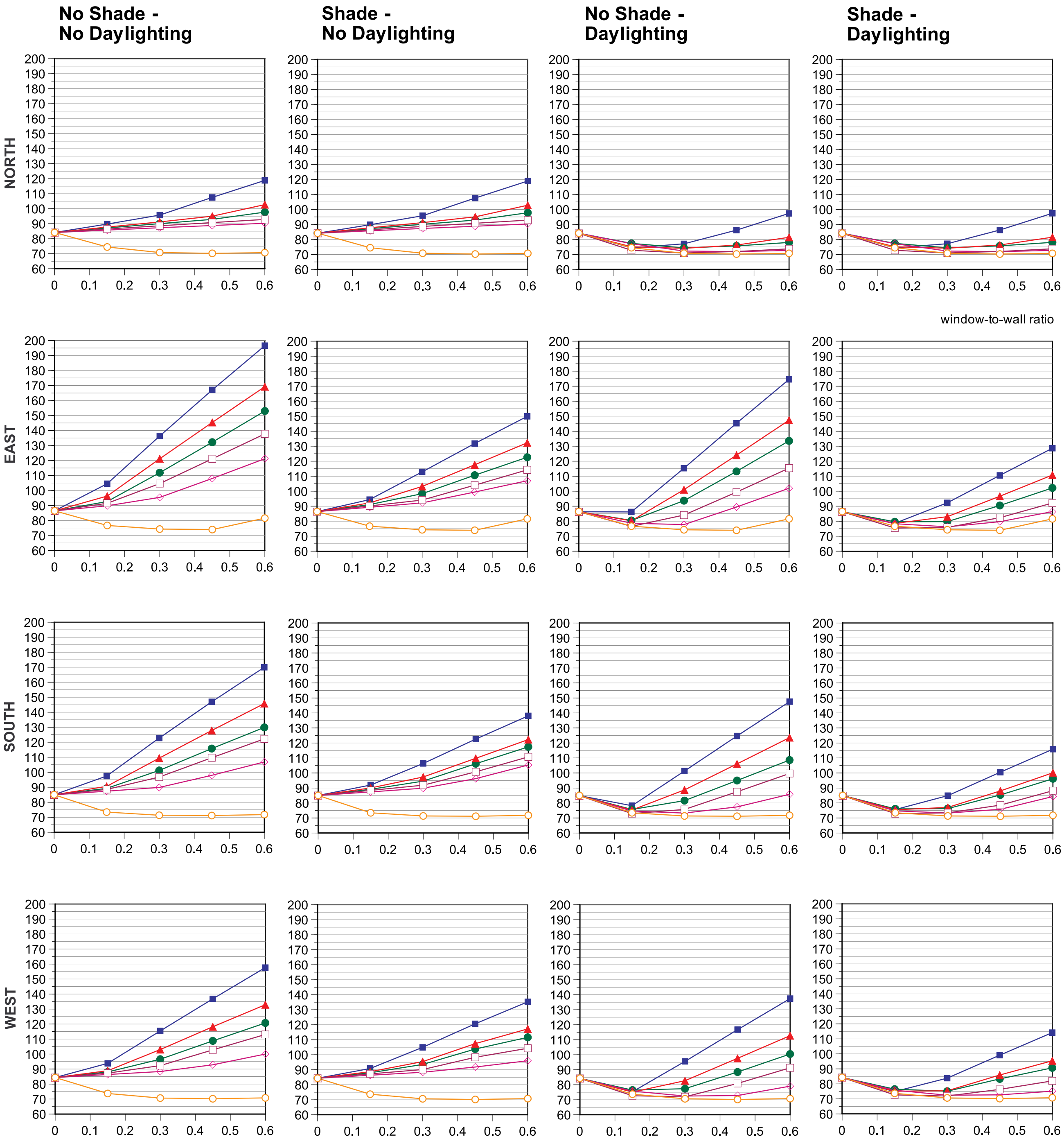
New York, New York Electrochromic Glazing
Small Office, New Vintage
Figure 5e

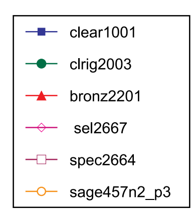




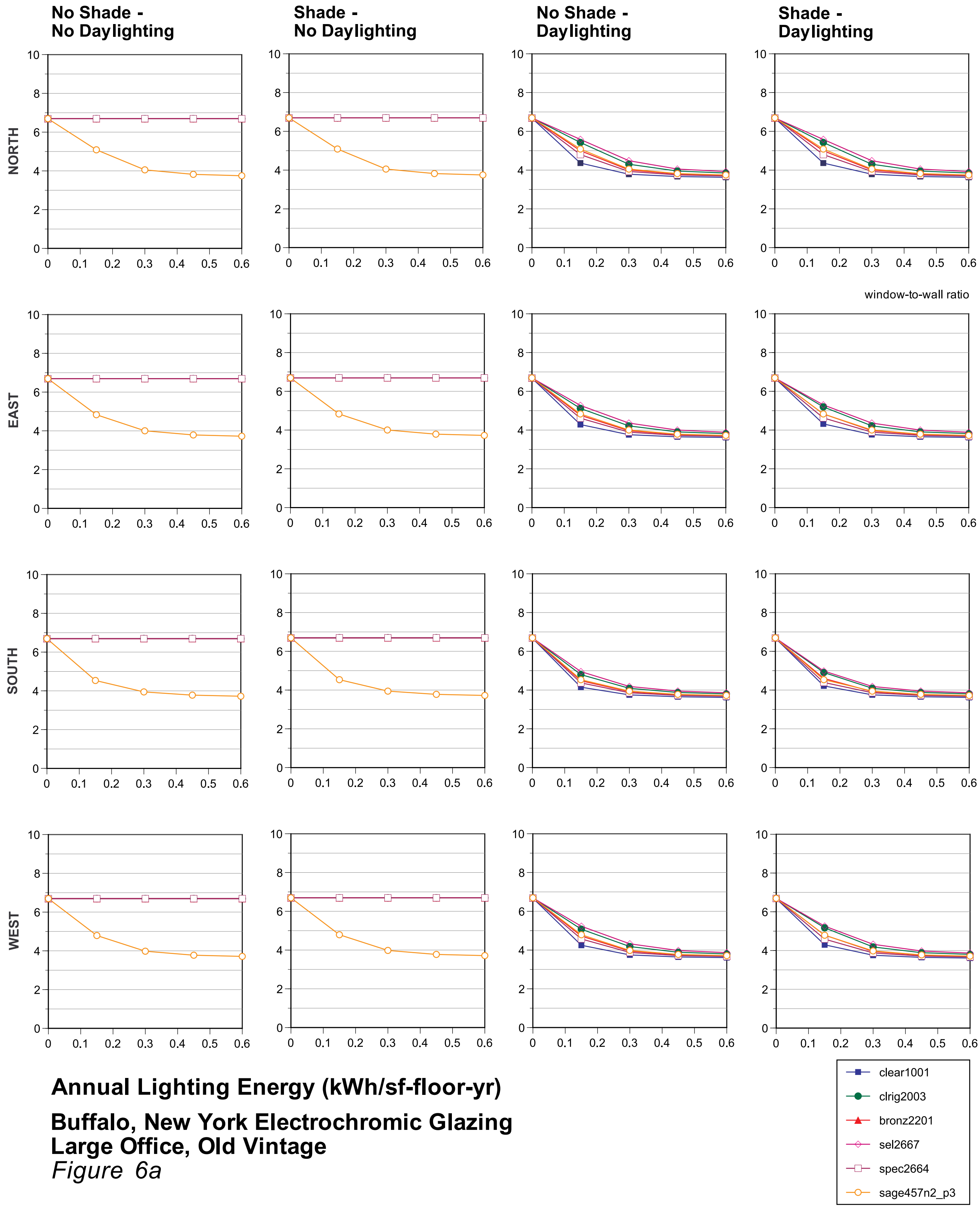
Energy Cost ($unit/sf-floor-yr)
Fuel Ratio Cost of 1:1

New York, New York Electrochromic Glazing
Small Office, New Vintage
Figure 5f



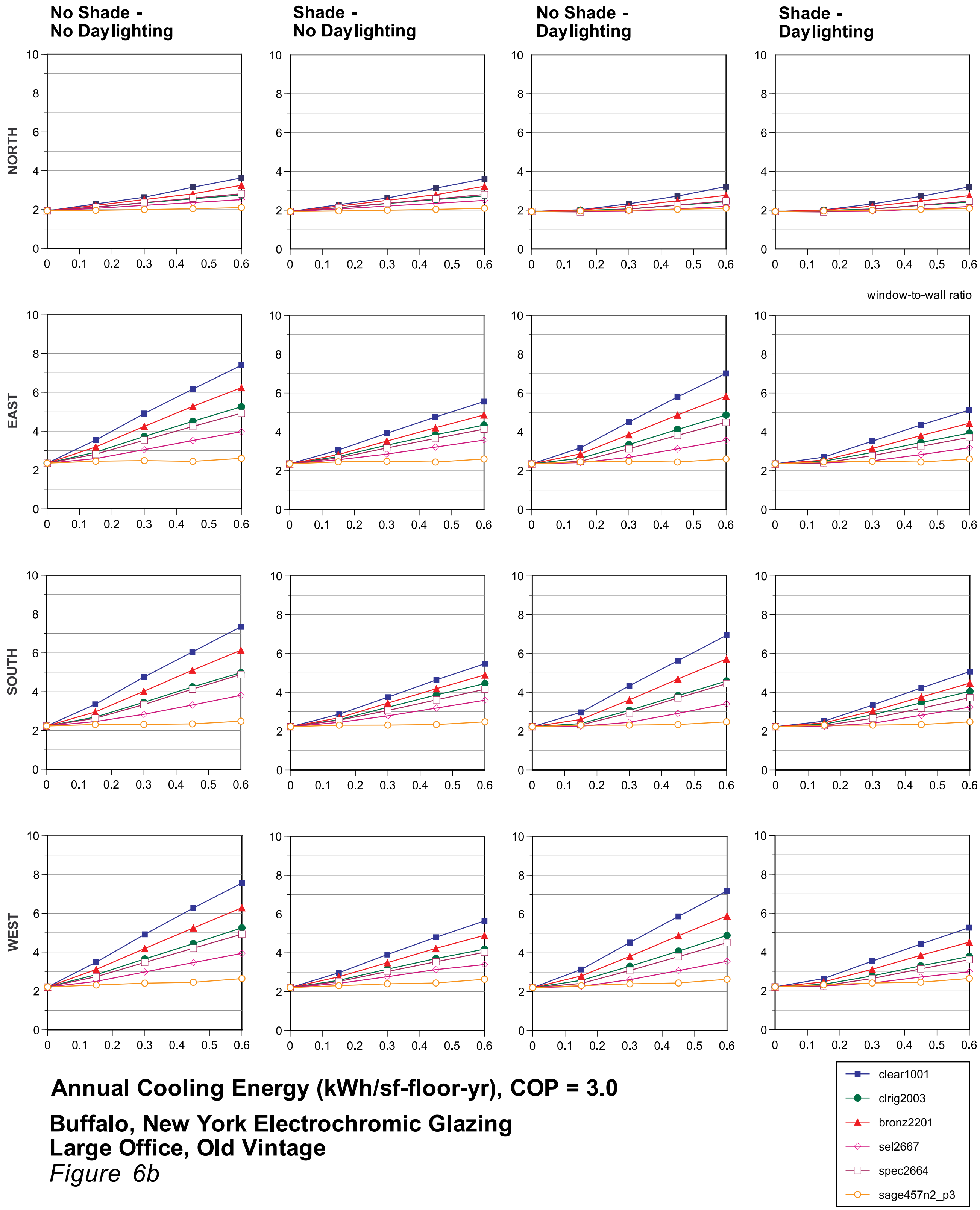


Energy Cost ($unit/sf-floor-yr)
Fuel Ratio Cost of 5:1
New York, New York Electrochromic Glazing
Small Office, New Vintage
Figure 5g



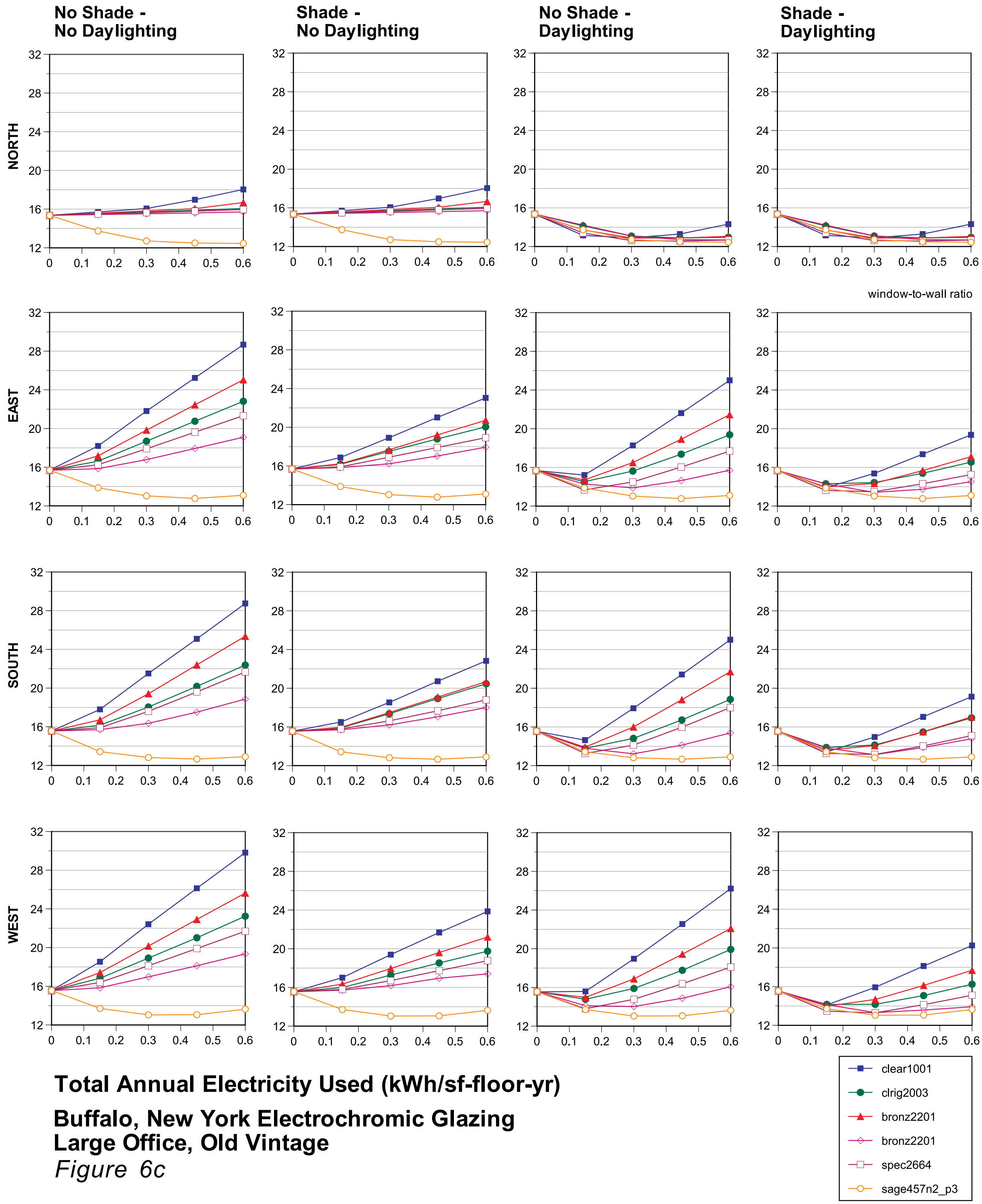
Annual Lighting Energy (kWh/sf-floor-yr)

Buffalo, New York Electrochromic Glazing
Large Office, Old Vintage
Figure 6a



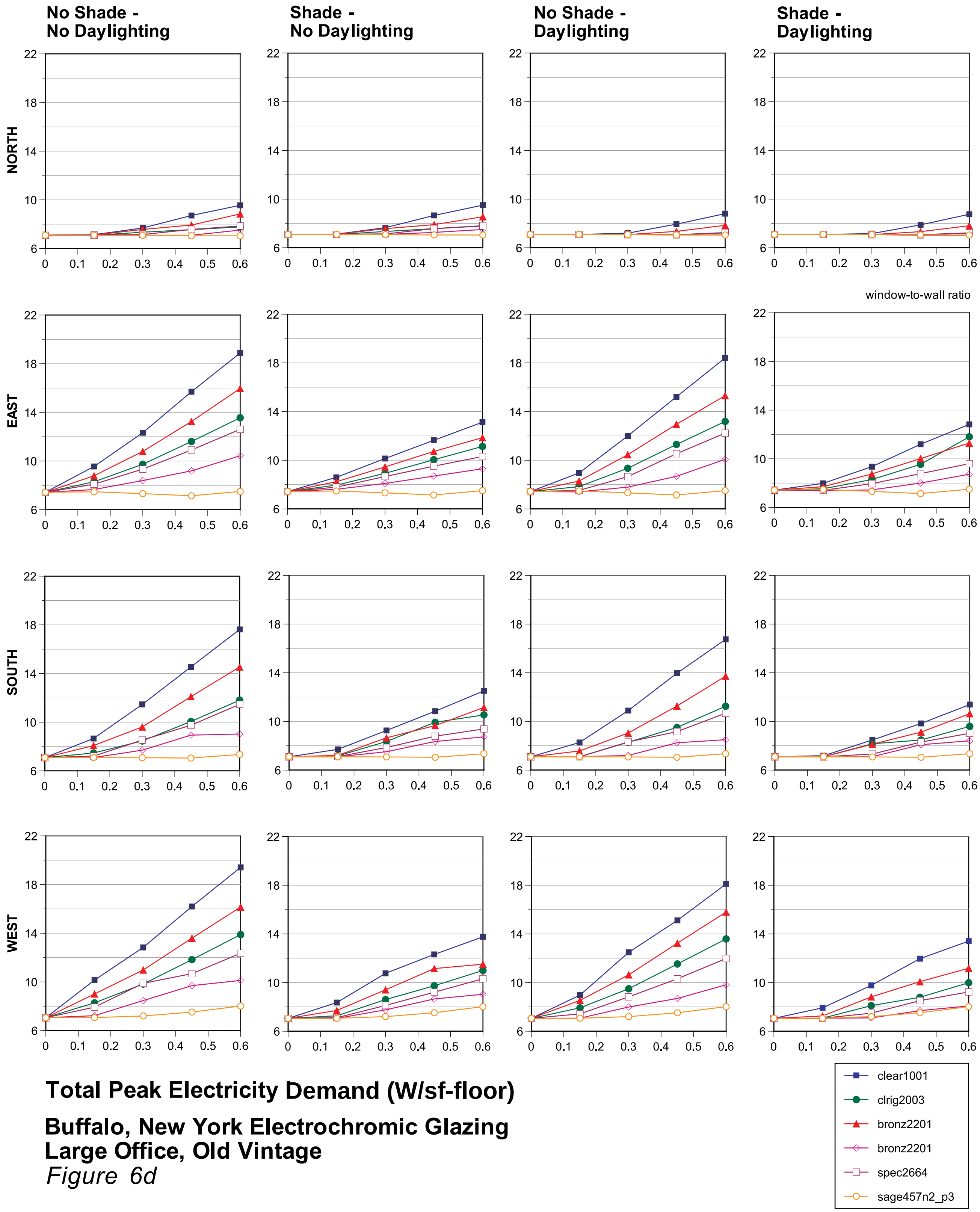
Annual Cooling Energy (kWh/sf-floor-yr), COP = 3.0

Buffalo, New York Electrochromic Glazing
Large Office, Old Vintage
Figure 6b



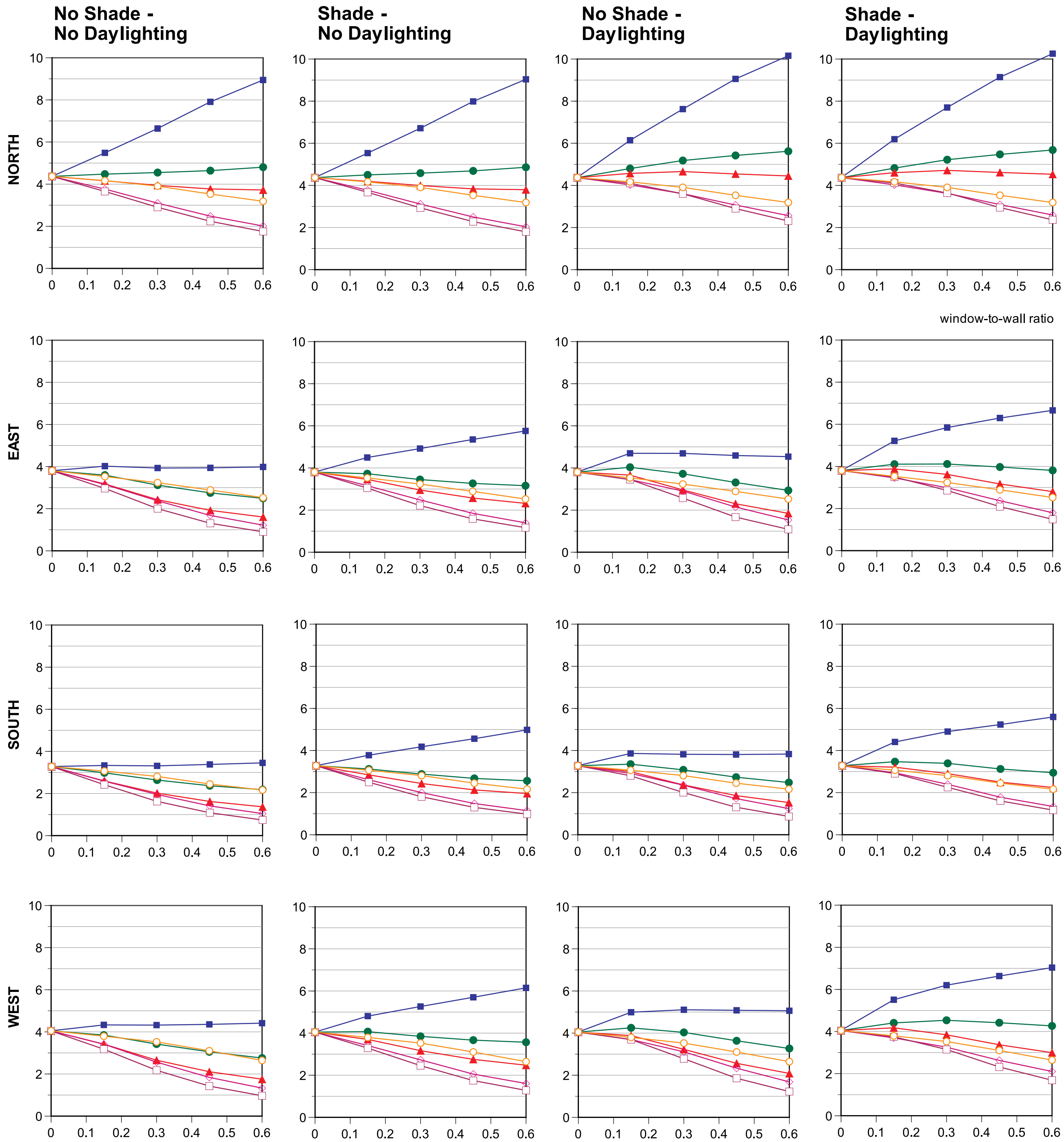
Total Annual Electricity Used (kWh/sf-floor-yr)

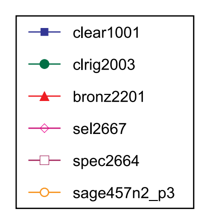
Buffalo, New York Electrochromic Glazing
Large Office, Old Vintage
Figure 6c



Total Peak Electricity Demand (W/sf-floor)

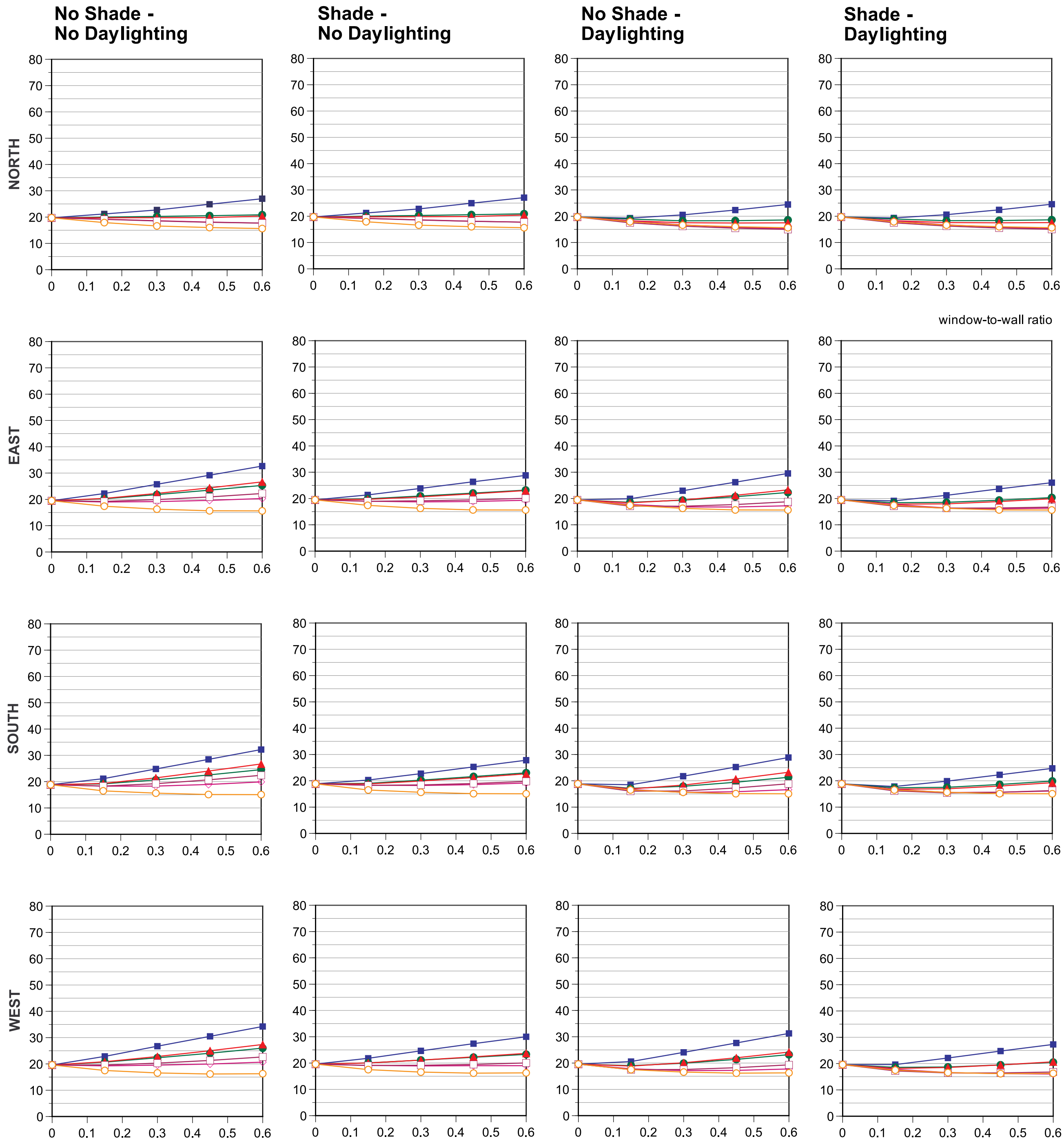
Buffalo, New York Electrochromic Glazing
Large Office, Old Vintage
Figure 6d

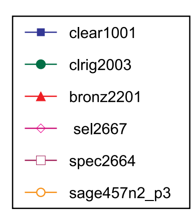




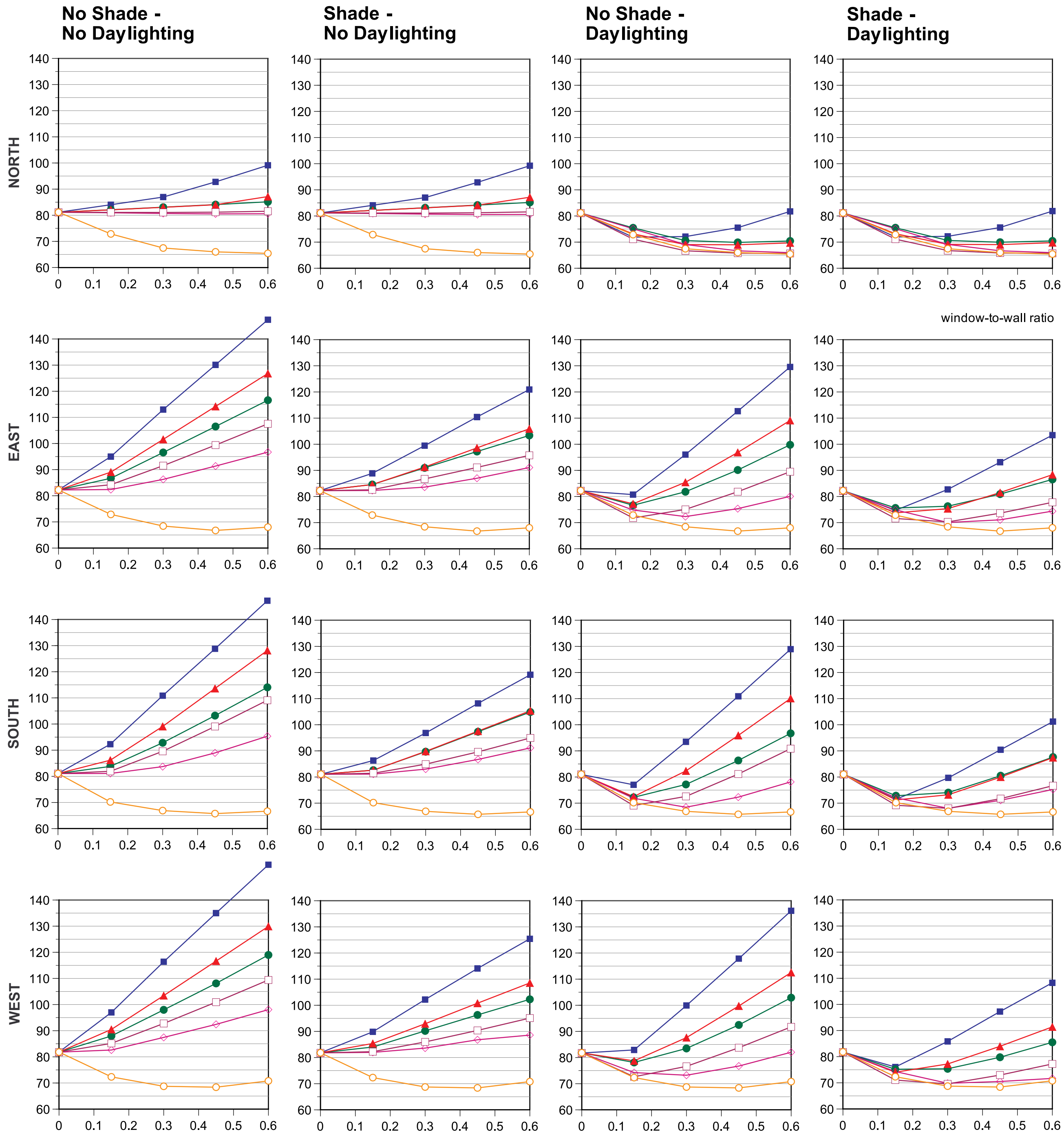
Total Annual Heating Energy Used (kWh/sf-floor-yr)

Buffalo, New York Electrochromic Glazing
Large Office, Old Vintage
Figure 6e



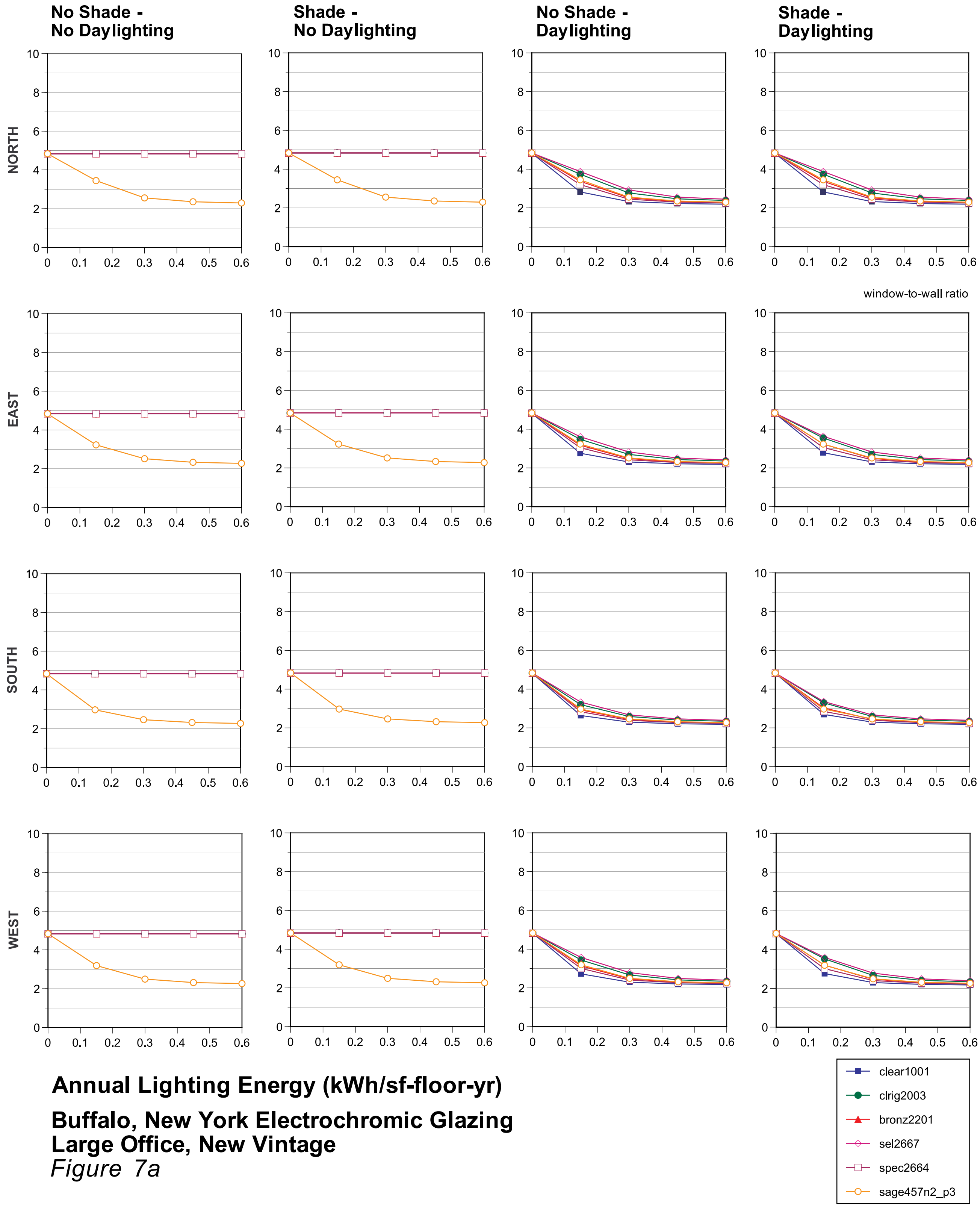


Energy Cost ($unit/sf-floor-yr)
Fuel Ratio Cost of 1:1
Buffalo, New York Electrochromic Glazing
Large Office, Old Vintage
Figure 6f



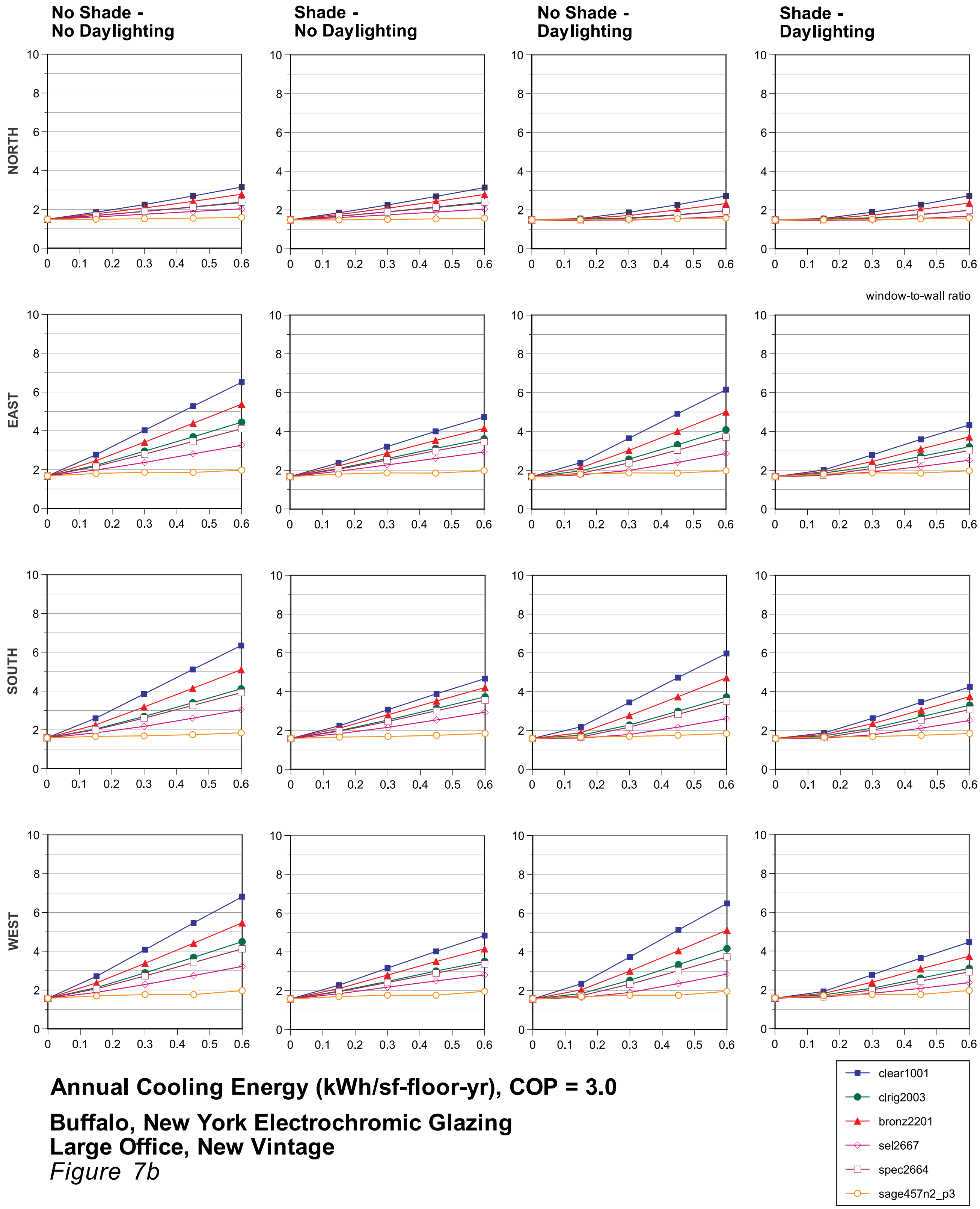
Energy Cost ($unit/sf-floor-yr)
Fuel Ratio Cost of 5:1

Buffalo, New York Electrochromic Glazing
Large Office, Old Vintage
Figure 6g



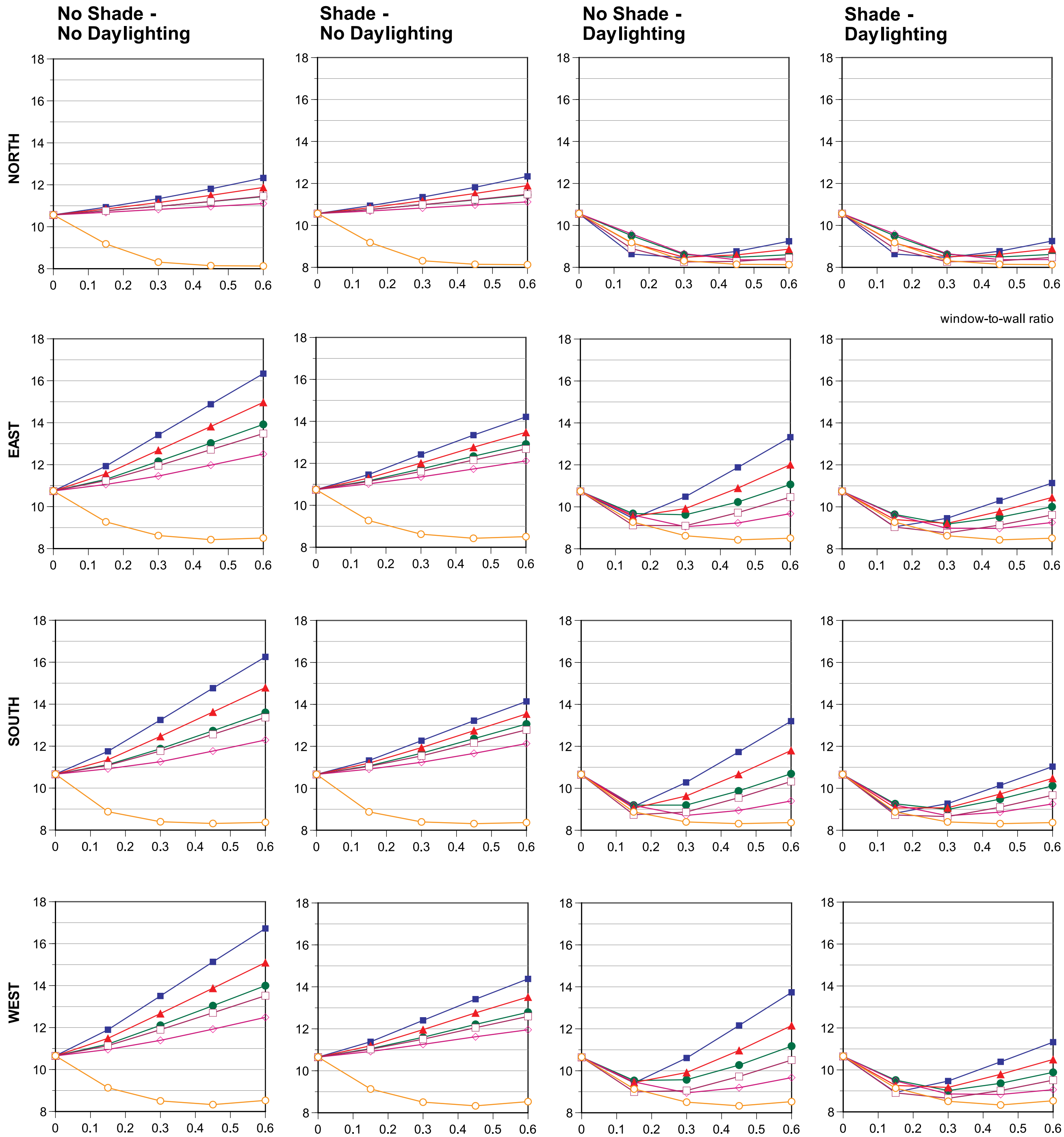
Annual Lighting Energy (kWh/sf-floor-yr)

Buffalo, New York Electrochromic Glazing
Large Office, New Vintage
Figure 7a



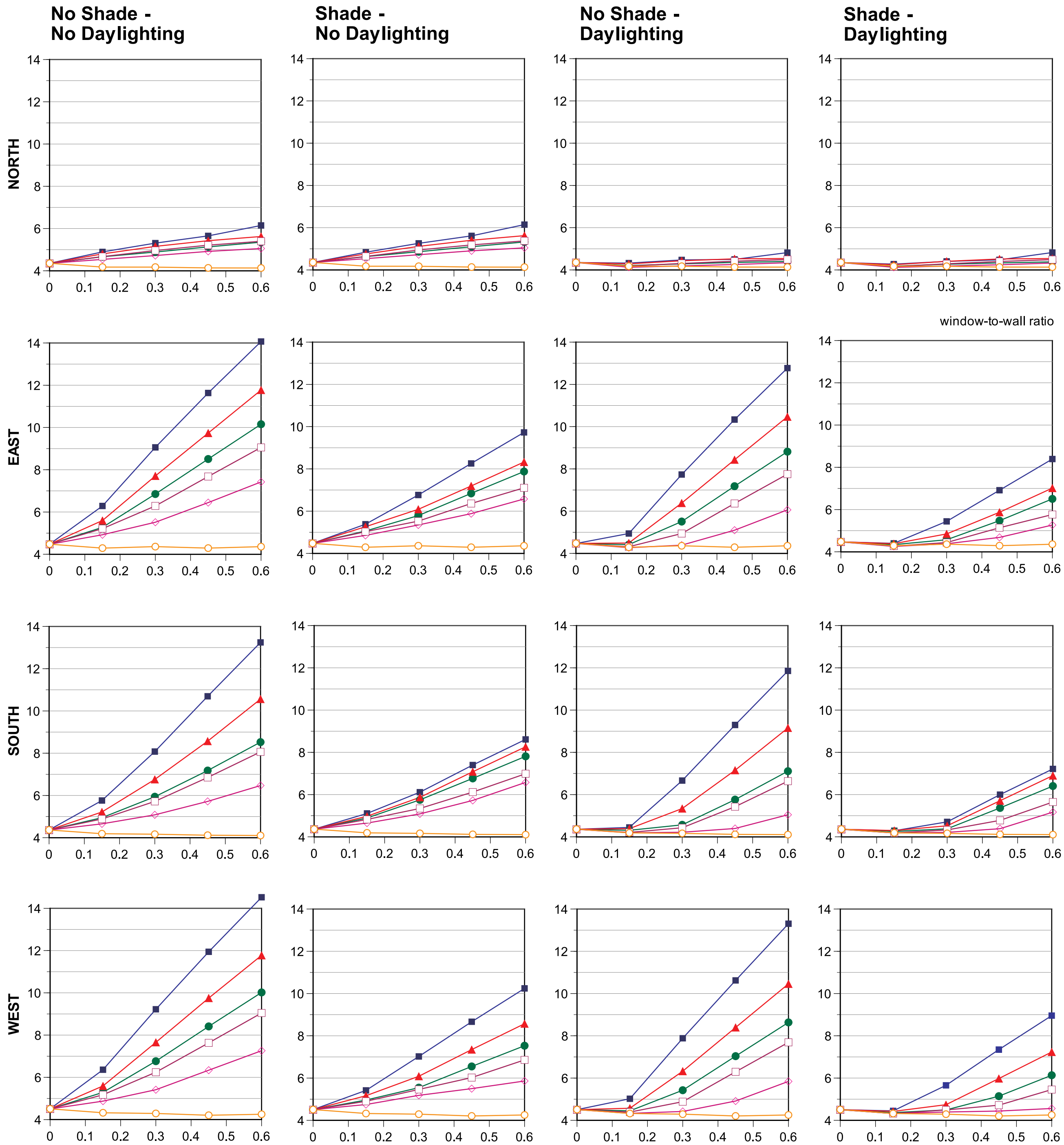
Annual Cooling Energy (kWh/sf-floor-yr), COP = 3.0

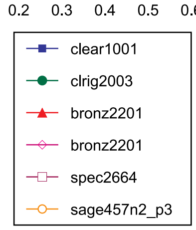
Buffalo, New York Electrochromic Glazing
Large Office, New Vintage
Figure 7b



Total Annual Electricity Used (kWh/sf-floor-yr)

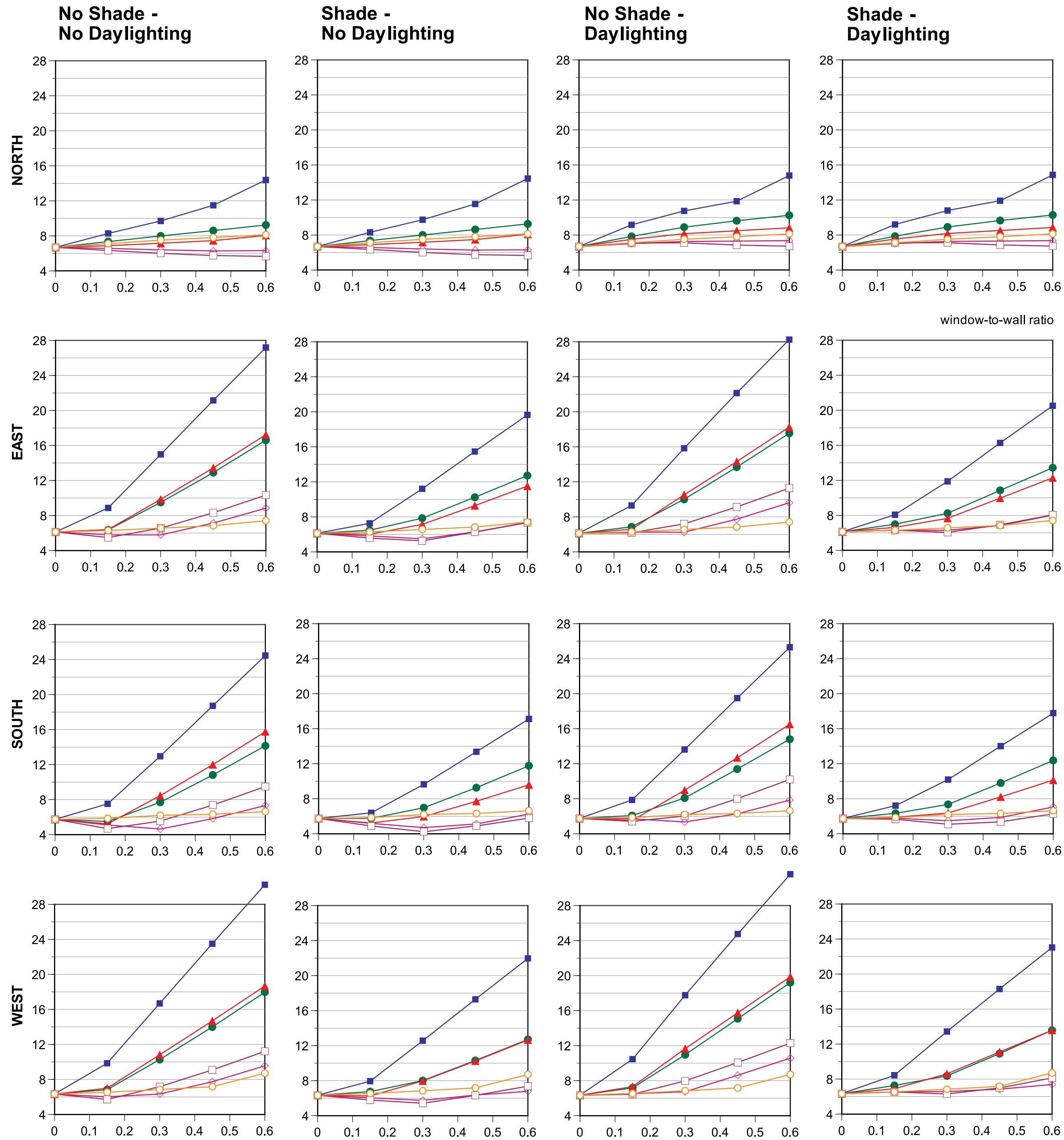
Buffalo, New York Electrochromic Glazing
Large Office, New Vintage
Figure 7c

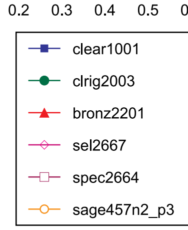




Total Peak Electricity Demand (W/sf-floor)

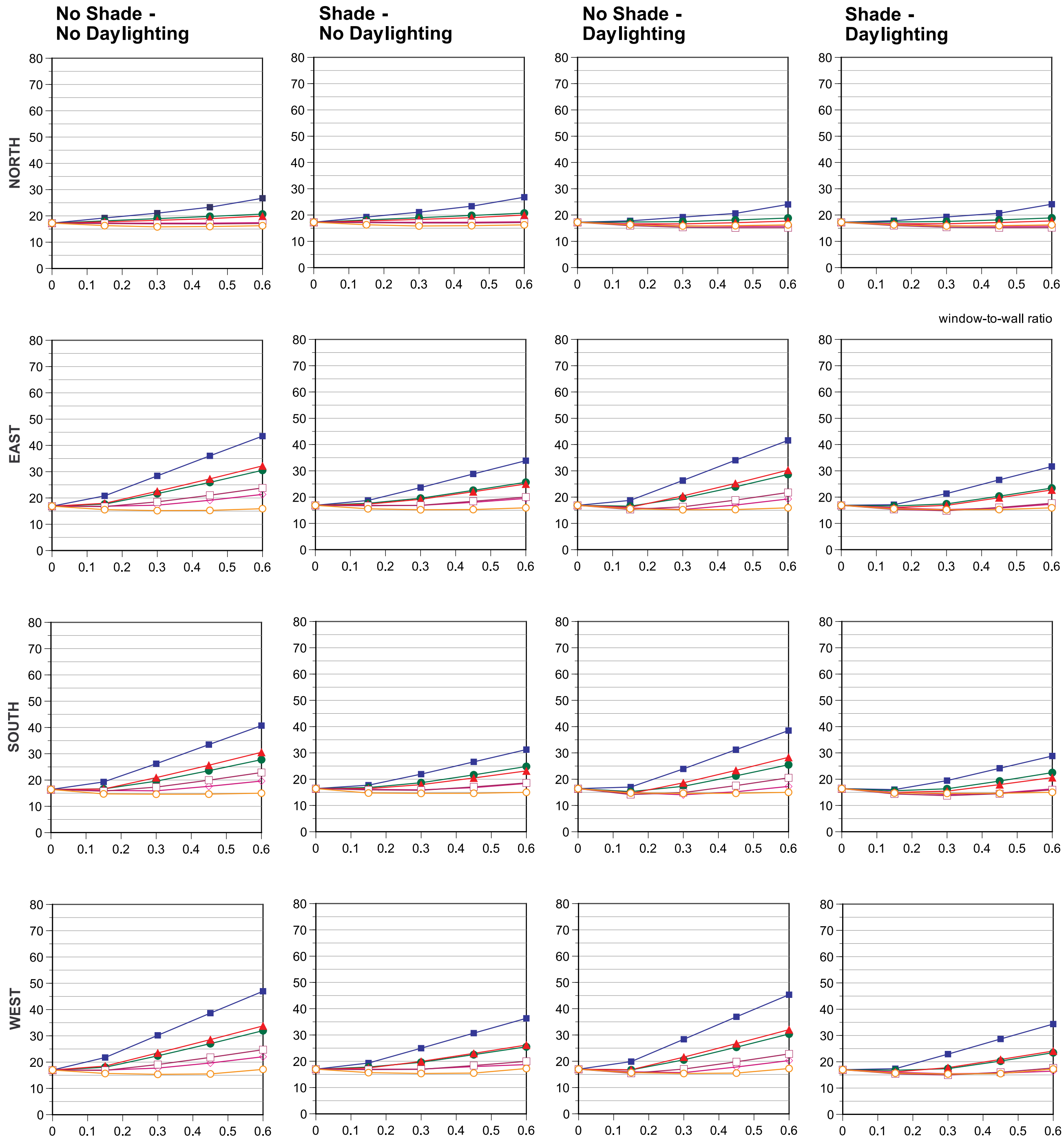
Buffalo, New York Electrochromic Glazing
Large Office, New Vintage
Figure 7d

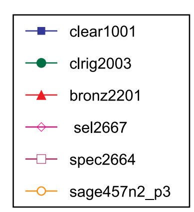




Total Annual Heating Energy Used (kWh/sf-floor-yr)

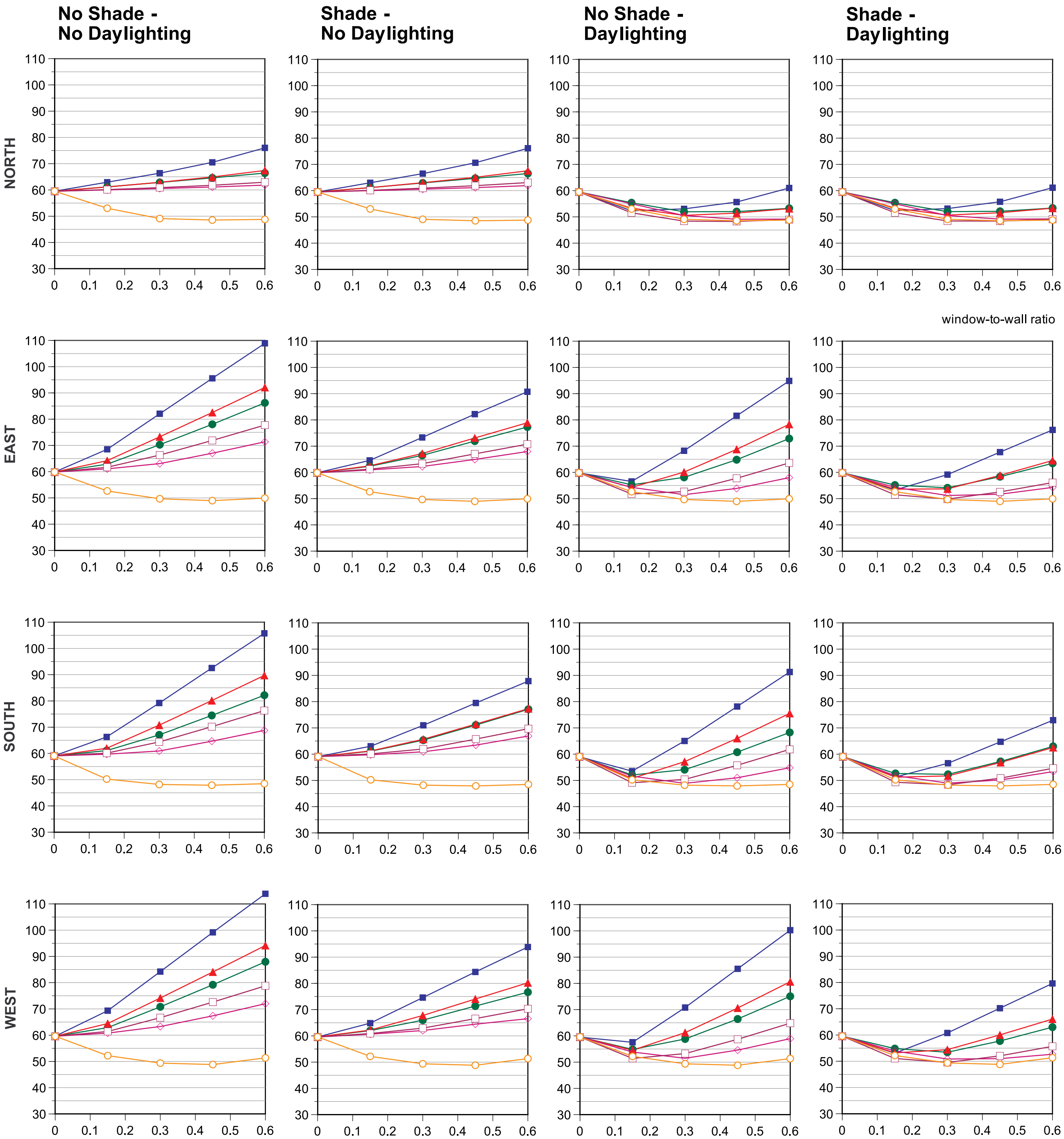
Buffalo, New York Electrochromic Glazing
Large Office, New Vintage
Figure 7e

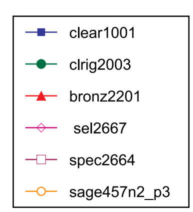




Energy Cost ($unit/sf-floor-yr)
Fuel Ratio Cost of 1:1

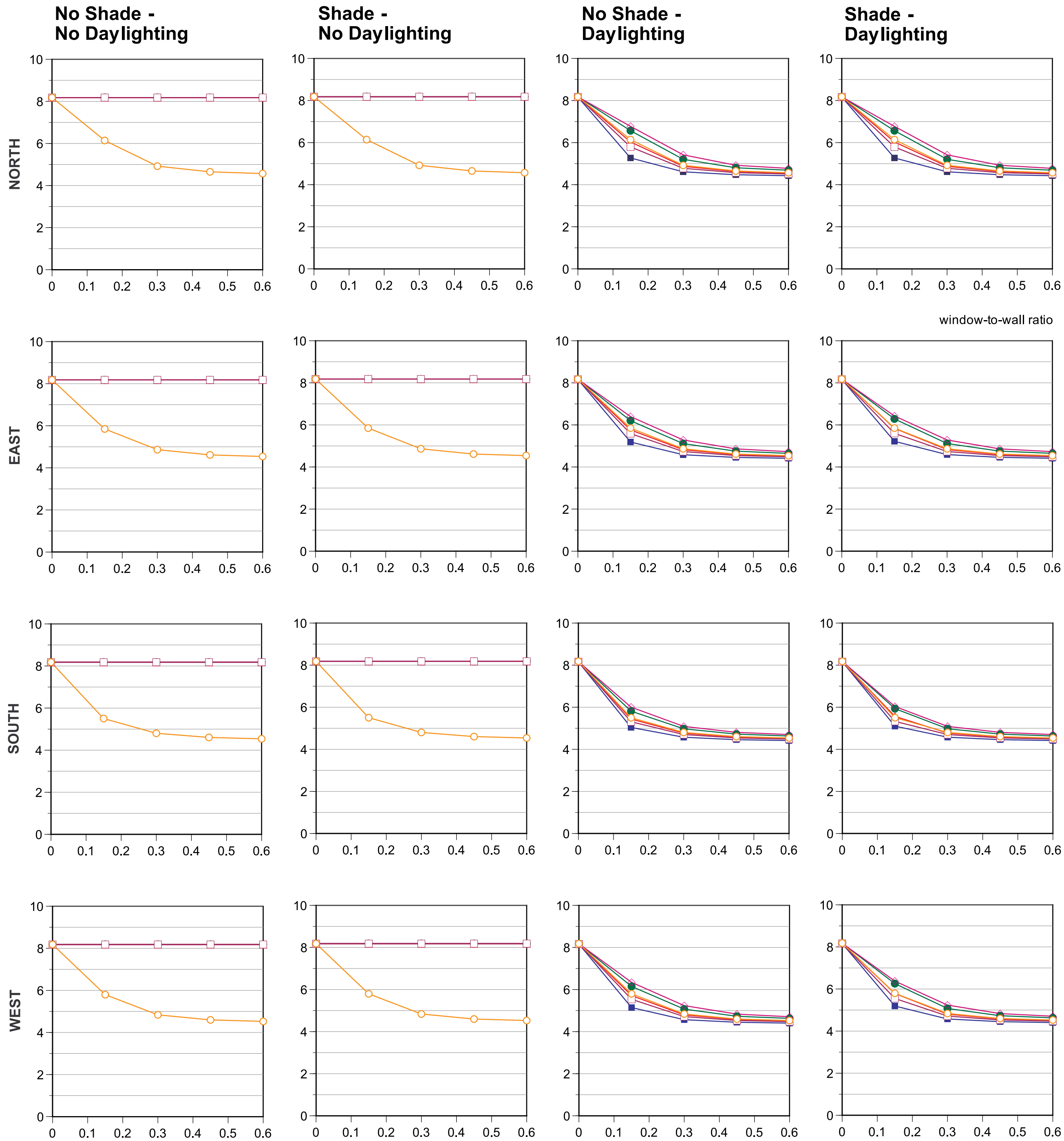
Buffalo, New York Electrochromic Glazing
Large Office, New Vintage
Figure 7f



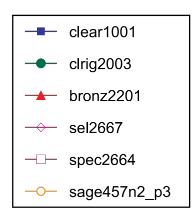


Energy Cost ($unit/sf-floor-yr)
Fuel Ratio Cost of 5:1

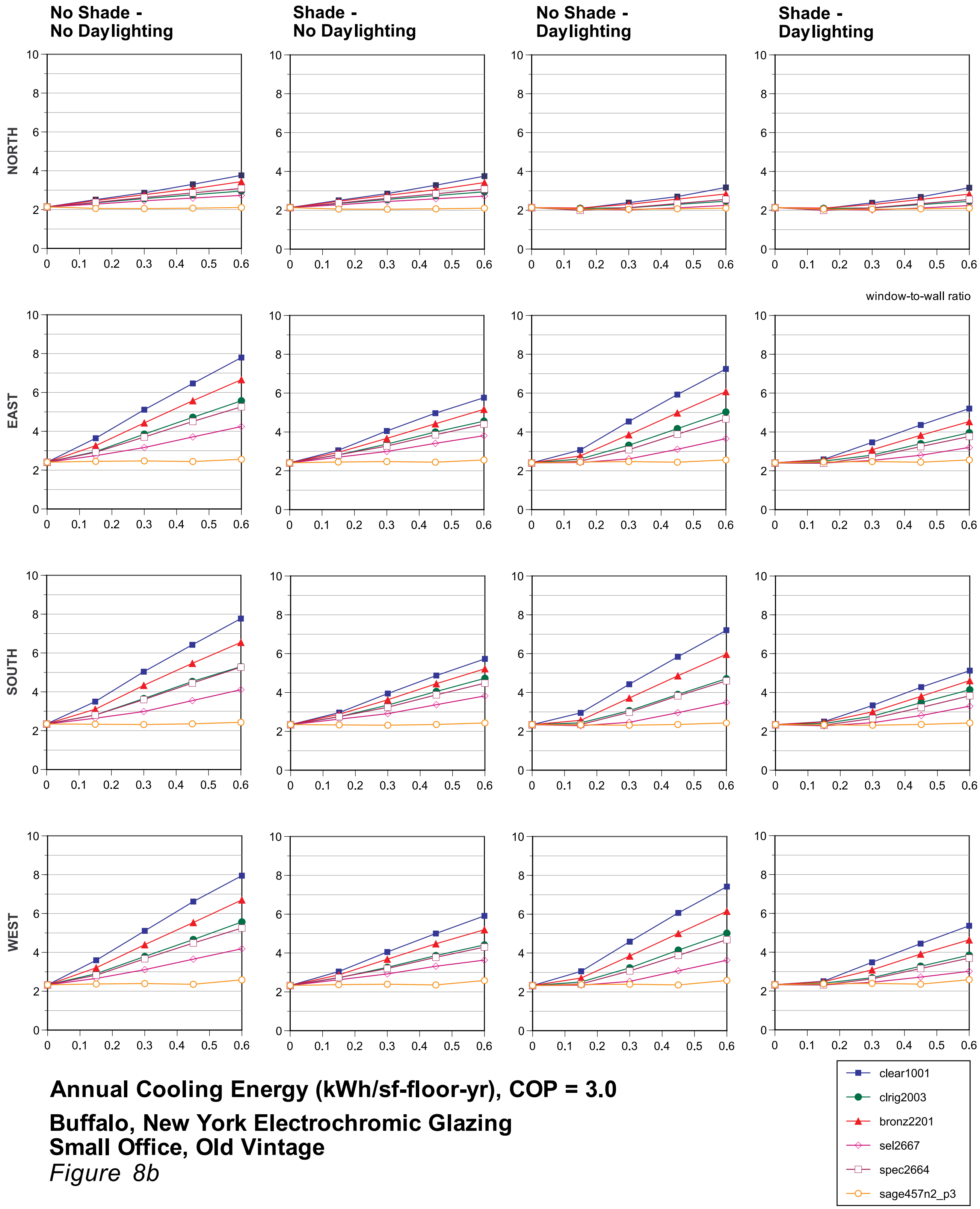
Buffalo, New York Electrochromic Glazing
Large Office, New Vintage
Figure 7g



Annual Lighting Energy (kWh/sf-floor-yr)

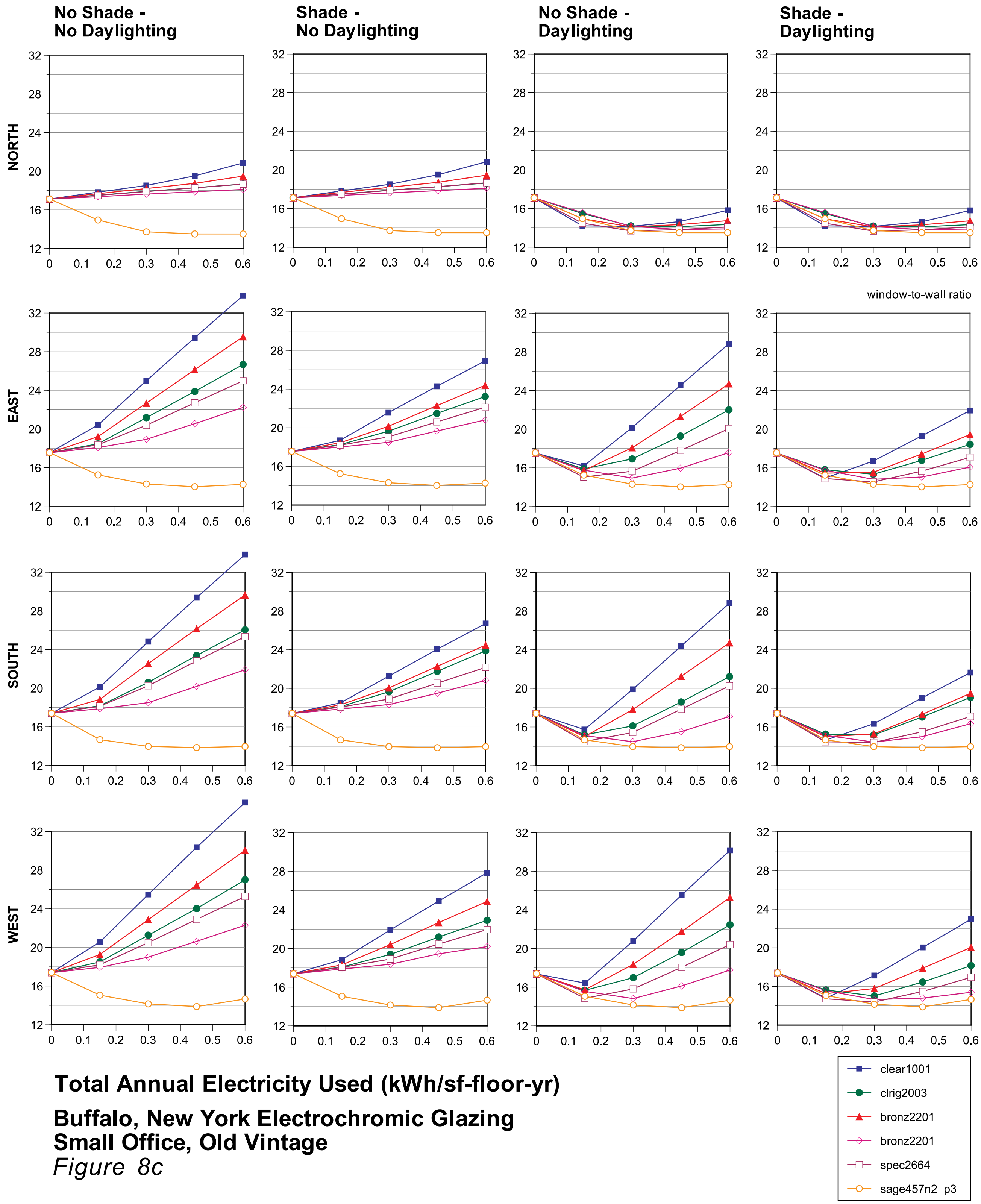


Buffalo, New York Electrochromic Glazing
Small Office, Old Vintage
Figure 8a



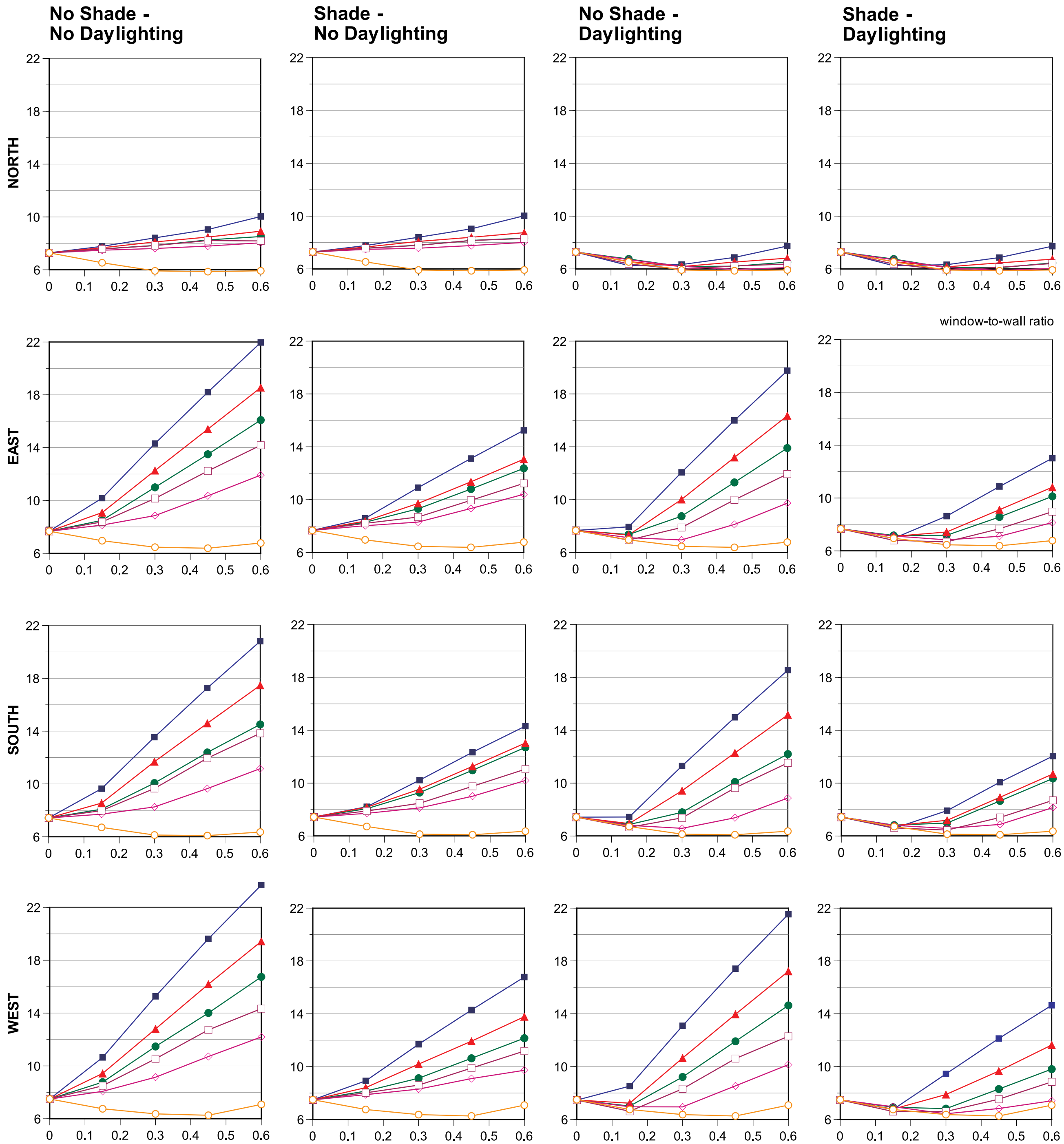
Annual Cooling Energy (kWh/sf-floor-yr), COP = 3.0

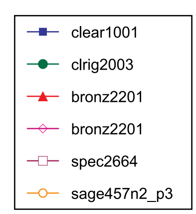
Buffalo, New York Electrochromic Glazing
Small Office, Old Vintage
Figure 8b



Total Annual Electricity Used (kWh/sf-floor-yr)

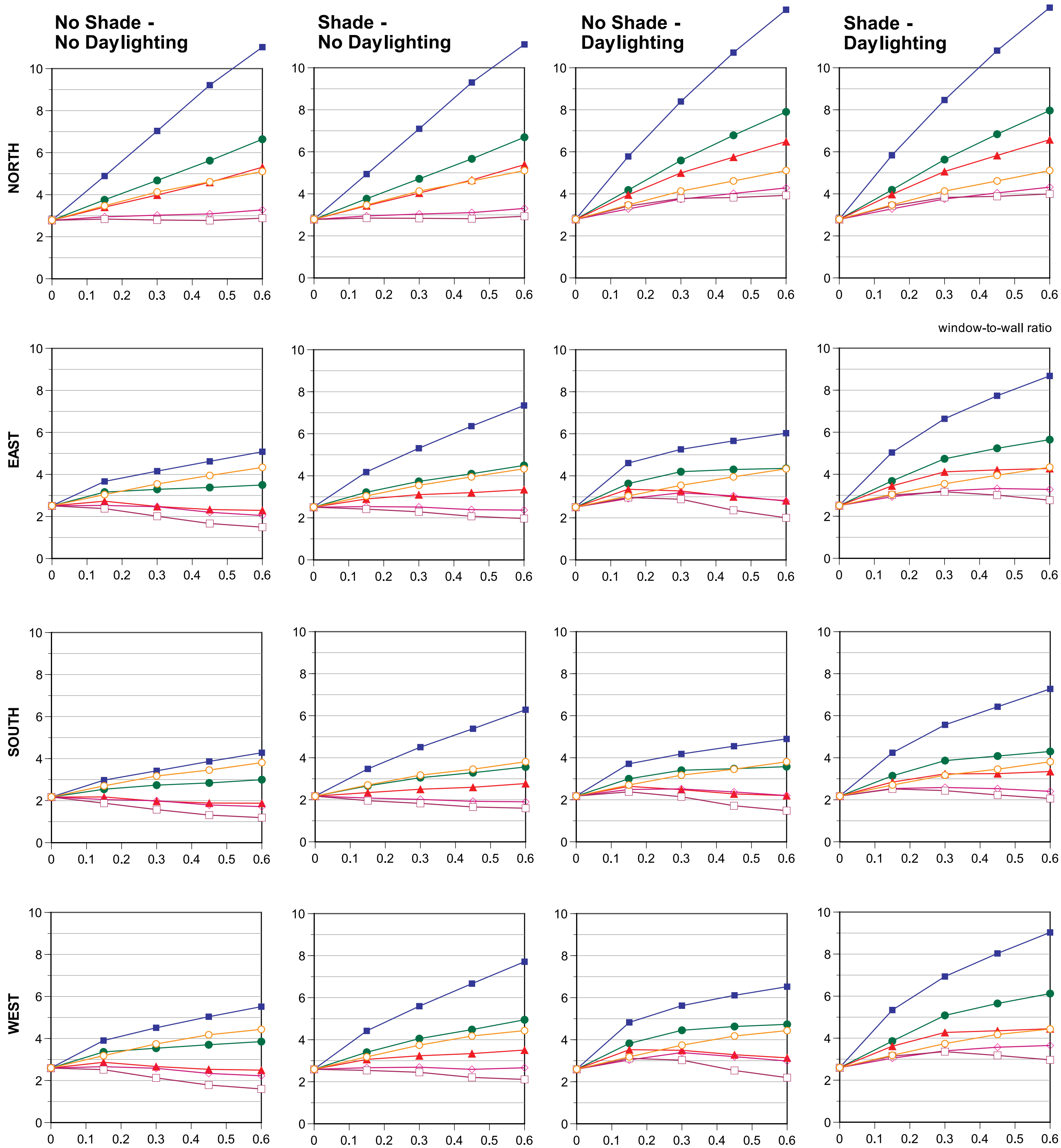
Buffalo, New York Electrochromic Glazing
Small Office, Old Vintage
Figure 8c





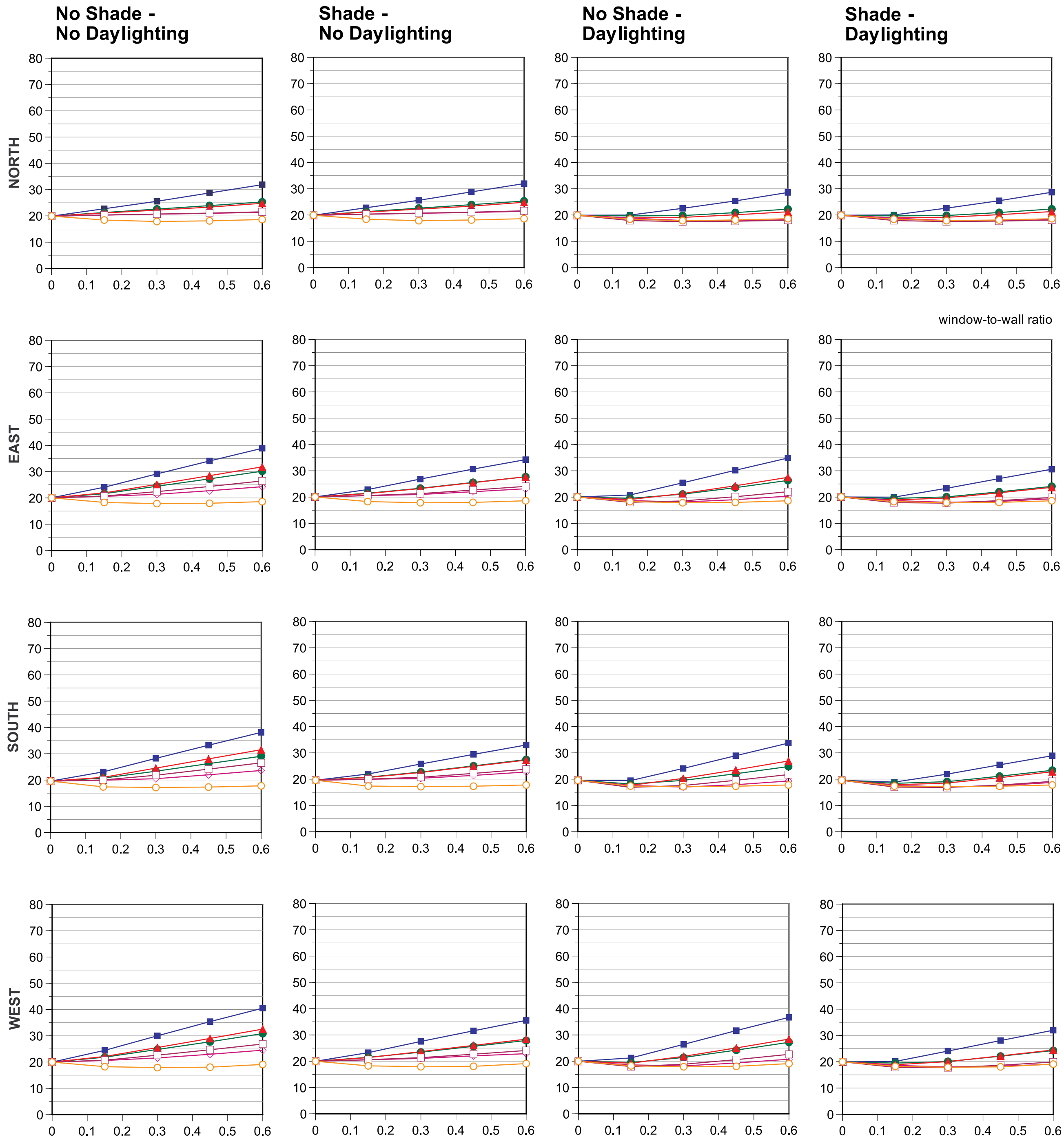
Total Peak Electricity Demand (W/sf-floor)

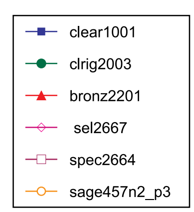
Buffalo, New York Electrochromic Glazing
Small Office, Old Vintage
Figure 8d



Total Annual Heating Energy Used (kWh/sf-floor-yr)

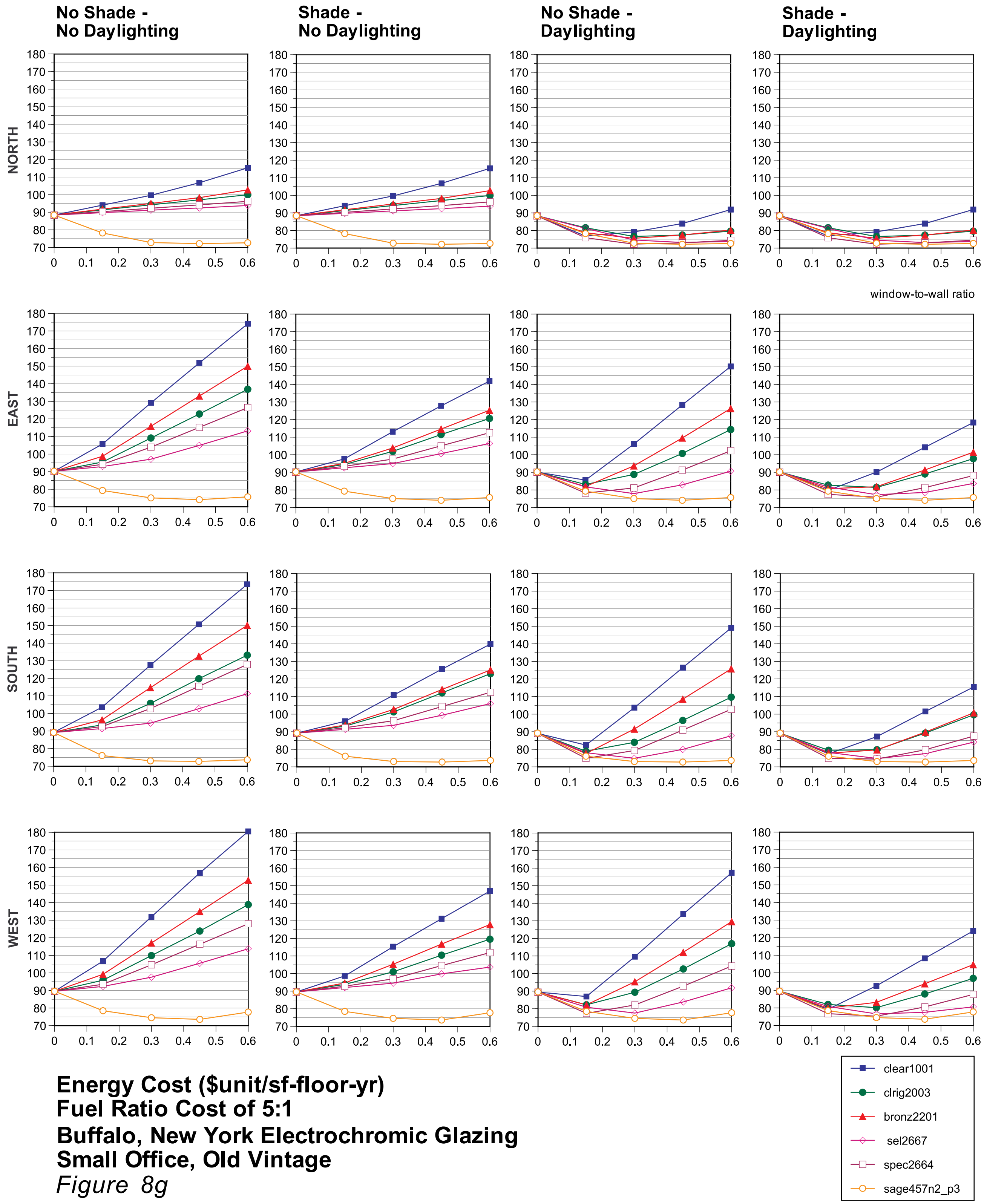
Buffalo, New York Electrochromic Glazing
Small Office, Old Vintage
Figure 8e



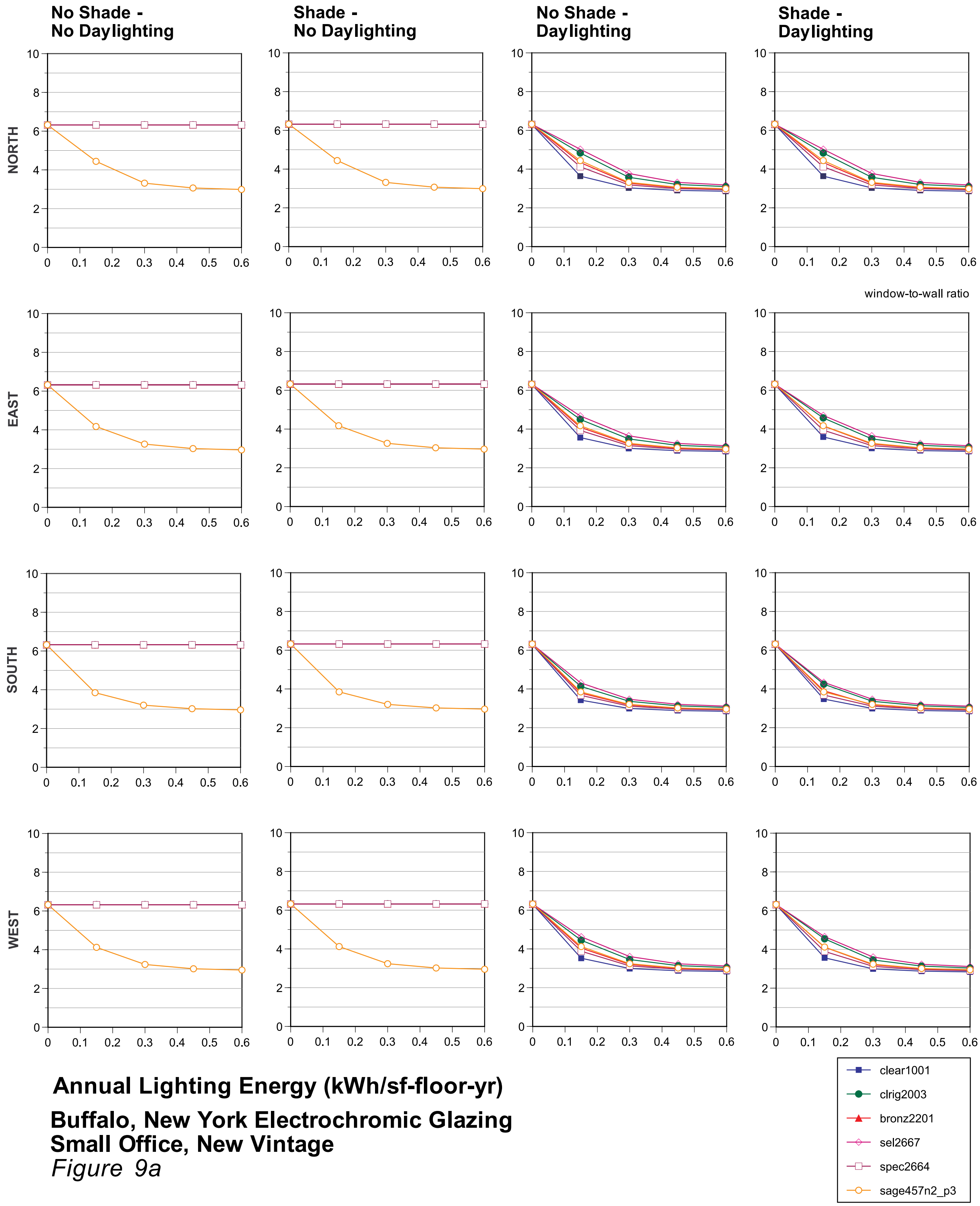


Energy Cost ($unit/sf-floor-yr)
Fuel Ratio Cost of 1:1

Buffalo, New York Electrochromic Glazing
Small Office, Old Vintage
Figure 8f

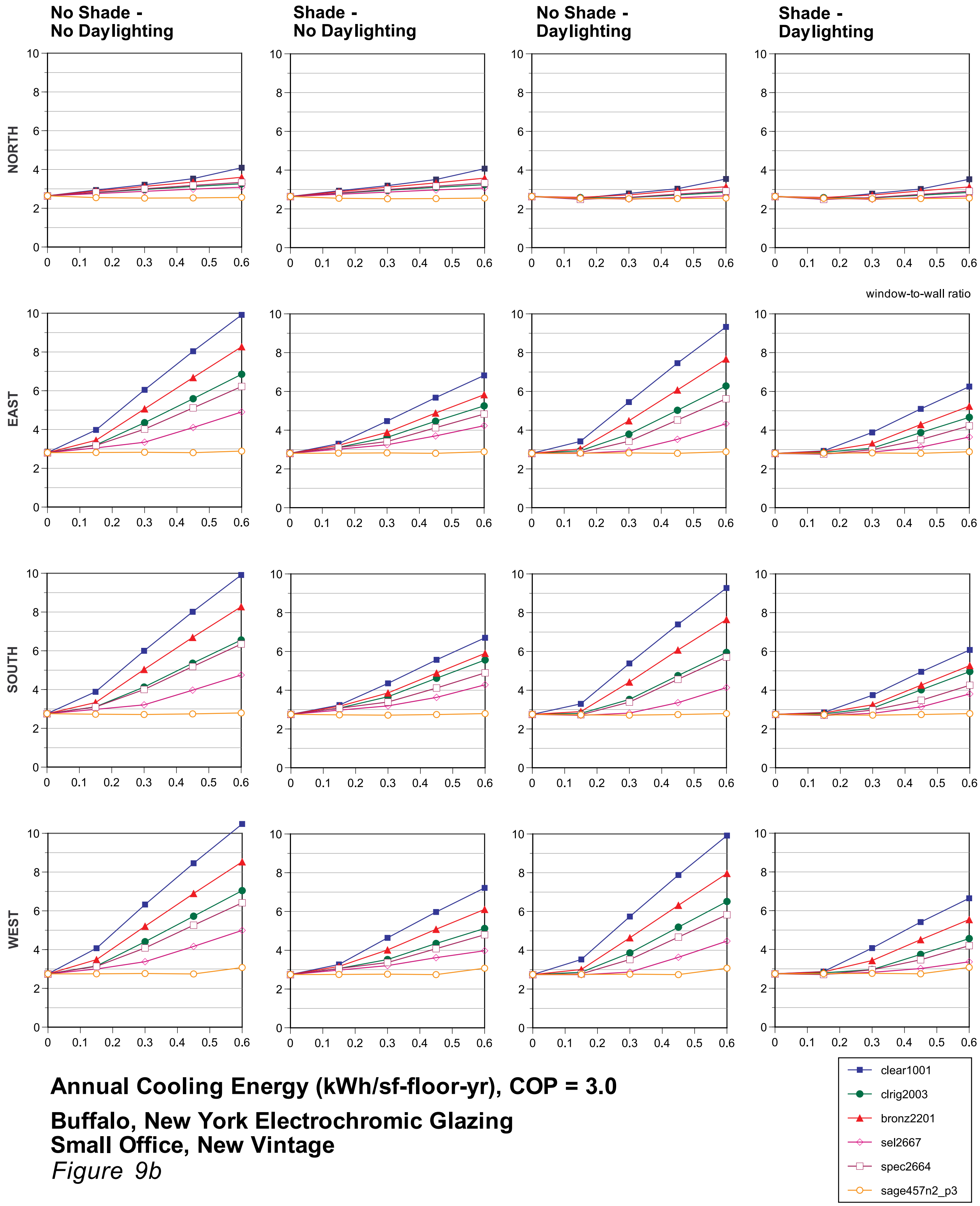


Energy Cost ($unit/sf-floor-yr)
Fuel Ratio Cost of 5:1
Buffalo, New York Electrochromic Glazing
Small Office, Old Vintage
Figure 8g



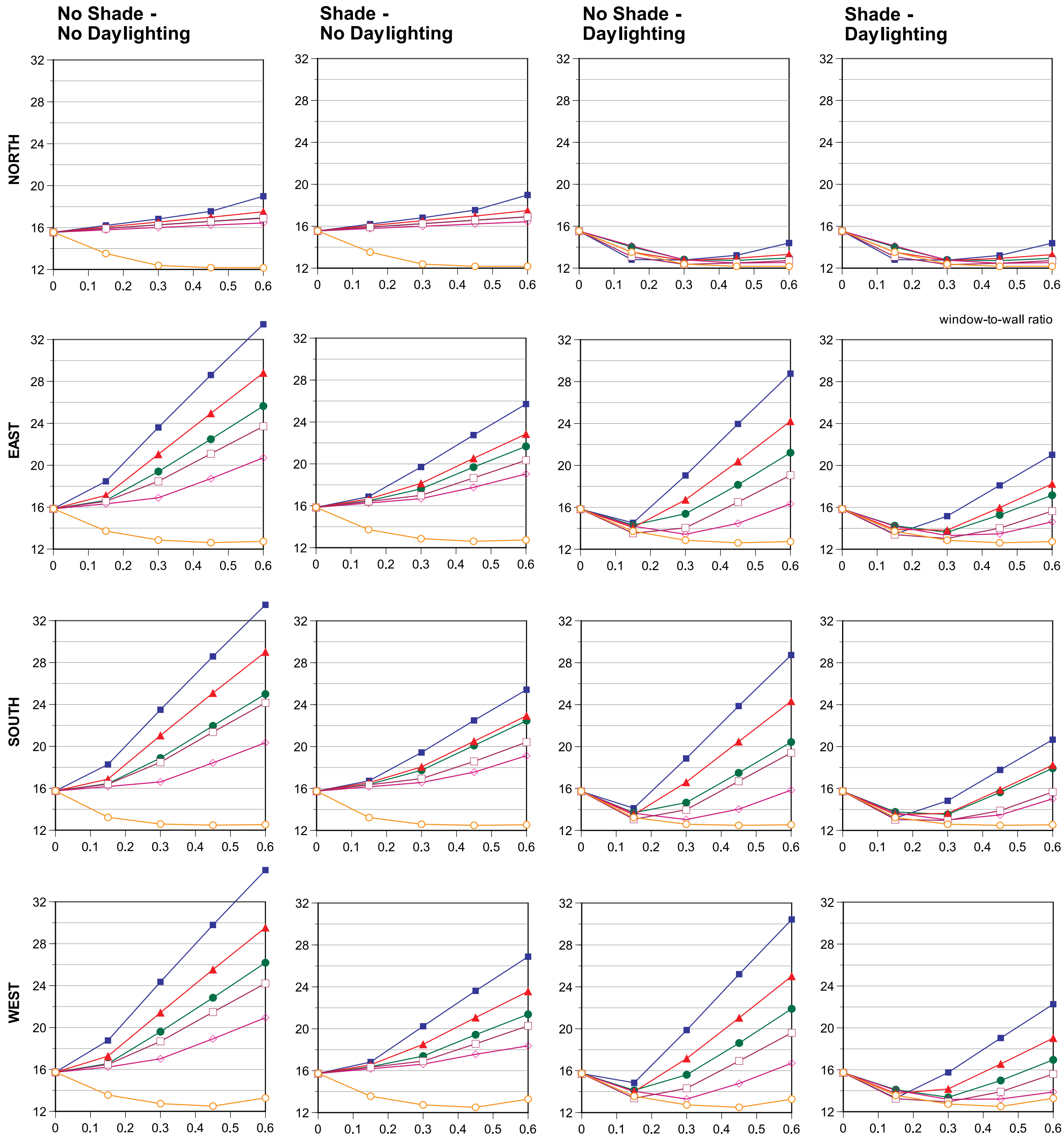
Annual Lighting Energy (kWh/sf-floor-yr)

Buffalo, New York Electrochromic Glazing
Small Office, New Vintage
Figure 9a



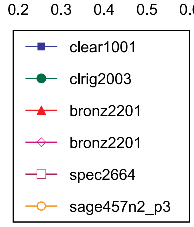
Annual Cooling Energy (kWh/sf-floor-yr), COP = 3.0

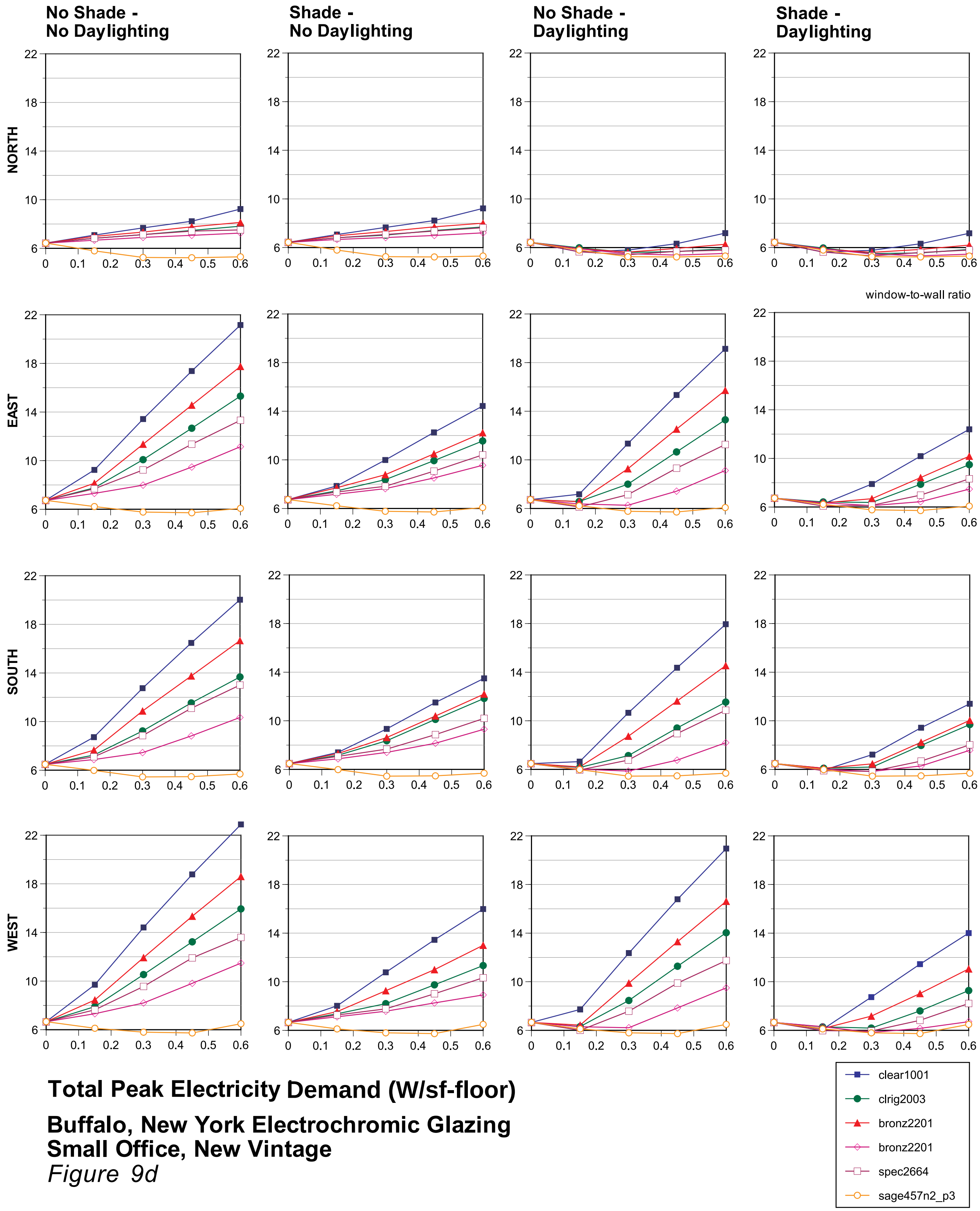
Buffalo, New York Electrochromic Glazing
Small Office, New Vintage
Figure 9b



Total Annual Electricity Used (kWh/sf-floor-yr)

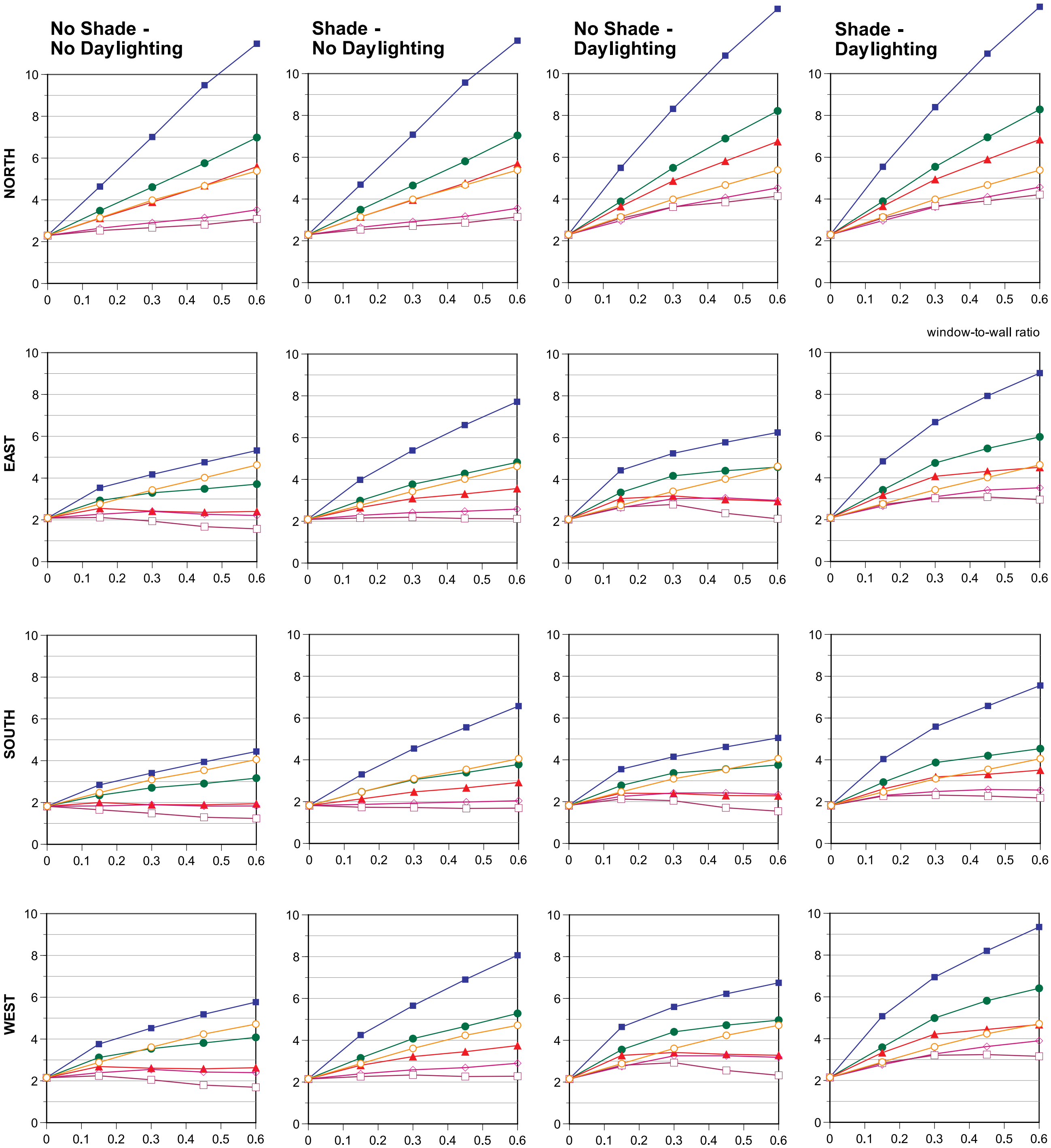
Buffalo, New York Electrochromic Glazing
Small Office, New Vintage
Figure 9c

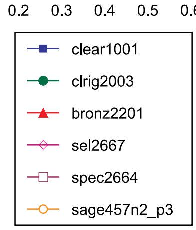




Total Peak Electricity Demand (W/sf-floor)

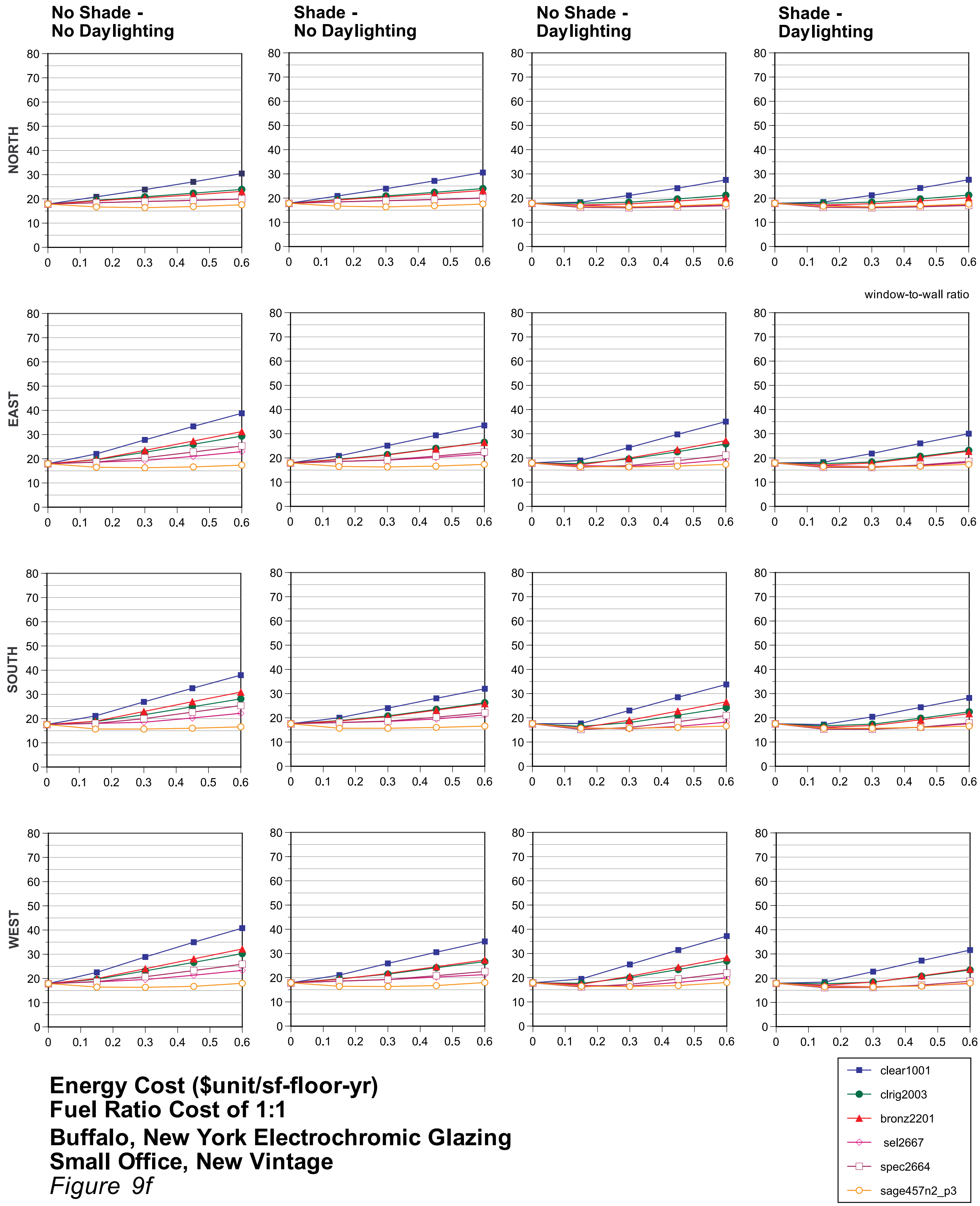
Buffalo, New York Electrochromic Glazing
Small Office, New Vintage
Figure 9d



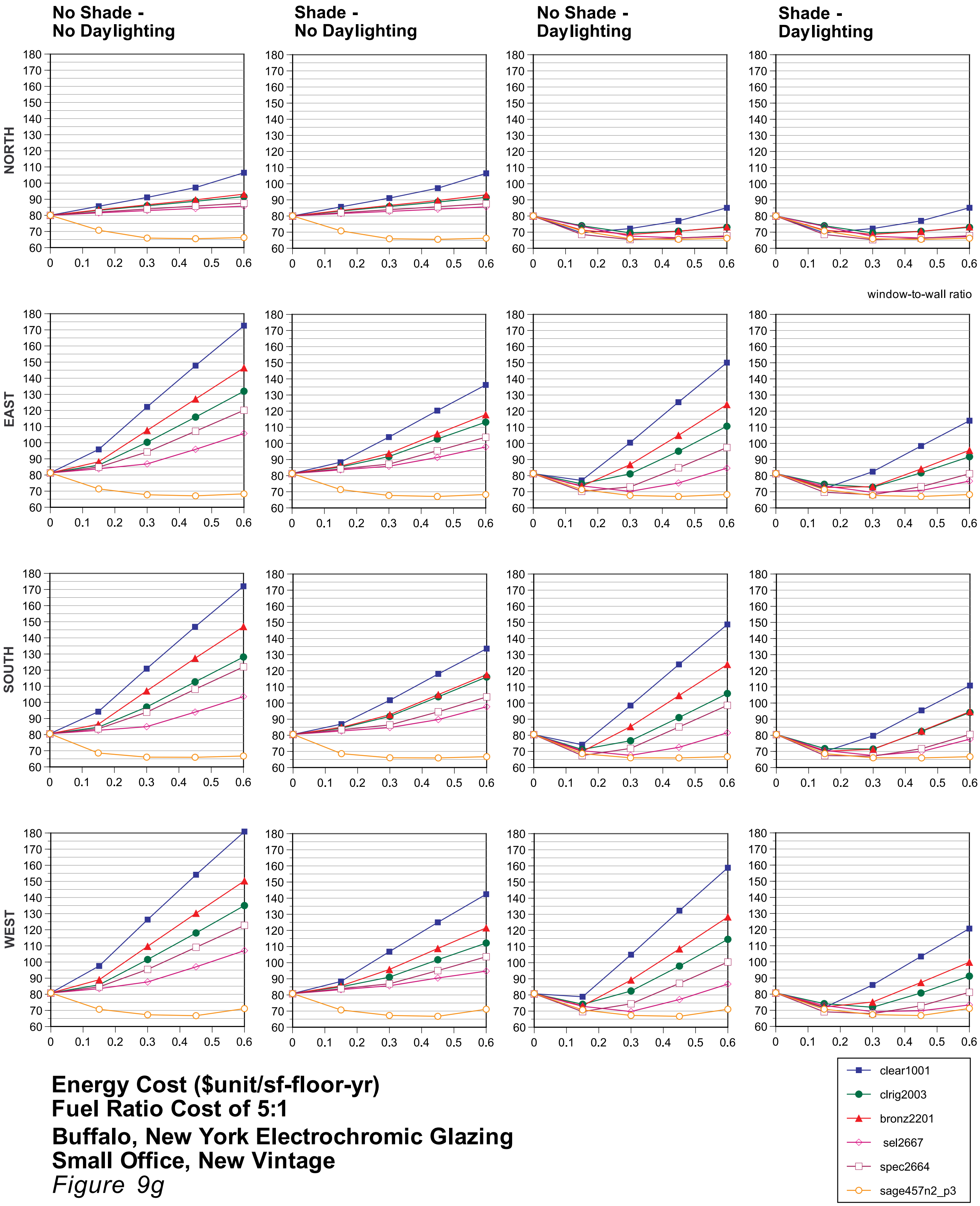


Total Annual Heating Energy Used (kWh/sf-floor-yr)

Buffalo, New York Electrochromic Glazing
Small Office, New Vintage
Figure 9e



Energy Cost ($unit/sf-floor-yr)
Fuel Ratio Cost of 1:1
Buffalo, New York Electrochromic Glazing
Small Office, New Vintage
Figure 9f



Energy Cost ($unit/sf-floor-yr)
Fuel Ratio Cost of 5:1

Buffalo, New York Electrochromic Glazing
Small Office, New Vintage
Figure 9g