Assessment of Energy Performance of Window Technologies for Commercial Buildings

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ABSTRACT

Windows play a significant role in commercial buildings toward the goal of net-zero energy. This article presents the analysis methodology and major findings of an assessment study of energy performance of window technologies for commercial buildings. A prototypical large office building was used as the baseline model which met the prescriptive requirements of ANSI/ASHRAE/IESNA Standard 90.1-2004. The building simulations with EnergyPlus and TMY3 weather data for five typical US climates were performed to calculate the energy savings potentials of six window technologies representing existing, new, and emerging technologies, which include ANSI/ASHRAE/USGBC/IES Standard 189.1 baseline windows; triple pane low-e windows; clear and tinted double pane highly insulating low-e windows; electrochromic windows; and highly-insulating EC windows representing the hypothetically feasible optimum technology.

Daylighting benefit from automatic continuously dimming and glare controls was evaluated separately. Simulation results indicated that the two types of electrochromic windows had the greatest energy savings potential compared to the Standard 90.1-2004 baseline windows, followed by the triple pane low-e windows and the highly-insulating double panel low-e windows. Windows with integrated daylighting controls, highly insulated, and capable of dynamic performance adjustment will be the future for commercial buildings.

Introduction

Windows are an essential part of buildings. Windows not only provide view and connection with outdoor for building occupants, but also have significant affect on a building’s energy usage, as they contribute to a building’s heating and cooling loads as well as lighting if daylighting sensors and controls are deployed. Despite past progress in window technology, windows are still a huge liability in terms of energy usage. In 1973, the typical window in most U.S. buildings was a single-pane clear window. The typical window is now double-pane with low E coating. Fenestration sales in the commercial sector are shown in Table 1 (LaFrance 2007). The market has largely shifted to double-pane products; triple-pane products are still only a tiny fraction (2 to 3%) of the total. Low-E has only half the penetration in this sector that it has in the residential sector, with reflective and tinted glass making up 26% of the sales, reflecting a concern for managing cooling loads.

Prior studies on energy performance of windows for the commercial sector focused on specific window technologies for specific building types located in specific climate zones. Lee (2002, 2004) studied the energy performance of EC windows in a New York office building and for the US commercial building sector. Arasteh (2006A, 2006B) studied the technical criteria of zero energy windows and their contribution to zero energy buildings (ZEBs). Huang (2007) estimated window energy savings for commercial buildings in Pacific Northwest region. Griffith (2007) looked at the potential energy savings of various window technologies as part of the package to reach zero energy buildings. Haves (2007) studied potential energy savings of windows shading and daylighting controls as part of the integrated building controls. Shen (2009) expanded Haves' work in evaluating the integrated window controls between windows, lighting, and HVAC systems.

Table 1. Profile of Commercial Window Sales

Window Type	Percent of Sales	U-factor Btu/(hr-ft^2-°F)	SHGC
Single Pane, Clear Glass	11%	1.16	0.74
Double Pane, Clear Glass	30%	0.62	0.63
Double Pane, Tinted Glass	6%	0.65	0.13
Double Pane, Reflective Glass	20%	0.62	0.46
Double Pane, Low-e Glass	30%	0.51	0.34
Triple Pane, Low-e Glass	3%	0.51	0.34
Average Properties	100%	0.65	0.48

DOE-2 (LBNL) was used as the calculation engine for most of these studies (Lee 2002, 2004; Arasteh 2006A, 2006B; Huang 2007). More recent studies (Griffith 2007; Haves 2007; Shen 2009) started using EnergyPlus (DOE), which has capabilities of modeling low-energy buildings with innovative design and technologies that could not be modeled by other simulation tools such as DOE-2.

The goal of the assessment was to determine the technical potential of advanced window technologies in energy savings for US commercial buildings. The focus of the assessment was different from prior studies. The large office building was chosen as the baseline building based on the fact that office buildings are the most common type of commercial buildings (EIA 2006), and large office buildings normally have more window area. The prototypical large office models, part of the DOE commercial building benchmarks (Torcellini 2008), were used as the baseline energy models meeting the prescriptive requirements of ANSI/ASHRAE/IESNA Standard 90.1-2004 (ASHRAE 2004). The building simulations were performed with EnergyPlus and TMY3 weather data for five typical US climates to calculate the energy savings potentials of six windows technologies. The six window technologies include ANSI/ASHRAE/USGBC/IES Standard 189.1P (ASHRAE 2010) baseline windows; triple-pane low-e windows; clear and tinted double-pane highly-insulating low-e windows; electrochromic windows; and highly-insulating EC windows representing the hypothetically feasible optimum windows. The existing stocks based on average commercial windows sales were included in the analysis for benchmarking purposes.

Assessment Methodology

Computer simulation has been a proven and effective way to assess the energy performance of windows for commercial buildings. This assessment looked at the energy performance of windows with the whole-building energy performance approach, taking into account the integration and interaction of building components and systems.

The prototypical large office building, chosen from the US Department of Energy (DOE) commercial building benchmarks, was used in the assessment. The building characteristics, including envelope constructions, lighting, and HVAC were set to meet the prescriptive requirements of Standard 90.1-2004. Six window technologies were studied together with different types of interior shading controls. Daylighting energy savings were estimated separately by comparing cases with daylighting controls to same cases without daylighting controls.

Window energy effects were quantified as a set of performance metrics including end uses, peak electric demand, design cooling and heating capacities. The site energy and source energy are calculated as follows for all five climates:

Site Energy (kBtu) = Electricity (kWh) *3.413 + Natural Gas (kBtu)

Source Energy (kBtu) = Electricity (kWh) *3.413*3.095 + Natural Gas (kBtu) *1.092

where 3.095 and 1.092 are source factors for electricity and for natural gas.

The site energy use intensity (EUI) was calculated as,

Site Energy EUI (kBtu/ft^2) = Annual Site Energy (kBtu) / Building Floor Area (ft^2)

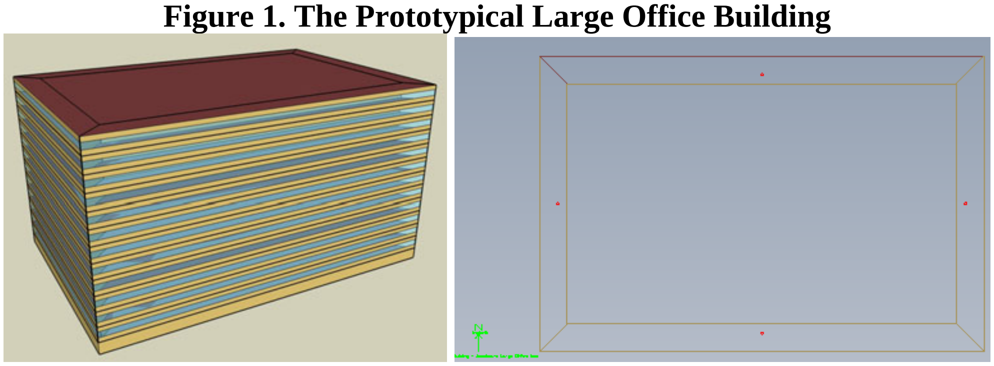
EnergyPlus version 2.2 was used to calculate the energy performance of. EnergyPlus has advanced features and uses more accurate approach than DOE-2 to model windows, shading controls, daylighting, thermal and visual comfort. EnergyPlus is a new generation building energy simulation program that builds on the most popular features and capabilities of BLAST and DOE-2. EnergyPlus has innovative simulation capabilities including time steps of less than an hour, and modular systems simulation modules that are integrated with a zone heat balance simulation. EnergyPlus calculates space temperature, occupant thermal comfort, cooling and heating loads, HVAC equipment sizes, energy consumption, utility cost, air emissions, water usage, renewable energy, etc. EnergyPlus has been evolving since its first release in April 2001. Every release of EnergyPlus went through a suite of tests for quality assurance.

The TMY3 weather data was used in the simulations. The TMY3 weather data represented typical weather conditions during 1991 to 2005 and was available for download at EnergyPlus web site.

Characteristics of the Prototypical Large Office Building

The prototypical large office building has 12 conditioned stories above the ground and 1 unconditioned basement story. The building has a rectangle shape (240 ft X 160 ft) with the long axis along the East-West and an aspect ratio of 1.5. The total conditioned building floor area is 460,000 square feet. Each of the conditioned floors is modeled as four perimeter zones and one core zone with the space height of 10 feet. The perimeter zone depth is 15 feet. The total area of perimeter zones is about 29% of the building floor area.

Figure 1. The Prototypical Large Office Building



The building has a window-to-wall-ratio (WWR) of 40% with windows evenly distributed on the four facades of the 12 above ground floors. The total window area is 38,388 square feet. The building has no skylights. Windows are modeled as continuous horizontal bands. For the Std. 90.1-2004 baseline windows, there are interior shades with medium reflectance and medium transmittance listed in Table 2. When shades are on, the transmitted solar and visible light are cut by 60%. The interior shades are assumed to be down when the glare index exceeds 22 which is a typical setpoint for office spaces. For the EC windows, there are no interior shades.

Table 2. Properties of Interior Shades for the Baseline Windows

Property	Value
Solar transmittance	0.4
Solar reflectance	0.5
Visible transmittance	0.4
Visible reflectance	0.5

The building is served by a central variable air volume system with zone reheat, one water-cooled electric chiller, and one gas-fired hot water boiler. The chiller has a coefficient of performance of 4.9 and the boiler has an efficiency of 80%. The cooling and heating capacities and air flow of HVAC equipment is autosized by EnergyPlus according to the peak loads calculated on the summer and winter design days. No exterior shading from adjacent buildings, trees, hills, overhangs, or side fins were considered in the assessment. The design lighting power density (LPD) for all conditioned spaces is 1.0 W/ft^2; the design electric plug load density (EPD) is 0.75 W/ft^2; and the design occupant density is 3.63 person/1000 ft^2 with a total of 1670 occupants in the building. Typical office occupancy schedules were used in the simulations.

Each perimeter zone has a daylight sensor located at the center of the zone with a working desk height of 0.8 meters above the floor and 10 feet away from the windows. The view azimuth used to calculate the DGI is parallel to the windows. The daylight sensor has an illuminance setpoint of 46.5 footcandles (500 lux). For the daylighting runs, the daylight sensors continuously dim the electrical lighting of the perimeter zones based on the amount of daylight they receive. If the available daylight is equal to or greater than 500 lux, the electrical lighting power remains at a minimum of 10%. Five typical US climates were selected for the assessment.

Table 3. The Five Typical Climates

Climate Zone	City	Climate
1A	Miami, FL	Hot – Humid (Tropical)
2B	Phoenix, AZ	Hot – Dry (Subtropical)
3C	San Francisco, CA	Warm – Marine (Mediterranean)
5A	Chicago, IL	Cool – Humid (warm summer, cold winter)
7	Duluth, MN	Very Cold (cool summer, very cold winter)

Window Technologies to Evaluate

Various window technologies were evaluated: existing stock, code baseline (Std. 90.1-2004), high-performance building standard (Std. 189.1P), emerging window technologies, and hypothetically optimum technically feasible. The VT of the windows is not usually regulated explicitly by building energy code and standards like Std. 90.1-2004. In this study, the VT of a window is assumed to equal the SHGC if not specified explicitly. Table 4 summarizes the windows with their overall performance data for the window assembly: U-factor, SHGC, and VT. Window frames were not directly modeled.

Various shading control strategies were evaluated in the assessment. Static (non switchable) windows have interior fabric shades that were either always on (Shade OnAll), always off (Shade OffAll), or on if the calculated DGIs at either daylight reference point exceeded the maximum allowable value (Shade OnIfHG). The EC windows did not have interior shades and operated in one single state - clear if shading control is always off, dark if shading control is always on. When shading control is to meet daylight illuminance setpoint, EC windows are first dimmed continuously to meet the daylight illuminance setpoint. If the glare control is active and the DGI exceeds the maximum allowable value, EC windows are then switched to fully dark state – it does not further dim to meet the DGI criteria while still providing some daylight. This was a limitation of EnergyPlus 2.2 released during the assessment work.

Table 4. Summary of Windows to be Evaluated

Windows	Description	U-factor (Btu/h-°F-ft²)	SHGC	VT
Base Case – San Francisco	ASHRAE 90.1-2004 baseline	1.219	0.338	0.339
Base Case – Phoenix, Miami	ASHRAE 90.1-2004 baseline	1.219	0.249	0.25
Base Case – Chicago	ASHRAE 90.1-2004 baseline	0.574	0.39	0.498
Base Case – Duluth	ASHRAE 90.1-2004 baseline	0.574	0.491	0.486
AvgComSales	Existing commercial stock (average commercial sales, double pane low-e)	0.62	0.48	0.48
Triple_Lowe	Triple pane with low-e	0.201	0.25	0.25
High_R_Tint	Highly-insulating double pane tinted	0.291	0.28	0.28
High_R_Clear	Highly-insulating double pane clear	0.291	0.42	0.42
189.1 – San Francisco	ASHRAE 189.1 baseline	0.549	0.25	0.25
189.1 – Phoenix	ASHRAE 189.1 baseline	0.75	0.25	0.25
189.1 – Miami	ASHRAE 189.1 baseline	1.20	0.25	0.25
189.1 – Chicago	ASHRAE 189.1 baseline	0.45	0.35	0.35
189.1 – Duluth	ASHRAE 189.1 baseline	0.35	0.45	0.45
EC_Window	Electrochromic, auto switchable	0.298	0.39 clear 0.086 dark	0.599 clear 0.034 dark
EC_HR_Window	Electrochromic, highly insulating	0.118	0.349 clear 0.043 dark	0.557 clear 0.031 dark

Simulation Results and Discussions

Simulation results and the calculated energy savings are summarized in tables and graphs for all window technologies with three types of window shading controls in all five climates. Table 5 shows the whole building energy use and breakdown into end uses for the no daylighting cases with shades on if high glare. The whole building energy use includes four metrics: annual electricity in kWh, annual natural gas in Therms, annual site energy in MBtu (million Btu), and annual source energy in MBtu. The electricity use percentages of lighting, receptacle, and HVAC are also listed. For cases without daylighting controls, the annual lighting energy use is always 1,427,703 kWh, representing from 20.4% of total electricity use in Miami to 28.5% in Duluth.

Tables 6 and 7 listed the energy savings per square foot of window area for the seven windows compared to the baseline windows. The cells in two tables were filled with colors: the red color represents negative energy savings while the green for positive savings. The depth of the colors represents the relative magnitude of energy savings – the darker the color, the more energy saved (if green) or consumed (if red). Table 8 shows similar data for cases with window shades always off, while Table 9 is for cases with window shades always on.

By comparing energy savings without daylighting controls to those with daylighting controls, the relative energy savings percentages of the seven window technologies compared to the baseline windows across all five climates are not changed noticeably. On the other hand, by comparing the same window technology with and without daylighting controls, the energy savings of daylighting cases in terms of electricity, site energy, and source energy are significant.

Table 5. Whole Building Energy Use (Shades On If High Glare, No Daylighting)

		End Uses								Whole Building Energy Use				Electricity End Uses		
Climates	Windows	Lighting kWh	Receptacle kWh	Cooling kWh	Fan kWh	Pump kWh	Cooling Tower kWh	Space Heating Therm	Water Heating Therm	Electricity kWh	Gas Therm	Site Energy MBtu	Source Energy MBtu	% Lighting	% Receptacle	% HVAC
San Francisco	base case	1,427,703	1,680,681	627,514	989,314	271,431	141,539	12,835	3,359	5,138,180	16,194	19,143	56,003	27.8%	32.7%	39.5%
	AvgComSales	1,427,703	1,680,681	710,458	1,102,031	301,483	157,742	5,635	3,358	5,380,097	8,993	19,247	57,770	26.5%	31.2%	42.2%
	Triple_Lowe	1,427,703	1,680,681	659,306	1,024,017	279,758	146,306	1,823	3,358	5,217,767	5,181	18,313	55,640	27.4%	32.2%	40.4%
	High_R_Tint	1,427,703	1,680,681	662,103	1,029,525	281,703	147,331	2,486	3,359	5,229,045	5,844	18,417	55,831	27.3%	32.1%	40.6%
	High_R_Clear	1,427,703	1,680,681	718,636	1,108,331	302,633	158,331	2,539	3,358	5,396,314	5,898	18,993	57,603	26.5%	31.1%	42.4%
	189.1	1,427,703	1,680,681	629,531	986,500	271,639	141,683	5,131	3,358	5,137,733	8,489	18,371	55,156	27.8%	32.7%	39.5%
	EC_Window	1,427,703	1,680,681	597,025	943,100	256,906	134,086	2,683	3,359	5,039,500	6,042	17,791	53,852	28.3%	33.4%	38.3%
	EC_HR_Window	1,427,703	1,680,681	607,244	960,261	262,578	137,236	2,025	3,359	5,075,705	5,383	17,848	54,163	28.1%	33.1%	38.8%
Miami	base case	1,427,703	1,680,681	1,663,342	1,145,481	467,161	259,489	523	1,989	6,643,856	2,512	22,909	70,401	21.5%	25.3%	53.2%
	AvgComSales	1,427,703	1,680,681	1,826,983	1,283,881	509,667	283,114	217	1,988	7,012,025	2,206	24,134	74,254	20.4%	24.0%	55.7%
	Triple_Lowe	1,427,703	1,680,681	1,728,131	1,200,097	483,925	268,817	73	1,989	6,789,350	2,062	23,360	71,888	21.0%	24.8%	54.2%
	High_R_Tint	1,427,703	1,680,681	1,736,317	1,207,914	485,206	269,528	93	1,988	6,807,347	2,082	23,424	72,080	21.0%	24.7%	54.3%
	High_R_Clear	1,427,703	1,680,681	1,823,622	1,281,947	508,447	282,439	95	1,988	7,004,836	2,084	24,098	74,165	20.4%	24.0%	55.6%
	189.1	1,427,703	1,680,681	1,665,192	1,146,939	467,603	259,736	509	1,988	6,647,855	2,497	22,921	70,442	21.5%	25.3%	53.2%
	EC_Window	1,427,703	1,680,681	1,664,597	1,154,511	471,722	262,036	104	1,988	6,661,250	2,093	22,927	70,539	21.4%	25.2%	53.3%
	EC_HR_Window	1,427,703	1,680,681	1,652,617	1,151,297	471,556	261,944	73	1,989	6,645,797	2,061	22,871	70,372	21.5%	25.3%	53.2%
Phoenix	base case	1,427,703	1,680,681	1,286,656	1,417,478	426,742	230,269	8,814	2,210	6,469,528	11,024	23,166	69,491	22.1%	26.0%	52.0%
	AvgComSales	1,427,703	1,680,681	1,410,358	1,549,469	459,092	249,172	5,015	2,210	6,776,475	7,226	23,833	72,316	21.1%	24.8%	54.1%
	Triple_Lowe	1,427,703	1,680,681	1,291,736	1,426,906	425,514	230,544	2,886	2,210	6,483,081	5,096	22,619	68,986	22.0%	25.9%	52.1%
	High_R_Tint	1,427,703	1,680,681	1,304,919	1,437,269	428,383	232,097	3,330	2,210	6,511,053	5,540	22,759	69,330	21.9%	25.8%	52.3%
	High_R_Clear	1,427,703	1,680,681	1,384,783	1,522,528	451,031	244,925	3,178	2,210	6,711,647	5,388	23,428	71,431	21.3%	25.0%	53.7%
	189.1	1,427,703	1,680,681	1,288,883	1,421,286	427,747	230,961	6,215	2,210	6,477,264	8,426	22,933	69,288	22.0%	25.9%	52.0%
	EC_Window	1,427,703	1,680,681	1,230,422	1,375,781	415,686	224,469	3,874	2,210	6,354,742	6,084	22,280	67,740	22.5%	26.4%	51.1%
	EC_HR_Window	1,427,703	1,680,681	1,203,497	1,354,758	410,500	221,669	3,070	2,210	6,298,805	5,281	22,009	67,061	22.7%	26.7%	50.7%
Chicago	base case	1,427,703	1,680,681	738,592	1,262,981	360,744	136,667	39,537	3,771	5,607,367	43,308	23,454	63,916	25.5%	30.0%	44.6%
	AvgComSales	1,427,703	1,680,681	786,994	1,334,906	382,847	143,897	39,362	3,771	5,757,028	43,133	23,947	65,476	24.8%	29.2%	46.0%
	Triple_Lowe	1,427,703	1,680,681	725,717	1,195,917	352,550	133,878	24,136	3,771	5,516,442	27,907	21,604	61,274	25.9%	30.5%	43.7%
	High_R_Tint	1,427,703	1,680,681	732,642	1,220,681	356,786	135,214	28,234	3,771	5,553,708	32,005	22,141	62,115	25.7%	30.3%	44.0%
	High_R_Clear	1,427,703	1,680,681	786,378	1,290,764	379,078	143,003	26,544	3,771	5,707,603	30,315	22,497	63,555	25.0%	29.4%	45.5%
	189.1	1,427,703	1,680,681	748,633	1,261,747	364,575	137,981	34,318	3,771	5,621,317	38,089	22,980	63,493	25.4%	29.9%	44.7%
	EC_Window	1,427,703	1,680,681	681,714	1,147,603	335,456	128,492	29,697	3,771	5,401,647	33,468	21,769	60,670	26.4%	31.1%	42.5%
	EC_HR_Window	1,427,703	1,680,681	681,586	1,130,233	337,011	128,872	22,785	3,771	5,386,083	26,555	21,024	59,751	26.5%	31.2%	42.3%
Duluth	base case	1,427,703	1,680,681	523,767	1,340,217	307,889	97,392	63,889	4,572	5,377,647	68,460	25,186	64,238	26.5%	31.3%	42.2%
	AvgComSales	1,427,703	1,680,681	537,747	1,367,958	316,361	99,339	65,372	4,572	5,429,789	69,943	25,512	64,950	26.3%	31.0%	42.8%
	Triple_Lowe	1,427,703	1,680,681	484,292	1,208,703	285,942	91,636	40,592	4,572	5,178,956	45,164	22,179	59,596	27.6%	32.5%	40.0%
	High_R_Tint	1,427,703	1,680,681	484,800	1,229,500	285,436	91,819	47,022	4,572	5,199,939	51,594	22,893	60,520	27.5%	32.3%	40.2%
	High_R_Clear	1,427,703	1,680,681	543,461	1,316,361	319,508	99,708	44,123	4,572	5,387,422	48,695	23,243	62,182	26.5%	31.2%	42.3%
	189.1	1,427,703	1,680,681	547,447	1,335,986	321,900	100,381	47,957	4,572	5,414,095	52,529	23,717	62,883	26.4%	31.0%	42.6%
	EC_Window	1,427,703	1,680,681	432,175	1,137,372	253,031	84,631	50,830	4,572	5,015,589	55,402	22,645	58,990	28.5%	33.5%	38.0%
	EC_HR_Window	1,427,703	1,680,681	436,572	1,117,936	257,636	85,839	38,431	4,572	5,006,369	43,004	21,374	57,539	28.5%	33.6%	37.9%

Table 6. Whole Building Energy Use and Savings (Shades On If High Glare, No Daylighting)

		Energy Savings per ft² of Window Area						Whole Building Energy Use				
Climates	Windows	Electricity kWh/ft²	Gas kBtu/ft²	Site Energy kBtu/ft²	% Site Energy	Source Energy kBtu/ft²	% Source Energy	Electricity kWh	Gas Therm	Site Energy MBtu	Source Energy MBtu	Site Energy EUI kBtu/ft²
San Francisco	base case	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	5,138,180	16,194	19,143	56,003	41.6
	AvgComSales	-6.3	18.8	-2.7	-0.5%	-46.0	-3.2%	5,380,097	8,993	19,247	57,770	41.8
	Triple_Lowe	-2.1	28.7	21.6	4.3%	9.5	0.6%	5,217,767	5,181	18,313	55,640	39.8
	High_R_Tint	-2.4	27.0	18.9	3.8%	4.5	0.3%	5,229,045	5,844	18,417	55,831	40.0
	High_R_Clear	-6.7	26.8	3.9	0.8%	-41.7	-2.9%	5,396,314	5,898	18,993	57,603	41.3
	189.1	0.0	20.1	20.1	4.0%	22.1	1.5%	5,137,733	8,489	18,371	55,156	39.9
	EC_Window	2.6	26.4	35.2	7.1%	56.0	3.8%	5,039,500	6,042	17,791	53,852	38.7
	EC_HR_Window	1.6	28.2	33.7	6.8%	47.9	3.3%	5,075,705	5,383	17,848	54,163	38.8
Miami	base case	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	6,643,856	2,512	22,909	70,401	49.8
	AvgComSales	-9.6	0.8	-31.9	-5.3%	-100.4	-5.5%	7,012,025	2,206	24,134	74,254	52.4
	Triple_Lowe	-3.8	1.2	-11.7	-2.0%	-38.7	-2.1%	6,789,350	2,062	23,360	71,888	50.8
	High_R_Tint	-4.3	1.1	-13.4	-2.2%	-43.7	-2.4%	6,807,347	2,082	23,424	72,080	50.9
	High_R_Clear	-9.4	1.1	-31.0	-5.2%	-98.1	-5.3%	7,004,836	2,084	24,098	74,165	52.4
	189.1	-0.1	0.0	-0.3	-0.1%	-1.1	-0.1%	6,647,855	2,497	22,921	70,442	49.8
	EC_Window	-0.5	1.1	-0.5	-0.1%	-3.6	-0.2%	6,661,250	2,093	22,927	70,539	49.8
	EC_HR_Window	-0.1	1.2	1.0	0.2%	0.8	0.0%	6,645,797	2,061	22,871	70,372	49.7
Phoenix	base case	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	6,469,528	11,024	23,166	69,491	50.3
	AvgComSales	-8.0	9.9	-17.4	-2.9%	-73.6	-4.1%	6,776,475	7,226	23,833	72,316	51.8
	Triple_Lowe	-0.4	15.4	14.2	2.4%	13.2	0.7%	6,483,081	5,096	22,619	68,986	49.1
	High_R_Tint	-1.1	14.3	10.6	1.8%	4.2	0.2%	6,511,053	5,540	22,759	69,330	49.5
	High_R_Clear	-6.3	14.7	-6.8	-1.1%	-50.5	-2.8%	6,711,647	5,388	23,428	71,431	50.9
	189.1	-0.2	6.8	6.1	1.0%	5.3	0.3%	6,477,264	8,426	22,933	69,288	49.8
	EC_Window	3.0	12.9	23.1	3.8%	45.6	2.5%	6,354,742	6,084	22,280	67,740	48.4
	EC_HR_Window	4.4	15.0	30.1	5.0%	63.3	3.5%	6,298,805	5,281	22,009	67,061	47.8
Chicago	base case	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	5,607,367	43,308	23,454	63,916	51.0
	AvgComSales	-3.9	0.5	-12.8	-2.1%	-40.6	-2.4%	5,757,028	43,133	23,947	65,476	52.0
	Triple_Lowe	2.4	40.1	48.2	7.9%	68.8	4.1%	5,516,442	27,907	21,604	61,274	46.9
	High_R_Tint	1.4	29.4	34.2	5.6%	46.9	2.8%	5,553,708	32,005	22,141	62,115	48.1
	High_R_Clear	-2.6	33.8	24.9	4.1%	9.4	0.6%	5,707,603	30,315	22,497	63,555	48.9
	189.1	-0.4	13.6	12.3	2.0%	11.0	0.7%	5,621,317	38,089	22,980	63,493	49.9
	EC_Window	5.4	25.6	43.9	7.2%	84.6	5.1%	5,401,647	33,468	21,769	60,670	47.3
	EC_HR_Window	5.8	43.6	63.3	10.4%	108.5	6.5%	5,386,083	26,555	21,024	59,751	45.7
Duluth	base case	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	5,377,647	68,460	25,186	64,238	54.7
	AvgComSales	-1.4	-3.9	-8.5	-1.3%	-18.5	-1.1%	5,429,789	69,943	25,512	64,950	55.4
	Triple_Lowe	5.2	60.7	78.3	11.9%	120.9	7.2%	5,178,956	45,164	22,179	59,596	48.2
	High_R_Tint	4.6	43.9	59.7	9.1%	96.9	5.8%	5,199,939	51,594	22,893	60,520	49.7
	High_R_Clear	-0.3	51.5	50.6	7.7%	53.6	3.2%	5,387,422	48,695	23,243	62,182	50.5
	189.1	-0.9	41.5	38.3	5.8%	35.3	2.1%	5,414,095	52,529	23,717	62,883	51.5
	EC_Window	9.4	34.0	66.2	10.1%	136.7	8.2%	5,015,589	55,402	22,645	58,990	49.2
	EC_HR_Window	9.7	66.3	99.3	15.1%	174.5	10.4%	5,006,369	43,004	21,374	57,539	46.4

Table 7. Whole Building Energy Use and Savings (Shades On If High Glare, With Daylighting)

		Energy Savings per ft² of Window Area						Whole Building Energy Use				
Climates	Windows	Electricity kWh/ft²	Gas kBtu/ft²	Site Energy kBtu/ft²	% Site Energy	Source Energy kBtu/ft²	% Source Energy	Electricity kWh	Gas Therm	Site Energy MBtu	Source Energy MBtu	Site Energy EUI kBtu/ft²
San Francisco	base case	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	4,807,681	18,697	18,266	52,787	39.7
	AvgComSales	-5.8	22.0	2.1	0.4%	-37.6	-2.7%	5,031,731	10,253	18,185	54,230	39.5
	Triple_Lowe	-2.3	33.9	26.1	5.5%	12.8	0.9%	4,895,753	5,672	17,264	52,295	37.5
	High_R_Tint	-2.4	31.7	23.5	4.9%	9.1	0.7%	4,900,239	6,537	17,365	52,437	37.7
	High_R_Clear	-6.3	31.6	10.1	2.1%	-32.0	-2.3%	5,049,525	6,578	17,879	54,017	38.8
	189.1	-0.3	23.3	22.2	4.7%	22.1	1.6%	4,819,703	9,745	17,412	51,937	37.8
	EC_Window	2.3	28.6	36.3	7.6%	55.0	4.0%	4,721,189	7,700	16,871	50,674	36.7
	EC_HR_Window	1.2	30.6	34.6	7.3%	45.8	3.3%	4,762,628	6,936	16,936	51,028	36.8
Miami	base case	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	6,304,295	2,617	21,762	66,828	47.3
	AvgComSales	-8.7	0.9	-28.6	-5.0%	-90.4	-5.2%	6,636,739	2,260	22,860	70,298	49.7
	Triple_Lowe	-3.9	1.4	-11.9	-2.1%	-39.5	-2.3%	6,453,331	2,088	22,217	68,344	48.3
	High_R_Tint	-3.9	1.3	-11.9	-2.1%	-39.6	-2.3%	6,453,467	2,113	22,220	68,348	48.3
	High_R_Clear	-8.5	1.3	-27.5	-4.9%	-87.9	-5.0%	6,629,053	2,111	22,819	70,201	49.6
	189.1	-0.1	0.0	-0.2	0.0%	-0.8	0.0%	6,307,267	2,600	21,770	66,858	47.3
	EC_Window	0.2	1.2	1.9	0.3%	3.4	0.2%	6,296,850	2,141	21,689	66,698	47.1
	EC_HR_Window	0.5	1.4	3.1	0.6%	7.0	0.4%	6,284,306	2,098	21,642	66,561	47.0
Phoenix	base case	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	6,147,642	12,048	22,171	66,205	48.2
	AvgComSales	-6.7	10.6	-12.3	-2.1%	-59.5	-3.5%	6,406,408	7,967	22,645	68,490	49.2
	Triple_Lowe	-0.1	16.6	16.3	2.8%	17.0	1.0%	6,152,014	5,663	21,547	65,554	46.8
	High_R_Tint	-0.7	15.3	13.0	2.2%	9.5	0.6%	6,173,797	6,183	21,673	65,840	47.1
	High_R_Clear	-5.0	15.8	-1.4	-0.2%	-36.0	-2.1%	6,341,453	5,979	22,225	67,588	48.3
	189.1	-0.1	7.1	6.9	1.2%	7.1	0.4%	6,150,353	9,310	21,906	65,934	47.6
	EC_Window	4.0	13.0	26.6	4.6%	56.2	3.3%	5,995,092	7,044	21,150	64,048	46.0
	EC_HR_Window	5.4	15.2	33.7	5.8%	73.6	4.3%	5,940,233	6,207	20,879	63,378	45.4
Chicago	base case	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	5,242,081	46,343	22,512	60,392	48.9
	AvgComSales	-3.9	1.2	-11.9	-2.0%	-39.4	-2.5%	5,390,047	45,878	22,970	61,903	49.9
	Triple_Lowe	1.6	43.7	49.0	8.4%	64.2	4.1%	5,182,155	29,568	20,630	57,927	44.8
	High_R_Tint	1.1	32.6	36.3	6.2%	47.0	3.0%	5,200,411	33,847	21,120	58,587	45.9
	High_R_Clear	-2.5	36.4	27.8	4.7%	13.3	0.8%	5,338,503	32,369	21,443	59,883	46.6
	189.1	-0.6	15.5	13.5	2.3%	10.9	0.7%	5,263,966	40,396	21,992	59,973	47.8
	EC_Window	5.2	25.4	43.3	7.4%	83.0	5.3%	5,041,397	36,581	20,851	57,207	45.3
	EC_HR_Window	5.7	44.6	63.9	10.9%	108.4	6.9%	5,024,705	29,240	20,060	56,229	43.6
Duluth	base case	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	5,015,975	72,958	24,402	60,911	53.0
	AvgComSales	-1.2	-3.7	-7.8	-1.2%	-16.6	-1.0%	5,061,731	74,377	24,700	61,549	53.7
	Triple_Lowe	4.5	64.7	80.1	12.6%	118.3	7.5%	4,842,553	48,140	21,329	56,371	46.3
	High_R_Tint	4.0	46.2	59.9	9.4%	92.7	5.8%	4,862,470	55,207	22,104	57,353	48.0
	High_R_Clear	-0.1	54.2	53.9	8.5%	58.1	3.7%	5,019,836	52,140	22,334	58,679	48.5
	189.1	-0.8	43.3	40.6	6.4%	39.0	2.5%	5,046,408	56,317	22,842	59,415	49.6
	EC_Window	8.9	29.9	60.3	9.5%	126.7	8.0%	4,673,706	61,492	22,088	56,047	48.0
	EC_HR_Window	9.4	65.8	97.8	15.4%	171.0	10.8%	4,655,564	47,692	20,646	54,348	44.9

Table 8. Whole Building Energy Use and Savings (Shades Always Off, No Daylighting)

Climates	Windows	Energy Savings per ft² of Window Area						Whole Building Energy Use				Site Energy EUI kBtu/ft2
		Electricity kWh/ft²	Gas kBtu//ft²	Site Energy kBtu/ft²	% Site Energy	Source Energy kBtu/ft²	% Source Energy	Electricity kWh	Gas Therm	Site Energy MBtu	Source Energy MBtu	
San Francisco	base case	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	5,138,192	16,178	19,141	56,001	41.6
	AvgComSales	-6.3	19.2	-2.4	-0.5%	-45.7	-3.1%	5,380,736	8,817	19,232	57,757	41.8
	Triple_Lowe	-2.1	28.8	21.7	4.3%	9.5	0.6%	5,217,900	5,140	18,309	55,637	39.8
	High_R_Tint	-2.4	27.1	19.0	3.8%	4.6	0.3%	5,228,972	5,785	18,411	55,824	40.0
	High_R_Clear	-6.8	27.0	4.0	0.8%	-41.9	-2.9%	5,397,861	5,797	18,988	57,608	41.3
	189.1	0.0	20.2	20.2	4.1%	22.2	1.5%	5,137,639	8,438	18,365	55,150	39.9
	EC_Window	-4.1	25.7	11.6	2.3%	-15.4	-1.1%	5,296,202	6,316	18,694	56,592	40.6
	EC_HR_Window	-3.5	29.0	17.0	3.4%	-5.6	-0.4%	5,273,856	5,033	18,489	56,216	40.2
Miami	base case	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	6,641,616	2,502	22,901	70,376	49.8
	AvgComSales	-9.8	0.8	-32.5	-5.4%	-102.2	-5.6%	7,016,374	2,194	24,148	74,298	52.5
	Triple_Lowe	-3.9	1.2	-12.2	-2.0%	-40.0	-2.2%	6,791,716	2,060	23,368	71,912	50.8
	High_R_Tint	-4.4	1.1	-13.8	-2.3%	-45.0	-2.5%	6,809,772	2,078	23,432	72,105	50.9
	High_R_Clear	-9.6	1.1	-31.7	-5.3%	-100.2	-5.5%	7,010,472	2,079	24,116	74,224	52.4
	189.1	-0.1	0.0	-0.3	0.0%	-0.9	-0.1%	6,645,172	2,488	22,911	70,412	49.8
	EC_Window	-6.3	1.1	-20.3	-3.4%	-65.0	-3.5%	6,882,388	2,089	23,681	72,873	51.5
	EC_HR_Window	-4.8	1.2	-15.1	-2.5%	-49.1	-2.7%	6,824,944	2,045	23,480	72,262	51.0
Phoenix	base case	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	6,471,664	10,979	23,169	69,508	50.3
	AvgComSales	-8.2	10.3	-17.5	-2.9%	-74.8	-4.1%	6,784,736	7,006	23,839	72,379	51.8
	Triple_Lowe	-0.4	15.5	14.1	2.3%	12.6	0.7%	6,487,328	5,022	22,626	69,023	49.2
	High_R_Tint	-1.1	14.4	10.6	1.8%	3.9	0.2%	6,514,728	5,448	22,763	69,359	49.5
	High_R_Clear	-6.4	14.9	-7.0	-1.2%	-51.7	-2.9%	6,719,194	5,242	23,439	71,494	50.9
	189.1	-0.2	6.9	6.1	1.0%	5.1	0.3%	6,480,414	8,343	22,935	69,313	49.8
	EC_Window	-2.9	14.2	4.3	0.7%	-15.3	-0.8%	6,583,878	5,511	23,005	70,096	50.0
	EC_HR_Window	0.0	16.9	17.1	2.8%	18.9	1.0%	6,470,006	4,478	22,513	68,781	48.9
Chicago	base case	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	5,606,753	43,110	23,432	63,888	50.9
	AvgComSales	-3.9	0.9	-12.5	-2.1%	-40.6	-2.4%	5,758,328	42,752	23,913	65,448	52.0
	Triple_Lowe	2.3	40.2	48.1	7.9%	68.5	4.1%	5,517,116	27,694	21,585	61,258	46.9
	High_R_Tint	1.3	29.5	34.1	5.6%	46.4	2.8%	5,555,036	31,784	22,123	62,105	48.1
	High_R_Clear	-2.7	34.5	25.3	4.2%	9.4	0.6%	5,709,658	29,873	22,459	63,528	48.8
	189.1	-0.4	13.8	12.4	2.0%	10.9	0.7%	5,621,764	37,831	22,955	63,470	49.9
	EC_Window	0.9	32.4	35.3	5.8%	44.5	2.7%	5,573,586	30,676	22,076	62,180	48.0
	EC_HR_Window	1.8	50.7	56.8	9.3%	74.2	4.5%	5,538,574	23,636	21,252	61,041	46.2
Duluth	base case	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	5,379,661	67,977	25,144	64,206	54.6
	AvgComSales	-1.3	-3.8	-8.4	-1.3%	-18.3	-1.1%	5,431,130	69,442	25,466	64,909	55.3
	Triple_Lowe	5.2	60.3	78.0	11.9%	120.8	7.2%	5,179,850	44,832	22,149	59,570	48.1
	High_R_Tint	4.7	43.6	59.5	9.1%	96.9	5.8%	5,200,375	51,239	22,859	60,486	49.7
	High_R_Clear	-0.3	52.1	51.1	7.8%	53.8	3.2%	5,390,650	47,988	23,183	62,139	50.4
	189.1	-1.0	42.1	38.8	5.9%	35.6	2.1%	5,417,442	51,801	23,656	62,838	51.4
	EC_Window	3.5	47.0	58.8	9.0%	87.8	5.3%	5,247,111	49,916	22,886	60,835	49.7
	EC_HR_Window	5.2	78.9	96.7	14.8%	141.3	8.5%	5,179,064	37,674	21,430	58,780	46.6

Table 9. Whole Building Energy Use and Savings (Shades Always On, No Daylighting)

Climates	Windows	Energy Savings per ft² of Window Area						Whole Building Energy Use				Site Energy EUI kBtu/ft2
		Electricity kWh/ft²	Gas kBtu//ft²	Site Energy kBtu/ft²	% Site Energy	Source Energy kBtu/ft²	% Source Energy	Electricity kWh	Gas Therm	Site Energy MBtu	Source Energy MBtu	
San Francisco	base case	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	5,083,739	8,246	18,162	54,560	39.5
	AvgComSales	-3.0	4.6	-5.7	-1.2%	-26.8	-1.9%	5,199,586	6,484	18,381	55,590	39.9
	Triple_Lowe	-1.0	8.5	5.1	1.1%	-1.2	-0.1%	5,121,736	4,983	17,965	54,605	39.0
	High_R_Tint	-1.6	7.4	2.0	0.4%	-8.5	-0.6%	5,143,948	5,412	18,084	54,886	39.3
	High_R_Clear	-3.6	7.6	-4.8	-1.0%	-30.1	-2.1%	5,223,536	5,330	18,347	55,717	39.9
	189.1	0.5	4.8	6.4	1.3%	10.1	0.7%	5,065,944	6,403	17,917	54,171	38.9
	EC_Window	1.8	2.0	8.3	1.8%	21.6	1.5%	5,013,130	7,469	17,844	53,730	38.8
	EC_HR_Window	0.9	3.1	6.1	1.3%	12.8	0.9%	5,049,514	7,051	17,926	54,068	38.9
Miami	base case	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	6,643,044	2,193	22,875	70,358	49.7
	AvgComSales	-3.3	0.3	-10.8	-1.8%	-34.1	-1.9%	6,767,992	2,096	23,291	71,666	50.6
	Triple_Lowe	-2.5	0.3	-8.0	-1.4%	-25.6	-1.4%	6,737,422	2,065	23,184	71,340	50.4
	High_R_Tint	-2.4	0.3	-7.8	-1.3%	-24.8	-1.4%	6,734,489	2,076	23,175	71,310	50.4
	High_R_Clear	-4.0	0.3	-13.4	-2.2%	-42.1	-2.3%	6,797,392	2,062	23,388	71,973	50.8
	189.1	0.0	0.0	-0.1	0.0%	-0.4	0.0%	6,644,508	2,190	22,879	70,373	49.7
	EC_Window	0.9	0.2	3.2	0.5%	9.6	0.5%	6,608,714	2,132	22,751	69,989	49.4
	EC_HR_Window	1.4	0.2	4.9	0.8%	14.8	0.8%	6,590,074	2,099	22,685	69,788	49.3
Phoenix	base case	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	6,380,644	7,793	22,540	68,200	49.0
	AvgComSales	-2.8	5.0	-4.4	-0.8%	-23.7	-1.3%	6,486,397	5,888	22,710	69,108	49.3
	Triple_Lowe	-0.8	6.9	4.2	0.7%	-0.9	0.0%	6,411,358	5,143	22,379	68,234	48.6
	High_R_Tint	-1.0	6.1	2.6	0.4%	-4.3	-0.2%	6,420,620	5,452	22,442	68,366	48.8
	High_R_Clear	-2.7	7.1	-2.0	-0.3%	-20.4	-1.2%	6,483,172	5,080	22,618	68,985	49.1
	189.1	-0.3	2.3	1.3	0.2%	-0.5	0.0%	6,391,642	6,922	22,490	68,220	48.9
	EC_Window	2.1	2.6	9.6	1.6%	24.6	1.4%	6,301,436	6,803	22,171	67,255	48.2
	EC_HR_Window	3.7	4.3	17.0	2.9%	43.9	2.5%	6,238,128	6,141	21,889	66,515	47.6
Chicago	base case	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	5,459,600	34,812	22,101	61,428	48.0
	AvgComSales	-1.2	1.3	-2.9	-0.5%	-11.5	-0.7%	5,506,494	34,319	22,211	61,869	48.3
	Triple_Lowe	0.0	20.3	20.3	3.5%	22.1	1.4%	5,459,880	27,018	21,322	60,580	46.3
	High_R_Tint	0.1	14.1	14.4	2.5%	16.0	1.0%	5,457,386	29,387	21,550	60,812	46.8
	High_R_Clear	-1.4	17.6	12.7	2.2%	3.9	0.2%	5,515,236	28,062	21,615	61,278	47.0
	189.1	-0.2	6.3	5.8	1.0%	5.3	0.3%	5,465,447	32,382	21,877	61,225	47.5
	EC_Window	2.4	-4.1	4.3	0.7%	21.3	1.3%	5,365,872	36,372	21,937	60,609	47.7
	EC_HR_Window	3.1	13.4	24.0	4.2%	47.3	3.0%	5,340,806	29,667	21,181	59,613	46.0
Duluth	base case	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	5,140,158	55,431	23,073	60,308	50.1
	AvgComSales	-0.6	-2.0	-3.9	-0.7%	-8.3	-0.5%	5,162,394	56,185	23,224	60,625	50.5
	Triple_Lowe	1.5	31.2	36.2	6.0%	49.7	3.2%	5,083,372	43,467	21,683	58,402	47.1
	High_R_Tint	1.4	20.4	25.4	4.2%	37.6	2.4%	5,084,722	47,585	22,099	58,866	48.0
	High_R_Clear	-0.8	25.9	23.3	3.9%	20.0	1.3%	5,170,366	45,474	22,180	59,540	48.2
	189.1	-0.9	20.0	16.9	2.8%	12.2	0.8%	5,175,516	47,736	22,424	59,841	48.7
	EC_Window	4.0	-12.1	1.4	0.2%	28.7	1.8%	4,987,916	60,070	23,018	59,208	50.0
	EC_HR_Window	4.5	20.1	35.6	5.9%	69.8	4.4%	4,966,374	47,700	21,707	57,630	47.2

Figures 2 and 3 graphed the data in Table 5**Error! Reference source not found.** on the basis of per square foot of window area and building floor area. Considering the Standard 90.1-2010 target of site energy 33.3 kBtu/ft² and the 2003 US national average commercial buildings site energy usage of 91 kBtu/ft² (EIA 2006), the energy savings potentials of windows technologies **Error! Reference source not found.**are significant, especially for EC windows (except for Miami) and high-R windows as defined in Table 4 in cold climates.

Figure 2. Energy Savings per Square Foot of Window Area, No Daylighting Controls, Shades On If High Glare

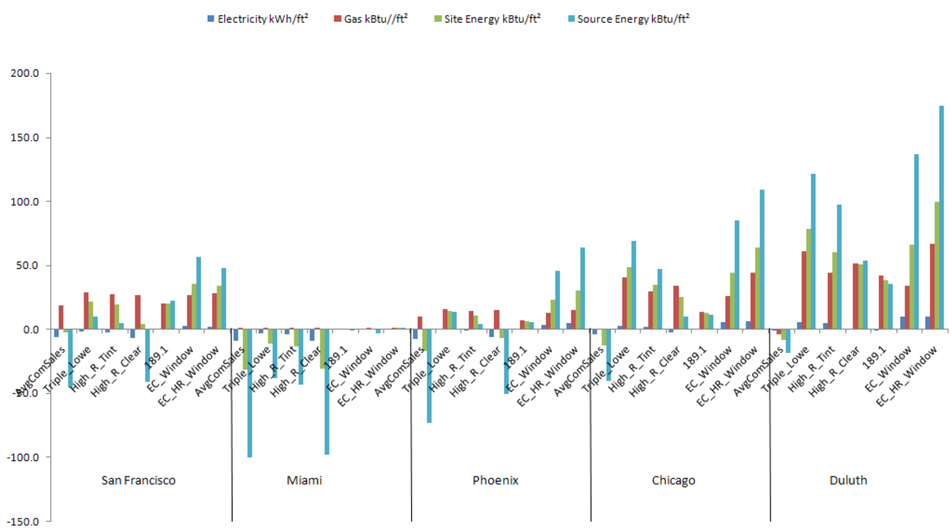
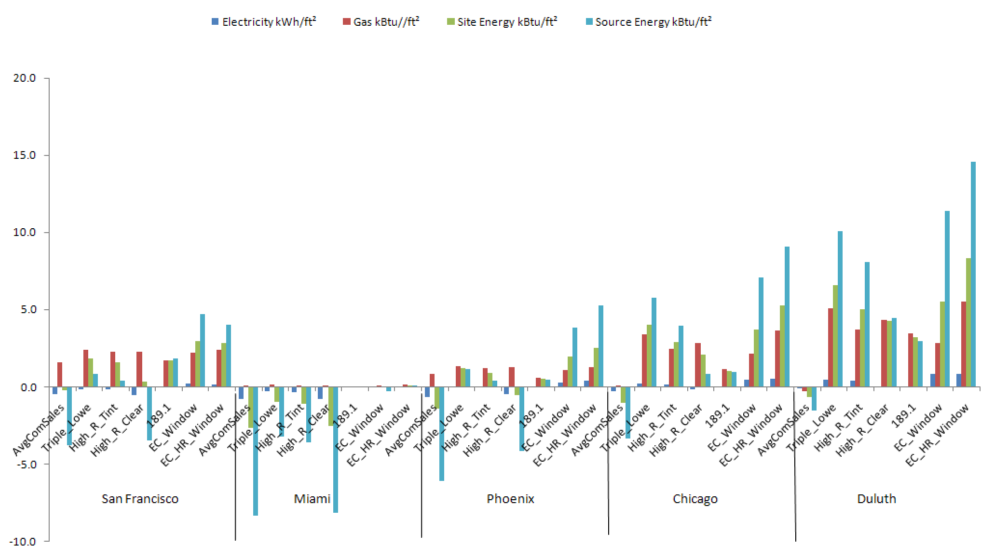


Figure 3. Energy Savings per Square Foot of Floor Area, No Daylighting Controls, Shades On If High Glare



Energy savings from other technologies like HVAC or lighting are better quantified on the basis of building floor area, while the windows energy savings are better quantified on the basis of window area or the perimeter zone floor area. The calculated energy savings per window area are only applicable to the studied cases (WWR = 40% etc), be cautious to use the savings results for other cases with different window area or different daylighting controls.

As perimeter zones only cover 29% of the building floor area, 71% of the floor area is core zones which do not have energy savings directly related to the changes of windows on perimeter zones. Therefore, if the percentages of energy savings were calculated on the perimeter zones basis, they would be much higher. In general, we can observe the following:

By windows technologies,

- Buildings with existing commercial windows used more energy than the Std. 90.1-2004 baseline windows across all five climates. All six windows technologies save heating energy compared with Std. 90.1-2004 windows: savings are much higher in cold climates.
- The two EC windows show the best energy savings potential followed by the triple pane low-e windows, the tinted and clear double pane highly insulating low-e windows, and the Std. 189.1P windows.
- The highly-insulating EC windows demonstrate the best energy performance for Duluth, Chicago, and Phoenix; while for San Francisco, the normal-EC windows are the best.
- The Triple low-e windows show better energy performance in cold climates such as Duluth and Chicago, while they are still more energy efficient than the Std. 90.1-2004 windows in other climates such as San Francisco and Phoenix.
- The Std.189.1P baseline windows show better energy performance than the Std. 90.1-2004 windows in Duluth and San Francisco, while savings are marginal in Phoenix and Chicago.
- The two highly insulating windows only show better energy performance than Std. 90.1-2004 windows in cold climates such as Duluth and Chicago.

By climate zones,

- For Miami where cooling is dominated and heating is almost not required, none of the seven windows technologies demonstrate site or source energy savings. This is probably due to the low SHGC and high U-factor of the Std. 90.1-2004 windows for Miami.
- For mild climate such as San Francisco, the normal-EC windows save the greatest source energy, followed by the high-R EC windows and the Std. 189.1P windows.
- For hot and dry climate such as Phoenix, the two EC windows save most energy, followed by the triple low-e windows which are marginally better than the Std. 90.1-2004 windows.
- For cold climate such as Duluth and Chicago, the two EC windows save most energy, followed by the triple low-e windows and the double tinted high-R low-e windows.
- In general, windows with a low U-factor demonstrate the greatest energy savings potentials except for cooling dominated climate such as Miami.

Daylighting energy savings (Table 10) are significant when comparing daylighting cases **Error! Reference source not found.**to no daylighting cases for same types of windows. On the basis of per square foot of window area, the electricity savings range from 8.2 kWh/ft² in San Francisco to 9.8 kWh/ft² in Miami; the site energy savings range from 14.5 kBtu/ft² for the EC windows in Duluth to 33.3 kBtu/ft² for the double clear high-R low-e windows in Miami; while the source energy savings range from 76.7 kBtu/ft² for the EC windows in Duluth to 103.3 kBtu/ft² for the double clear high-R low-e windows in Miami. On the whole-building electricity use basis, the daylighting saves from 5% of the Std. 90.1-2004 windows in Phoenix to 7% of the high-R EC windows in Duluth; while on the whole building source energy basis, the daylighting savings are from 4.7% of the 90.1-2004 windows in Phoenix to 6.2% of the double high-R clear windows in San Francisco.

Table 10. Daylighting Energy Savings, Shades On If High Glare

		Energy Savings per ft² of Window Area				Energy Savings %			
Climates	Windows	Electricity kWh/ft²	Gas kBtu//ft²	Site Energy kBtu/ft²	Source Energy kBtu/ft²	Electricity	Gas	Site Energy	Source Energy
San Francisco	base case	8.61	-6.52	22.8	83.8	6.4%	-15.5%	4.6%	5.7%
	AvgComSales	9.07	-3.28	27.7	92.2	6.5%	-14.0%	5.5%	6.1%
	Triple_Lowe	8.39	-1.28	27.3	87.1	6.2%	-9.5%	5.7%	6.0%
	High_R_Tint	8.57	-1.81	27.4	88.4	6.3%	-11.9%	5.7%	6.1%
	High_R_Clear	9.03	-1.77	29.0	93.4	6.4%	-11.5%	5.9%	6.2%
	189.1	8.28	-3.27	25.0	83.9	6.2%	-14.8%	5.2%	5.8%
	EC_Window	8.29	-4.32	24.0	82.8	6.3%	-27.4%	5.2%	5.9%
	EC_HR_Window	8.16	-4.05	23.8	81.7	6.2%	-28.8%	5.1%	5.8%
Miami	base case	8.85	-0.28	29.9	93.1	5.1%	-4.2%	5.0%	5.1%
	AvgComSales	9.78	-0.14	33.2	103.1	5.4%	-2.4%	5.3%	5.3%
	Triple_Lowe	8.75	-0.07	29.8	92.3	4.9%	-1.3%	4.9%	4.9%
	High_R_Tint	9.22	-0.08	31.4	97.2	5.2%	-1.5%	5.1%	5.2%
	High_R_Clear	9.79	-0.07	33.3	103.3	5.4%	-1.3%	5.3%	5.3%
	189.1	8.87	-0.27	30.0	93.4	5.1%	-4.1%	5.0%	5.1%
	EC_Window	9.49	-0.13	32.2	100.1	5.5%	-2.3%	5.4%	5.4%
	EC_HR_Window	9.42	-0.10	32.0	99.3	5.4%	-1.8%	5.4%	5.4%
Phoenix	base case	8.39	-2.67	25.9	85.6	5.0%	-9.3%	4.3%	4.7%
	AvgComSales	9.64	-1.93	30.9	99.7	5.5%	-10.3%	5.0%	5.3%
	Triple_Lowe	8.62	-1.48	27.9	89.4	5.1%	-11.1%	4.7%	5.0%
	High_R_Tint	8.79	-1.67	28.3	90.9	5.2%	-11.6%	4.8%	5.0%
	High_R_Clear	9.64	-1.54	31.3	100.1	5.5%	-11.0%	5.1%	5.4%
	189.1	8.52	-2.30	26.8	87.4	5.0%	-10.5%	4.5%	4.8%
	EC_Window	9.37	-2.50	29.4	96.2	5.7%	-15.8%	5.1%	5.5%
	EC_HR_Window	9.34	-2.41	29.4	95.9	5.7%	-17.5%	5.1%	5.5%
Chicago	base case	9.52	-7.91	24.5	91.8	6.5%	-7.0%	4.0%	5.5%
	AvgComSales	9.56	-7.15	25.5	93.1	6.4%	-6.4%	4.1%	5.5%
	Triple_Lowe	8.71	-4.33	25.4	87.2	6.1%	-6.0%	4.5%	5.5%
	High_R_Tint	9.20	-4.80	26.6	91.9	6.4%	-5.8%	4.6%	5.7%
	High_R_Clear	9.61	-5.35	27.5	95.7	6.5%	-6.8%	4.7%	5.8%
	189.1	9.31	-6.01	25.7	91.7	6.4%	-6.1%	4.3%	5.5%
	EC_Window	9.38	-8.11	23.9	90.2	6.7%	-9.3%	4.2%	5.7%
	EC_HR_Window	9.41	-6.99	25.1	91.7	6.7%	-10.1%	4.6%	5.9%
Duluth	base case	9.42	-11.72	20.4	86.7	6.7%	-6.6%	3.1%	5.2%
	AvgComSales	9.59	-11.55	21.2	88.6	6.8%	-6.3%	3.2%	5.2%
	Triple_Lowe	8.76	-7.75	22.1	84.0	6.5%	-6.6%	3.8%	5.4%
	High_R_Tint	8.79	-9.41	20.6	82.5	6.5%	-7.0%	3.4%	5.2%
	High_R_Clear	9.58	-8.97	23.7	91.3	6.8%	-7.1%	3.9%	5.6%
	189.1	9.58	-9.87	22.8	90.3	6.8%	-7.2%	3.7%	5.5%
	EC_Window	8.91	-15.87	14.5	76.7	6.8%	-11.0%	2.5%	5.0%
	EC_HR_Window	9.14	-12.21	19.0	83.1	7.0%	-10.9%	3.4%	5.5%

Conclusions and Further Research

The assessment results indicated that the two types of EC windows had the greatest energy savings potential compared to ANSI/ASHRAE/IESNA Standard 90.1-2004 baseline windows, followed by the triple pane low-e windows and the highly-insulating double panel low-e windows for the prototypical large size office building in the five US climates. Based on the source energy savings compared to the Std. 90.1-2004 baseline windows, the best window technology is the highly-insulating electrochromic window for three of the five climates studied: Phoenix, Chicago, and Duluth. For San Francisco, the normal electrochromic windows save the greatest energy. For Miami, only the highly-insulating electrochromic windows show marginal energy savings compared to the Std. 90.1-2004 baseline windows.

Daylighting potential of windows is significant. For the prototypical large office building, the daylighting electricity savings range from 8 to 10 kWh per square foot of window area per year, representing 5 to 7% of the whole building electricity use.

Windows with integrated daylighting controls, highly-insulating, and capable of dynamic performance adjustment could be the future for commercial buildings. This assessment did not address any non-energy aspects of windows, such as installation cost and maintenance. It should be cautious to extrapolate the energy savings from this assessment to other scenarios with different building types or configurations, window types, window area, and/or climate zones.

Further studies can focus on a few areas:

- Other climate zones. For example, Zone 3A is a humid-mixed climate where several major cities (Dallas, Memphis, Atlanta) are located, and is an area that optimizing windows for one season can have noticeable detrimental effects for annual energy use.
- Other building types such as medium-size office buildings and large hotels. The medium-size office buildings are more representative than the large office buildings in the US according to CBECS. Large hotels tend to have higher WWR than other building types so energy savings could be more attractive, although the HVAC systems and lighting designs are very different for hotels than offices.
- ZEBs that have less internal loads due to efficient lighting systems and ENERGY STAR appliances, better insulation of building envelope, and high-efficient HVAC systems.
- Other window technologies, for example, the thermochromic windows whose solar properties depend on the thermochromic layer temperature.
- National energy impact estimate. The calculated energy savings by different types of window technologies are based on specific building types in certain climates and could be normalized on the basis of per unit of building floor area or window area. Data of national profile of commercial building stocks or commercial window sales is needed to estimate the national energy impact.
- Optimized window shading controls integrated with dynamic facades, daylighting, and HVAC operations. Latest version of EnergyPlus adds more types of window shading controls that can capture the best scenarios for energy savings.

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