A Study of Glazing Design for Energy Savings in Sustainable Construction

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I. Introduction

Glazing – the combination of materials that fills openings in a building's exterior walls, primarily glass and framing – serves many purposes other than to provide occupants with a view. Glazing permits light and heat transfer from outside, and the design of glazing systems profoundly affects interior conditions. In general, building interiors aim for climate control, maintaining a constant temperature and light level. Artificial lighting, heating, and air conditioning require a considerable amount of energy to operate; in fact, buildings currently account for 72% of electricity consumption in the U.S., and this proportion is increasing. [1] Since glazing systems permit natural light and heat into a building, they present a significant potential energy savings. As sustainable construction – building design that emphasizes environmental consequences and long-term conservation [2] – becomes standard practice in the industry, this potential for energy savings makes proper glazing design all the more valuable.

The most effective glazing systems have a fairly high construction cost, but users recoup these losses in long-term savings. Until recently, building industry professionals, in designing a structure, have tended to consider only capital cost and ignore potential savings in long-term costs. [3] In the past decade, however, the emergence of Leadership in Energy and Environmental Design (LEED) certification, a third-party recognition of a building's performance developed by the United States Green Building Council (USGBC) in 1998, [4] has at last kindled an interest in sustainable construction. Whereas environmental ethics for their own virtue may not interest some businessmen, LEED has given some incentive for all builders to build green by demonstrating that sustainable design effects cost savings throughout a building's lifetime. Showing the potential contributions of glazing toward such a goal was the purpose of this study.

One factor this study did not address was the recycling of any materials as part of the energy-saving qualities. It is worth noting that many glazing materials may be recycled, and the material savings incurred can help satisfy certain LEED requirements. [5] An analysis of recycling costs and energy use, however, bears little relevance to glazing design, as it is generally built into the manufacturing process. If a piece of glass or a frame needs to be replaced, it does not matter from a financial standpoint how the new material is acquired.

II. Sources

The majority of my sources are journal articles and papers from conference proceedings relating to sustainable construction and effective glazing design. Examples include the journal *Energy and Buildings* and the American Society of Mechanical Engineers (ASME) *International Solar Energy Conference*. To learn about LEED certification I used a handbook published by USGBC and class notes from the Cornell University course CEE 406: Civil Infrastructure Systems. To learn about software pertaining to energy savings, I read guides to the software found online. I have also found relevant information in texts on sustainable design, such as Ian C. Ward's *Energy and Environmental Issues for the Practising Architect: A Guide to Help at the Initial Design Stage*.

III. Discussion

A. Components of a Glazing System

1. Glass

Modern construction entails that all exterior windows contain at least two parallel panes of glass, also known as lites, with insulating cavities in between. The resulting structure, called double- or triple-glazing depending on the number of lites, is shown in Figure 1. The cavities contain either air or an inert gas, such as argon or (less commonly) krypton. In commercial construction, lites are commonly 1/4 inch thick and gaps are commonly 1/2 inch thick. Insulating "warm edges" hold the structure together along the perimeter.

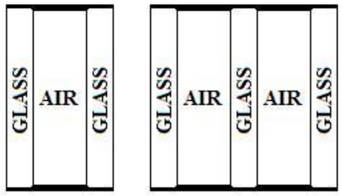


Figure 1: Double-Glazing and Triple-Glazing (cross sections)

Several factors contribute to a window's energy performance. Aydin has demonstrated that the energy efficiency of a window depends largely on the width of the cavity. [6] The infill gas makes a significant difference in thermal regulation: argon, krypton, and other inert gases suppress convection better than air. [7] Weir and Muneer have studied infill thickness in terms of insulative properties and have determined that the optimum thickness depends on the gas used, because heavier inert gases provide better thermal protection. Balancing insulative properties with molecular weight, the optimum gap thickness is 20mm for an air infill, 16mm for an argon infill, 12mm for a krypton infill, and 8mm for a xenon infill. [8] Weir and Muneer also studied the energy consumption needed to produce each of the inert gases to enable a simple calculation of embodied energy, the energy required to manufacture and supply a material. [9] Weir and Muneer's results are given in Table 1. [10] The study found the embodied energy values for argon, krypton, and xenon gas to fill the gap suggested above in a 1.2m square window to be 11.83kJ, 508.2MJ, and 4.5GJ, respectively. [11] Despite their excellent properties of both thermal protection and glare reduction, krypton and xenon infills are impractical options due to their high initial energy costs.

Table 1: Energy Consumption for the Production of Inert Gases [10]

Gas	Yield volume/hour	Energy consumption rate	Specific energy consumption
	(hr-1)	(kW)	(kJ/L)
Argon	900000	168	0.672
Krypton	44.43	475.5	38500
Xenon	3.39	475.5	511400

For further thermal protection, low-emissivity (low-e) coatings on one or more glass surfaces help prevent excessive heat gains by blocking wavelengths outside the spectrum of visible light. [12] Windows with low-e coatings also produce much less frequent glare problems than windows without. [13] All of these glass components contribute to lessening the electricity load on the building and therefore reducing CO_2 emissions.

Menzies et al. have performed an extensive study comparing the long-term cost, in money and energy, of several common glass configurations. For six different window types, the study compiles the U-value (the energy lost per unit area of glass) and embodied energy; the results are

Table 2: U-Values and Embodied Energy for Common Window Specifications [14]

Window Type (glazing, infill, coating)	Specification[a]	Glazing Unit[b] U-value (W/m^2K)	Add'l Embodied Energy/Window [MJ]
Double, air, no coating	4 - 20Air - 4	2.76	standard specification
Double, air, low-e	4e - 20Air - 4	1.58	8.42
Double, argon, low-e	4e - 16Ar - 4	1.31	8.43
Double, krypton, low-e	4e - 12Kr - e4	0.94	525.04
Triple, argon, low-e	4e - 16Ar - 4 - 16Ar - e4	0.65	161.56
Triple, krypton, low-e	4e - 12Kr - 4 - 12Kr - e4	0.52	1167.14

[a] Glass specification details the width of glass pane (in mm), width of gap (mm) and infill gas, and width of second glas pane (mm). 4e represents a 4mm glass pane with one low-emissivity coating.

[b] U-value is for complete glazing unit, including glass panes, inert gas and low-e coating.

displayed in Table 2. [14] Note that as the specification improves – air infill to argon infill to krypton infill, no coating to low-e coating – the U-value decreases and the embodied energy increases. The optimum glass specification is the one whose U-value effects the greatest net energy savings, a quantity that also depends on embodied energy and material lifetime.

It has been suggested that structural design expand the double-glazing concept to encompass an entire building, creating two separate walls of glass with a buffer zone in between. [15] Called a double-skin façade, this design has been proposed in engineering sustainability conferences as the ultimate strategy for energy savings. At this time, however, the cost of a double-skin façade is two to three times that of standard construction, making the design infeasible no matter the gain in energy performance. [16]

2. Frames

Window frames typically cover 10% to 30% of the total area of a window opening, [17] and as such their functioning greatly affects a window's overall sustainability performance. Three common framing materials are aluminum, polyvinyl chloride (PVC), and timber. In a finished window, the glass never actually touches the frame – it sits on small setting blocks and is held in place around the perimeter with caulking or gaskets. These materials, known as glazing accessories, insulate well and do not contribute significantly to a window's total area. Therefore, a window's total thermal performance turns out to be a simple combination of the factors from glass and framing only, and one may regard the energy contributions of glass and framing to be independent of one another.

A study by Asif et al. shows timber frames to have the lowest embodied energy of any frame, at 738 MJ for a 1.2-meter square window. [18] Aluminum-clad timber frames are the next lowest at 899 MJ for a window of the same size, PVC frames follow at 2657 MJ, and aluminum-only frames are the most costly at 5978 MJ. The study also considers the service life of each frame material, and determines that aluminum frames have the longest life with a mean of 43.6 years while PVC frames have the shortest life with a mean of 24.1 years. [19] Finally, Asif et al. look qualitatively at maintenance and repair factors, and determines that aluminum is the lowest-maintenance and timber is the highest. The Asif study concludes that timber is the most environmentally friendly material, though the versatility of a sturdier material such as aluminum may affect the frame choice in buildings with complex glazing system geometries.

Some studies consider window frames to be a weak point in the insulation capacity of glazing systems, in which case they would have a significant effect on thermal performance. In practice, though, frames are erected with weather seals and thermal breaks that provide significant thermal separation between interior and exterior. If frames are assumed to be perfect insulators, then the energy calculations for a glazing system may be adjusted easily to account for the financial cost, embodied energy, and lifetime of its framing as well as its glass.

3. Configurations

Window configurations determine how much light enters a building, and where. The amount of light incident on an area is measured in illuminance. Office buildings often demand a constant illuminance, perhaps 500 lux, and daylight levels typically range from 100 lux to 750 lux. [20] (10 lux equals one footcandle, or roughly the illuminance from a candle at a distance of one foot.) Thus, electric lighting loads may be measured by the average extra illuminance needed to light a building throughout a day. Interior rooms are much harder to illuminate than perimeter ones; it has been shown that, in order for an entire building to receive at least 2% of direct sunlight, the building cannot be more than about eight meters wide. [21] One might suggest developing all buildings in long, narrow shapes, but such an approach is likely to hinder thermal regulation, as the efficiency of a thermal system is proportional to the ratio of a building's volume to its surface area.

To alleviate the problem, light redirection systems can help sunlight penetrate deeper into wide buildings. A common window configuration gives perimeter offices an eye-level window for views and a clerestory window set near ceiling height to illuminate as far into the interior as possible. Interior glass walls help spread the daylight beyond the perimeter offices. When clerestory windows are used, a sunshade – an overhang above a clerestory window that blocks direct sunlight at high sun angles – may protect occupants from midday glare. Often, sunshades are louvered so that they still allow plenty reflected of light in, as opposed to solid overhangs which would create shadows. In the continental United States, Canada, and Europe, the sun always shines on the south side of a building, so sunshades may be unnecessary on other façades.

East- and west-facing façades would not benefit from sunshades because at high sun angles they receive sunlight from the side (not from above), but these façades may incorporate vertical fins along the edges of glazed areas. [22] As horizontal sunshades provide shading from vertical sunlight, so vertical fins provide shading from horizontal sunlight. The reflective abilities of sunshades and fins can make a big difference: in one case study on an office building in central Pennsylvania, an increase in louver reflectance from 60% to 80% resulted in a 75% increase in illuminance. [23]

A light shelf, shown in Figure 2, [24] may be built just inside of a clerestory window, angled to reflect even more light into the core of a building. The above-mentioned case study showed that

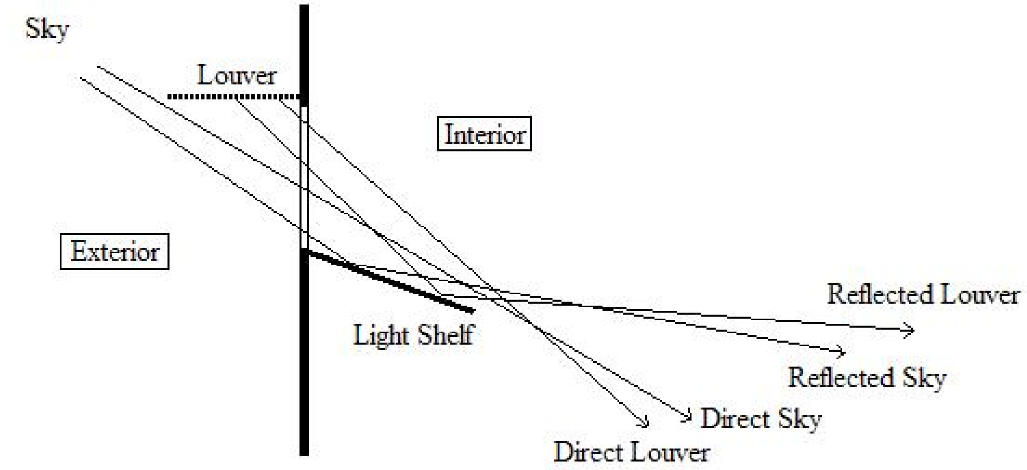


Figure 2: Ray diagram showing effect of a louvered sunshade and a light shelf [24]

a 92%-reflective light shelf with a tilt of 25 degrees from horizontal increased illuminance of the interior by about 30%. [25] As suggested before, interior all-glass walls are gaining popularity as tools to help sunlight penetrate as much of an office as possible.

Several authors have made the disturbing finding that occupants of heavily glazed buildings fail to realize the potential benefits of the glass. One study showed that, on average, blinds and screens are closed for 99% of office hours, and electric lighting is used heavily even when natural daylight would provide more than enough illuminance. [26] Even though occupants tend to favor perimeter offices, they rarely take advantage of the views and natural lighting such offices offer. For this reason, authors like Moeck and Noggle emphasize the value of building both vision and clerestory windows – separate windows to provide views and lighting. [27]

While some occupants close their blinds simply to enjoy the comforts of climate control, others do so to avoid a persistent difficulty associated with heavily glazed façades: glare. The modern office features a computer screen at every workstation, and occupants who experience glare take whatever measures they can to lessen its debilitative effects. Through well-designed configuration geometry and the appropriate use of low-e coatings, sunshades, and fins, proper glazing can prevent occupants from closing blinds unnecessarily.

B. Calculations

1. The payback period

Sustainable construction is concerned with two types of payback periods. The energy payback period is the amount of time a system in use takes to recover its embodied energy through energy savings, and the financial payback period is the amount of time a system in use takes to recover its initial cost through cost savings. The energy payback period varies widely among different types of windows. As a rudimentary test, consider a glazing system to be sustainable if its lifetime – typically 20 to 60 years before replacement [28] – exceeds its payback period. Note that for a glazing system to appeal to owners it is not the energy payback period but the financial payback period that must be shorter than the lifetime of the glass. Double-glazed, argon-filled windows, depending on their configuration, may have an energy payback period of less than one year. In contrast, the energy payback period for triple-glazed, krypton-filled windows may exceed 100 years, meaning these windows (with a lifetime of no more than 60 years) will never make up for the energy spent to produce them. [29] The addition of a low-e coating may have an energy payback period of merely one month, and a financial payback period of five years or less. [30] Clearly, low-e coatings are an excellent investment.

2. Calculating thermal loads

The energy payback period for an entire building's glazing depends on many more factors than the glazing specifications for individual windows. In particular, the building's geometry, latitude, climate, and percentage of façade covered with glass must be taken into account. [31] A computer thermal analysis tool such as eQuest enables construction engineers to calculate the thermal energy needs of a building through the creation of a thermal model. [32] (eQuest, along with overviews and tutorials for using the program, may be downloaded for free off the eQuest website: http://www.doe2.com.)

The energy payback period and the existence of thermal analysis tools like eQuest suggest a method for determining the energy efficiency of a glazing system. First, a U-value is determined for each glass type to be used. The U-value is such a ubiquitous measure of energy efficiency that window vendors typically quote U-values in their literature, but it may be determined through an independent laboratory test or an analytical model. Second, a model of the structure is created in eQuest, accounting for building geometry, dimensions and U-values for each façade, and other relevant factors. [33] eQuest provides a figure for the building's raw thermal energy load. To determine the effects of glazing, the engineer can consider energy loads relative to a base case that differs only in its glazing specifications. This base case, specified in American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 90.1, stipulates maximum U-values for residential and nonresidential structures given a climate zone and a percentage, up to 50%, of wall area covered with glazing. [34] Third, a comparison is made between the systems' total embodied energy and calculated energy load on the building to determine the energy payback period. Financial payback period may be found easily once the energy payback period is known, with the additional data of nominal glazing costs and energy costs.

3. Calculating lighting loads

A procedure similar to the above can be used to calculate the payback periods of a glazing system for lighting loads. Software exists for testing lighting models, as well. (Lumen Micro, available at http://www.lighting-technologies.com, is but one example.) Lighting load reductions depend on maximizing the percentage of a building interior that receives direct sunlight. A clerestory window, louvered sunshade, and light shelf may allow daylight to penetrate deeper alcoves of a building (recall Figure 2).

Each type of glass permits a certain percentage of light to pass through. A glass's T_{vis}, or visible transmittance, is defined as the ratio of transmitted light to incident light; [35] note that this property of lighting transmittance is analogous to the U-value of thermal transmittance. Lumen Micro accepts as inputs a building configuration and orientation, properties of sunshades and light shelves, T_{vis} for each glazing system, and interior electric light attributes. The software then provides as output the lighting load on the building. As with the method described for thermal loads, payback periods may be calculated for lighting loads relative to an ASHRAE base case by comparing lighting load savings with embodied energy.

A persistent design problem is the need to minimize a window's U-value and maximize its T_{vis} at the same time. One shortcoming of a low-e coating is its reduction of a window's T_{vis}. [36] A solution to this design problem may be found in the emerging technologies of switchable glazing. For instance, suspended particle device (SPD) technology uses a film containing randomly dispersed particles that align with increasing amounts of applied electric voltage. The film may thus allow any amount of light transmittance as it ranges from nearly opaque to nearly transparent. [37] SPD film is highly durable and adjustable (by manual dial or photo sensor) over a continuous spectrum of transmission levels. The cost of switchable glazing is currently prohibitive for most large scale applications, at over $100 per square foot, but it is steadily decreasing. [38]

In order to verify the calculations described, it is important to note that thermal loads and lighting loads are independent of one another. [39] The effect of stronger electric lighting on total thermal loads, for instance, is negligible. Thus, a sort of superposition may be used to find the total energy needs of a proposed building and the total payback period for a proposed glazing system.

C. LEED Certification

1. Importance

One of an engineer's foremost objectives in using sustainable construction is to achieve Leadership in Energy and Environmental Design (LEED) certification. This system comprises a variety of "credits" that may be earned for incorporating various green initiatives into the design of the structure, and certification requires a specific number of credits. Coming in several levels of achievement and in a variety of formats for different types of construction, LEED certification carries significant prestige in real estate and can increase the market value of a new building significantly – to say nothing of the environmental benefits. In practice, an engineer designs glazing systems not only to reduce energy loads on the building as much as possible but also to gain as many LEED credits as possible. [40]

2. Relevant credits

The following LEED credits pertain to glazing design:

EA Credit 1: Optimize Energy Performance. Projects may receive one to ten points for showing, through simulation or empirical measurement, a percentage energy cost savings in their design compared to a "baseline" building design. [41] The baseline building is designed according to ASHRAE Standard 90.1 and utilizes the same geometry as a proposed construction with glazing on either 40% of the wall area or the proposed fraction of the wall area (whichever is less), set flush to the wall and distributed evenly around the four orientations. [42] To merit credit, the percentage energy cost savings required varies from 10.5% for one point to 42% for ten points.

LEED divides all energy loads on a building into two types, process energy and regulated energy. These types are analogous to live loads and dead loads in structural engineering: process energy powers items whose energy loads vary over time, like office equipment and kitchen appliances, while regulated energy powers items with roughly constant energy loads, like lighting and the combined thermal systems of heating, ventilation, and air conditioning (HVAC). LEED places a flat process energy load equal to 25% of the total energy load on the baseline building and does not allow changes in process energy to contribute to energy savings. [43] Thus, in order to achieve 42% total savings from the 75% regulated energy, HVAC and lighting costs must in fact be reduced by 56%. It is unlikely that a glazing system alone could have such a drastic effect on energy loads; this credit depends on the combined energy performance of all of a building's systems.

EQ Credit 6.1: Controllability of Systems: Lighting. Projects may receive one point for giving personal lighting controls to at least half of a building's occupants. [44] "Lighting controls" include not only artificial lighting controls, but also window blinds and switchable glazing. As an addition to manual controls, photo sensors may be installed to regulate the transmittance of switch glass and the amount of artificial lighting, thus minimizing energy loads. [45]

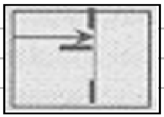
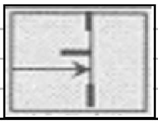
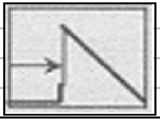
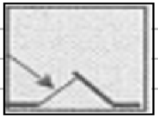
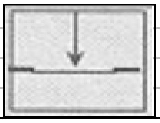
EQ Credit 6.2: Controllability of Systems: Thermal Comfort. Projects may receive one point for giving personal thermal comfort controls to at least half of a building's occupants. [46] One way to satisfy this credit for individuals around a building's perimeter is to install operable windows, units that may be opened and closed. While the specific requirements and effects of operable windows were beyond the scope of this study, it is worth noting that modern office buildings throughout the United States frequently use operable windows, as they provide an economic means of climate control.

EQ Credit 8.1: Daylight & Views: Daylight 75% of Spaces. Projects may receive one point for daylighting at least 75% of occupied spaces, by floor area. [47] Daylighting is defined by LEED as having a daylight illumination level of at least 25 footcandles at 30 inches above the floor at noon on the equinox, a requirement that may be demonstrated using a Lumen Micro model. It is alternately defined as having a glazing factor (G.F.) of at 2%, which is roughly the minimum amount of daylight for a room not to require artificial lighting. [48] G.F. is calculated for each room via the following formula: [49]

$$G.F. = \frac{Window\ area}{Floor\ area} \times Geometry\ Factor \times \frac{Actual\ T_{vis}}{Minimum\ T_{vis}} \times Height\ Factor$$

The geometry factor, miminum T_{vis}, and height factor for several window orientations are given in Table 3. [50] If a room has several types of windows (that is, having different orientations or

Table 3: Factors for LEED EQ Credit 8.1 [50]

Window Type		**Glazing Factor**	**Minimum T_{vis}**	**Height Factor**	**Best Practices for Glare Control**
Sidelighting Daylight glazing		0.1	0.7	1.4	Adjustable blinds Interior light shelves Fixed translucent exterior shading devices
Sidelighting Vision glazing		0.1	0.4	0.8	Adjustable blinds Exterior shading devices
Toplighting Vertical monitor		0.2	0.4	1.0	Fixed interior Adjustable exterior blinds
Toplighting Sawtooth monitor		0.33	0.4	1.0	Fixed interior Exterior louvers
Toplighting Horizontal skylight		0.5	0.4	1.0	Interior fins Exterior fins Louvers

T_{vis} values), G.F. is calculated by applying the formula for each window type and summing the results. The floor area of each room for which G.F. meets or exceeds 2% counts toward the necessary total of 75% of occupied spaces.

EQ Credit 8.2: Daylight & Views: Views for 90% of Spaces. Projects may receive one point for providing direct lines of sight to the outdoors from 90% of occupied spaces, by floor area. [51] This credit aims to improve worker productivity through the most obvious quality of glazing – providing occupants with a view – but its favoring of narrow buildings and very large areas of glass may undermine thermal energy performance. Lines of sight are constructed as shown in Figure 3, [52] and can pass through interior glazing but not through solid walls or solid doors. Note that in general, all perimeter rooms have lines of sight throughout. If the percentage of a room with a direct line of sight exceeds 75%, then the entire floor area of the room may be counted towards the necessary total of 90% of occupied spaces; otherwise, the percentage itself is counted. [53]

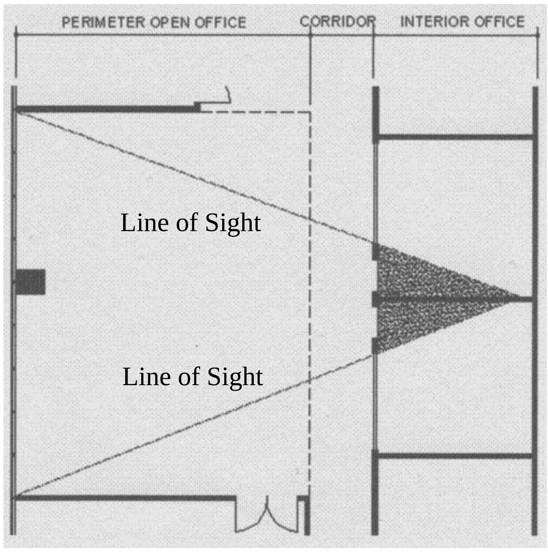


Figure 3: Line of Sight Construction for LEED EQ Credit 8.2 [52]

IV. Review

The glazing systems of a building provide its primary thermal and visual interactions with the outside environment, and as such their design contributes heavily to the thermal and lighting loads on a building. Glass specifications, framing types, geometrical configurations, and components like louvered sunshades and light shelves may all be chosen to optimize the amount of thermal energy and natural light a building receives from the sun. These efforts help keep energy costs for the building to a minimum and contribute to the pursuit of sustainable construction. The LEED system has emerged in the last decade to promote sustainable construction, and builders, by working to achieve relevant LEED credits, may obtain excellent designs for their glazing.

V. Glossary

clerestory window:	a window positioned near ceiling height that allows light into a room but does not provide a view
embodied energy:	the amount of energy required to manufacture and supply a material
footcandle:	a unit of illuminance roughly equal to the illuminance from a candle on a surface one foot away
glazing:	the combination of glass, framing, and other materials that fills openings in a building’s skin
glazing system:	the glazing specifications and configurations for a building
illuminance:	a measure of the intensity of incident light on a surface
light shelf:	an angled surface on the interior side of a window that reflects light further into a building
lite:	a single piece of window glass
louvered:	having successive opened and closed areas to control the amount and direction of a penetrating substance such as light
lux:	a unit of illuminance roughly equal to one tenth of a footcandle
payback period, energy:	the amount of time it takes an object to recoup its embodied energy through energy savings
payback period, financial:	the amount of time it takes an object to recoup its initial cost through running cost savings
sunshade:	a component on the exterior side of a window that blocks direct light from high sun angles, reducing glare
sustainable design:	a method of building that aims to give future generations the same resources available today
transmittance:	the percentage of incident light that passes through a material
U-value:	the percent of thermal energy lost through a material

VI. List of Abbreviations

ASHRAE:	American Society of Heating, Refrigerating, and Air Conditioning Engineers; an organization that publishes standards for thermal design in buildings
ASME:	American Society of Mechanical Engineers; an organization that publishes standards for mechanical design
G.F.:	glazing factor; the amount of natural daylight that illuminates a room, as calculated analytically in LEED standards
HVAC:	heating, ventilation, and air conditioning; an umbrella term for all thermal regulation systems in a building
LEED:	Leadership in Energy and Environmental Design; a rating system to recognize buildings that achieve certain environmental standards
low-e:	low-emissivity; transmitting less thermal energy that normal, as with a coating on construction glass
SPD:	suspended particle device; an emerging switchable glazing technology that involves a film of randomly oriented particles that align with the application of an electrical current
T_{vis}:	visible transmittance; the portion of incident light on a surface that is transmitted
USGBC:	United States Green Building Council; a nonprofit organization that promotes sustainable design in construction, most notably through the development of the LEED system

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