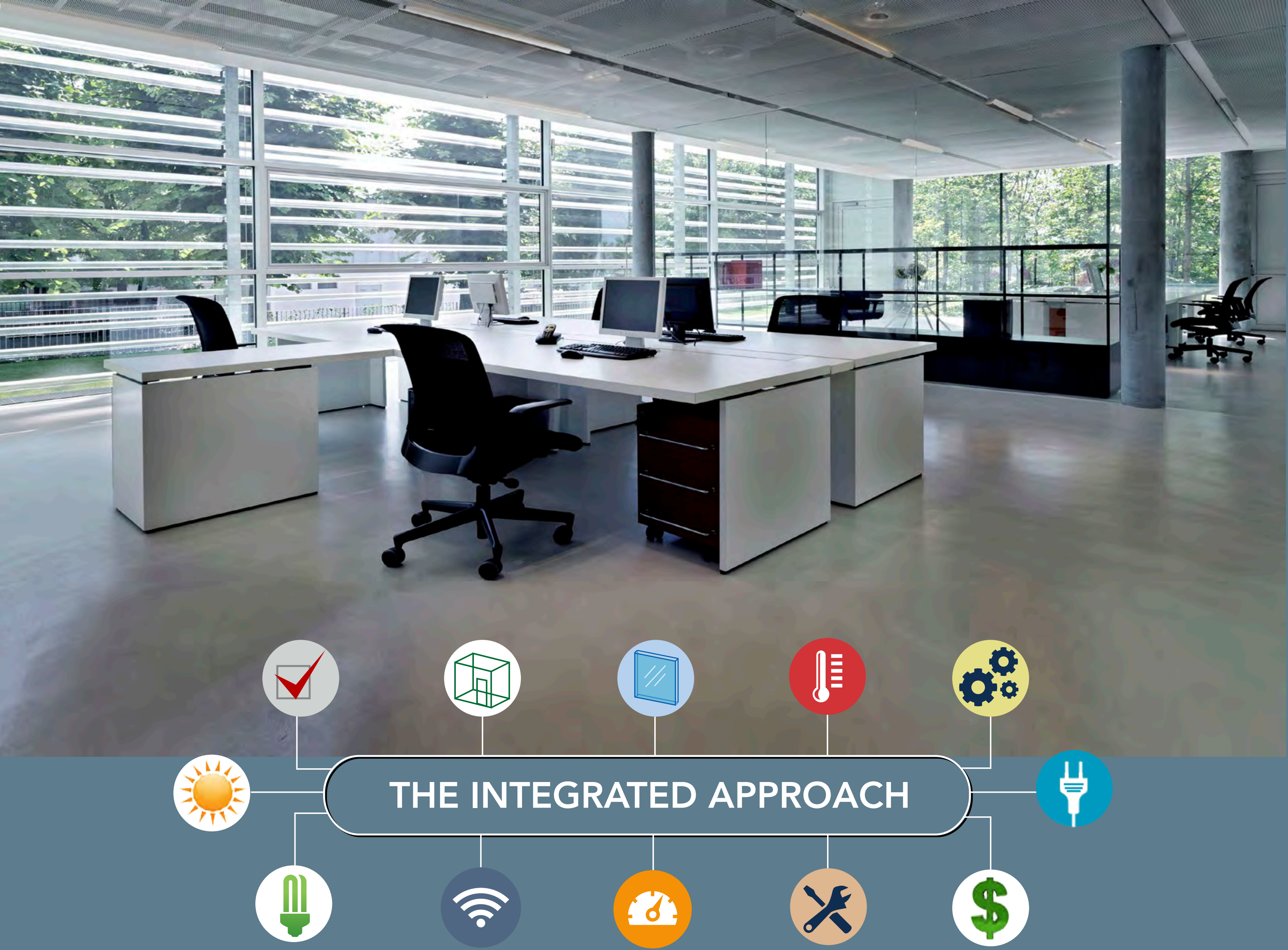

Tips for Daylighting with Windows

BERKELEY LAB
Lawrence Berkeley National Laboratory
U.S. DEPARTMENT OF ENERGY

Disclaimer

Acknowledgements

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The Commercial Building Partnerships (CBP) program is a public-private, cost-shared initiative that demonstrates cost-effective, replicable ways to achieve dramatic energy savings in commercial buildings. Through the program, companies and organizations, selected through a competitive process, team with DOE and national laboratory staff, who provide technical expertise to explore energy-saving ideas and strategies that are applied to specific building project(s) and that can be replicated across the market.

Using this Guide

These guidelines provide an integrated approach to the cost-effective design of perimeter zones in new commercial buildings and existing building retrofits. They function as a quick reference for building designers, through a set of easy steps and rules-of-thumb, emphasizing “how-to” practical details. References are given to more detailed sources of information, should the reader wish to go further.

The design method used in this document emphasizes that building decisions should be made within the context of the whole building as a single functioning system rather than as an assembly of distinct parts. This integrated design approach looks at the ramifications of each individual system decision on the whole building. For example, the decision on glazing selection will have an effect on lighting, mechanical systems, and interior design. Therefore, the entire design team should participate and influence this glazing decision—which typically rests with the architect alone. The benefit of an integrated design approach is a greater chance of success towards long-term comfort and sustained energy savings in the building.

Basic Guidelines

No guidelines can answer all possible questions from all types of users. However, this document addresses the most commonly occurring scenarios. The guidance here is limited by the medium; short paper documents can only go so far in assisting a designer with a unique project. This document has been carefully shaped to best meet the needs of a designer when time does not permit a more extensive form of assistance.

These guidelines are primarily applicable to typical commercial buildings with office-like occupancy (including schools, laboratories, and other working environments), standard construction, and windows as the primary source of natural light (skylights are not addressed).

These guidelines are distinguished from existing materials in their how-to focus and their explicit support of design integration. Background material (basic principles, for example) is not included.

The design professional is ultimately responsible for all design decisions. The user is assumed to have a basic knowledge of lighting and daylighting principles.

Advice is given in a simplified, rule-of-thumb format. More detailed and accurate assistance is best provided by an expert consultant or an advanced computer tool.

Contents

1 Integrated Approach

OBJECTIVE: Work as a team towards the shared goal of a high-performance daylighted building.

- Share decisions and information across the entire design team, from project conception through to occupancy.
- Design carefully with regards to limiting peak energy requirements, as the design will affect both first costs and annual operating costs for systems.

What is the Integrated Approach?

These guidelines are a concise reference for a design approach that emphasizes teamwork. A high-performance, cost-effective, comfortably daylighted building requires the design team to practice integration:

- Adopt a universal design approach, where the building is viewed as a whole and not just a collection of parts. Common practice often fails to address the critical interactions between the building facade (which admits heat and light) and the electric lighting system, resulting in an uncomfortable and inefficient building that is expensive and difficult to retrofit. The potential to eliminate or "design out" unnecessary systems through an integrated approach is an attractive and often achievable scenario.
- Share appropriate decisions across disciplines.
- Regularly evaluate decisions for any building-wide ramifications.

What is a high-performance building?

One that:

- Meets low energy design objectives.
- Maximizes occupant comfort and productivity.
- Minimizes occupant complaints.
- Maximizes building value to the owner.
- Yields a lifetime of energy efficiency and lower operating costs.

Why pursue daylighting?

Daylighting is the use of light from the sun and sky to complement or replace electric light. Appropriate fenestration and lighting controls are used to modulate daylight admittance and to reduce electric lighting, while meeting the occupants' lighting quality and quantity requirements. Daylighting is a beneficial design strategy for several reasons:

- Pleasant, comfortable daylighted spaces may increase occupant and owner satisfaction and may decrease absenteeism. Productive workers are a valuable business asset.

- Comfortable, pleasant, daylighted spaces may lease at better-than-average rates.
- Comfortable, pleasant spaces typically have lower tenant turnover rates.
- Lighting and its associated cooling energy use can constitute over 40% of a commercial building's total energy use. Daylighting is the most cost-effective strategy for targeting these uses (better than using an R-11 insulated wall). Both annual operating and mechanical system first costs can be substantially reduced as a result of installing smaller capacity systems or eliminating them through an integrated approach. Capacity reduction also reduces demand charge costs and feeds back upstream, improving grid security.
- The Uniform Building Code, BOCA, and State Energy Codes regulate the "proper" use of windows in buildings.
- Energy-efficient buildings generally provide higher returns on developer investment and yield higher cash flows.
- Smart decisions up front save retrofit dollars later.
- Energy-efficient daylighted buildings reduce adverse environmental impacts by reducing the use and need for power generating plants and their polluting by-products.
- Daylight contributes to a more sustainable design approach and lets users capitalize on the opportunity for energy savings from daylight dimming and other integrated controls strategies.

How to use this guide

Quick tips, tools, and **procedures** are supplied here to point designers towards appropriate decisions and to help the design team stay focused on integration and coordination. Information is restricted to daylighting issues; broader building concerns are left to the designers.

Twelve sections in these guidelines address the critical activities, from schematic design through occupancy, that influence daylighting performance. Each section contains specific design assistance with respect to that stage of design and flags important integration reminders.

The **Tab Index**, shown below, is included to support navigation through the guide and relate the various sections to the design phase within which they are applicable. This Tab appears on the top right of each section title page and the bottom right of each subsequent page in each section.

Section Title Headings ***Building Design Phase***

Section Title tab showing location in the document

Design Phase(s) tab applicable to the highlighted Section Title tab, indicating which phases are relevant to each Section

Traditionally, target audiences (such as architects, engineers, or owners) would be relevant at specific stages of the design process, but integrated design principles are such that all parties should remain engaged throughout. Where appropriate, specific roles within the integrated design team are identified as being crucial to specific aspects of project design.
Each section is formatted in the following manner:

KEY IDEAS

Lists design tips, rules of thumb, and other clear instructions.

PROVISOS

Notes particular exceptions from the Key Ideas.

INTEGRATION ISSUES

Reviews the design and energy-efficiency measure (EEM) selection process to emphasize integrated design objectives and outcomes. Highlights any areas of design coordination and impacts on other systems covered in this section, across a matrix of six design concerns: Architectural Design; Interior Design; Heating, Ventilating and

Air Conditioning (HVAC) System; Lighting System; Cost Effectiveness; and Occupant Comfort.

LINKS

Dynamic links are included from relevant highlighted text:

Daylighting the New York Times Headquarters Building

QR codes will take you to relevant online content; the image can be recognized by most "smart" phone-cameras using a barcode reader application, which will then take you to the website or upload the linked document. The QR code here links to the LBNL page for the New York Times Daylighting Project:

TOOLS & RESOURCES

Lists ways to analyze decisions or other places to go for help. In some cases, quick calculation tools are provided. Where simulation software is appropriate, this is also mentioned. We have aimed to provide a balance of the practical and the synthetic approaches which both contribute significantly to the design process.

Two principal online resources are referred to repeatedly: the Tips for Daylighting website, and the Commercial Windows website. Both contain design data, economic assessment tools, and reference material which usefully supports and expands upon information presented here.

Tips for Daylighting website
windows.lbl.gov/tips-for-daylighting

Commercial Windows website
www.commercialwindows.org/

CHECKLIST

Gives a sequenced reminder of important steps in the section. Includes activity recommendations broken down by available time.

At the end of each section we provide step-by-step guidance on necessary tasks or actions in the design and construction process, categorizing our tips as "Good Practice," "Better Practice," and "Best Practice." These tasks reflect an increasing level of detail (and likely, cost) and are useful indicators of the recommended overall design approach.

Getting Started

These guidelines should function as a quick reference through all stages of design and building occupancy.

Pre-design (Mainly Retrofit application)

Use the rules-of-thumb in Section 11, COST-BENEFIT ANALYSIS, to quickly determine if daylighting holds good investment potential. See Section 2, DAYLIGHT FEASIBILITY, to quickly check that daylighting makes sense for site and program.

Conceptual Design, Programming

The goals established at this early planning stage will set the foundation for an integrated, energy-efficient building design.

- Establish performance goals together with the owner and make achieving these high-performance goals a priority.
- Include comfort (thermal and visual) goals.
- Identify any system-level goals (e.g., carbon neutral, emphasize natural ventilation, 100% daylit, no perimeter heating system).
- Aim for an effective daylighting design.
- Establish schedule and budget parameters: more time available allows for more analysis; allow for energy and lighting/glare analysis early in design stages; more budget allows for appropriate consultants.
- A focus on building massing and orientation emphasizes good solar access and minimized heat gain.
- Using narrow floor plates promotes effective use of daylight over a large fraction of net floor space.
- Conceptualize and program interior spaces by daylight and view needs. Organize spaces that see infrequent use in core zones.

The first design decisions are critical to energy efficiency and daylighting. Get started on the right foot by reviewing **Key Ideas** in ENVELOPE AND ROOM DECISIONS (Section 3), GLAZING SELECTION (Section 5), and SHADING STRATEGY (Section 5). It would be useful to refer to MECHANICAL COORDINATION (Section 6), LIGHTING COORDINATION (Section 7), and SENSOR AND CONTROLS (Section 8) to understand the implications of these systems in relation to the daylighting design.

Identify any major system comparisons to be made that would have the most impact on building design (e.g., natural ventilation versus mixed mode versus sealed air-conditioned building), and which might have different shading and solar control measures used. Perform integrated design and analysis of these options. Use the approaches highlighted in Section 11, COST-BENEFIT ANALYSIS, to quickly determine if daylighting holds good investment potential. The Tips for Daylighting website is kept up to date with content relevant to daylighting design and economic assessment of daylight harvesting systems. Refer to Section 2, DAYLIGHT FEASIBILITY, to quickly check that daylighting makes sense for a specific site and program.

Schematic Design / Design Development

Priorities at this stage should include:

- Review of project design goals to reestablish objectives.
- Refinement of envelope, room, and shading design.

Sections on ENVELOPE AND ROOM DECISIONS (Section 3), GLAZING SELECTION (Section 4), SHADING STRATEGY (Section 5), MECHANICAL COORDINATION (Section 6), and LIGHTING COORDINATION (Section 7) should now be viewed in detail, as should SENSORS AND CONTROLS (Section 8). This is a critical time for coordination among design team members, as it is the last opportunity to make design changes without compromising the design and/or incurring significant additional project costs.

Construction Documents

At this stage, the design is nearing completion, so any final modifications are likely to be minor. The following steps should be included as part of the completion process:

- Review project design goals to reestablish objectives.
- Ensure glazing, shading, lighting, and control systems are properly specified.
- Include calibration, commissioning, and maintenance plans as part of the construction documents (review those sections now).

Pre-Occupancy

Review Section 9, CALIBRATION AND COMMISSIONING, in detail, and take appropriate action.

Post-Occupancy

Review Section 10, MAINTENANCE, and keep it, along with the maintenance plan, on electronic and hardcopy file in the building.

References

The *ANSI Whole Systems Integrated Process Guide* provides greater depth on this subject and can be downloaded at www.delvingdeeper.org/pdfs/wsip.pdf.

Integrated Approach
Feasibility
Envelope/Room
Glazing
Shading
Mechanical Coordination
Lighting
Sensors & Controls
Calibration/Commissioning
Maintenance
Cost-Benefit Analysis

Preparation
Pre-Design
Conceptual Design & Programming
Schematic Design/Design Development
Construction Documents
Pre-Occupancy
Post-Occupancy

The Windows for High-Performance Commercial Buildings website (www.commercialwindows.org) contains information that can help users better understand what the project design objectives and limitations are likely to be and which tools are appropriate for the pre-design early-concept stage of a project, where theories and ideas can be tested. Use the Facade Design Tool to familiarize the project team with the interactions of the different daylighting systems.

Factor Ten Engineering Design Principles by the Rocky Mountain Institute (RMI, 2010) is an instructive insight into real integrated design practice, emphasizing the need to look at the whole system together to realize the benefits. It can be downloaded at www.rmi.org/Knowledge-Center/Library/2010-10_10xEPrinciples.

Integrative Design: A Disruptive Source of Expanding Returns to Investments in Energy Efficiency (RMI, 2010) provides greater detail on the same topic. It can be downloaded at www.rmi.org/Knowledge-Center/Library/2010-09_IntegrativeDesign.

Whole Building Design, by the National Institute of Building Sciences (NIBS, 2011) is an excellent resource for general information. Visit www.wbdg.org.

2 Daylight Feasibility

OBJECTIVE: Determine how much daylight you can use in various areas of your building.

- Because windows are not used simply to illuminate an interior space (e.g., they provide a view, outdoor connection, ventilation, egress), the issue is not whether or not to use a window, but whether one can capitalize on it to increase occupant comfort, satisfaction, and perhaps performance.
- Determine how much daylight can be used to offset electric lighting needs.

KEY IDEAS

- **Windows must see the light of day.** A high-density urban site may make daylighting difficult if the windows will not see much sky.
- **Glazing must transmit light.** A strong desire for very dark or reflective glazing generally diminishes the capacity to daylight in all but very sunny climates.
- **Install daylight-activated lighting controls.** To save energy, lights are dimmed or turned off with controls. Automated lighting controls in a daylighted building can have other cost-saving applications (e.g., occupancy, scheduling) and benefits.
- **Design daylight for the task.** If the occupants require very bright light, darkness, or a highly controllable lighting environment, tailor the design solutions to meet their needs.
- **Assess daylight feasibility for each different portion of the building.** Spaces with similar orientation, floor height, sky views, ground reflectance, and interior design can be treated together. Within a single building, the feasibility and cost-effectiveness of daylighting may vary greatly by orientation and space type.

PROVISOS

- A low-rise building can be adequately daylighted with skylights or roof clerestories (neither are addressed in any detail in these guidelines).

TOOLS & RESOURCES

Rapid Feasibility Study Calculation to Estimate Potential Lighting Energy Savings

(Feasibility = "how much glass" x "how transparent" x "obstructions blocking light")

Complete this analysis for each major type of space in the building.

Step 1: Calculate the planned window-to-wall ratio (WWR) for a typical office space or bay.

Net glazing area (window area minus mullions and framing, or ~80% of rough opening) divided by gross exterior wall area (e.g., multiply width of the bay by floor-to-ceiling height) equals window-to-wall ratio (WWR).

____________ / __________________ = _________

net glazing area   gross interior wall area   WWR

Or:

If unknown, estimate for your building style; for example, using 0.35 for a typical, moderately strip-glazed building. For larger windows or curtain wall, use 0.50. For smaller punched windows, use 0.25.

Step 2: Make a preliminary glazing selection and note the visible transmittance (V_T).

If you don't know the glass properties, go to the Tips for Daylighting webpage to access typical product values.

Tips for Daylighting website
windows.lbl.gov/tips-for-daylighting

Step 3: Estimate the obstruction factor (OF).

Visualize a typical task location, 10 feet (3.3 meters, m) in from a window and centered on the window. What is the view through the predicted window from desk height? Pick a location that represents an average view for the building. Sketch the window elevation and shade in anticipated objects seen from this viewpoint; this can include objects such as trees that might be near to the window or buildings that might be a little further away but still impede the view of the sky. Select the obstruction factor, as shown in Figure 1.

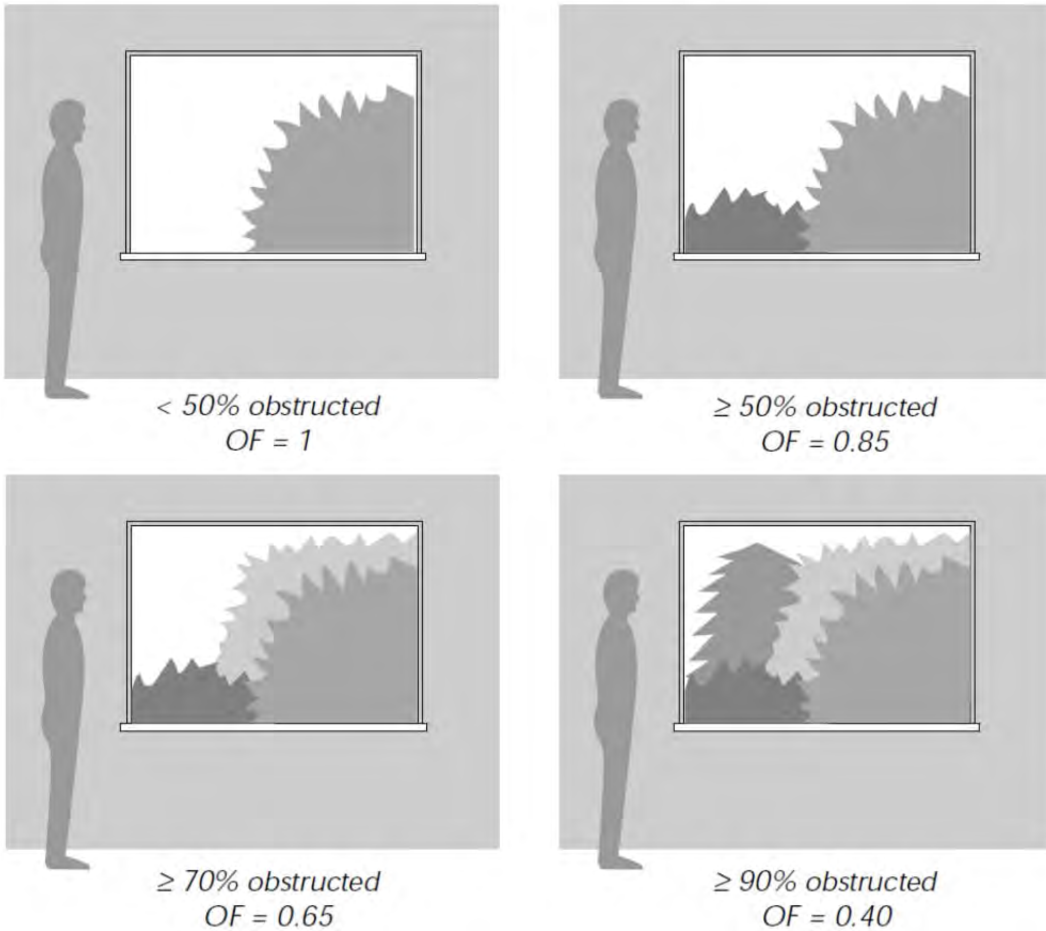

Figure 1: Estimating the obstruction factor

Step 4: Calculate the daylight feasibility factor.

Window-to-wall ratio multiplied by visible transmittance multiplied by obstruction factor equals feasibility factor.

______ x ______ x ______ = ________________

WWR V_T OF Feasibility Factor

If the Feasibility Factor is ≥ 0.25, then daylighting has the potential for significant energy savings for this building zone.

If the Feasibility Factor is < 0.25, then consider removing obstructions, increasing window area, or increasing V_T. If these modifications are not possible, it is unlikely that daylighting will be a cost-effective energy-saving strategy. However, windows can still be designed to provide views and to control glare. Use these guidelines for glare-reducing ideas.

3 Envelope and Room Decisions

OBJECTIVE: Design siting, massing, façade, windows, and interior to maximize daylight effectiveness, provide occupant comfort, and minimize glare.

- These decisions determine the potential for useful daylight and energy savings.
- Architectural decisions of this nature can influence the building's lifetime energy use more than mechanical and lighting decisions.

KEY IDEAS

Building Form and Skin

- **Increase exposure to daylight.** The higher the skin-to-volume ratio, the greater percentage of floor space is available for daylighting. Long and narrow footprints are preferable to square ones, up to a limit, although a high skin-to-volume ratio may lead to a heating or cooling penalty.
- **Shape building for self-shading.** Building form can assist cooling by providing self-shading through wings and other mass articulations, balconies, deep reveals, or arcades.

Take a deep facade approach. A facade with some depth creates a buffer zone that can contain shading elements and other modifiers to filter glare and block sun, as

Figure 2 illustrates.

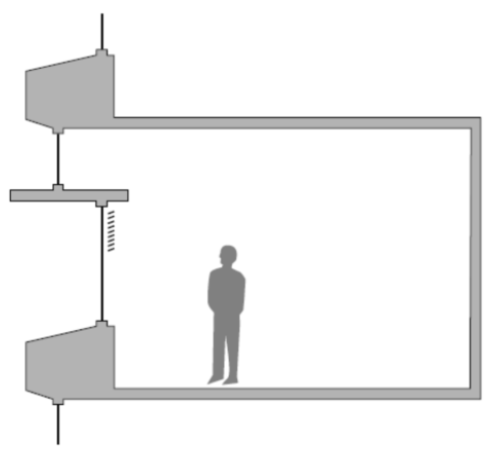

Figure 2: Section drawing illustrating a deep wall section providing some self-shading. This allows easy integration of a light shelf, creates surfaces that mitigate glare, and reduces noise

transmission. Sloped surfaces also help soften glare. A blind or shade can be added in the clerestory to manage glare from a low sun angle.

- **Capitalize on other building elements to integrate shading.** For example, air intakes, overhangs, louvers, fins, PV panels, and light shelves can be integrated both structurally and visually with the exterior structural system.
- **Incorporate envelope features that improve daylighting.** Deep reveals, splayed reveals (as shown in Figure 3), exterior fins, and similar characteristics of the envelope structure improve daylight distribution and control glare. These facade projections can also attenuate noise. Rounded edges soften light contrasts. Effective reveals are 9 to 12 inches (23 to 30 centimeters, cm) deep, at an angle of 60˚ to the window plane.

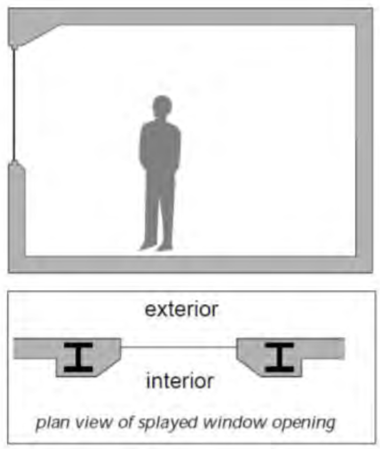

Figure 3: A splayed window opening, such as this one, helps to soften glare. These surfaces should be light-colored and provide an intermediate brightness between window and room surfaces, making an easier transition for the eye.

- **Balance daylight admittance.** Spaces with windows on two sides often have better daylighting distribution.
- **Keep private offices somewhat shallow.** Keep the depth of perimeter rooms within 1.5 to 2.0 times the window head height for adequate illumination levels and balanced distribution at the back of the room. If an office will have a mix of open plan office and private offices, consider locating the open office spaces along the facade and locating private offices away from the facade. This approach is consistent with the LEED goals of providing a large fraction of occupied spaces with daylighting and views.
- **Consider color and texture of exterior surfaces.** Light-colored surfaces will reflect more daylight than dark surfaces. Specular surfaces (e.g., glazed tile or mirrored glazing) may create glare if viewed directly. Diffuse ground-reflected daylight can increase daylight availability.

Integrated Approach
Feasibility
Envelope/ Room
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Shading
Mechanical Coordination
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Sensors & Controls
Calibration/ Commissioning
Maintenance
Cost-Benefit Analysis
Preparation
Pre-Design
Conceptual Design & Programming
Schematic Design/ Design Development
Construction Documents
Pre-Occupancy
Post-Occupancy

Windows

The challenge in providing daylight by effective use of windows is to allow adequate amounts of daylight as deep into the space as possible, with a distribution within the space that is visually comfortable and does not create glare. A designer can control window area, location type, glazing properties, shading systems, ceiling parameters, and interior design features to achieve these goals. The sections below provide some guidance on the importance of each of these design parameters.

- **The higher the window, the deeper the daylighting zone.** The practical depth of a daylighted zone is typically 1.5 to 2 times the window head height, as shown in Figure 4. With a reflective light shelf, this zone may be extended further. If a corridor is beyond this zone and separated with a partially glazed wall, it may be adequately lit with the spill light from the room. With standard window and ceiling heights (between 9 and 10 ft; 2.7 to 3 m), plan on adequate daylight within 20 feet (6.1 m) from the window.

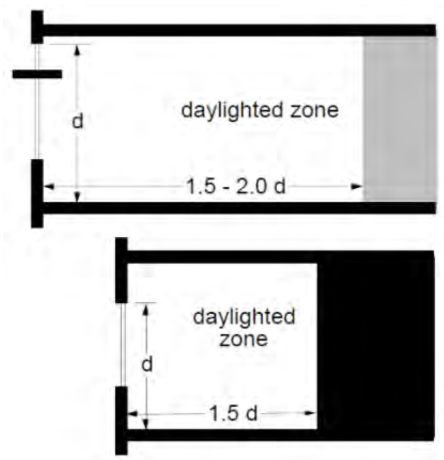

Figure 4: Typical daylight penetration rule-of-thumb

- **Strip windows provide more uniform daylight**. The easiest way to provide adequate, even daylighting is with a nearly continuous strip window (Figure 5). Punched windows are acceptable, but the breaks between windows can create contrasts of light and dark areas. This is not a problem if work areas are paired with windows or if other glare measures, such as splayed window openings, are taken.

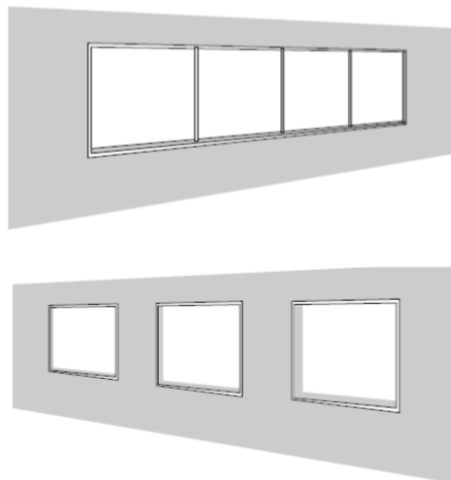

Figure 5: Strip windows are an easy way to provide uniform daylighting. Punched windows should be paired with work areas when possible.

- **Large windows require more control.** The larger the window, the more important glazing selection and shading effectiveness are to control glare and solar heat gain. Insulating Glazing Units (IGUs) with low-E coatings control winter heat loss and improve thermal comfort. See Tools & Resources, below, for additional sizing help.
- **Size the windows and select glazing at the same time**. The larger the glass area, the lower the required visible transmittance. Use the effective aperture (EA) approach to make these trade-offs (see Figure 6). Select glazing and window area to target an EA around 0.30. See Tools & Resources, below, for additional sizing help.

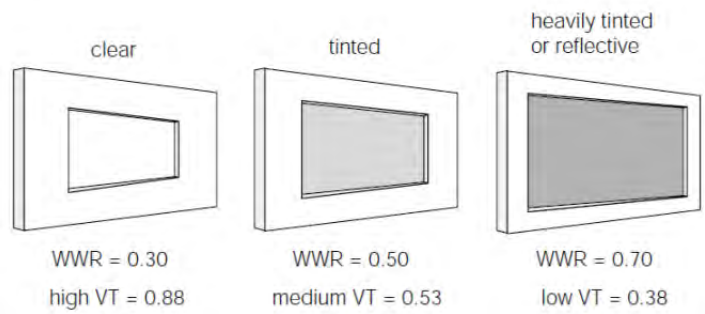

Figure 6: Effective Aperture (EA) is visible transmittance (VT) x window-to-wall ratio (WWR). These three examples all have the same EA of 0.26.

- **Keep occupants away from large areas of single-pane glass.** Avoid big windows very close to task areas since they can be a source of thermal discomfort.
- **Design separate apertures for view and daylight.** A good approach for excellent daylighting and glare control is the separation of view and light windows, as shown in Figure 7. Use high-transmission, clearer glazing in clerestory windows, and lower-transmission glazing in view windows to control glare.

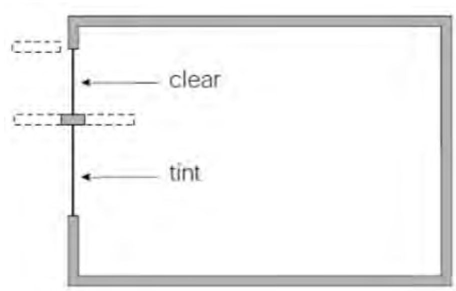

Figure 7: A section view illustrating different apertures for daylight and view: clear glazing above for maximum daylight, and some form of lower transmission glazing below for glare control. The structure between the two provides a visual break and an opportunity to attach a light shelf or shading device. Both apertures will likely require some form of solar control unless they are north facing.

- **Position windows to direct light onto the ceiling.** Taller ceilings and high windows provide the opportunity for better light distribution. Keep the ceiling smooth and light-colored. A sloped ceiling (high near the window, as shown in Figure 8) is one way to fit a high window within normal floor-to-floor heights.

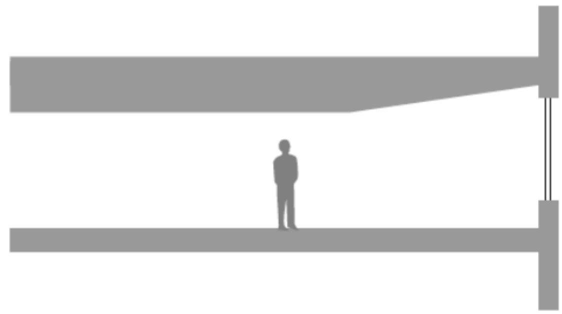

Figure 8: A sloping ceiling at the perimeter raises the window head without increasing floor-to-floor height.

- **Introduce more light-colored interior surfaces for good daylight distribution.** Deep reveals, and ceiling baffles, if they are light in color, keep daylighting more even. Interior walls and furniture systems also enhance interior light levels if they are light-colored.
- **Incorporate shading elements with windows.** Shading devices perform triple duty: they keep out the sun's heat, block uncomfortable glare from direct sun, and soften harsh daylight contrasts. See Section 5, SHADING STRATEGY, for more detail. Figure 9 shows how a well-designed exterior shading system can block sun but boost interior light levels compared to a simple overhang.

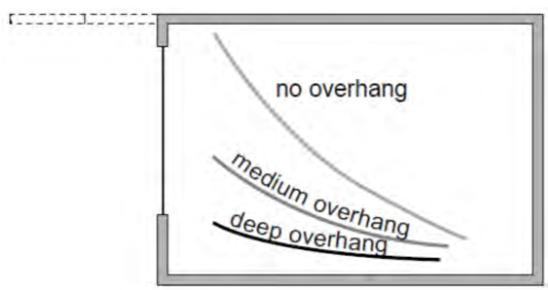

Figure 9: A room section with curves indicating the effects of shading systems on light levels according to room depth. Overhangs can block direct sun and reduce light and glare near the window, creating a softer gradient in the room; they can also reduce daylight availability.

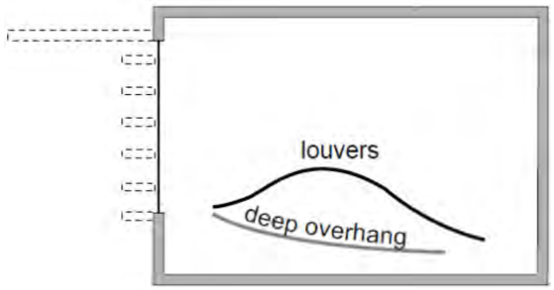

Figure 10: Illustration of the use of horizontal shapes to create a better distribution of daylight.

- **Use horizontal window shapes.** Horizontal shapes provide more even light distribution; vertical windows are more likely to create light/dark contrasts, although taller windows provide deeper penetration. Long and wide windows are generally perceived as less glaring than tall and narrow ones of the same area. Occupants generally prefer wider openings when the primary views of interest are of nearby objects or activities.
- **Place view windows wisely.** Complex views with changing activities are preferable to static views. The key is the information content of the view and its ability to capture interest/attention. Sky alone is not a preferred view. Views that include the horizon are better.
- **Locate windows near room surfaces** (beams, walls) that bounce the light inward for good distribution—these surfaces help reflect and redistribute daylight.
- **Windows on every orientation can provide useful daylight.** However, treat each window orientation differently for best results (see Figure 11).
    - North: High-quality consistent daylight with minimal heat gains, but thermal loss during heating conditions and associated comfort problems. Shading possibly needed only for early morning and late afternoon.
    - South: Good access to strong illumination (the original source), although varies through the day. Shading is “easy.”
    - East and West: Shading is difficult. Shading is critical for comfort on both sides and heat gain too, especially on the west.
- **Don’t waste glazing area where it can’t be seen,** such as below desk height. It wastes energy, causes discomfort (especially in winter), and provides little benefit.

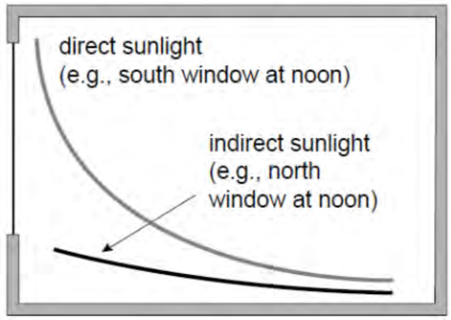

Figure 11: Illustration of light levels as a function of window orientation. Curves show light levels when window is facing the part of the sky that has the sun versus facing away from the sun (daylight only, no direct solar beam in the room).

About Clerestories (any window with its sill above eye level)

- Good for getting the light source out of a direct sightline. Good for effective ceiling illumination (which provides deeper penetration and good distribution). Good for computer visual display terminals (VDTs) and other glare-sensitive tasks.
- Loss of view; the only view may be of the glaring sky.
- An effective approach is the use of high-reflectance blinds with clerestory glazing. A 1-foot (0.3-m) high south clerestory with specular blinds can light a 150-square foot (14 square meter, m^2), 12-foot (3.7-m) deep office under sunny conditions.
- Higher windows provide better light distribution, as shown in Figure 12.

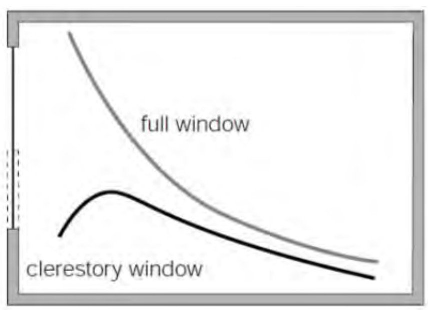

Figure 12: The curves indicate light levels for a full window and a clerestory, with the clerestory giving a softer gradient.

About Light Shelves (horizontal elements above eye level)

- Light shelves can improve illuminance distribution and reduce glare, as shown in Figures 13 and 14.

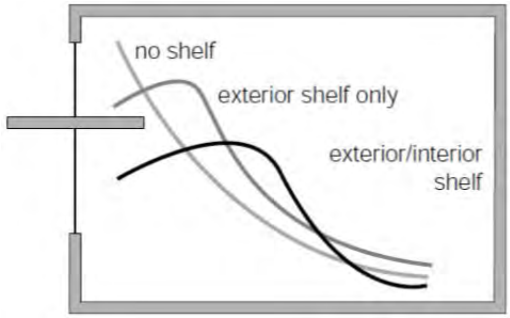

Figure 13: Illustration of how a light shelf improves daylight distribution and softens the light gradient within the room.

- Shelves double as shading devices, if designed to block direct sun.
- Best used on the building's south side, in a predominantly clear sky climate.
- Consider using clearer glass above for high daylight admission and tinted glass below for glare control.
- Exterior shelves are better than interior, but use both for best year-round distribution.
- The top of the shelf should be matte white or diffusely specular, and not visible from any point in the room.
- The ceiling should be smooth and light-colored.
- Consider using more advanced shapes and materials to redirect sun, block direct sun, and control glare.

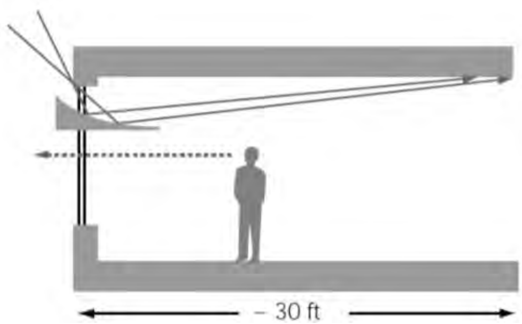

Figure 14: Direction of light at high level using a light shelf

Space Planning

- **Locate activities according to light requirements.** Put rooms with little need for daylight (e.g., infrequent use, service, washrooms, VDTs) in non-perimeter areas. Locate tasks with higher lighting needs nearer the windows. Group tasks by similar lighting requirements for efficient use of electric lighting, and by similar schedules and comfort needs. Accommodate user preference and satisfaction when space planning as far as possible.
- **Locate activities according to comfort requirements.** Place flexible tasks or low-occupancy spaces where there may be unavoidable glare, not enough daylight, or direct sun penetration. These spaces may at times be

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thermally or visually uncomfortable. If tasks are fixed and inflexible, comfortable glare-free conditions are required.

- **Maintain daylight access.** Furniture layout should not block light for spaces farther from the window. Do not position full-height partitions, bookshelves, or files parallel to window wall if possible. Consider using low-level (< 4 ft; 1.2 m) furniture partitions to allow greater light penetration into the space.
- **Use light-transmitting materials for partitions where possible.** Use clear or translucent materials in the upper portion of high partitions. If this approach is taken in corridor walls, corridors may be adequately lighted just by this spill light.
- **Shield occupants from views of highly reflective surfaces outside,** such as mirrored-glass buildings, water, snow, and large white surfaces.
- **Shield sensitive occupants from bright windows.** In highly glare-sensitive areas (e.g., with wide use of computer screens), shield occupants from view of sky and provide glare-controlling window coverings.
- **Keep reflected view of bright windows out of computer screens.** Be very careful where screens are placed. Either keep them away from windows or block the screen and occupant's view of the window. Use partitions or position the screen with the window to the side and slightly turned away from window. Figure 15 illustrates how furniture placement affects optimal lighting for workers.

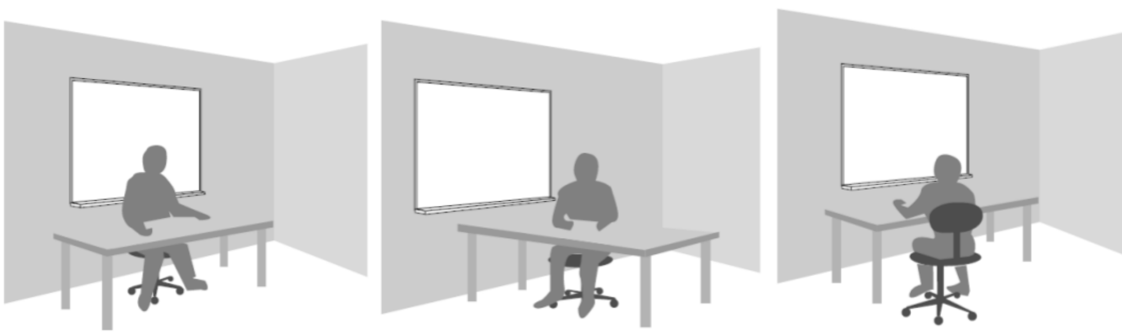

Figure 15: Illustrations of effects of, to the left, having a window behind a worker; you may shade your task, making it too dark to see easily. Also, your computer screen may be too difficult to see if light reflects from the window. In the center is the preferred seating arrangement. The task is well illuminated and the source is not in direct line of sight, as is the case on the right; this is very tiring for the eyes to have both in the same field of view.

- **Use west zones for service spaces.** Minimize use of exposed west zones as occupied work areas. Large areas of west glazing make for difficult daylighting, high cooling loads, and uncomfortable occupants.
- **Integrate personal shading / glare control systems into personal workspaces.**

Interior Design

- Don't use large areas of dark color. Generally avoid all dark colors except as accents, and keep them away from windows. Dark surfaces impede daylight penetration and cause glare when seen beside bright surfaces (such as windows or light-colored walls). For good distribution throughout the room, it is

especially important that the wall facing the window be light-colored. Mullions or other solid objects next to windows should be light-colored to avoid silhouette contrasts. Keep sills and other reveal surfaces light to improve daylight distribution and soften contrast. Dark artwork can reduce daylight effectiveness.

- Aim for recommended surface reflectances. Desirable reflectances (Illuminating Engineering Society recommendations) are: ceilings >80%; walls 50%–70% (higher if wall contains window); floors 20%–40%; and furniture 25%–45%.
- Choose matte over specular surface finishes. Matte finishes are recommended for good distribution of daylight and no reflected glare (hot spots).
- Use light-transmitting materials. Translucent or transparent partitions are best when possible—daylight can pass through to other spaces.
- Supply window coverings that allow individual control to accommodate different glare tolerances. Shading controls should be easily accessible to encourage their regular use. Interior window shading should be light-colored for the best cooling load reduction.
- Choose colors under the right light. Choose interior colors and finishes under daylight and under the proposed electric lamps to avoid surprises in color rendering.

INTEGRATION ISSUES

Architecture

Facade design must be driven by interior results as much as exterior appearance. Form, siting, and skin decisions strongly influence daylighting performance, cooling loads, and occupant comfort.

Interior

In daylighted spaces, it is critical that light colors be dominant, especially for walls and ceilings.

Window coverings should allow for some light penetration while providing sun and glare control and prevent unwanted solar gain. A priority should be to achieve an appropriate balance of solar gain and capacity of mechanical cooling systems, to ensure integrated systems efficiency.

Interior design must consider the role of interior finishes and objects as light modifiers within a daylighted space—these factors influence daylighting performance.

HVAC

High skin-to-volume ratio is good for daylighting but may adversely affect thermal balance.

Use building form and exterior shading to best reduce peak cooling load—this can save on HVAC first costs. Work with an engineer to establish the magnitude and relative importance of envelope decisions.

Lighting

Window design and exterior and interior modifiers determine the nature of daylight in the space. Lighting design and control strategy are critical.

Interior colors, furniture placement, and partition heights are critical to lighting design—make these decisions with lighting designer input.

Cost Effectiveness

High skin-to-volume ratio is good for daylighting, but may not yield a high enough ratio of rentable space and may be more costly to construct.

A deep or layered building skin is more expensive than thin cladding but offers long-term benefits if used to best advantage for sun and glare control. Analysis of building performance with energy simulation software and careful cost estimates are required for determining cost effectiveness.

Occupant Comfort

The best lighting and mechanical systems can't make up for architectural errors with respect to perimeter zone comfort. The priorities here should be to specify appropriate perimeter insulation and carefully consider where to locate and orient occupants. Window and room design must provide for thermal and visual comfort of the occupants.

Occupant satisfaction will depend on the fit between the environment and task needs. Know the intended use of the space before designing it.

Occupant Control

Occupants should be given the ability to make personalized adjustments to their workspaces to balance daily and seasonal changes in daylight availability, glare, as well as desire for views and privacy. Care should be taken to understand the range of conditions acceptable and preferred by occupants before selecting operable systems.

PROVISOS

- Dark-tinted glazings diminish the capacity to daylight.
- Sometimes daylighting with windows is simply not compatible with glare-sensitive tasks like computer work.
- Don't forget about lighting controls. Lowering the lighting power density may provide energy savings, but savings will be increased further through use of lighting controls.

TOOLS & RESOURCES

Leadership in Energy and Environmental Design (LEED)

The LEED Rating Systems are balloted every four years to establish the consensus standard for the new version. The comments below are specifically related to the LEED 2009 version of the rating systems, which are currently being utilized by industry.

There are different approaches to assess the performance of a daylight design and/or to evaluate various parameters. Daylight simulation has become more prevalent in recent years, and it is starting to become a requirement or compliance for some building codes, as well as being part of the LEED Rating Systems. In addition to simulation, other calculations can be easily done, such as "Determining Required Net Glazing Area," which can effectively inform a daylight design.

The credits for daylighting in the different versions of the LEED Rating Systems and that relate to decisions on envelope and room design include the following:

- Indoor Environmental Quality Credit 8.1 – Daylight and Views – Daylight: Demonstrate with simulation* that 75% of all regularly occupied spaces receive a minimum of 25 footcandles (fc) and a maximum of 500 fc on September 21 at 9 a.m. and 3 p.m.
- Indoor Environmental Quality Credit 8.1 – Daylight and Views – Views: A daylight design approach increases the potential to meet the credit

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requirements for a visual connection to the outdoors. Simulation is not required.

*This credit also has a prescriptive path to meeting the requirements where for windows above 30" above the floor, meet the following range criteria 0.150 < VLT x WFR < 0.180, where VLT = Visible Light Transmittance and WFR = Window-to-Floor Ratio.

The proposed 2013 simulation requirements for the Daylight and Views credit specific to daylight will be focused on analyzing Spatial Daylight Autonomy (the percentage of the occupied time for a year when a space can be illuminated by daylight alone). The requirement will be to demonstrate that 55%, 75%, or 90% of the regularly occupied spaces achieve spatial daylight autonomy.

Determining Required Net Glazing Area

- **Use this information as a starting point for estimating required window size.** Alternatively, use the equation to roughly find the average daylight factor (indoor horizontal illuminance divided by outdoor horizontal illuminance) for a given window size. The equation assumes that room depth is no more than 2.5 times window head height. It also assumes an overcast sky. For regions with predominantly clear skies, window area can be smaller than is calculated here.
- **The equation below yields the required net glazing area.** To translate this to total window area, which includes framing and mullions, multiply by 1.25.

$$\text{Required Net Glazing Area} = \frac{2 \times \text{Average Daylight Factor} \times \text{Total Area of Interior Surfaces} \times \left(1 - \text{Area-Weighted Average Reflectance of all Interior Surfaces}\right)}{\text{Visible Transmittance} \times \text{Vertical Angle of Sky Visible from Center of Window}}$$

- **Average Daylight Factor.** Use:

    1 if low-light spaces are desired.

    2 if average spaces are desired.

    5 if bright spaces are desired.

Note: The Daylight Factor concept has limitations as a metric for developing and assessing daylighting solutions, but it also has value, so we use it here and refer to it elsewhere in this guide.

- **Total Area of Interior Surfaces.** Add up total surface area of walls, ceiling, and floor.

- **Area-Weighted Average Reflectance.** Ratio between 0 and 1. Add up total surface area of walls, ceiling, floor, windows, partitions, and furniture, and

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calculate the weighted average reflectance (see equation), or use 0.5 as a default.

$$\text{Area-Weighted Average Reflectance} = \frac{\text{Wall Area X Wall Reflectance}}{\text{Total Surface Area}} + \frac{\text{Ceiling Area X Ceiling Reflectance}}{\text{Total Surface Area}} + \ldots\text{etc.}$$

- **Visible Transmittance.** Use:

  0.70 for small windows.

  0.50 for medium windows.

  0.30 for large windows.

- **Vertical Angle of Sky.** Estimate the angle, as shown in Figure 16, from the center of the window. Value between 0 and 90. If no obstruction, the vertical angle is 90˚.

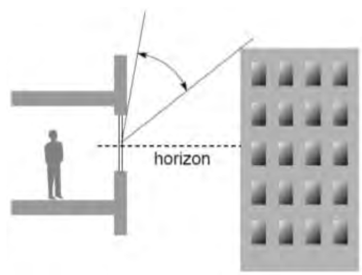

Figure 16: Vertical angle of sky. Source: "A Sequence for Daylighting Design," J. Lynes, Lighting Research and Technology, 1979.

Five methods to quantify daylighting levels and energy impacts

1. **Computer Daylighting Models.** Daylighting simulation software can deliver increasingly fast and accurate results in the hands of a skilled user. Most lighting simulation software can also perform daylight calculations. Limitations on the range of conditions that can be assessed and their accuracy vary by software. Typical limitations arise from either the inability to generate a suitably complex model or the inability to accurately define reflectance and transmission properties of a material. Choosing the right software depends on fully understanding your daylight simulation needs.

   Relying on calculations or past experience alone may not yield satisfactory results in the final product because of the complex, dynamic qualities of daylight. Scale models (item 2 in this list) are useful tools, but there is a limit to what information they can provide to the designer. Software typically used for this analysis includes the following:

   COMFEN is a single-zone facade energy analysis tool that can be used to evaluate a range of facade configurations in order to understand the impact of different design variables on facade performance. A more detailed description can be found in section 12, TOOLS AND RESOURCES SUMMARY, or downloaded along with the program from the COMFEN website: http://windows.lbl.gov/software/comfen/comfen.html.

RADIANCE is a ray tracing program that calculates light levels at specific points in a simulated daylit space using space geometry, glazing properties, luminaire specifications, and other site-specific information. It can be downloaded from http://radsite.lbl.gov/radiance/. It is a powerful tool that can produce physically based rendering of designs that are close to what the user will experience in the space. Radiance is an engine that utilizes a command line input so it is only suitable for dedicated users, but its capabilities can be assessed via DAYSIM, COMFEN, and other tools.

DAYSIM is a RADIANCE-based program that calculates annual availability of daylight in buildings and estimates how building occupants will react to it in terms of how they control the space lighting and blinds. It will also calculate energy savings from automated lighting controls such as occupancy sensors and daylight dimming and calculate annual glare and useful daylight illuminance. It is available from www.daysim.com.

AGI32 is a software tool for making photometric predictions, assisting the designer in creating optimum lighting designs. It includes an architectural visualization capability, where a virtual mock-up provides the designer with a visual feedback of their modeling and analysis. It is available from www.agi32.com.

The Windows for High-Performance Commercial Buildings design tool at www.commercialwindows.org is based on COMFEN and is useful at the pre-design stage for experimentation and idea testing. A book and user guide accompanies the website; they outline the principles and background and provide a knowledge base for the reader. The website contains greater technical detail on daylighting specifics.

During the design process, the architect and lighting designer should work together to assess the nature of the anticipated daylighted space and confirm their intuition with observations of window glare, daylight quality, and distribution.

When using simulation models, care must be taken to determine and define the parameters to be used in the model: for thermal performance, construction material and wall thickness are key factors; for daylighting, size of windows and depth of reveals are important. See section 12, TOOLS AND RESOURCES SUMMARY, at the back of this guide for further information on daylight simulation tools.

2. **Scale Model.** Simulation is slowly replacing the physical model as the primary architectural design tool, but physical models are still used for determining daylight levels in a space at all design stages. A rough assessment of how well the design mitigates glare and controls direct sun can also be made. Models such as those shown in Figure 17 are helpful for fine-tuning decisions, for convincing clients, and for flagging potential construction problems.

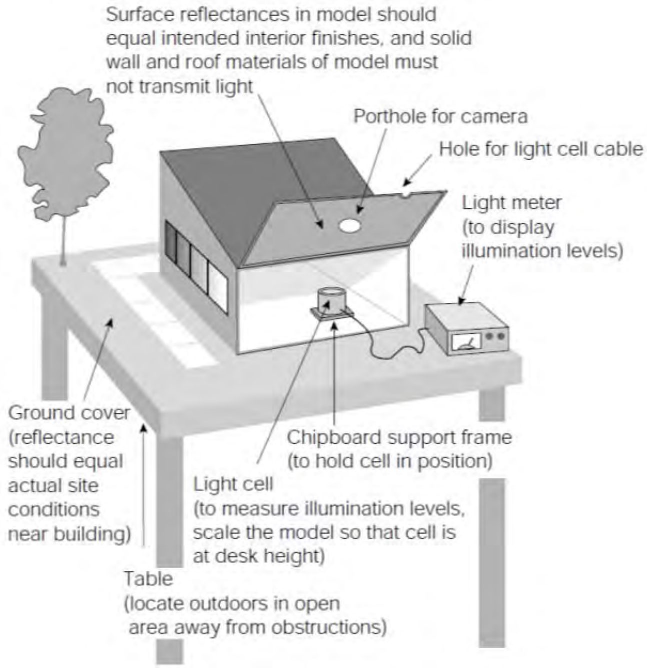

Figure 17: Scale models studied outdoors show the quality of lighting, flag glare problems, and provide measured daylight readings. Source: *Concepts in Architectural Lighting,* by M. D. Egan, McGraw-Hill, 2001.

The most important thing when constructing a model is to ensure that materials and joints are completely opaque. Cover joints with black tape; paint or cover exterior surfaces if not opaque. Also, ensure that all 3-D features are included on the model. Add furniture and other details for realism and scale. If possible, measure illumination and calculate the daylight factor (horizontal indoor illuminance divided by horizontal outdoor illuminance) for several different task locations. These tools may be available from your local utility company. If you have not included glazing in the model, multiply your readings by the visible transmittance of the intended glazing.

3. **Search for a nearby heliodon.** This apparatus is used to mock up solar conditions either indoors with an artificial sun or outdoors using the real sun and sky. It will allow the collection of data for a scale model under conditions representing a full year (as opposed to scale models studied outdoors for which data would be collected for a day at a time). Facilities with heliodons should be able to assist in understanding their own specific best uses and limitations.
4. **Ask at local utility or architecture school for possible assistance.** Otherwise, see the books listed below for more tips.
5. **Whole-Building Energy Software.** Refine window sizing, early glazing decisions, building form, and siting with preliminary mechanical load calculations. See the list of energy analysis software in the Mechanical Coordination section of these guidelines. Calculation of daylight availability in whole-building energy software is only an approximation of daylight illuminance. For best accuracy it may be necessary to couple daylight simulation software with whole-building energy simulation software.

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- **IESNA** Visit the Illuminating Engineering Society website at www.iesna.org for daylighting publications.
- **ASHRAE** The American Society of Heating, Refrigerating, and Air Conditioning Engineers offers a wide range of reference materials. Visit www.ashrae.org.
- **Utility Company** Inquire at local utility about possible incentives and design assistance.
- **Papers and Books**

A Guide for Building Daylight Scale Models, by Magali Bodart, Arnaud Deneyer, André De Herde, and Paul Wouters (Unit of Architecture, University of Louvain, 2006).

Concepts in Architectural Lighting, by M. David Egan (McGraw-Hill, 2001) has a helpful section on window and interior design.

Daylight Performance of Buildings, by Marc Fontoynont (Routledge, 1999) is a compendium of 60 building case studies that were observed and measured, consisting of a range of building types from different eras. It is available from online bookstores.

Daylight Design of Buildings: A Handbook for Architects and Engineers, by Nick Baker and Koen Steemers (Routledge 2002) builds on the research carried out by Marc Fontoynont (above), using examples from the case study buildings.

Daylighting Performance and Design, by Gregg D. Ander (Van Nostrand Reinhold, 2003).

Daylight in Buildings: A Source Book on Daylighting Systems and Components (IEA, 2000) is a good general guide. It can be downloaded at www.iea-shc.org/task21/.

Sunlighting as Formgiver for Architecture, by William M. C. Lam (Van Nostrand Reinhold, 1986) has been discontinued in print but is available from the author's website at www.wmclam.com/images/pdfs/safa/safa_complete.pdf.

Also see section 12, TOOLS AND RESOURCES SUMMARY, for additional sources.

CHECKLIST

1. Know the true north orientation of the site and include it on all plan drawings. Lot property lines are typically given relative to true north.
2. For new construction, if the site allows, the first attempt at building placement should be with the long axis running east to west.
3. Minimize apertures on the east and west; especially on the west. Low sun angles for these orientations make shading extremely difficult without blocking the entire window.
4. Study the potential for (a) an articulated form that yields a high percentage of perimeter space, (b) an envelope structure and cladding that can integrate shading, and (c) opportunities for the building to shade itself.
5. Develop initial thoughts about shading strategy and glazing type.

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6. Determine whether your project budget will allow consideration of a light shelf or exterior projecting shading elements.
7. Begin window design with both interior considerations and exterior appearance concerns simultaneously. Place windows primarily to provide view and light. Size and place windows for best glare-free daylighting with minimal energy penalty. A mechanical engineer should perform preliminary calculations at this point to help in window design and to determine the importance of glazing and shading decisions yet to come. If a light shelf or exterior shading are under consideration, include these elements in the calculations.
8. Build a rough digital model to explore options or use referenced websites to examine alternative building design options.
9. Build a rough physical model to study daylighting effects with the proposed skin, ceiling height, and room depth.
10. Interior design should begin to select light colors for finishes and window coverings. Remember that rendering of interior colors will be affected by glass color.
11. Identify which occupant tasks best benefit from daylight before laying out task locations on floors. Put tasks requiring low, uniform light levels or with periodic occupancy (e.g., telephone closet) in the building core.
12. Discuss daylighting concepts with a lighting designer or consultant to ensure that electric lighting layout and controls address daylight needs at the start of the lighting design process.
13. Check coordination issues with lighting, structural, and mechanical design. Keep the ceiling as smooth and high as possible.

Envelope and Room Decisions

Good Practice

1. Minimize window area on the east and west; especially on the west.
2. Keep window area to a 30%–40% window-to-wall ratio.
3. If tenants are unknown, use a strip window.
4. If tenants are known and punched windows are used, plan task areas to correspond with windows.
5. Keep interior finishes light-colored.
6. Try to increase surface area of the window opening, and splay these surfaces if possible.

Better Practice

In addition to the above:

1. If preliminary glazing decision has been made, use engineer's early calculations to refine window area.
2. Explore envelope alternatives that could incorporate shading elements or light shelves.
3. Investigate appropriate computer design tools, and websites such as those mentioned above.
4. Build a simple model and view it outdoors to assess lighting quality and glare.
5. Visit similar buildings and observe occupant behavior and light levels.

Best Practice

In addition to the above:

1. Build a more accurate model, and view and photograph outdoors. Whole-building models can be developed more quickly by photographing the building and importing the images into tools that will do a lot of the work for you. If photometric equipment is available, measure the daylight in the model. Refine the design as necessary.
2. Commission an optimization study at single zone level (COMFEN is perfect for this task) or at whole-building level. An engineer looks for opportunities for equipment downsizing or elimination of unnecessary systems.
3. Hire a daylighting consultant.

4 Glazing Selection

OBJECTIVE: Make an informed glazing selection from all design perspectives.

Choose glazing to maximize daylight effectiveness and occupant comfort, and to minimize energy use, while still meeting architectural objectives.

KEY IDEAS

Glazing Technology

There are a number of glazing properties to consider when choosing a product. Glazing selection should be a careful process of evaluating and weighing trade-offs and prioritizing performance characteristics. Review all of the critical characteristics of glazing, listed in product brochures, for a good all-around selection. See a brief explanation of these properties below. For greater detail and supporting data and graphics, visit www.commercialwindows.org, which is a very useful reference for all of the technical issues referred to in this section.

- **Visible Transmittance,** sometimes called "daylight transmittance," is the percentage of visible light striking the glazing that will pass through. Visible transmittance values account for the eye's relative sensitivity to different wavelengths of light. Glazings with a high visible transmittance appear relatively clear and provide sufficient daylight and unaltered views; however, they can create glare problems. Glazings with low visible transmittance are best used in highly glare-sensitive conditions, but can create both "gloomy" interiors under some weather conditions and diminished views; they are unsuitable for most daylighting applications, since they do not provide enough light for typical visual tasks. Note that some glazings can have a high visible transmittance but obscure views (e.g., frosted or patterned options).
- **U-Value** ($W/m^2 \cdot K$, $Btu/h \cdot ft^2 \cdot {}^\circ F$) is a measure of heat transfer through the glazing due to a temperature difference between the indoors and outdoors. U-Value is the rate of the heat flow, therefore lower numbers are better. Glazing products usually list U-Value. Center-of-glass U-values are generally lower than whole-window U-values, which account for the effect of the frame and mullions. This property is important for reducing heating load in cold climates, for reducing cooling load in extremely hot climates, in any applications where comfort near the windows is desired, and where condensation on glass must be avoided.
- **Solar Heat Gain Coefficient (SHGC) or Shading Coefficient (SC)** are indicators of total solar heat gain. SHGC, which has replaced SC, is the ratio of total transmitted solar heat to incident solar energy, typically ranging from 0.1 to 0.9, where lower values indicate lower solar gain. These indices are dimensionless numbers between 0 and 1. These properties are widely used in cooling load calculations and are closely related to visible transmittance values. Generally, SC ≈ 1.15 x SHGC.
- **Visible Reflectance,** or "daylight reflectance," indicates to what degree the glazing appears like a mirror, from both inside and out. It is the percentage of light striking the glazing that is reflected back. Most manufacturers provide both outside reflectance

(exterior daytime view) and inside reflectance (interior mirror effect at night). All smooth glass is somewhat reflective; various treatments such as metallic coatings increase the reflectance. High reflectance brings with it low visible transmittance and all the interior disadvantages that may be associated with that characteristic.

- **Ultraviolet Transmittance** indicates the percentage of ultraviolet radiation (a small portion of the sun's energy) striking the glazing that passes through. Ultraviolet radiation (UV) is responsible for sunburn of people and plants, and it contributes to fabric fading and damage to artwork. Many energy-efficient glazings also help reduce UV transmission.
- **Spectral Selectivity** refers to the ability of a glazing material to respond differently to different wavelengths of solar energy; in other words, to admit visible light while rejecting unwanted invisible infrared heat (Figure 18). Newer products on the market have achieved this characteristic, permitting much clearer glass than previously available for solar control glazings. A glazing with a relatively high visible transmittance and a low solar heat gain coefficient roughly indicates that a glazing is selective. Spectrally selective glazings use special absorbing tints or coatings, and are typically either neutral in color or have a blue or blue-green appearance.
- **Glazing Color** affects the appearance of view (bronze will dull a blue sky, for example) and the appearance of interior finishes. Examine carpet, fabric, and paint samples in daylight that comes through the intended glazing to be sure colors are not changed undesirably. Glazing color is also a dominant determinant of the exterior appearance of the building facade. Color is the property that often dominates glazing selection and can thus unnecessarily constrain or complicate daylighting design. For example, a strong color preference for gray or bronze may make a good glazing selection more difficult. Staying more flexible with respect to color will keep more opportunities open.
- **Sound Transmission** is an important glazing system property in some projects, and many energy-efficient glazings deliver improved acoustic performance as a side benefit. Outdoor-to-indoor transmission class (OITC) is the property used to express sound attenuation characteristics. The higher the OITC rating, the better the unit will insulate against sound. Multilayer assemblies, especially those with a laminated layer, generally have high OITC ratings.

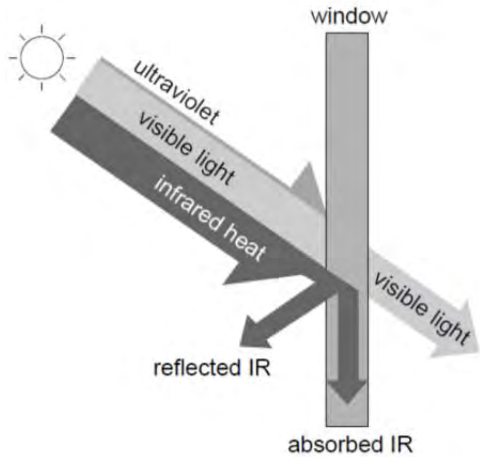

Figure 18: An ideally spectrally selected glazing admits only the part of the sun's energy that is useful for daylighting.

Selection Process

- **Choose an insulating glazing.** This is the first decision in glazing selection. Almost all glazings today are double glazed or better, and many have low-E coatings (a double glazing with low-E coatings has a similar U-value to a triple-glazed unit without, and a triple with low-E is even better). Therefore, it is important to refer to the U-value of the window and not only its construction. Although higher in first cost, low-E double- and triple-pane insulating glazing typically reduces mechanical loads in buildings with large window-to-wall ratios and in climate zones that have a significant range in diurnal and/or seasonal temperature. Double glazing is typically more cost effective and is appropriate across a greater range of conditions, and at present it offers greater flexibility in product selection. There are exceptions where single glazing is an acceptable option, but most new energy-efficient buildings should use insulating glazing, and in most climates this will be a code requirement. For more technical information on selecting multiple glazing panes, visit **www.commercialwindows.org**.
- **Choose a spectrally selective glazing.** Select a moderate visible transmittance for glare control (the range of 40%–70% is a good starting point, depending on visual tasks, window size, and glare sensitivity; the larger the windows or the more critical the glare control, the lower the desirable visible transmittance). Examine manufacturer literature for good glazing candidates. Find the product tables for insulating or single-pane units, depending on your initial selection, and look for products with your desired visible transmittance and the lowest possible solar heat gain coefficient.
- **Balance the conflict between glare and useful light.** A physical model studied outdoors is a good tool to assess glare qualitatively. If glare is an anticipated problem, and if an architectural solution to glare (moving windows out of the field of view, using deep reveals, shading systems, and other physical modifiers) is not possible, then select a glazing visible transmittance that is a compromise between glare and light. A visible transmittance as low as 25% may still provide adequate daylight.

- **Big windows require better glazing.** The bigger the window, the lower the required solar heat gain coefficient and visible transmittance, and the greater the need for insulating glazing. Large areas of inefficient glazing bring major comfort and energy cost penalties and cooling system penalties, and may not be permitted by building codes.
- **Don't assume that dark glass provides good solar control.** Many dark glazings block more light than heat, and therefore only minimally reduce cooling load. Dark glass can produce a gloomy interior atmosphere and may affect productivity and absenteeism. Consult product brochures or manufacturer representatives to be sure you are aware of the range of product choices today. Dark glass not only reduces daylight, it also increases occupant discomfort on a sunny day, particularly in single-glazed form. The glass absorbs solar energy and heats up, turning it into a virtual furnace for anyone sitting near it. Today, solar control is available in clear glazings.
- **Don't count on glazing alone to reduce heat gain and discomfort.** If direct solar beams come into the building, they still create a mechanical cooling load and discomfort for occupants in their path. Exterior shading combined with a good glazing selection is the best window strategy. Interior shading options can also help control solar heat gain.
- **Vary glazing selection by facade, if possible.** A lower solar heat gain coefficient on the south, east, and especially west windows will reduce the cooling load. There may be a trade-off with the window size involved in this decision, depending on latitude.

INTEGRATION ISSUES

Architecture

Prioritize glazing properties that are important to the design, as this will also influence the optimization of the building mechanical systems. A good glazing for daylighting, with a relatively high visible transmittance, will appear fairly transparent from the outside. A desire for an opaque or mirrored facade is often not compatible with daylighting.

Interior

Glazing color strongly affects color rendering of interior finishes in daylighted areas.

Color and visible transmittance affect the nature of the view out and occupants' sense of connection with the outdoors. High-transmittance glass in a neutral or soft color help make windows effective links to the world outside.

Low-transmittance glazing makes interiors feel gloomy when overcast or sunlight levels are low, and can make the outdoors look gloomy, even on a clear, sunny day.

HVAC

Glazing characteristics are a significant factor in heating and cooling loads. A mechanical engineer should help determine optimal glazing properties for an efficient mechanical system. High-performance glazing generally reduces annual energy use, peak loads, individual zone fluctuations, wide differences in coincident zone loads, and

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occupant complaints. Insulating glass may also eliminate the need for a perimeter heating system.

Examine equipment downsizing opportunities with glazing improvements. Model the entire fenestration system correctly when calculating cooling load and optimum glazing properties. In particular, include any exterior shading in the model, as this reduces the importance of a low glazing solar heat gain coefficient.

Simplified mechanical load calculations do not accurately model the energy behavior of windows, due to the complexity of that behavior and the oversimplification inherent in commonly used glazing properties. Do not rely on these calculations in making a decision; use them as guidelines only.

Remember that modeling software is a crude approximation of the complex physical behavior of buildings. Rough approximate mechanical calculations may indicate that single-pane glazing is more desirable than insulating glazing for commercial buildings in some climates; for example, California. This has not been empirically supported.

Lighting

Visible transmittance determines how much daylight will be admitted once the window size is set. Meet and discuss desired light levels with the owner if possible, as this may affect your glass selection (i.e., the owner may be willing to either go below the IES surface level recommendations, or may be open to achieving them in a different way (such as overhead lighting and task lighting). The lighting designer must assess expected daylight levels before final glazing selection. If daylighting levels are not satisfactory, choose an alternate glazing with a different visible transmittance or increase the glazing area.

Glazing color affects color temperature of the daylight, and should be considered when matching electric sources in daylighted zones.

Cost Effectiveness

High performance glazings are now the norm for modern buildings, and they pay for themselves in four ways: reduced energy bills, reduced first costs in mechanical equipment, increased occupant productivity, and avoided future retrofit costs (in added mechanical equipment or window fixes, due to commonly unanticipated occupant discomfort). Mechanical load calculations can provide an estimate of the first two savings opportunities. Case study and anecdotal evidence supports the second two benefits.

Really high performance windows can carry a higher price tag, but there are often higher performance options in the same price range, especially when considering the range of possible locations, settings, and designs. A designer should spend plenty of time identifying and assessing the most promising options before making a final selection.

Occupant Comfort

Single-pane glass or low-quality double glazing (without a thermal break) near an occupant can create a hot or cold sensation regardless of interior air temperature. When it is cold outdoors, the body radiates heat to the cold glass surface and is chilled.

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Sun striking glass, especially a tinted unit, heats the unit up well above skin temperature, which then radiates heat to the body and induces a sense of overheating. The mechanical system cannot easily overcome these situations, since it typically adjusts air temperature only and not the temperature of the glass.

Cold glass will also induce a chilly downdraft.

When windows will be near occupants, insulating glazing is the best choice for comfort. Tinted glass in an insulating unit does not cause the radiation problem described above, since the tinted piece is in the outboard pane.

Glazing with a high visible transmittance can cause glare if preventive measures are not taken. Some examples of glare avoidance discussed elsewhere in these guidelines include user-operated shading devices, architectural modifiers, and balancing window brightness with other light sources.

PROVISOS

- Renovations in historic buildings typically need extra care in glazing selection, as historic preservation rules usually require the look of the facade to remain the same. This means any new glazing must appear the same as the original; in most cases, clear. Select an advanced, insulating, spectrally selective glazing for an efficient, comfortable, and daylighted renovation.
- Some tinted glazings cannot tolerate partial shading due to the thermal stresses caused by a large temperature range across a single piece of glass. Consult the glazing manufacturer regarding the building's shading scheme.
- A strong desire for extremely dark or mirrored glazing is not normally compatible with daylighting design.
- Consult glazing suppliers for information on structural aspects of glazing. Specific applications may require tempered, laminated, or other glazings to meet performance requirements.

TOOLS & RESOURCES

- **LEED requirements** that simulation be used to demonstrate that 75% of all regularly occupied spaces receive a minimum of 25 fc and a maximum of 500 fc on September 21 at 9 a.m. and 3 p.m. sets some boundaries for glazing selection.
- **Manufacturer Technical Literature and Product Representatives** are free sources of information and assistance. Most manufacturers will readily supply samples (typically 12" by 12" or smaller). Some manufacturers will also perform energy calculations for you.
- **The National Fenestration Rating Council (NFRC)** compiles a directory of window products with associated thermal, solar, and optical properties. While the emphasis is on residential applications, much of the information is useful for commercial buildings. NFRC data and window labels provide a consistent and accurate way to compare product properties (similar to refrigerator labels). Visit www.nfrc.org.

- **International Glazing Database** is a publicly available online directory of more than 4,000 glazing products from around the world, and is a valuable reference for designers. It is a reference data set for several daylighting design tools, such as WINDOW and RADIANCE. Visit http://windows.lbl.gov/materials/IGDB to find out more.
- **The Windows for High-Performance Commercial Buildings Windows website** contains useful information for the concept development stage of a project design and an early stage design tool that allows quick and easy assessment of glazing options, at www.commercialwindows.org.
- **Software.** Mechanical engineer's standard calculations are useful for comparing peak loads and annual energy use with different glazing options. Remember that this software can only approximate the behavior of glazings and buildings. The WINDOW program is public domain software that accurately analyzes the thermal properties of fenestration products. It is widely used in the glazing industry, but is intended to serve designers as well when choosing between different product options. It is available through the National Fenestration Ratings Council at www.nfrc.org and at http://windows.lbl.gov.
- The EnergyPlus software is an advanced building simulation package. Because it has a variety of features to accurately model glazing and shading properties, dynamic window management, and daylighting effects, it is one of the best software tools available to assist in energy-efficient design, although it requires time and expertise (or hiring a consultant). Use this program to make an optimal glazing selection. Versions of EnergyPlus can be downloaded from the U.S. Department of Energy (DOE) website at http://apps1.eere.energy.gov/buildings/energyplus/. COMFEN uses the EnergyPlus engine to analyze facades and glazings performance for typical rooms or zones in a building: download at http://windows.lbl.gov.
- **Scale Model.** A model studied outdoors can be an accurate and easy way to anticipate glare potential and evaluate daylight levels and direct sun control. See Section 3, ENVELOPE AND ROOM DECISIONS, for information on measuring daylight in a model.
- **Books.** There are only a few up-to-date materials available to designers on glazing. The best source for timely information may be the architectural journals, which occasionally run glazing articles in their technical sections.

  ASHRAE Handbook of Fundamentals (American Society of Heating, Refrigerating and Air Conditioning Engineers 2011) is a source for technical information and generic glazing properties. Visit www.ashrae.org.

  Window Systems for Commercial Buildings by John Carmody, Stephen Selkowitz, Dariush Arasteh, Eleanor Lee, and Todd Wilmert (Norton, 2004) provides good insight into the technical issues of glazing. It can be found at www.csbr.umn.edu/research/commbook.html.

- **Utility Company.** Inquire at your local utility about possible design assistance or financial incentives.

CHECKLIST

1. Review and document your fenestration design decisions to date, as these will guide the glazing selection. Since there are many conflicting performance goals

(e.g., glare control versus daylight admittance), it is best to document the rationale for a particular selection as it is made.

2. Use the effective aperture target as discussed to determine the range of desirable visible transmittances, based on your window-to-wall ratio.
3. Decide between insulating glazing options (or in rare circumstances, single glazing). Mechanical engineer's calculations, comfort concerns, and construction budget data will help in this decision.
4. Identify to what extent color, reflectance, UV transmittance, and sound will influence glazing selection, and then decide what glass types are appropriate for each floor of your building/facade orientation.
5. Determine via mechanical engineer or building code requirements the desirable range of values for U-Value and solar heat gain coefficient. If the building has good exterior shading, glazing solar control becomes less critical.
6. Review product literature and select candidate glazings that meet the above criteria.
7. Evaluate glare potential, ideally with a physical model, and take preventive measures if necessary. Use a COMFEN model to evaluate different glazing types for different facade orientations.
8. Contact product representatives for samples, further information, assistance, and pricing.

High-Performance Glazing

Good Practice

1. Size windows for a 30% window-to-wall ratio.
2. Specify glazing with visible transmittance 50%–70%, solar heat gain coefficient 0.50 or lower (or to code maximum, whichever is lowest), and U-Value to meet code. Choice of color may be limited.
3. Present above criteria to glazing representatives from two or more manufacturers for further assistance in finding products that match. Request representatives to perform (free) energy calculations for you if undecided between products. Consult the project engineer on heating/ cooling system sizing issues.

Better Practice

1. See glazing brochures from product vendors, then call specific glazing representatives for more information, pricing, and free performance calculations for your project.
2. For a broader range of options, determine a set of alternative scenarios (different-sized windows, different potential glazings), perhaps with a mechanical engineer's assistance. An engineer can evaluate these alternative designs using standard load software and derives optimum values for U-value, solar heat gain coefficient, and visible transmittance. Present these values to glazing representatives for a product match.

Best Practice

1. Determine an optimum set of values for U-value, solar heat gain coefficient, and visible transmittance through more rigorous computer modeling with software such as DOE-2 that can compute energy savings from daylighting in

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addition to standard building performance energy calculations. This usually requires hiring an energy consultant with EnergyPlus experience.

2. This consultant should also assist in predicting occupant satisfaction (comfort) and in fine-tuning the proposed window area. The consultant could also prepare building code compliance documentation. Present results of this optimization study to glazing representatives for a product match, or select glazing yourself from Sweets brochures.

5 Shading Strategy

OBJECTIVE: Control intense direct sunlight to ensure a comfortable workspace.

- This is critical for occupant visual and thermal comfort and for minimizing mechanical cooling loads.
- Direct sun is more acceptable in less-demanding spaces (e.g., circulation zones, lobbies, eating areas), although its impact on cooling should be carefully assessed.
- To progress towards net-zero energy, incorporation of external shading is recommended.
- Increase the time during which interior blinds are open, establishing a beneficial connection to the outdoors.

KEY IDEAS

Exterior Devices

- **Use exterior shading,** either a device attached to the building skin or an extension of the skin itself, to keep out unwanted solar heat. Exterior systems are typically more effective than interior systems in blocking solar heat gain. Figure 19 illustrates some exterior shading options. Making these operable for occupants provides the greatest potential benefit in terms of occupant satisfaction (and, potentially, energy savings).
- **Use a horizontal form for south windows.** For example, awnings, overhangs, and recessed windows. Also somewhat useful on the east and west. Serves no function on the north.
- **Design the building to shade itself.** If shading attachments are not aesthetically acceptable, use the building form itself for exterior shading. Set the window back in a deeper wall section or extend elements of the skin to visually blend with envelope structural features.

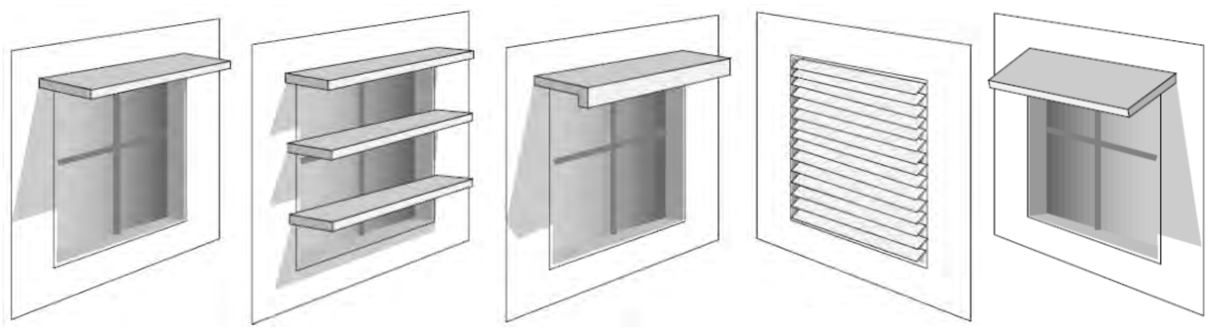

Figure 19: Far left, a standard horizontal overhang shade, and other shading options with reduced projection from the envelope

- **Use a vertical form on east and west windows.** For example, angled vertical fins (Figure 20) or recessed windows. Also useful on the north to block early morning and late afternoon low sun.

Figure 20:Vertical louvers or fins for east, and especially west, facades

- **Give west and south windows shading priority.** Morning sun is less serious in terms of contribution to heat gain. If your budget is tight, invest in west and south shading only. Zone secondary spaces that may not require views on western exposures.
- **Design shading for glare relief as well.** Use exterior shading to reduce glare by partially blocking occupants' view of the too-bright sky. Exterior surfaces also help smooth out interior daylight distribution.

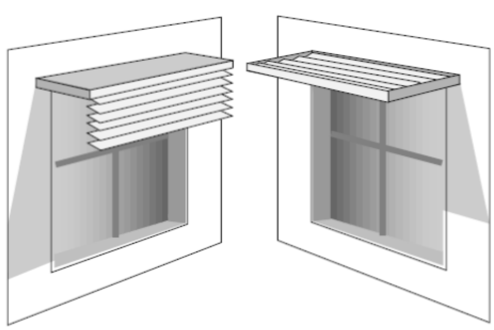

Figure 21: The use of louvers in place of a solid dropped edge (left) or solid overhang (right) provides diffuse natural light while still shading.

- **The shade's color modifies light and heat.** Exterior shading systems should be light-colored if diffuse daylight transmittance is desired, and dark colored if maximum reduction in light and heat gain is desired.
- **Fixed versus movable shading.** Use fixed devices if your budget is tight. Use movable devices for more-efficient use of daylight and to allow occupant adjustment; first cost and maintenance costs are higher than with fixed devices. Use movable devices that are automatically controlled for the best energy savings. Reliable systems have been in use around the world for years and have only recently become available as cost-effective options in the United States.
- **Influence of shading on design of building mechanical systems.** Astute shading design may result in significant costs savings associated with reduction in first cost and operating costs of mechanical systems. Integrating design of shading and HVAC systems may offer the optimum solution in terms of cost benefit, comfort, and energy efficiency. Reduction in HVAC system cost can help pay for the shading.
- **Avoid thermal bridging between shading elements and internal space.** Ensure that the building interior is appropriately thermally isolated from external shading system infrastructure.
- **Consider permeability/openness of the shading system if natural ventilation is being considered.** The openings in the building envelope must support the flow of adequate air volumes. To facilitate this, minimize the reduction of effective cross-sectional area of openings as far as possible. Consider wings on building facades placed near openings and operable windows that shade windows but also help funnel air into the occupied spaces.
- **Consider subdividing exterior shading system to preserve views in the view zone.** Glare in the view zone can be addressed with interior shading.

In the Window Plane

- **Use exterior shade screens for a smooth facade.** Exterior shade screens (Figure 22) are highly effective on all facades and permit a filtered view. These can be insect screens, perforated metal scrims, or roller shades. The openness of shades determines the effectiveness of shading. Moveable roller shades provide greater energy efficiency.

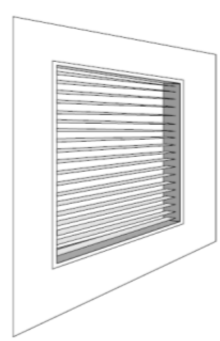

Figure 22: An exterior shade screen fits neatly within window framing, a bit away from the glass. Design for easy removal, to ease cleaning.

- **Use roller shades for a movable alternative.** Open-weave exterior shades are not as effective, but acceptable.

- **Don't rely on dark glazing to control beam sunlight**. Glazing treatments (reflective coatings, heavy tints, and reflective retrofit film) can be effective at reducing heat transfer, but they still allow direct sun penetration. Even with reduced intensity this may not be an effective shading strategy from an occupant's perspective. The transmittance must be very low (e.g., 1%) to control glare from the orb of the sun. Fritted glass, with a durable diffusing or patterned layer fused to the glass surface, can also provide some degree of sun control, depending upon the coating and glass substrate properties, but it may also increase glare.
- **Between glass systems.** Several manufacturers offer shading systems (e.g., blinds) located between glazing layers. Some are fixed and others are adjustable. These systems reduce heat transfer, and are more effective than systems installed within the envelope. See related comments on interior devices below.

Interior Devices

- **Interior shading alone has limited ability to control solar gain.** All interior systems are less effective than a good exterior system because they allow the sun's heat to enter the building. They also depend on user behavior, which can be variable. Interior shading products include shades, blinds, and draperies.

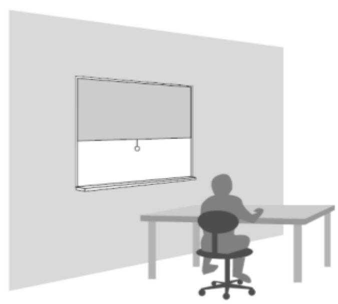

Figure 23: Shades can be used to control solar gain, but their effectiveness relies on whether or not users employ them consistently.

- **If interior devices are the only shading, specify light colors facing outward** in order to reflect the sun's heat back out. Light-colored blinds or louvers are best. Light-colored woven or translucent shades are acceptable, but may not control glare under bright summer conditions. Tighter weaves provide more solar heat gain control and block beam sunlight but reduce access to daylight.
- **Interior shading is best used for glare control and backup shading.** Supply user-operated devices that occupants can easily adjust to their individual comfort needs.
- **Use devices that still allow daylight in.** Blinds and open-weave shades are good choices for filtering, but not blocking, all light.
- **Don't use dark devices unless exterior shading is used.** Dark-colored interior devices provide glare control but offer only small energy savings. Open-weave shades are easiest to see through if their interior surface is dark, but they perform best if their exterior surface is light-colored.
- **Consider using an upper and lower shading solution on separate high clerestory windows and lower vision windows.** The ideal solution

allows them to be independently managed to control glare and solar gain but to admit daylight, as shown in Figure 24 .

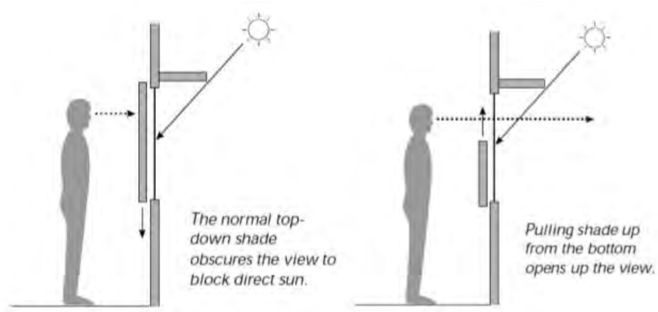

Figure 24: Left, the normal top-down shade obscures the view to block direct sun whereas pulling shade up from the bottom, right, opens up the view.

INTEGRATION ISSUES

Architecture

Exterior shading projections work well with an articulated or layered facade and can integrate well with structural members.

Exterior shading elements can add dynamics to the appearance of different facades over the course of the day.

Exterior screens can make windows look dark.

If interior devices are the only shading, many occupants will always keep them closed. This can mean the window is no longer transparent.

Use exterior shading to avoid the facade clutter of variously adjusted interior coverings by reducing the periods during which occupants feel they need to have interior blinds down.

Interior

Choose light-colored window coverings for best energy savings and comfort.

Choose interior window treatments that allow occupants to make adjustments for individual comfort needs.

Bottom-up interior blinds versus top down can increase the daylight distribution within interior spaces and increase energy savings from daylight dimming.

HVAC

Good permanent shading provides cooling-load reductions and may significantly reduce capital cost if some HVAC systems can be downsized or eliminated. The

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mechanical engineer and shading designer should work together to identify balanced systems that offer the best value in terms of life-cycle cost and energy reductions.

The mechanical engineer should perform iterative calculations that incorporate the designer's estimates on performance of moveable shading systems, whilst acknowledging that systems may not be deployed when needed.

Lighting

Shading devices modify the intensity and distribution of daylight entering the space. The lighting design scheme and placement of control zones may be affected.

Cost Effectiveness

Proper shading devices can be partially or fully paid for by reduced cooling equipment and cooling energy costs. However the likelihood of proper use by occupants must be considered. The mechanical engineer should calculate these savings and compare them to any additional construction costs for the shades, calculating the simple payback for the shading.

Automated movable systems can have an added maintenance cost and a higher first cost relative to other shading schemes. However, the operation should be more reliable than with manually operated systems. Careful calculation of expected energy savings are needed to determine cost effectiveness for this approach.

Occupant Comfort

Direct sun in the workplace is almost always a comfort problem, particularly for net-zero energy buildings where low-energy cooling strategies are being used, such as natural ventilation or radiant technologies. Uncomfortable occupants will be less productive, close their window coverings, bring in energy-using portable fans, and reduce the thermostat setting if possible. Good shading means occupants will have minimal complaints.

Shading reduces glare. Exterior elements partially shield occupants' view of the bright sky, as well as direct sun. Screens, glazing treatments, and shades reduce the brightness of the window. Exterior elements and venetian blinds reduce contrast by sending some light deeper into the space (improving distribution).

! PROVISOS

Use of sunlight to illuminate building interiors may be appropriate in some cases.

Direct sunlight:

- Aids the growth of plants.
- Provides strong illumination that enhances details, texture, shape, and color.
- Gives a dynamic vitality to a space through its daily variation—especially beneficial in relieving institutional monotony in schools, hospitals, and public buildings.
- Provides a visual and emotional link to the outdoor world.

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- Provides a real and suggested warmth in winter.

Direct sunlight may be more appropriate in circulation areas, transition areas, and other spaces that do not contain critical visual tasks. Be sure to account for the peak cooling and annual cooling cost of such designs.

Balance the needs for sun control against the usefulness of daylight admittance. Some sun-control strategies may severely reduce daylighting opportunities.

TOOLS & RESOURCES

- **LEED requirements** that simulation be used to demonstrate that 75% of all regularly occupied spaces receive a minimum of 25 fc and a maximum of 500 fc on September 21 at 9 a.m. and 3 p.m. sets some boundaries for shading selection.
- Do some quick and easy shading analysis using the Facade Design Tool on the **www.commercialwindows.org**. This supports testing of pre-design stage concepts and ideas and quantifies their knock-on effects in terms of operation of other systems and overall energy impact.
- **COMFEN** can be used to do a more detailed evaluation of a range of facade configurations, in order to understand the impact of different design variables on facade performance.
- **Use software such as Sketch-up or Ecotect** to visualize shadows within interiors.
- **Sizing Equations.** Use the equations given on page later in this section for a simple start at sizing overhangs and fins.
- **Pilkington Sun Angle Calculator.** A more thorough and accurate method uses this easy manual tool (Figure 25, available online for $25 from the Society of Building Science Educators at www.sbse.org/resources/sac). The instruction manual is also available for free download on the SBSE website. Similar software tools can now be found on the web.

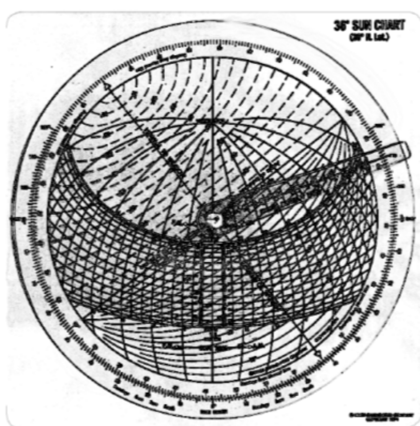


Figure 25: For more exact sizing, use the Pilkington Sun Angle Calculator

- **Shading Masks.** Use this simple graphic method to both study and document shading device performance over the entire year, all captured in a single diagram that is easy to construct. See *Architectural Graphic Standards* for instructions. Online versions are now also available.

- **Engineering Software.** Once the shading scheme is established (the geometry of exterior elements is determined or an interior system is selected), use mechanical engineer's software, such as EnergyPlus, to calculate the cooling load with and without the proposed shading. The mechanical engineer or energy consultant must accurately model the impacts of the shading scheme. Computed savings can then be compared to added costs for the shading, for a simple payback calculation. This will be a conservative estimate, as there is no credit taken for savings associated with comfort (unshaded occupants will turn down thermostats or bring in electric fans).
- **Manufacturer Technical Literature and Product Reps** are free sources of information or assistance.
- **Books**
  Sun, Wind, and Light by G. Z. Brown and Mark DeKay (Wiley, 2013) offers more thorough explanations of some tools and ideas described here, in a friendly format and available from several online outlets.

  Architectural Graphic Standards John Hoke ed. (Wiley, 1999) has a section on shading masks, with instructions. It is available from many online bookstores.

  ASHRAE Handbook of Fundamentals (American Society of Heating, Refrigerating, and Air Conditioning Engineers, 2009 or any older edition) is a highly technical source for generic solar heat gain coefficient data and all other aspects of building and fenestration energy behavior.

SCALE MODELS AND SUNDIALS

Scale models can be studied outdoors under direct sun or indoors using a lamp as a simulated sun. The primary benefit is to determine when and where sun penetration will occur. To position the model accurately relative to the sun, place a sundial beside the model and adjust the model position until the desired time is shown on the sundial.

1. Determine the objective of the study (e.g., sunlight penetration, glare assessment) to help determine the model requirements. Build a simple model with accurate geometry. You can study the whole building or just a portion of the facade.
2. Select the sundial with latitude closest to your site (use 28° for Southern States, 36° for Central, 44° for Northern). Mount a copy of the sundial on your model. It should be horizontal, oriented properly with true south on the model, and in a position where it will not be shaded by the model (roof or southern portion of model base are good places). Note that true north is typically depicted on city property line zoning maps, not magnetic north.
3. Make a peg the length shown in Figure 26 and mount it on the cross mark just under the June 21 curve (a straight pin works well for this).
4. Take the model in the sun and tilt it so that the end of the peg's shadow falls at various intersections of the time and day lines. For example, when the model is tilted so that the peg shadow ends at the intersection of the 3 p.m. line and the October 21/February 21 curve, then the sun and shadow affects you observe are exactly as they will be at that time on both those days. You can now quickly see how well your shading scheme works all year round.

5. Take some photographs. Adjust design details as necessary.

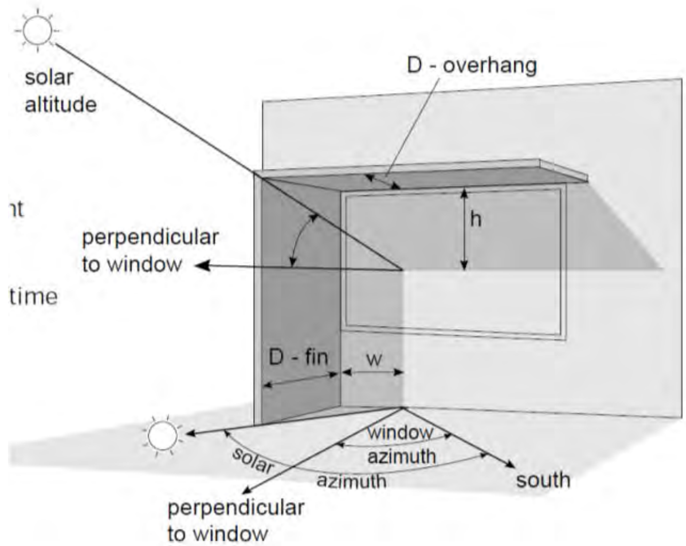
Figure 26: Sundial for 36°N

Source: G. Z. Brown, *Sun, Wind and Light: Architectural Design Strategies*, Wiley & Sons, 1985 (newer edition listed above) or find sundials for your latitude online.

SIZING OVERHANGS AND FINS

Figure 27 shows the elements that need to be accounted for when sizing overhangs and fins. Use the solar geometry equations below to find starting dimensions for shading elements. Do the calculations to find either:

- the depth required for a shading element, or
- the extent of shadow cast by a shading element with given depth.



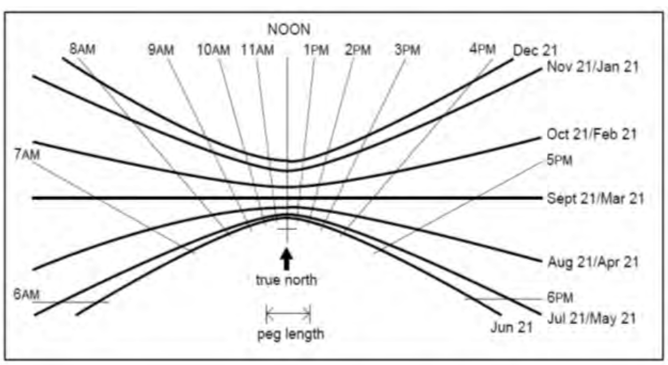


Figure 27: Sizing of fins and overhangs

1. For each facade, select a critical month and time for shading. You should try to reflect peak incident sun energy, so we suggest for south windows use September noon, for east use September 10 a.m., and for west use September 3 p.m. Alternatively, ask a mechanical engineer for an estimate of peak cooling time in east, south, and west zones.

2. Find solar altitude and azimuth for the target month and hour from the sun path diagram (page 54).
3. Use the formulas below to size overhang, fin, or both. Results are a minimum starting point.
4. If the overhang is too big, try breaking it into several smaller elements or dropping part of it down for an equivalent depth, as suggested in Key Ideas above.
5. If sizing an overhang for an east or west window, you may notice that a fin must be added for adequate shading; otherwise the overhang becomes unreasonably deep.
6. Test the solution with a physical model and sundial.
7. Improvements: Extend the ends of the overhang wider than the window or use a continuous element. Make the overhang deeper or add another horizontal element partway down the window. Add vertical elements to the scheme.

$$\text{For an overhang:} \quad h = \frac{D \times \tan(\text{solar altitude})}{\cos(\text{solar azimuth} - \text{window azimuth}) \ \ddagger}$$

- For total shade at your target month/hour, set h to height of the window from sill to head and solve for D, required overhang depth.
- For partial shade, set h to the acceptable height of the shadow (perhaps 2/3 of window height) and solve for D, required overhang depth.
- With a given overhang, set D to its depth and find h, the height of shadow it will cast at your target month/hour.

$$\text{For a fin:} \quad w = D \times \tan(\text{solar azimuth} - \text{window azimuth}) \ \ddagger$$

- Solve for either w (width of shadow) or D (depth of fin), as with the overhang equation.

‡ Be sure to observe the proper signs. If both solar and window azimuths are on the same side of the south vector, then both values are positive. If they are on opposite sides of the south, then set one azimuth as negative. For example: solar azimuth - (-window azimuth) = solar azimuth + window azimuth. Referring to **Error! Reference source not found.** when reading this description may be helpful.

Source: David Ballast, *The Architect's Handbook of Formulas, Tables, and Mathematical Calculations*, Prentice Hall, 1988.

SUN PATH DIAGRAMS

This diagram gives you the solar altitude and azimuth for any hour and day off the year. Choose the sun path with latitude closest to your site (use 28° for Southern States; 36° for Central, such as that shown in Figure 28; and 44° for Northern). Find the intersection of the two curves corresponding to the month and hour of interest. From this point, read the solar altitude from the scale at right, and read the solar azimuth from the scale below. This is the sun's position at that month and hour.

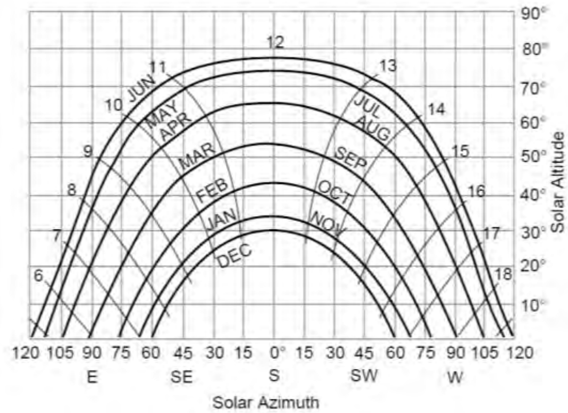


Figure 28: Sun path diagram for 36° north

Source: Claude Robbins, *Daylighting: Design and Analysis*, Van Nostrand Reinhold, 1986, or available online: search for “sun path diagram by latitude.”

✓ CHECKLIST

1. Characterize your shading needs. Long axis running east-west: shading is relatively simple (overhang or deep reveal on south may be all that’s needed). Large area of glazing on west: shading becomes more critical and more difficult if daylight is to be maintained. Budget design time accordingly. You must know your true north orientation.
2. Review options for shading and select a basic approach (e.g., exterior versus interior, an architectural projection, an off-the-shelf attachment, blinds, drapes, shades).
3. For exterior schemes, calculate preliminary size of projections. Use rules of thumb given here or use the Pilkington Sun Angle Calculator method.
4. Refine with Pilkington Sun Angle Calculator (if you are still working on paper), through quick physical model studies (for easier 3-D analysis), or through use of appropriate simulation programs, such as COMFEN.
5. Select an interior shading product and get solar heat gain coefficient data from manufacturer literature or product reps. See the *ASHRAE Handbook of Fundamentals 2009*, Chapter 17, for tables of generic products or check the product libraries in COMFEN.
6. Get solar heat gain coefficient data for preliminary glazing selection from manufacturer literature, product reps, or the generic table in Section 4, GLAZING SELECTION, or in the *ASHRAE Handbook of Fundamentals 2009*, Chapter 17. COMFEN has a database with the optical properties of virtually all glass sold in the United States.
7. Have a mechanical engineer calculate cooling load, accounting for exterior shading elements and proper solar heat gain coefficients for glass plus interior coverings. For venetian blinds, see the *ASHRAE Handbook of Fundamentals 2009*, Chapter 17, for proper treatment of an angle-dependent solar heat gain coefficient.
8. A mechanical engineer can provide a rough estimate of savings due to shading, realized through reducing (a) cooling plant capacity, and (b) annual

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mechanical systems operation. Get a preliminary first-cost estimate for shading and compute the simple payback.

9. Provide description of the shading scheme to the lighting designer.

Approach to Shading

Good Practice

1. Minimize window area on east and west.
2. Use sizing rule of thumb for a horizontal projection or reveal on south windows.
3. Use sizing rule of thumb for a vertical projection or reveal on west windows.
4. If no exterior shading is possible, a lower solar heat gain coefficient for the glazing will be mandatory (see Section 4, GLAZING SELECTION), and interior shading will be required as well.
5. For the best occupant comfort, provide either a light-colored venetian blind or light-colored translucent shade on all windows in occupied areas. For energy savings, these are desirable to include even with exterior shading; they are mandatory if there is no exterior shading.

Better Practice

In addition to the above:

1. Use the LOF Sun Angle Calculator method for preliminary sizing of exterior projections instead of rule of thumb, or to refine schematic design after using rule of thumb.
2. Browse through online catalogs for ideas on shading strategies and products.
3. If undecided on best shading approach to take, a mechanical engineer's simple calculations can help compare cooling reductions with different options.
4. Explore shading options with COMFEN.

Best Practice

In addition to the above:

1. Begin with COMFEN or equivalent modeling of energy-related performance.
2. Mechanical engineer takes special care to properly model shading elements and solar heat gain coefficients with more sophisticated computer calculations.
3. If there is a large area of east or west glazing, have the mechanical engineer perform more complex calculations to determine cost effectiveness of an automated exterior system. The mechanical engineer can help to explore opportunities for cooling equipment downsizing or elimination through optimum shading. Refine shading design to yield the smallest possible cooling equipment.
4. In some cases, a scale model might help show the interplay of different daylight and sunlight sources.

6 Mechanical Coordination

OBJECTIVE: Design a mechanical system to serve a low-energy building and create a comfortable environment, optimizing the use of daylighting and shading design elements.

- Cooling energy savings are a key factor in the cost-effectiveness of daylighting.
- Low-energy daylighting and lighting systems can affect mechanical system selection, potentially reducing system costs; reduction in costs of utility connection arising from careful design is another consideration.
- Efficient, low-energy mechanical system design requires good coordination between the mechanical engineer and the rest of the design team.
- Use caution to ensure that unmanaged daylight apertures do not exacerbate solar heat gain.

KEY IDEAS

Help Guide Early Architectural Decisions

- **Reduce cooling loads aggressively.** Look for opportunities where architectural decisions can save operating costs, reduce mechanical first costs, and reduce mechanical space requirements. Figure 29 shows some areas to consider. Reducing cooling loads provides many benefits. Size shading to reduce direct solar gain in the cooling season. Smaller mechanical rooms and shafts yield more leasable space. Smaller plenums allow higher ceilings (an interior amenity, also helpful for daylighting performance) or possibly additional floors within the building height allowance. Smaller equipment is less visible on the roof and easier to accommodate within normal floor-to-floor heights.

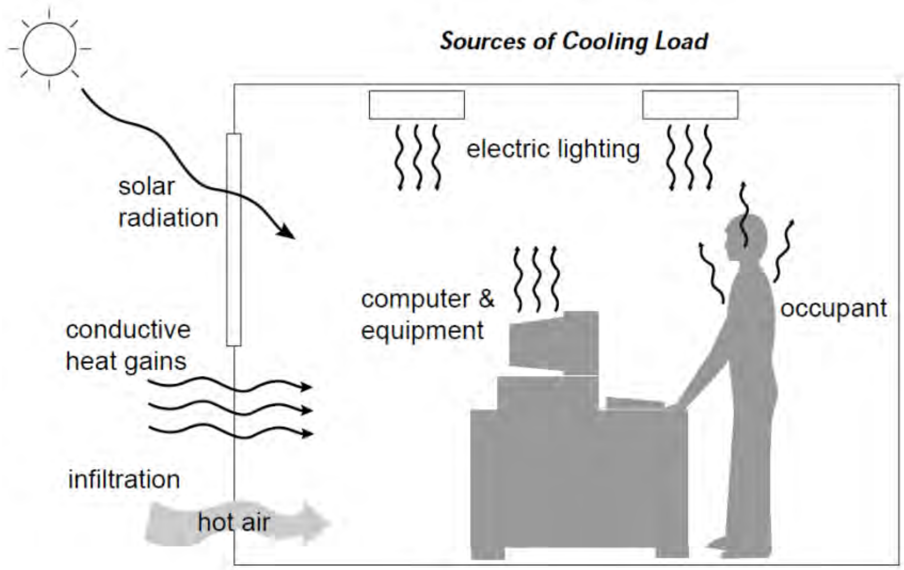

Figure 29: Multiple sources of cooling load

- Look for opportunities to have shading elements perform more than one duty (e.g., integrated shading and lightshelf package, shading and PV support frame, shading and natural ventilation intakes).
- Utilize architectural/engineering features that support natural ventilation where appropriate (where conditions are able to provide cooling for a significant portion of the year).
- Adopt shading design with the aim of reducing cooling plant capacity.
- Design for specified plug load heat gains.
- Select glazing on the basis of design heat and cooling balance, and with an understanding of the necessary heat exchange with the external conditions.
- A lower lighting power density with daylighting dimming and other lighting controls can reduce internal heat gains.

- **Calculate building energy use starting in schematic design,** even if this requires many assumptions about unknown details, and refine the calculation as the building becomes more defined. These early data can be critical in guiding architectural decisions, before important siting and envelope decisions are set.
- **The mechanical engineer should be an integral team player from the beginning.** Integrated design means all team members influence important building elements, and mechanical concerns can help keep architectural decisions on the right track. Their understanding of design goals and input on interactions between building systems may lead to identification of an optimal systems balance and trade-offs available for reducing the number of energy systems, their capacities, and their overall energy use. This is a departure from the traditional model of building design procedure, where the mechanical engineer enters the design process after major architectural decisions are already established. Mechanical expertise is not fully capitalized if not used in all design stages.
- **Assist in an optimal glazing selection.** High performance glazing is like any other technology: forever developing. Dark or reflective glazings are no longer the only choices for solar heat reduction. Most glazings today use

spectrally selective coatings that reject near-infrared energy but transmit most daylight. Consider carefully the radiant effect of windows when weighing the benefit of an improved U-value or the disadvantages of a darkly tinted glazing. The mechanical system typically will respond to air temperature, yet occupant comfort in perimeter zones is highly affected by mean radiant temperature. Glazing with a poor U-value has a cold surface temperature in winter, while a dark (highly absorptive) glazing can get very hot in direct sun.

- **Explore the potential of effective exterior and interior shading.** Cooling loads and occupant comfort will benefit. Mechanical equipment savings may offset some costs of shading devices.
- **Remember that windows and skylights are not necessarily an HVAC penalty.** Careful daylighting design with shading can result in lower cooling loads than with electric lighting, even if glazing area is large. Proper modeling with energy analysis software that calculates daylighting with dimming controls will show this.
- **Use accurate glazing and exterior shading device properties in final load calculations, not generic values.** Use manufacturer's data for architect's preliminary glazing and shading device selection. Model it accurately in calculations to estimate the full mechanical benefit from reduced solar load. Since there is no guarantee that interior shades will be closed at appropriate times, mechanical engineers typically do not include these devices in their calculations.
- **Keep ceilings uncluttered.** Try to place the lighting system's ceiling-mounted photosensor so that it remains unobstructed by HVAC or other equipment. Ensure that proper installation and commissioning are completed.
- **Flag potential conflicts early,** such as inadequate space allocation, poor location or access for equipment rooms, and crowded ceiling plenums.

Reduce First Costs

- **Calculate the peak cooling load and energy use with reduced perimeter electric lighting load, and size the mechanical system accordingly.** Be sure to specify proven and reliable daylight controls that will dim or switch electric lighting during peak cooling conditions. Ask vendors to provide details of previous installations, including performance monitoring data. Also ask for references for previous clients who you may contact.
- **Examine cooling system downsizing or alternate system selection opportunities with various glazing and shading options.** Work with the architect to possibly fine-tune window sizing, window location, shading strategy, and glazing selection for a smaller and more efficient system.
- **Insulating glazing may eliminate the need for a terminal reheat system at the perimeter in moderate climates.** Winter morning warm-up may be accomplished by the central heating system with appropriate controls. In addition to the energy savings, first costs may be lower with improved glazing than they are with added mechanical equipment.
- **Aggressive targets for low-energy building cooling loads may result in significantly different HVAC system selection,** such as radiant cooling systems, which could have cost or comfort benefits.

Reduce Operating Costs

- **Calculate the annual energy saved with improved fenestration elements.** Even if there are no mechanical first cost savings, reduced operating costs decrease the payback period. Calculations will show some of the benefit of exterior over interior shading, lower solar heat gain coefficient glazings, and daylighting controls. Glazing selection should consider the impact on peak energy demands, as peak reduction will have capacity and demand cost benefits; be sure to account for these where appropriate. Reduction in building peak demand also improves grid security.
- **Select an effective energy management system** to optimize building systems operation and tie together all HVAC, lighting, and automated shading controls. Investing in an energy information system (EIS) that suits the needs and priorities of the design is a way to further understanding of how systems operation can be optimized to reduce energy use and cost. A good guide as to what products are currently available and how they work can be found in the Energy Information Handbook, available online at http://eis.lbl.gov.
- **Set a larger temperature deadband for circulation spaces.** Areas in which people spend relatively little time may be considered unoccupied spaces (residency of less than 15 minutes at any one time), where maintaining tight thermal comfort criteria is not as critical. Temperature set points can be relaxed for these spaces to lower energy use. Let these and other non-critical spaces drift more than task areas.
- **Where elements of natural ventilation, radiant heating/cooling or under-floor air distribution are utilized, adaptive comfort criteria should be used to define thermal comfort standards.** These criteria should determine mechanical systems deadbands.

Maintain Thermal Comfort

- **Window and shading design are strongly linked to perimeter zone comfort, regardless of air temperature.** Hot or cold glass behaves like a radiant panel and affects occupant comfort independent of air temperature. The asymmetric nature of this heat gain or loss is an added discomfort. Occupants will respond by adjusting the thermostat, wasting energy without satisfactorily improving comfort. Similarly, unshaded direct sun striking occupants causes discomfort independent of air temperature. Consider comfort as seriously as energy when advising the architect on fenestration design. Low-energy design may make radiant HVAC systems (panels, slab) viable, which will help to provide additional comfort and at lower energy rates.
- **Consider the effects of the window's surface temperature on thermal comfort.** Dark tinted glazings or absorptive window films increase the window's surface significantly in summer. Poorly insulated windows (high U-value) decrease the surface temperature in winter. Since the mechanical system controls the room's air temperature, occupants near the windows can be very uncomfortable. As noted above, a low U-value and low solar absorption will keep the glazing surfaces closer to room temperature. Radiant heating and cooling systems can provide some advantages in control of the thermal environment but are not yet commonly used in buildings. Good low-energy design can make them viable, however, as their impact in the space becomes more influential in delivering the required energy outputs and acceptable thermal comfort conditions.

- **Design only goes so far in reducing energy – occupant behavior plays a big role.** Ongoing occupant feedback and education can be a positive influence if occupant control strategies are effectively utilized. If they are ignored, the benefits of the design may not be realized.

INTEGRATION ISSUES

Integrated Design Process

The objective of integrated design is to view the building as a whole and understand the interactions between systems. In doing so, the design team is able to make logical decisions about building design and all the systems that support it, with the aim of capitalizing on system synergies and use of multi-purpose features whilst minimizing systems conflicts. Through this approach, it should be possible to optimize performance to minimum life-cycle cost and lowest energy use intensity. The process should continually restate objectives and goals, refocusing the design team at each stage of the design process and building a collective mindset amongst the team. Using this approach, it is less likely that the design will be subject to drift.

Architecture

Provide adequate space for mechanical equipment, or system efficiency may be impaired, and allow for adequate maintenance access. Architectural decisions that reduce heating and cooling loads mean less space required for equipment—smaller mechanical rooms, smaller shafts, and less ceiling plenum height. Resolve aesthetic concerns with visible mechanical elements such as exposed ducts, diffusers and grilles, facade louvers, and rooftop units.

Interior

Tall partitions may disturb intended air flow for open offices. Diffusers, grilles, exposed ductwork, and thermostats may be important visual elements to coordinate. Contractors should be given accurate placement specifications that meet both functional and aesthetic desires. Diffuser location should take into consideration any potential for draft or radiative comfort issues (see Occupant Comfort, below).

Lighting

Diffusers and light fixtures should be coordinated; fixtures may disrupt the intended air flow if surface-mounted or pendant-hung, or if placed too close to diffusers. Account for the effect of lighting control on lower heat gains from electric lighting.

Cost Effectiveness

An efficient mechanical system reduces operating costs.

A building with reduced mechanical loads requires less mechanical equipment space and therefore yields more leasable space.

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A thermally comfortable building retains tenants.

A cost-benefit study will show the trade-offs available between architectural and mechanical elements; advanced glazings and effective shading devices can reduce mechanical first costs and operating costs.

Occupant Comfort

Remember that thermostats don't respond to surface temperatures. Don't put them in direct sun or over computers. Increase thermal comfort by focusing on the radiative component of glazing in the glazing selection. Consider the use of radiant conditioning systems, such as radiant panels, to increase comfort where discomfort is largely due to radiative asymmetry; or as a last resort, wash large glazing areas with conditioned air to reduce radiant heat transfer. This approach is not recommended as a first course of action due to the increased energy used to provide the conditioned air.

! PROVISOS

- Rule-of-thumb or simplified load calculations do not accurately model the energy behavior of today's high-performance windows, due to the complexity of window behavior and properties. Use these tools initially if needed to understand general trends. Use more refined tools that properly model glazing, shading, and daylight for design development trade-offs and to help make final decisions.
- Energy calculations sometimes indicate that glazing with a higher U-value uses less energy in commercial buildings in mild climates. This has not been empirically supported. Remember that modeling software does not always account for all of the complex physical behavior of buildings.
- Solar heat gain coefficients with different associated visible transmittances should be explored and the best combination selected to achieve desired performance. Additionally, manually operated interior shading should not be considered a reliable means for solar heat gain reduction, due to unpredictability of user behavior.

TOOLS & RESOURCES

- **ASHRAE** The American Society of Heating, Refrigerating and Air Conditioning Engineers offers a wide range of technical support materials, including the monthly A*SHRAE Journal*. See www.ashrae.org/ for a publications list. For *ASHRAE Journal* subscription information, see www.ashrae.org/publications/page/540.
- **Books** ASHRAE has many book titles available addressing maintenance (see above), including the useful *ASHRAE 2011 HVAC Applications Handbook* and *2009 Fundamentals Handbook.*

  Mechanical and Electrical Equipment for Buildings, 10th ed. by W. Grondzik, A. Kwok, B. Stein, and J. Reynolds (Wiley, 2005) is a good general reference.

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Building Control Systems, 2nd Ed. by V. Bradshaw (Wiley, 1993) is another helpful general reference.

- **Utility Company** Many utilities offer incentives for energy-efficient mechanical equipment. Inquire at your local utility about new construction or retrofit programs.
- **Load Calculations by Hand** This method is cumbersome and rough, but acceptable for a first cut at peak energy demand. ASHRAE publications and the books above are good sources for instructions.
- **Energy Analysis Software** These programs simulate building energy use, a useful way to compare energy-efficient alternatives, estimate energy costs, perform life-cycle cost analysis, show code compliance, estimate peak power demands, disaggregate energy end uses, and—most commonly—compute loads for HVAC equipment sizing. They require extensive learning time and subsequent user experience. Simpler, easier-to-use analysis software exists but it does not have the level of accuracy required in the most detailed phases of daylighting design.

  EnergyPlus is the best example. A DOE-developed simulation tool, it models all facets of building energy systems, but this ability results in inherent complexity, and only people with the appropriate training will be able to utilize it effectively and derive consistent, reliable results. Therefore for detailed HVAC modeling, a mechanical design or energy modeling firm should be engaged to do this work. The software is available at: http://apps1.eere.energy.gov/buildings/energyplus/. LBNL has released a new easy-to-use interface for EnergyPlus called Simergy. It is available at http://buildings.lbl.gov/simulation-research-group.

- **ASHRAE/IESNA** Standard 90.1 Compliance and ASHRAE Publications www.ashrae.org/
- **Consult the International Building Code and International Mechanical Code** (www.iccsafe.org/) for compliance issues.
- **Consult Local or State Energy Codes** A reference to state energy codes is available through the U.S. Department of Energy's Energy Efficiency & Renewable Energy website (www.energycodes.gov/adoption/states).
- **Energy Consultants** Helpful for additional daylighting expertise, software analysis, code or standard compliance, and mechanical system optimization.

CHECKLIST

1. Ensure that the project's mechanical engineer is involved in the decision-making process.
2. Do mechanical energy calculations early to assist in glazing selection, shading scheme, and other architectural opportunities to reduce loads.
3. Refine these calculations as design develops. Remember to use actual glazing properties, accurately reflect shading (both designed and that resulting from other structures or objects), and full credit for lighting reductions due to daylight controls.
4. Use energy simulation data in the cost/benefit analysis to explore trade-offs between envelope improvements, and mechanical first and operating costs.

5. Look for further opportunities to reduce peak loads and energy use throughout schematic design and design development, and consider the potential role of the building within a smart grid.
6. Plan for HVAC controls, an energy management system, integration with other building system controls, commissioning protocols, and maintenance procedures concurrent with mechanical system design.
7. Flag potential space and ceiling conflicts.
8. Coordinate visible mechanical elements with other design team members.
9. Discuss comfort and loads with project team prior to final envelope design.

Integrating Mechanical Design

Good Practice

1. Discuss ramifications and opportunities of envelope decisions on comfort and energy with the design team during early schematic design.
2. Select energy management strategies that are compatible with lighting controls.
3. Do preliminary load calculations partway through schematic design, using assumptions where necessary, to assist architectural decisions.

Better Practice

In addition to the above:

1. Do load calculations with credit taken for daylighting controls and with shading and glazing properly modeled.
2. Plan for maintenance procedures, controls integration, and commissioning now.

Best Practice

In addition to the above:

1. Perform several rounds of load calculations, starting from early schematics, to maximize benefit of energy analysis to architectural decisions.
2. Use software that can model building energy use and daylight. Consider the use of an outside energy consultant if this software expertise is not available to the design team.

7 Lighting Coordination

OBJECTIVE: Design the lighting system to best integrate with daylight and provide controls for high-performance, comfortable, and energy-efficient lighting.

- Lighting design must include daylight from the beginning
- The cost-effectiveness of daylighting depends primarily on lighting energy savings
- Cost effectiveness may be further supported by reducing electricity demand and providing the facility for demand response
- Effective controls help capture maximum savings from daylighting

KEY IDEAS

Use a Lighting Strategy that Integrates with Daylight

- **Make daylight integration part of lighting design from the beginning**. Lighting strategy, fixture selection, and method of control are all affected by the goal of daylight integration. For buildings primarily occupied during the day (e.g., schools, retail) that do not have tasks requiring higher illumination at night, design the electric lighting to augment daylight.
- **Choose a task/ambient strategy for easy integration with daylighting.** Daylighting can provide required ambient lighting for most operating hours. Provide user-controllable task lights to assure that task illumination requirements are met at all locations when supplemental lighting is necessary. Users near windows will often use daylight as their primary task source. In general, design ambient illumination levels to be significantly less than task levels (but not less than 1/3 of task levels).
- **Use direct/indirect lighting to avoid glare and match daylight distribution.** Direct/indirect lighting keeps the brightest light sources out of view, and is a good pair with daylight spatial distribution. These systems require a clean, high-reflectance ceiling and adequate ceiling height. Don't use pendant-style direct/indirect fixtures if ceiling height is less than 9' 6". For best light distribution, pendants should be hung at least 1' 6" from the ceiling. A direct/indirect system will generally be more efficient at providing task illuminance than an indirect system.

Figure 30 illustrates some ceiling-mounted lighting options.

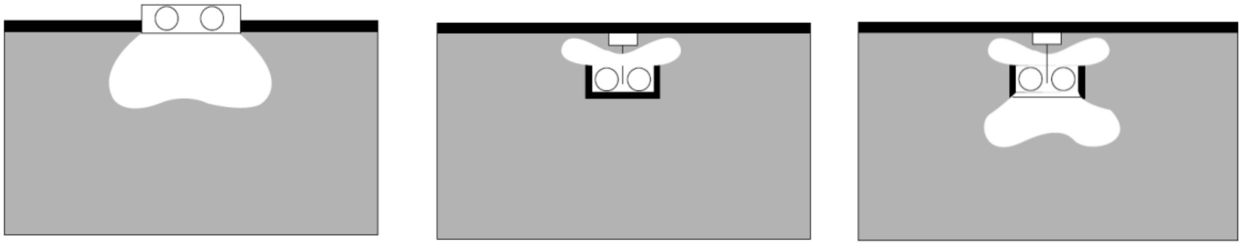

Figure 30: Illustrations of typical candlepower distribution for different ceiling-mounted lighting designs; left, direct lighting; center, indirect lighting; right, direct/indirect lighting

- **Balance the light in a deep room.** In daylighted spaces greater than 15 feet in depth, provide vertical illumination on the back wall (using ceiling fixtures within two feet of wall or with wallwashers) to balance luminances and prevent a gloomy feeling. Use walls or partitions with high reflectance, light-colored surfaces.
- **Organize fixture layout and controls to match daylighting distribution.** To ensure adequate illumination, group fixtures by areas of similar daylight availability (e.g., in rows parallel to the window wall). Luminaires should be associated with each window. Arrange lighting circuits in zones parallel to the window wall for daylighting even if controls are not specified, to allow the possibility for controls to be added as retrofit. Recircuiting is generally difficult and costly in a retrofit project. However, retrofits for daylighting control are possible even with non-optimal circuiting, due to newer dimming and ballast control technology and wireless controls.

Choose the Right Hardware

- **Use efficient lamps, such as T8s and T5 tri-phosphor fluorescent lamps or LEDs and dimming ballasts.** Fluorescent lighting is the source of choice for both dimming and switching applications, because it can be efficiently dimmed over a wide range without changes in color and can be turned on and off virtually instantaneously. Most dimming fluorescent ballasts dim to 10%–20% light output (@ 30% power), but “architectural” dimmers dim to 1% (these dimmers come at a cost premium).
- **Choose energy-efficient hardware.** No matter what the lighting strategy, always choose the most cost-effective lighting technologies and the most effective controls available within the design budget.

Maximize Visual Comfort

- **Follow recommended practice guidelines regarding downlight glare**. To minimize direct glare, electric lighting should generally have a minimum Visual Comfort Probability (VCP) of 80% for computer-based tasks and 70% for other office tasks. Note that VCP is not defined for indirect lighting or any fixture with an upward component. VCP is defined as the percentage of people who find the lighting free of discomfort glare.
- **Keep ambient lighting low for users of computer screens.** If computers are present, ambient lighting should not exceed 30 fc (300 lux). But make sure that user-controlled task lighting is available for hard-copy tasks. A rule of thumb for spaces with video display terminals (VDTs): provide as little

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light as possible on computer screens, 15–30 fc (150–300 lux) for surround lighting, and 50 fc (500 lux) on adjacent hard-copy tasks. Download the IES RP-1 Guidelines (see details in section 12, TOOLS AND RESOURCES SUMMARY) or view other IES literature for assistance.

- **Keep lamp reflectance out of computer screens.** Limit the potential for reflected glare from ceiling lights in computer screens. If ceiling downlights are used, limit high-angle brightness to no more than 850 candelas per square meter at 55 degrees altitude (preferably) and at 65 degrees (definitely). When installing computers, verify that the placement of the computer does not result in reflected images of ceiling fixtures in screen. If reflections are evident, adjust position or locations of the screen or apply anti-reflection filters to the computer screen face.
- **Watch ceiling brightness with computers.** Indirect or direct/indirect lighting is good for computer users, but observe some rules about the ceiling brightness. Ceiling luminance for on-screen tasks ideally has a ratio across the ceiling of less than 4 to 1. Ceiling and wall surface luminances should be less than 850 candelas per square meter at any angle as averaged over a 2 by 2-foot (0.6 m by 0.6 m) area. In open plan areas, VDT workspaces benefit from lower, uniform lighting.
- **Avoid brightness glare from exposed lamps in the field of view.** Obstruct direct views of sources to avoid glare. Direct/indirect lighting is one method. Careful space planning is another.
- **Use lighting strategies to balance window glare if anticipated.** Keep luminance of interior environment high to balance window brightness if there are no architectural modifiers such as deep reveals, shading devices, or elements to filter daylight. (See Section 4, GLAZING SELECTION, and Section 5, SHADING STRATEGY, to control window glare). A slight wall or ceiling wash towards the back of the space (farthest area from window) is generally effective. A small increase in energy use for this purpose is acceptable.
- **Balance lighting quality and energy efficiency.** Occupant comfort or satisfaction needs to be balanced with higher energy savings. Higher energy savings may not be cost-effective if they come at the expense of occupant productivity.

Coordination

- **Flag potential conflicts early**, such as furniture or colors that will interfere with light distribution, poor location or access for electrical rooms, and crowded ceiling plenums. Pick bright surround colors. Keep ceilings and walls as bright as possible.
- **Balance window glare with well-placed lighting.** Slightly raise the luminance of walls and ceiling regions away from the windows, to soften the contrast between the two. As noted above, this is especially important in deeper spaces.
- **Include calibration and maintenance plans in the construction documents.** Assemble a set of recommended procedures and schedules for calibration, other lighting system commissioning, operation, maintenance and replacement, and format in a clear and easy-to-use package. Make this documentation part of the lighting construction documents. Provide documentation that can be passed along to the ultimate occupants of the space so that they can understand how to best use the lighting systems and controls. The International Performance Measurement and Verification Protocol (IPMVP) is an excellent guide to the

various elements of commissioning and performance monitoring; for more details visit www.evo-world.org/.

INTEGRATION ISSUES

Architecture

Location of the windows directly influences lighting control strategies and placement of photocell sensors. Coordinate with lighting design.

Quality of the perimeter spaces depends on blending and balance between daylight and the very different nature of electric lighting.

Interior

Interior surfaces, and especially the ceiling, must be light-colored.

Coordinate workstations with window placement and fixture locations, especially for glare-sensitive workspaces (e.g., computers). Align VDT view direction parallel to the window wall.

Locations of partitions and other tall furniture should not interfere with daylight penetration. This may require reorienting partitions or using translucent panels rather than opaque ones.

HVAC

The lighting designer should supply a reasonable estimation of how much lighting power reduction is due to daylight controls, for the purpose of cooling load calculations. Expect the perimeter zones to have less than peak electric lighting loads at peak cooling periods (e.g., summer noon). Reduction of peak cooling loads should be an objective of the integrated design process, with elimination of unnecessary systems the ultimate reward. To unlock energy savings through integrated design, use energy modeling to determine the impacts of lighting on cooling loads. Estimates on lighting-associated cooling loads should inform estimates for required cooling capacity; carefully reviewing lighting design may help identify opportunities for cooling capacity reduction. Locations of lighting fixtures and supply/return registers should be coordinated so as not to disrupt air flow.

Cost Effectiveness

Cost of fixtures ranges widely depending on the aims of the designer/installer and depending what they wish to achieve. However, cost effectiveness of a lighting system may ultimately depend on occupant satisfaction and owner avoidance of future retrofits.

Many efficient lighting technologies have short paybacks and often qualify for utility rebates, due to the very large percentage of building energy use consumed by lighting. Costs of other technologies (e.g., dimmable electronic ballasts) continue to fall. Be sure to use current cost estimates in your analysis. Details of rebates can be found in the

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Database of State Incentives for Renewables and Efficiency, available online at www.dsireusa.org.

Occupant Comfort

A lighting system is not successful if occupants cannot comfortably perform their tasks.

Task illuminance under direct lighting is highly sensitive to the task location with respect to fixture and partition locations. Because lighting is fixed in place often long before furniture and partitions are installed, and because furnishings may be relocated in the future, direct lighting systems may be more likely to lead to occupant dissatisfaction than indirect systems will. An appropriate solution is to allow occupants to control overhead lighting for their workspace or office, or to provide supplementary task lights. For the latter to work, overhead lighting must not be too bright; it is better to set lighting levels to achieve an acceptable but low work surface light incidence.

PROVISOS

- Designing for 30–50 fc with a maximum of 0.9 watts per square foot for installed lighting is an easily achievable target. With efficient equipment and sensitive design, high-quality lighting can be achieved at 0.6 watt per square foot or even lower.
- Do not use pendant-style fixtures with ceilings less than 9 ft (2.74 m).
- Simple changes in a building, like wall redecoration or furniture relocation, can have a strong influence on lighting systems in distinct spaces. If such changes are anticipated, a more flexible approach to lighting is recommended.
- Consider dimming controls for all daylighting systems, as they are more versatile, less annoying, and provide larger savings. Costs have been high but are falling.

TOOLS & RESOURCES

- **Design Professionals** Use a lighting specialist whenever daylighting controls are planned. Lighting designers (as distinct from electrical engineers) are recommended in general for a higher-quality end result. The cost for the added service is easily recouped in ensured performance and occupant satisfaction, and lighting designers offer the best chance to achieve energy savings.
- **Books** There are many titles available on general lighting design, but less to assist high-performance lighting design with daylight controls. The IES may be the best source for literature. The lighting designer should distinguish between recommended and standard illuminance levels in the reference materials, reflecting the fact that there is an acceptable visual comfort range.

  For a list of currently recommended titles, visit the Tips for Daylighting website:

windows.lbl.gov/tips-for-daylighting

Advanced Lighting Guidelines, 2009, from the U.S. Department of Energy, is a thorough and informative guide to all aspects of various lighting technologies. It is also online at www.algonline.org/.

- **IESNA** The Illuminating Engineering Society is a resource for literature, standards, codes, guidelines, and a monthly journal covering lighting, daylighting, and visual comfort. These materials provide useful, up-to-date technical information. Local chapters also may offer classes or other resources. The IES handbook is an invaluable reference for detailed technical guidance and information. For publications visit their website at www.iesna.org.
- **EPRI** The Electric Power Research Institute has a strong collection of fact sheets, brochures, guidelines, and software available. Visit their website at http://lro.epri.com for more details.
- **LBNL Lighting Systems Research Group** is a good source of information on all aspects of energy-efficient lighting practices. For a publications list, visit the group's website at http://lighting.lbl.gov.
- **Lighting Research Center,** at Rensselaer Polytechnic Institute, is source of general information about lighting products and practice. Contact them at www.lrc.rpi.edu.
- **California Lighting Technology Center,** at the University of California, Davis, is a good source of information on energy-efficient lighting and daylighting technologies. Contact them at www.cltc.ucdavis.edu.
- **Utility Company** Many utilities offer incentives for energy-efficient lighting equipment. Inquire at your local utility about new construction or retrofit programs.
- **Calculation Methods** Well-established methods exist for calculating light levels with a proposed design. The best source for reference material on this topic is the IES (see above). Many lighting designers use software (DIALux, and AGI32 are good examples) in place of tedious hand calculations. A package which is capable of addressing daylight and electric light integration is recommended.
- **Scale Models** A physical model, built accurately with materials that match intended finish reflectances and viewed outdoors, is a good tool to assess window glare, daylight distribution, and quality of the daylighted environment. This is a quick and easy study activity useful for the architect and the lighting designer to perform together. See Section 3, ENVELOPE AND ROOM DECISIONS, for more information.
- **Full Scale Mock-ups** This is the only method for truly viewing the intended lighting scheme before construction. This can be costly and time consuming unless a local utility or lighting manufacturer offers assistance. As an example of what is possible with large building owners, see the experience of the *New York Times*, with a complete lighting and daylighting mock-up with extensive

testing. For more details on their daylighting efforts, see http://windows.lbl.gov/comm_perf/newyorktimes.htm.

CHECKLIST

1. Review the fenestration design and intended space plan for an initial estimate of daylighting and glare concerns.
2. Estimate daylight levels through calculations, computer modeling, or physical model photometry.
3. Select lighting strategy and type of control, depending on two points above.
4. Lay out the lighting system, coordinating with window placement and daylighting control zones. Strive for an installed lighting power density lower than the energy code maximum.
5. Estimate electric lighting illuminance levels. Determine daylight and electric lighting distribution throughout the lighting zone and ensure that dimming zones maintain a uniform distribution.
6. Select the most efficient technologies available that meet design objectives and are within the project budget. Check with your utility about lighting programs.
7. Calculate the expected electric lighting savings due to daylight controls, for use in a cost-benefit analysis (see Section 11, COST-BENEFIT ANALYSIS). Review cooling load estimates arising from electric light savings. and assess opportunities for cooling capacity reduction. Provide the expected lighting power reduction at peak times to the mechanical engineer for cooling load calculations.
8. Review glare issues with design team. If window design or selection of window coverings is not anticipated to be adequate, compensate for window glare by balancing interior luminance distribution with the lighting design.
9. Flag potential conflicts with interior design or other elements.
10. Include performance specifications, control system documentation, calibration instructions, other commissioning recommendations, and a maintenance plan with the lighting design documents.

LINKS

Achieving Energy Savings with Highly-Controlled Lighting in an Open-Plan Office

http://gaia.lbl.gov/btech/papers/3831.pdf

Lighting Coordination

Good Practice

1. Design a direct/indirect lighting system at no more than 0.9 watt per square foot, with supplemental task lighting if necessary, fixtures grouped with

windows and by daylighting zone, and special attention to glare in computer workspaces.
2. Estimate daylight levels before final system design and control strategy selection.
3. Check for utility rebates before the final design and specification.
4. Include previously described documentation with the construction documents.

Better Practice

In addition to the above:

1. Include a lighting specialist on the design team.
2. Review glare concerns and take appropriate measures.

Best Practice

In addition to the above:

1. Consider multiple lighting alternatives.
2. Use lighting software and/or physical model photometry to estimate daylight levels and the nature of the daylighted space.
3. Construct and evaluate a full-scale mock-up of a typical workspace.

8 Sensors and Controls

OBJECTIVE: Design and install a control system to dim lights and/or turn them off when there is adequate daylight.

- Reduce lighting energy consumption with automatic controls.
- Use a lighting specialist for best results with the control system.
- Provide the capability for demand reduction and demand response, to support a cost-effective daylight harvesting system.

KEY IDEAS

General

- Sensors “measure” light by looking at a wide area of the office floor and work surfaces from a point on the ceiling. The sensor’s signal is then used by the control system to dim the electric lights according to the available daylight. These simple components are what we use to harness the power of daylight.
- Controls can respond to many variables. To save lighting energy, controls are typically designed to respond to daylight and a host of other inputs (e.g., occupancy sensors, weekend/holiday/nighttime schedules).
- Compare conventional controls infrastructure with wireless controls when developing your design. Wireless controls are expected to be an important part of the controls marketplace due to their inherent flexibility.
- Include all control documentation in the construction documents. This should include clearly developed control schematics, control sequences, calibration instructions, maintenance plans and checklists, and clear testing procedures.
- Take special care to document integrated control systems. Control schematics are critical where different building systems (e.g., lighting, mechanical) come together. Identify responsibilities where integrated systems overlap, such as who adjusts each component, which warranties apply where, and so on.

Type of Lighting Control

- Choose either dimming or switching hardware for a particular lighting zone, which will also ideally have occupancy-based lighting control. The choice of dimming or switching (on/off) equipment is partly dictated by the control strategies selected:

  Daylighting. Lights are dimmed (reducing light output from the lamp) or switched (reducing the number of operating lamps in each fixture) in response to the interior daylight level.
  Scheduling. Lights are turned on, off, or dimmed according to day/night/holiday whole-building schedules.

Lumen Maintenance. Captures savings by dimming new lamps until their light output has dropped down to the design level through aging and dirt depreciation. Lumen maintenance employs the same hardware used for daylight dimming and saves up to 14% of lighting energy.

Tuning. Fine-tune lighting levels after occupancy. Fine tuning is a control strategy where lighting is dimmed to meet specific local ambient or task lighting needs, and may save up to 12% of lighting energy.

Load Shedding. A schedule of setback light levels can be agreed upon to accommodate needs for load reduction or demand response. This should prioritize gradual dimming and then switch off of lights in non-critical or transitional spaces and reduction of workspace lighting to meet minimum working (or egress) requirements.

- **Choose dimming hardware if daylighting, lumen maintenance, or tuning are the selected control strategies.** With the cost of dimming ballasts still high, dimming control is still more expensive than switching control (although ballast costs continue to fall) but it is the best for implementing these strategies. It is also generally the most acceptable to occupants, because changes in the electric light levels are least disturbing. Daylighting and lumen maintenance strategies integrate well, since they use the same hardware. Dimming is not cost effective in non-daylit areas unless coupled with occupancy or scheduling controls. Dimming can capture all possible daylighting savings. For spaces with adequate daylight all day long and for non-critical visual tasks, switching may be acceptable, since the lights may adjust only once or twice during stable daylight hours. Scheduling (either with automatic time controls or occupant sensors) can be implemented effectively with switching controls. Switching technologies are generally inexpensive, have a short payback period, and typically do not require specialized expertise to install. They are compatible with other lighting systems and are easily adjusted. Figure 31 shows payback curves for dimming and switching options.

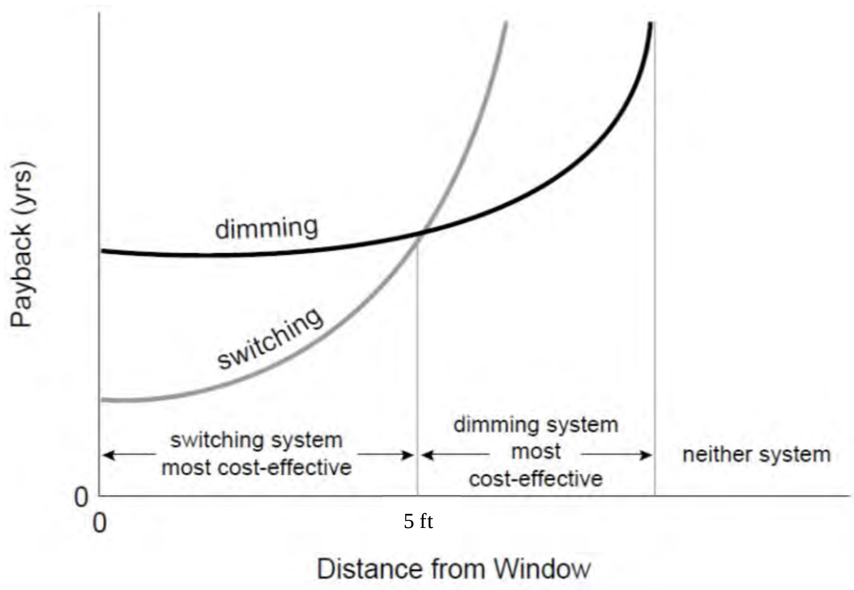

Figure 31: Dimming/Switching payback chart

- **Select switching for daylight control with caution.** This hardware is less expensive than dimming, but has the disadvantage of changing light levels abruptly. Switching is acceptable in intermittently occupied spaces or in spaces with fairly constant and adequate daylight all day (e.g., clear weather, large windows). In zones less than five feet deep from windows, simple on/off switching is the most cost-effective, especially if daylight is abundant. Do not use switching when it is anticipated that lights will turn on and off during occupied hours; case studies show occupants find this disruptive and will disable the system.
- **Do not count on manual controls**. Manual switching is already required by some codes, such as Title 24 in California, but it is generally not well used by the typical office occupant. Use automatic controls to ensure savings.
- **Use dual-level switching.** This wall-mounted switch reduces light level by turning off individual lamps in 2-, 3-, or 4-lamp fixtures. This is the minimum required by some codes, for example in California.
- **Use programmable time controls for a more sophisticated form of scheduling control than simple time clocks.** This is good for facilities with many different daily schedules. Sweep-off control (automatically sweeps off lights after building closing hour, after an initial warning) is effectively implemented with programmable controls and a manual override via wall switch or phone. This control strategy typically yields 15% savings in lighting energy and is helpful for picking up lights left on by after-hours workers or cleaning crews. If sweep-off control is used, wire lighting circuits back to the electric panel for operation by building controls.
- **Use occupancy sensors.** These are easily installed in wallboxes in lieu of manual switches. But only use wallbox occupant sensors if the sensor will have an unobstructed view of the space. If the sensor is obstructed, use a ceiling-mounted sensor instead. Occupancy control yields 15%–30% savings and is highly cost effective. Some units come with integrated photocells for both daylight and occupancy sensing.
- **Zones with daylighting should be separately switched from other zones, even if daylight controls are not installed.** This allows for future installation of daylighting controls if the project budget does not allow them in initial construction.

Zoning

- **Control zones should match areas of similar daylight availability and space function** (e.g., conference, computer). In open-plan areas with a uniform window facade, group fixtures in runs parallel to the window with separate control for each row in from the window (for strip windows) or in groups associated with each window (punched windows).
- **Design control zones to correspond to window shading device zones.** For example, if an individual office contains manually operable drapes or blinds, the entire office would generally form (at least) one control zone.
- **Limit the number of zones where possible.** Costs go up with the number of control zones, so make zones as large as practical. However, too large a zone can lead to some areas being underlit.
- **Any circulation space running along a window wall should be a separate control zone.** If this area is well-daylit, its lighting can often be switched off. The curves in Figure 32 show relative light levels from both

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daylight and electric light sources. As the daylight level falls off with distance from the window, the electric lighting makes up the difference so that total illumination is evenly maintained at design levels throughout the room.

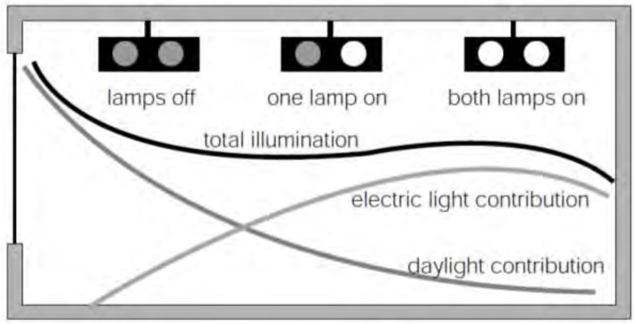

Figure 32: Schematic representation of lighting in a room with stepped lighting controls.

Daylight Algorithm

- **Daylight algorithms accommodate complexity.** These are the "smarts" that tell the electric lights what to do. Since the intensity and spatial distribution of daylight changes over time, these smarts are designed to provide sufficient light under these complex conditions. Figure 33 illustrates the process through which the ceiling-mounted photosensor adjusts the electric lighting as required to maintain the design level of total lighting through reading both electric light and daylight in the space.
- **Closed- and open-loop are the two basic algorithms for daylight controls.** "Closed-loop" and "open-loop" are common control terms that indicate whether information is fed back to the system to achieve control objectives (closed) or not (open). Closed-loop systems that work with daylight may cause electric light levels to drop below design light level under some conditions. Open-loop systems cannot compensate for electric light losses (lumen maintenance strategy), but afford greater flexibility in calibration than closed-loop systems. They are also more "forgiving" to errors in sensor placement or field of view.
- **For switching systems, both the time delay and setpoint deadband should be independently adjustable.** With variable cloudy conditions, the deadband adjustment alone may be insufficient to prevent system oscillation between the ON and OFF state ("hunting").
- **For switching systems, control trigger points should be carefully set to avoid occupant dissatisfaction.** The light level at which the device switches off should be at least twice the level at which it switches on (i.e., twice the light level produced by the luminaire) to ensure that the design illuminance is met at all times.
- **System should be slow in response to sudden daylight changes.** The dimming response time (the time it takes for the system to respond to a sudden change in light level) is typically set around 30 seconds, to avoid an unnecessary response to temporary conditions like moving clouds.

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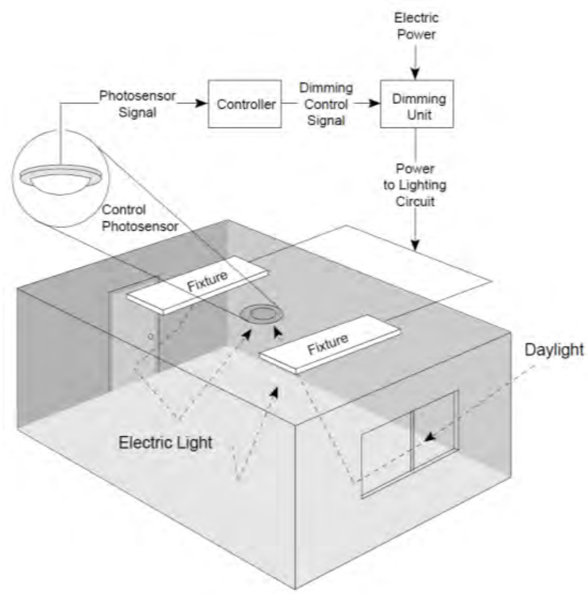

Figure 33: Schematic diagram of a room with a photoelectric dimming system

Sensor Location

- Place the sensor appropriate to the task location. In a room with only one task area, place the ceiling-mounted sensor above the task. In a room with more than one task area, place the ceiling-mounted sensor above the task that best represents the daylight available. Some controllers support inputs from more than one photosensor. This allows daylight to be sampled at more than one location.
- Sensor placement is determined by the daylight control algorithm. For closed-loop control systems, locate the sensor at a distance from the window equivalent to approximately two-thirds the depth of the daylight control zone. Photosensor location is less critical with open-loop systems, and can be compensated for during commissioning. With a light shelf and an open-loop control system, locate the sensor above the shelf.
- Sensor placement differs with the type of lighting system. With indirect and direct/indirect lighting systems, the photosensor should be located in the plane of the fixtures aimed downwards. Make sure that the sensors cannot directly "view" the electric lights they control. For direct lighting systems, recess the photosensor(s) in the ceiling.
- Sensor field of view is important. The photosensor's field of view should not be too narrow and restricted or the sensor will be too sensitive to small incidental changes (e.g., papers moving on a desk, people nearby). A ceiling-mounted closed-loop sensor should have a large field of view and be shielded from direct light from the window. Some sensors come with sun shields for cases where the cell cannot be placed far enough from the window. For switching systems, the photosensor (often a photorelay) is located so that it "views" the external daylight source with minimal (or no) view of the electric lights that it controls.

Hardware

- If you're using fluorescent lights, choose dimming electronic ballasts, now available from several vendors. All dimming ballasts operate fluorescent lamps in rapid-start mode, i.e., the fluorescent lamp cathodes are supplied with power at all times during operation.

- Choose a system with sufficient control flexibility. Switching systems should allow independent control of the ON setpoint light level (the light level on the photorelay that causes the lights to switch ON) and the OFF setpoint.
- Combine occupant sensors with photocells. Many occupant sensors (especially wallbox units) include daylight photosensors, although this is not an optimum location for sensing task daylight. If the photosensor determines that the daylight level is adequate, the occupant sensor will not turn on the lights automatically when the occupant enters. The occupant may manually switch on the lights if desired.
- Ensure compatibility of hardware components and controls infrastructure, which may be conventionally networked or wireless; especially when using controls from several different manufacturers (e.g., ballasts, ballast controllers, sensors, lamps). However, many integrated systems today are able to communicate with one another.

Occupant Satisfaction

- Switching hardware will be more acceptable if coupled with split-wired lighting. Split-wiring, also known as stepped switching, allows lights to be switched in discrete steps (OFF, 1/2, FULL or OFF, 1/3, 2/3, FULL), so the changes are not so abrupt.
- Avoid daylight controls on downlights. Switching hardware with daylighting control is generally not acceptable for downlight fixtures, especially if fixtures are turned on and off (rather than split-wired), because occupants find it disruptively noticeable.
- Occupants may sense that the system is beyond their control. In these cases, visible manual controls are important, and manual overrides, while they may result in lower savings, will increase user satisfaction. Another problem witnessed in case studies is that an office with lights on signals that its occupant is in the building. Dimming strategies may be useful here. These issues should be discussed with the building owner during design and followed up with occupant education during the commissioning and occupancy phases.
- Occupants will disable a system they find unsatisfactory. There may be any number of causes for negative user reaction to automatic controls. Choose an approach to controls that will most likely meet user needs, and ensure that the system will be installed and calibrated so that it operates properly. An unpredictable or poorly functioning system is a major cause of occupant dissatisfaction.

INTEGRATION ISSUES

Architecture

Window location, skylight location, task location, and shading strategy affect control zoning.

Interior

Space planning, finishes, and furnishings are strongly tied to control zoning.

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HVAC

Perform load calculations accurately, with lights dimmed at peak cooling conditions. The lighting designer should supply expected lighting power reductions to the HVAC designer, or use advanced energy analysis software that can model daylight controls. Control selection should include consideration of likely impacts on peak cooling requirements and energy and cost benefits associated with reduced operation of mechanical systems.

Lighting

Control system and hardware must be compatible with other lighting equipment.

Cost Effectiveness

Most building controls designed for energy efficiency are highly cost effective, especially when supported by utility incentives. Simple lighting controls such as occupancy sensors or scheduling controls are especially cost effective.

Occupant Comfort

Tolerance for fluctuation in electric lighting levels varies. We experience lighting fluctuation all the time in the natural environment but tend to find changes in the artificial environment disturbing.

Some people are uncomfortable with a highly automated environment. Others may want lights on for non-task reasons (e.g., employee is "in" the office). These and other reasons can cause occupants to disable the system. Discuss these issues with the building owner, building manager, and occupants.

! PROVISOS

- Never turn off lights automatically at night in an occupied space without a prior warning, such as flashing the lights ten minutes before shut off. This gives occupants a chance to manually override the shutoff.
- Calibration of automatic daylighting systems and occupant sensors should always be performed after furniture installation is complete (see Section 9, CALIBRATION AND COMMISSIONING).
- Daylight levels are hard to predict; however, it's important to have a good estimate of expected daylight in order to choose between dimming and the less expensive switching hardware. Photometry in a scale model is also an option, but computer-based calculation is increasingly used; both DAYSIM and RADIANCE can help you understand daylight levels in different parts of the occupied space.
- Savings from daylighting controls depend on their regular and maximum use. This in turn depends on adequate daylight entering the space. Be sure window glare has been properly addressed during design so that occupants will not always be deploying opaque window coverings to control glare.
- Provide building occupants with instructions on how to use the daylighting/lighting controls. Building users are frequently given insufficient information to allow them to control their working environment, which leads to dissatisfaction and a loss in productivity.

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- Be sure automated lighting controls will be acceptable to the building occupants on principle. Dissatisfied occupants frequently disable lighting control systems for a variety of reasons, only some of which are related to comfort or visual performance.
- Occupants may inadvertently disable controls by rearranging furniture, placing portable heaters near occupancy sensors, etc. Avoid this by educating occupants as to the function and operation of the control system.
- Note this section does not treat mechanical HVAC controls, as these are not generally linked directly with daylight controls. However, other lighting controls can be integrated with mechanical controls (occupancy sensors are a good example).

TOOLS & RESOURCES

- **Design Professionals** The use of a lighting designer with experience in daylighting controls is highly recommended.
- **Manufacturers** This is the primary source of assistance available for control system products. The more complex the system, the more critical it is to work closely with the manufacturer through design, calibration, and commissioning.
- **IESNA** The Illuminating Engineering Society is a resource for literature, standards, codes, guidelines, and a monthly journal covering lighting, daylighting, and visual comfort. These materials address a large range of useful and up-to-date technical information. Local chapters also may offer classes or other resources. For publications, visit www.iesna.org.
- **EPRI** The Electric Power Research Institute has a strong collection of fact sheets, brochures, guidelines, and software available. Visit www.epri.com for more information.
- **Calculation Methods** Accurate estimation of energy and peak demand savings due to daylighting controls is complicated and is best accomplished with advanced energy simulation software that can model daylighting (see Section 12, TOOLS AND RESOURCES SUMMARY).
- **ASHRAE** The American Society of Heating, Refrigerating and Air Conditioning Engineers offers a wide range of technical support materials for mechanical systems, including the monthly *ASHRAE Journal*. Up-to-date controls information may be found in this literature; visit www.ashrae.org/ for more information.
- **Utility Company** Some utilities offer incentives for controls in both new and retrofit projects. Inquire at your local utility company about these programs.
- **Books** Controls are changing so rapidly, especially in DDC (direct digital controls) and HVAC applications, that books on the topic are often quickly out of date. The most current information comes from manufacturers, the IES, and ASHRAE.

  Control Systems for Heating, Ventilating and Air Conditioning, 6th ed., by R. Haines and D. Little (Van Nostrand Reinhold 2006).

CHECKLIST

1. The design team should discuss controls, occupant behavior, and occupant expectations with the building owner.
2. Establish the zoning strategy to assist in determining the control strategy.

3. Select either switching or dimming hardware for each zone, depending on the control strategy.
4. Meet or exceed all lighting control requirements stipulated in your local building codes.
5. Don't rely on manual controls for savings.
6. Consider programmable time controls, occupancy sensors, and lumen maintenance, which are all good strategies for energy efficiency on top of daylighting.
7. If daylight controls get cut from the budget at this point, switch daylighted zones separately anyway, to allow for daylighting controls in the future.
8. Lay out control zones to match daylight availability and space usage.
9. Choose the most appropriate daylight control algorithm.
10. Specify proper sensor locations, depending on lighting system, task locations, control algorithm, and sensor field of view.
11. Choose the right hardware.
12. Take extra time to coordinate any integration between control systems, such as an occupancy sensor that triggers both lights and a variable air-volume (VAV) damper.
13. Include full documentation of controls, along with calibration and maintenance plans, in the construction documents.
14. During the design, commissioning, and occupancy phases, address occupant satisfaction and education.

Approach to Sensors and Controls

Good Practice

1. Use occupant sensors, and try to get a system that will be able to easily integrate daylighting controls in the future.
2. Use programmable time clocks and sweep-off control for after-hours savings.
3. Provide building user groups (e.g., O&M staff, office workers) with information on operation of daylighting/lighting controls
4. Follow local building code control requirements.

Better Practice

In addition to the above:

1. Include a lighting designer on the project team.
2. Use software to support your analysis of different controls strategies.
3. Use dimming daylight controls as much as possible in perimeter zones.
4. If the budget is restricted and daylight is abundant, use stepped switching instead of dimming hardware in perimeter zones.
5. Use simple on-off switching elsewhere.
6. Use occupancy sensors wherever appropriate.
7. Take care to anticipate occupant dissatisfaction with controls.
8. Make the control documents, including calibration and maintenance plans, part of the construction documents.

Best Practice

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In addition to the above:

1. Perform computer analysis to accurately estimate control savings and use results in a cost-benefit analysis to help determine the best control strategy combinations and types.
2. Use daylighting controls in a lumen maintenance strategy.
3. Use occupancy sensors wherever appropriate. Combine them with the photocell in perimeter zones.
4. Follow or exceed local building code control requirements.
5. Work with building owner to resolve any anticipated trouble with occupant acceptance of the control system.
6. Explore opportunities to integrate lighting controls with mechanical controls and tie into the energy management control system, if any.
7. Verify that occupants are satisfied with the controls after calibration and occupancy. Educate occupants and the building manager about the function and purpose of the sensors and the control system.

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9 Calibration and Commissioning

OBJECTIVE: Commissioning ensures that all lighting control systems function as close to design intent as possible after installation and before occupancy. This is an especially important and mandatory phase of work, as it is a major factor in determining the energy and cost performance of the overall lighting design.

KEY IDEAS

General

- **Establish budget, responsibility, and commitment to commissioning from the earliest project phase.** Plan for this critical step from the beginning. Identify special areas of concern to the commissioning phase as they arise during programming and design phases.
- **Consider the design intent before choosing systems and which types of sensors to use.** For example, some offices may be more suited to daylighting controls than others or may require more light than others. A walkway may need less light than an office setting.
- **Solve problems before occupancy through commissioning.** Many operations problems are there from start-up, and successful commissioning puts the building on the right track.
- **Use the commissioning phase also as a training period for Operations and Maintenance (O&M) staff**. Use this time to acquaint them with building systems.
- **Carefully follow all appropriate commissioning steps.** This is a general sequence of activity:

    1. Visually inspect that each piece of equipment is in the right place, installed correctly, and calibrated to meet design specifications.
    2. Verify that all sensors have been properly placed.
    3. Verify local control of each piece of equipment.
    4. Test interactions between pieces of equipment.
    5. Test system wide operation under various anticipated scenarios.

- **Do not end the commissioning phase until the building is handed off to O&M personnel.** A successful hand-off includes:

    - Documentation of building systems for O&M staff use.
    - Description of O&M plans, schedule, and responsibilities.
    - Performance standards for all building systems.

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- O&M staff training.

- **Leave adequate documentation behind for O&M staff.** The following materials should be left on file in the building, easily accessible, and in an easy-to-use format:
    - An index or directory of all documents on hand.
    - Equipment specifications, line diagrams, manufacturer's warranties, and contact information.
    - Operating manuals.
    - Maintenance procedures.
    - Test, calibration, and balance reports.
    - All construction documents, including as-builts.
    - Emergency procedures.

Note: Several lighting systems today are self-commissioning and only require the installation step. Once the installation step is complete, sensors can adjust themselves to the room and even set up daylighting controls. Some systems can also be commissioned through a web or computer interface, and do not require users to calibrate the sensor at the sensor level. In fact, some systems only require the installer to indicate what type of room it is, and the system will automatically configure itself to common settings for such a room. User-friendly systems are becoming a market trend.

Why Calibrate the Lighting Controls?

- **Establish baseline conditions.** Calibration will set the relationship between the light level detected by the control photosensor and the output of the electric lights that the photosensor controls.
- **Make sure actual electric lighting is as expected**. The response of any light-sensing control system must be calibrated after installation to ensure that the response of the electric lighting system is appropriate to the design lighting conditions in the building space.
- **Make sure actual daylighting is as expected.** The daylight levels in any space are highly dependent on local conditions (e.g., window size and transmittance, shading device and strategy, percentage of clear versus cloudy hours, room reflectances). Some systems will automatically calibrate the daylighting no matter what time of day it is.
- **Make sure the system is in good working order.** Calibrating the system helps to uncover any installation errors and provides an opportunity for it to be repaired before the vendor leaves the job.

When to Calibrate Lighting Controls

- **As soon as possible after system completion.** While it is better to commission after the furniture is in place, fine tuning can be done later when tenant improvements are made.
- **Lumen maintenance calibration should be performed shortly after installation**, after the initial breaking in of lamps (fluorescent lamps should be burned for at least 100 hours at full light output to assure stable lamp operation). In a retrofit installation, fixtures should be cleaned and relamped prior to calibration.

- **Recalibrate after changes in a space.** Photosensors must be recalibrated when room paint, carpet, wall art, or furniture is modified. However, if a function of a room is completely changed, there are systems where it is easy to change the room type to adjust to any changes.
- **For a daylighting system, calibrate according to the manufacturer's recommended environment.** Some systems suggest that you calibrate during the night (e.g., closed-looped system), while others should be calibrated during the day (e.g., an open-loop system). Some systems also allow calibration at any time of the day. These instructions are usually clearly indicated in the manufacturer's instructions.
- **Coordinate lighting commissioning with other subsystem (e.g., mechanical system) commissioning activities.**

How to Calibrate Lighting Controls

- In general, the commissioning agent should be directed to follow manufacturer's calibration instructions or request that commissioning be included with installation. Commissioning of controls generally requires specialized knowledge and skills. The following guidelines may be additionally useful for experienced electricians.
- Calibrate each independently controllable zone (control group) separately.
- Select an appropriate stationpoint in each zone (Figure 34).

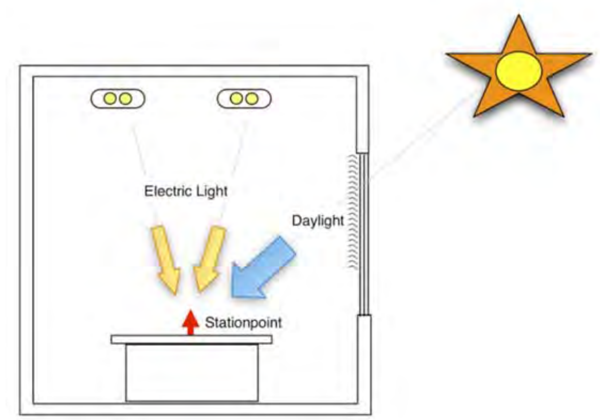

Figure 34: Diagram illustrating factors influencing selection of stationpoint

For each control zone, select one location that is representative of the daylighting and electric lighting conditions for that entire zone. This might be a desk that is a "typical" distance away from the nearest windows. A desk within eight feet of the control photosensor is a particularly convenient choice. These selected locations (at desktop height, or 30" above the floor, typically) are known as "stationpoints." For large control zones (over 500 square feet), it may be desirable to use more than one stationpoint to represent the entire zone. For an open-plan space with partitions, select the partitioned space nearest the photocell.

Calibrating an occupant sensor:

1. **First change the time delay to the minimum setting for calibration**. This allows the installer to test whether or not the sensor works, without waiting too long.
2. **Sit at a representative location and pantomime typical behavior, which can include typing at a computer.** If the lights time out with these motions, increase the sensitivity until it no longer times out.
3. **Set the time delay to 15 minutes for most spaces.** Some spaces, such as hallways, can have shorter time delays.
4. **Set light switch to Auto Off or Manual On, depending on what is preferred.** Almost all systems will have a default Auto Off.
    - Some systems have a walkthrough mode, which is useful for hallways and other spaces where occupants do not stay for extended time periods.
    - Some sensors will implement multiple sensors in order to detect occupant motion. This could include a motion sensor (such as a passive infrared sensor, PIR) and a sound sensor.

Daylighting systems may require commissioning at a critical point in the day, such as nighttime. These systems usually require that the desired light level (such as turning on the lights to the desired minimum light level) be measured, and then the system will match the minimum light required throughout the day. However, this also can be done on the sensor itself by, for example, turning a knob to indicate the desired light level instead of measuring the light output. Other systems will self-commission, and all the installer has to do is set up the sensor and ballast.

Commissioning Automated Shades:

- Follow the manufacturer's instructions or request that commissioning be included with installation.
- File any maintenance literature. Keep the manufacturer's recommended maintenance procedures for the shades on file with other O&M documents.

INTEGRATION ISSUES

Architecture

Calibration and commissioning activities have little impact on architectural design. If the architect is coordinating all construction documents (CDs), that person should ensure that the CDs include the calibration and commissioning plans. The same goes for maintenance plans.

Interior

Coordinate schedule of interior completion with the commissioning schedule. The system must be properly calibrated after the furniture and finishes are already in place.

HVAC

Commissioning is an important phase for proper mechanical systems operation in a high-performance building. Commissioning is especially important with advanced control systems.

Lighting

Daylighting controls may require calibration. Other lighting controls should be commissioned to the user's needs.

Cost Effectiveness

Cost effectiveness of daylighting relies on proper operation of lighting controls and occupant satisfaction. It is further improved where HVAC operation is linked to that of lighting, particularly where occupancy sensors are used. Calibration is critical for maintaining the value of any added investment for daylight design.

In general, commissioning has been shown to very cost effective in the few buildings documented.

Occupant Comfort

Check that occupants are satisfied with the lighting controls. If not, they may disable the system. Adjust the controls in response to occupant feedback. If occupants are resistant to automated controls, or if occupants dislike working under daylight alone, explain the environmental benefits of daylighting to them. Explore the source of their dissatisfaction before their minds are set against daylight controls.

PROVISOS

- If the lighting system is calibrated before furniture is installed, the control system response after occupancy could be unsatisfactory and may have to be recalibrated.
- Calibration procedures vary from system to system. Guidelines given here should be used as general protocol only. Always follow the manufacturer's calibration procedure first, then consult these guidelines for additional information. If there is a contradiction between the two, manufacturer instructions take precedence. Contact the manufacturer for clarification, if necessary.
- Commissioning requires someone with specialized knowledge and skills. It may also be useful to hire someone qualified to make electrical adjustments. Control systems often contain high voltages that may be lethal.
- When controls are not functioning properly, occupants will disable them. This will negate any intended energy savings and is why it is important to commission and properly maintain systems.
- Do not forget to schedule recommissioning after major changes such as space conversions, retrofits, and equipment replacements.

TOOLS & RESOURCES

- **Manufacturers** This is generally the only source of assistance available for calibration of daylighting controls and commissioning of advanced HVAC control systems. It is advisable to make an agreement with the supplier regarding proper installation and calibration to design specifications. In fact, manufacturer selection might be based on the level of calibration support promised.
- **The National Environmental Balancing Bureau** (NEBB) has a Procedural Guideline and also certifies firms that provide commissioning services; visit www.nebb.org/.
- **International Performance Measurement and Verification Protocol** (IPMVP) provides guidance on terminology, outlines best practice for verification of results for efficiency projects and provides online tools to support testing of new systems. Visit www.evo-world.com for more details.
- **LEED requirements** for new buildings follow Option D (Calibrated Simulation – Savings Estimation Method 2) of the IPMVP, as specified in *IPMVP Volume III: Concepts and Options for Determining Energy Savings in New Construction.*
- **ASHRAE** The American Society of Heating, Refrigerating and Air Conditioning Engineers offers a wide range of technical support materials for mechanical systems, including the monthly *ASHRAE Journal.* Up-to-date commissioning guidelines are often found in this literature. Visit www.ashrae.org for a publications list.
- **Utility Company** Some utilities offer incentives for commissioning in both new and retrofit projects. Inquire at your local utility about these programs.
- **Lighting Calibration Tools** Recommended tools for calibrating lighting controls:
    - Photometer in recent calibration (need not be expensive).
    - Powerful flashlight.
    - Opaque material to cover photosensor.
    - Reflected ceiling diagram showing control zone locations.
    - Walkie-talkies if calibration controls are not line-of-sight with the control zone(s) to be calibrated.
- **Diagnostic Tools** Calibration and commissioning are greatly assisted by appropriate measurement tools. A variety of devices from data loggers to handheld survey instruments can measure incident daylight levels and lighting electric power consumption, giving insight into the performance of the lighting system and controls.
- **Consultants** Specialized or unusual sensors and controls may require particular expertise. If the product manufacturer(s) will not provide assistance beyond installation, an outside specialist in calibration or commissioning activities may be advisable.
- **California Commissioning Guide: Existing Buildings** This guide by the California Commissioning Collaborative defines retrocommissioning and provides a process for building retrocommisioning. It covers costs and benefits, what happens during the process, who should be on the project team, how to make the benefits last, and how to get started on a project. The guide is mainly directed to building owners and managers, but anyone involved in the process will find it useful. See: www.documents.dgs.ca.gov/green/commissionguideexisting.pdf.
- **National Electrical Contractors Association (NECA) Guide to Commissioning Lighting Controls** This document describes the lighting controls commissioning process and details what is involved in each step. It describes different system settings and different sensors, and

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includes a troubleshooting guide. See: www.necanet.org/files/ACF363E.pdf.

CHECKLIST

1. Establish time, budget and responsibilities for the commissioning phase early in the building design process.
2. Have operation and maintenance staff on board during commissioning, for training.
3. Gather all building documentation, including the operation and maintenance plan and the system performance standards, in an orderly file, preferably stored in the building operator's office.
4. Confirm system performance standards (design light level, for example) before proceeding with calibration.
5. Review with installers all calibration and other commissioning steps outlined in the construction documents. These steps should follow the guidelines presented above, unless manufacturer instructions indicate otherwise.
6. Calibrate lighting controls after interior finishes and furniture are in place.
7. Commission the HVAC system any time after installation.
8. Commission automatic shades, if any, immediately after installation with help from the manufacturer/installer.
9. Verify proper interactions, if any, between those three systems.
10. Check occupant comfort and satisfaction shortly after occupancy. In particular, ensure that occupants understand the purpose of automated lighting controls and will not disable them.
11. The commissioning team should remain available until the O&M staff is comfortable with all building systems and the building is functioning as close to design specifications as possible. The commissioning scope should include a review of system performance 9–12 months after occupancy so the system performance can be evaluated prior to the end of the contractor's one-year warranty.
12. Keep any tools acquired for calibration, such as a photometer, for use by O&M staff.

LINKS

On the Calibration and Commissioning of Lighting Controls

http://gaia.lbl.gov/btech/papers/41010.pdf

Commissioning Practice

Good Practice

1. Be sure all systems are installed per design and manufacturer specifications.

2. Install mainly occupant sensors and use the default calibration (or room-specific calibration).
3. Be sure all available building and product documentation available is on file in the building.

Better Practice

In addition to the above:

1. Perform a thorough daylighting calibration. Secure agreement from the manufacturer for assistance before purchase. Some sensors have both occupant and daylighting sensors—this may be a good alternative.
2. Have the mechanical system commissioned as thoroughly as the budget allows, perhaps through some cooperative effort of manufacturer, installer, and mechanical engineer. At a minimum, ensure that space conditions are as intended.

Best Practice

In addition to the above:

1. Commission each set of sensors to more specific design needs. The commissioning team should be involved in O&M staff training.
2. Include a comfort evaluation shortly after occupancy in the commissioning phase. This should also address any dissatisfaction or misunderstanding among occupants about the lighting controls.
3. Adjust the calibration of sensors where comfort is not ideal.

10 Maintenance

OBJECTIVE: Ensure effective lifetime performance in energy efficiency and occupant comfort by operating building systems to design specifications.

- Confirm the degree to which the new building was commissioned and has been retrocommissioned periodically. This can be assessed through a review of building systems documentation and of relevant activity logs.
- As the building ages and occupants change, follow scheduled maintenance procedures to sustain building value and performance.

KEY IDEAS

General

- **Make monitoring and maintenance a priority.** Budget constraints and operations and maintenance (O&M) understaffing are a major cause for the poor operations of many buildings, leading to high, long-term energy cost and equipment penalties. Allocate a budget for timely repair and preventive maintenance. Schedule periodic monitoring programs to measure performance and operation. Train personnel.
- **Keep documentation on file and update it regularly**. Develop a set of easy-to-use recommended procedures and maintenance schedules and keep them readily accessible in the building, along with manufacturer literature and warranties. Keep as-built drawings in the mechanical room and in the operating engineer's office. Update as required. Log all maintenance or replacement activities, modifications to original systems, space usage changes, and other notable operations events. Keep track of the cost and effectiveness of upgrades and support this assessment, if possible, with any utility bill reductions due to the upgrade.
- **Proper commissioning gets O&M off on the right track.** When commissioning is successful, the building begins the following phase of occupancy with all systems functioning as close to design intent as possible. An accurate baseline for performance is established to guide O&M activities through the life of the building systems. O&M staff should be involved in commissioning, to assist in their training and to ease the hand-off of the building from commissioning personnel to O&M staff.
- **Involve building occupants.** Keep occupants informed of O&M activities when their comfort is a factor. Inform new occupants about design intent and use of control features (e.g., lighting controls). Locate occupants receptive to daylight utilization near the windows if possible. Suggestions or complaints can be used for troubleshooting. Occupants can be good team players for increased energy efficiency, if they are made aware of energy penalties in individual behavior patterns and encouraged to participate in reducing overall building energy use—undertake periodic occupant surveys to assess comfort and performance of installed systems.

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- **Keep an eye out for further energy-efficiency opportunities.** When equipment needs replacing, review energy-efficient technologies that may not have been available or affordable when the building was constructed or underwent its last retrofit. Also, check with the local utility for any possible incentives for replacement equipment. Evaluate the energy impact of any proposed architectural changes such as additions, retrofits, or major changes in space usage. Schedule periodic O&M procedure reviews to identify possible improvements. Using calibrated energy models to inform operations can assist with fault detection and in identifying inefficiencies.

Envelope and Lighting

- **Keep all light-reflecting surfaces clean.** Elements in the building intended to assist daylight penetration or distribution should be regularly cleaned of dirt: windows, skylights, light shelves, exterior reflectors, sills, blinds, and ceiling.
- **Clean light fixtures once a year.** It is good practice to clean the fixtures and lamps approximately once a year in relatively clean office environments; more often otherwise. Since lamps are typically replaced once every three years, fixtures are cleaned three times for each new set of lamps. Clean the photo sensor regularly.
- **Relamp in groups.** When using standard-color lamps (e.g., cool white, white) it is generally cost effective to do a group relamping at 50%–60% into the rated lamp life. If T8s are used and labor costs are low, it may be more cost-effective to spot relamp. When group relamping, functioning lamps should be appropriately marked and stored for spot-relamping needs. Group relamping is especially important to ensure effectiveness of lumen maintenance. At a minimum, wipe the fixture reflector and lens clean during relamping.
- **Replacement lamps must be compatible with existing fixtures.** If lamp type or manufacturer is changed, check ballast-lamp compatibility.
- **Check that all controls are functioning as intended.** Make sure time clocks, occupancy sensors, photocells, and nighttime setbacks are working properly and haven't been disabled or thrown off by building changes. Check at intervals recommended by the manufacturer or as changes are made to the building.
- **Recalibrate controls when interior is modified.** Recalibrate light control system with each space change (e.g., furniture location or color, paint, carpet). See Section 9, CALIBRATION AND COMMISSIONING.
- **Rebalance the air if occupancy or window/lighting system is changed.** For example, if the equipment load has been reduced considerably, the supply air requirement from constant volume systems can be cut back based on new calculations. Adjustments made to operation of the mechanical plant should follow rigorous testing procedures to ensure that, where possible, cost and system operating efficiency gains may be realized.
- **Changes to space usage should follow design intent.** Ceilings should be kept uncluttered, furniture placement should not block daylight, interior colors should be predominately light.
- **Outline the function performed by photocells and why they are used**. This should assist in user acceptance. Retune photocells to reflect occupant preferences for daylight. Where they are being disabled, find out why, and explore a solution together with the occupant(s) in question.

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INTEGRATION ISSUES

Architecture

Design and refit the building with maintenance in mind. Location and accessibility of equipment, complexity of systems, and longevity of materials and products are important factors. Follow manufacturer recommendations on access clearance and provide for safe and easy methods to access all items requiring maintenance, including stairwells and escapes.

Occupant Comfort

Ensure that the O&M team is familiar with the design intent of building systems. Adequate information and training must be provided to ensure that the building continues to operate at or near design intent once the commissioning process is completed.

PROVISOS

- Indoor air quality is a common occupant complaint. Treatment of this concern may conflict with the original energy-efficiency intentions of the mechanical system. Give indoor air quality priority.
- Occupant comfort and productivity are more important than energy savings. Comfort should be prioritized over O&M activities that preserve or increase energy efficiency.

TOOLS & RESOURCES

- **ASHRAE** The American Society of Heating, Refrigerating and Air Conditioning Engineers offers a wide range of technical support materials, including the monthly *ASHRAE Journal*. Up-to-date maintenance information is often found in this literature. For a publications list or subscription to the *ASHRAE Journal*, visit www.ashrae.org.
- **Books** ASHRAE has many book titles available that address maintenance (see above), including the useful *ASHRAE 2011 HVAC Applications Handbook*.

  Energy Management Handbook by W. Turner (Fairmont Press 2009) is somewhat dry, but very thoroughly covers maintenance issues for all building systems.

- **Utility Company** Many utilities offer incentives for energy-efficient equipment replacements. Inquire at your local utility about retrofit programs for lamp, ballast, and control system upgrades.
- **Consultants** Outside specialists in optimum O&M and energy management are an option. For lighting control specialists, check with the manufacturer's support services or a local lighting engineer.

CHECKLIST

1. Verify that O&M documents are on file. If not, create this file. It should contain:

    - An index or directory of all documents on hand.
    - Operating manuals and manufacturer warranties.
    - Performance standards for all building systems.
    - Maintenance procedures.
    - Responsibilities of the O&M staff.
    - Test, calibration, balance, and commissioning reports. Commissioning reports should be present for when the new building was handed over, where retrocommissioning was undertaken and where ongoing monitoring-based commissioning is practiced.
    - All construction documents, including as-builts.
    - Emergency procedures.
    - O&M staff training procedures.

2. Promptly update documents with each equipment modification or replacement.
3. Regularly follow all maintenance procedures as prescribed in the O&M documents.
4. Log all maintenance activities and changes in space usage.
5. Modify the recommended maintenance procedures or schedule, if appropriate. Note this change in the O&M documents.
6. Keep the photometer on hand and in good working order. Recalibrate it before a required sensor recalibration.
7. Acquire diagnostic tools if regular maintenance alone isn't leading to specified system performance.
8. Choose energy-efficient equipment when replacements are due. Contact the utility company for possible replacement incentives.
9. Watch for further energy-efficiency opportunities.
10. Monitor building energy data through the monitoring-based-commissioning process for any sign of savings erosion or any unusual energy use patterns. Find the problem and take corrective measures.
11. Engage building occupants as energy efficiency team players.

Maintenance Practice

Good Practice

1. Follow recommended O&M procedures according to the recommended schedule, to the best of the building operator's ability.
2. Promptly repair any equipment failures.
3. When replacements are due, choose the most energy-efficient equipment available within the allowed budget.

Better Practice

In addition to the above:

1. Perform a comprehensive window and lighting systems evaluation once a year.
2. Periodically evaluate individual spaces for adequate performance of local controls.

Best Practice

In addition to the above:

1. Maintain a dedicated, full-time O&M staff; size of the staff should correspond with building size and complexity.
2. Perform continuous local evaluations, sweeping through the building space by space. Complete the loop within a maximum of one year.
3. Enable O&M staff to work directly with occupants in reviewing individual energy-efficiency opportunities.
4. Keep O&M staff informed of utility incentive programs and current equipment and control technologies.

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11 Cost-Benefit Analysis

OBJECTIVE: Make design decisions that deliver the best economic value to the building owner and future tenants.

- Conduct a cost-benefit analysis to clarify the trade-offs between first costs and operating costs. Unless the owner or designer can assign a monetary value for incremental benefits such as improved comfort, productivity, and well-being, they are not normally considered in the analysis.
- Examine economic consequences at all stages, starting with planning, and continuing through occupancy, maintenance, and demolition.

KEY IDEAS

- **Treat the building as a form of investment,** where the best investment scenario minimizes life-cycle cost and is probably not the lowest first cost.
- **Work with the owner/tenant to treat amenity and comfort as a value.**
- **Try to develop a value system for occupant comfort, productivity, increased building amenity due to daylighting, and other factors even if they are difficult to quantify.** If the non-energy benefits are difficult to quantify, consider assessing the cost of doing nothing. Thermal and visual comfort from lack of shading is clearly a negative productivity factor, even if it can't be quantified.
- **Use life-cycle cost-benefit analysis as a sales tool for energy efficiency.**
- **Understand the owner's economic objectives before starting design.** Agree on the parameters of the life-cycle cost analysis, such as time period and energy escalation rate and the owner's economic horizon and financial requirements.
- **Clarify the daylit zones in the building that are subject to the economic analysis.** The economic benefits of daylight harvesting cannot be applied to the whole building; they apply to the perimeter zone of a building only, whose depth may vary with design parameters and orientation.
- **Different technologies (and therefore performance and costs) may be applied to different facades and orientations.**
- **Gather the data needed for an energy efficiency cost-benefit analysis:**
    - Owner's investment criteria (such as available funds, discount rate, desired payback period, length of ownership)
    - Energy cost and escalation rates
    - Building and system energy usage
    - Construction costs
    - Maintenance and repair costs
    - Replacement schedule and costs
    - A more complete analysis may include additional factors, such as financing costs, taxes, and salvage costs.
- **Determine all energy benefits from daylighting systems and assign economic values.**
- **The cost information required depends on analysis objectives:**

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- Assess consequences of a given decision, such as a change in equipment specification, which requires comprehensive data.
- Choose among multiple design options: only differential cost data are required.

Energy Cost Savings Analysis

This section looks at analyzing costs and savings of a variety of different daylighting systems and scenarios. Beyond energy savings, the design team and other stakeholders will have to agree on the value of more subjective aspects of systems performance, such as their contribution towards achieving comfort or reducing glare.

To summarize energy savings opportunities and costs associated with daylighting design, assess seven building systems types:

- Stepped daylight dimming controls
- Continuous daylight dimming controls
- Interior manually operated shading
- Interior adaptive shading
- High-performance glazing
- Exterior static shading
- Exterior motorized shading

Energy Prices

This analysis used a baseline electricity price of $0.10 per kilowatt-hour and a baseline gas price of $0.027 per kilowatt-hour (the average retail prices for the U.S. commercial sector at the time of writing).[1,2] However, energy prices are generally trending upwards, so it is important to either incorporate price escalation in your analysis or identify it as a project risk and assign a probability and impact to it in the project risk register.

To determine the energy price inputs needed for your project, you can check current prices using the QR codes or websites below:

[1] Electric power monthly at www.eia.gov/electricity/monthly/
[2] Natural Gas Monthly at www.eia.gov/naturalgas/monthly/

U.S. Commercial Electricity Prices

www.eia.gov/electricity/monthly/

U.S. Commercial Gas Prices *(Note: divide by 0.3 to convert to $/kWh from published $/000s ft^3 units[3])*

www.eia.gov/naturalgas/monthly/

There is significant variation in U.S. energy prices; at the time of writing the cheapest average kilowatt-hour of electricity for the commercial sector was ~ 7 cents per kilowatt-hour, and the most expensive electricity in the continental United States was 16 cents per kilowatt-hour. Electricity prices in Hawai'i are between 2.5 and 3 times as expensive as on the mainland. Note that time-of-use rates can produce much higher hourly rates for shorter periods of peak demand, for example, during hot summer afternoons.

Calculating Energy Savings

Energy savings were calculated using COMFEN, simulation software using the EnergyPlus engine, which supports evaluation of various fenestration systems and daylight dimming controls for commercial buildings. (For more information on COMFEN, visit http://windows.lbl.gov/software/comfen/comfen.html.) The inputs to COMFEN include a range of key settings and conditions, such as:

- Climate zone: Phoenix (hot), Washington D.C. (temperate), and Minneapolis (cold).
- Interior window-to-wall ratios of 0.2, 0.4, 0.6, and 0.8.
- Facade orientations: north, east, south, and west.

Every permutation of climate zone, window area, and facade orientation was modeled for several daylighting system types.

The COMFEN outputs presented here are in terms of energy cost savings only and reflect energy savings for both electricity (for lighting and cooling) and gas (heating). Outputs such as thermal comfort or glare were not considered. The results are approximate and comparative, simply to present guidance and rules-of-thumb to designers and building owners and operators. The results are not optimized solutions but just a partial exploration of the performance and cost issues you are likely to find in evaluating daylighting solutions.

[3] Assuming 1,028 Btu per standard cubic foot of gas

Building Equipment Costs

Equipment costs were gathered from recently published information, cost data (available online), and/or industry sources. Specific prices will fluctuate, but the cost ranges for equipment used here give a ballpark range that is adequate for this guide. Longer term, some key equipment unit prices are likely to decrease due to improved manufacturing processes and increased sales volumes.

Cost data reflect either (1) incremental costs over and above an alternative or "business-as-usual" case, or (2) the total equipment cost. For example, dimming systems data includes only the cost of dimming controls equipment and supporting infrastructure, not basic lighting infrastructure such as luminaires and other equipment, as these would be present in any building lighting system. This approach is followed for the following systems:

- Stepped dimming
- Continuous dimming
- High-performance glazing

Total equipment costs are used for:

- Interior manually operated shading
- Interior adaptive shading
- Exterior static shading
- Exterior motorized shading

Labor Costs

Labor costs are highly variable; they vary seasonally by geographic area and according to the skill level required on the project. They are significantly higher for retrofit projects than they are for new construction, as they include the cost of equipment disconnection and/or removal in addition to replacement. Where possible, quotes and costs are used for completed projects; if not available, the analysis used cost estimator data contained in the COMFEN cost database.[4] The uncertainty associated with retrofit projects is reflected in the cost ranges. For example, lighting retrofits in older buildings will recognize issues such as encountering ceiling asbestos and be priced accordingly.

For a summary of Equipment and Labor Costs, view the data table in Appendix A.

Valuing Energy Efficiency for Retrofit Projects

It is important to recognize the differences between the economic assessment of retrofit cases and that of new construction cases. When valuing equipment or system upgrades to new construction, it is only necessary to include costs for items unique to each design option: incremental cost differences for equipment and labor and the annual value of

[4] For some systems, the installed equipment cost includes labor cost—see Appendix A, and the (cost database, at http://windows.lbl.gov/software/comfen/4.1/Cost.htm.

energy cost savings is sufficient to determine the relative cost effectiveness of each design.

The project team should assess the total cost of each design option and any associated trade-offs, to confirm that all energy-related costs have been identified. This will help to ensure that there are no nasty surprises later (unforeseen credits are also a possibility!) and that the cost consequences of design and equipment selection are fully understood.

ECONOMIC ASSESSMENT FOR DAYLIGHTING

Simple Payback

Simple payback is the least complex approach to undertaking economic assessments. Despite its tendency towards the short-term, it remains one of the main economic decision-making methods currently used in the commercial sector. Its calculation is based on the following simple equation:

$$\text{Simple Payback} = \frac{\text{First Costs Investment}}{\text{Annual Cost Savings}}$$

It is used when the building owner is interested primarily in identifying options that pay for themselves in as short a time period as possible. Payback Period equals Initial Cost of the Technology (or differential cost over its equivalent) divided by Annual Energy Cost Reductions. With access to energy savings and cost information (including utility rates), you can easily perform this calculation.

A mechanical engineer's standard load calculation can provide energy information, while the product vendor or contractor can give you cost estimates. In other cases, you may not need a detailed performance analysis. For example, you can use a simple payback analysis to choose between two different pieces of lighting equipment, simply by using the power rating of the equipment, an estimate of how many hours a year the equipment will run, the typical electricity charge (ask the local utility), and the product cost (ask a manufacturer's representative).

Energy Savings and Payback Analysis

To identify and support meaningful decision-making at the early daylighting design stage, you can use results from the COMFEN analysis, which allows you to compare and illustrate the implications of investment in each system type.

We have "mapped"" the characteristics of each daylighting system, to indicate roughly what might be expected in terms of:

1. energy use reduction and
2. corresponding simple payback period.

The maps show the results for all of the systems on the same axes, so it is possible to compare cost effectiveness and energy performance, and a balance of the two. The

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results offer what can be expected in terms of energy performance of commonly available systems rather than a guarantee of what you can expect or their potential.

The performance maps are separated for (1) new construction, and (2) retrofit projects, as the energy savings characteristics for each can be very different. This is because (1) the baseline energy intensity of older buildings is higher (and thus, they offer potentially greater energy savings opportunities), and (2) retrofit costs are often higher than those for new construction.

The results are based on energy cost savings and the capital costs of the different systems—the payback for each system is calculated from these two parameters. As these results are not site specific, we have not attempted to account for considerations such as occupant comfort, productivity, and visual connection to the outdoors, which are often important considerations when selecting such systems/equipment. This analysis used a limit of 15 years as the acceptable threshold for simple payback period, since few investments are made with paybacks this long and since this approximates to an assumed lifetime for many systems (glazing excepted).[5]

This approach does not account for other costs associated with some measures; for instance, the overall cost to the building owner of vacating the space and relocating workers to other areas during a refurbishment project.

Understanding and Using the Performance Maps: Audience and Method

The maps graphically represent the energy performance of daylighting systems, where each of several parameters in the analysis may be varying. They are meant for all members of the project design team, but principally for designers, architects, and building owners/operators. Use them as a guide during the preliminary design process to indicate what one might expect in terms of energy savings and payback from each of the assessed daylighting systems.

1. The position of each mapped strategy relative to the horizontal x-axis indicates the range of energy savings for that daylighting system per unit of floor area within the daylit zone. The variation in range is due to different orientations, climates, window areas, etc. Understanding this range may help to prioritize daylighting systems according to:
    a. Design and energy savings objectives established by the project design team.
    b. Stated energy savings targets; for example, in the pursuit of energy points under the LEED framework.

2. The position of each mapped strategy relative to the vertical y-axis indicates the range of payback periods for each daylighting system per unit floor area within the daylit zone. This conceptual analysis framework allows you to compare technologies directly and establish a system hierarchy according to their relative economic performance.

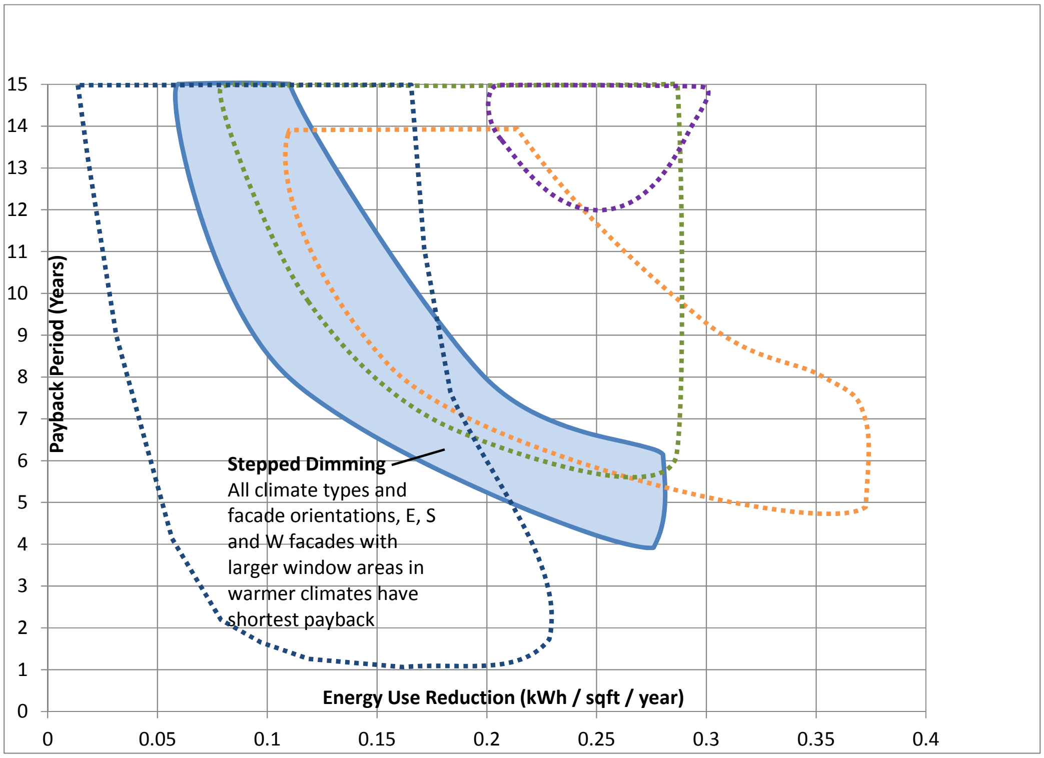
The position of a given point relative to both axes relates the energy saving performance to the economic performance. If a single space in one climate with one window was analyzed, the data would be a point. Since this analysis modeled hundreds of combinations of glazing, shading, orientation, climates, and other factors, there is a “cloud” of points which are shown typically as a colored, typically L-shaped, figure in the charts below. The L-

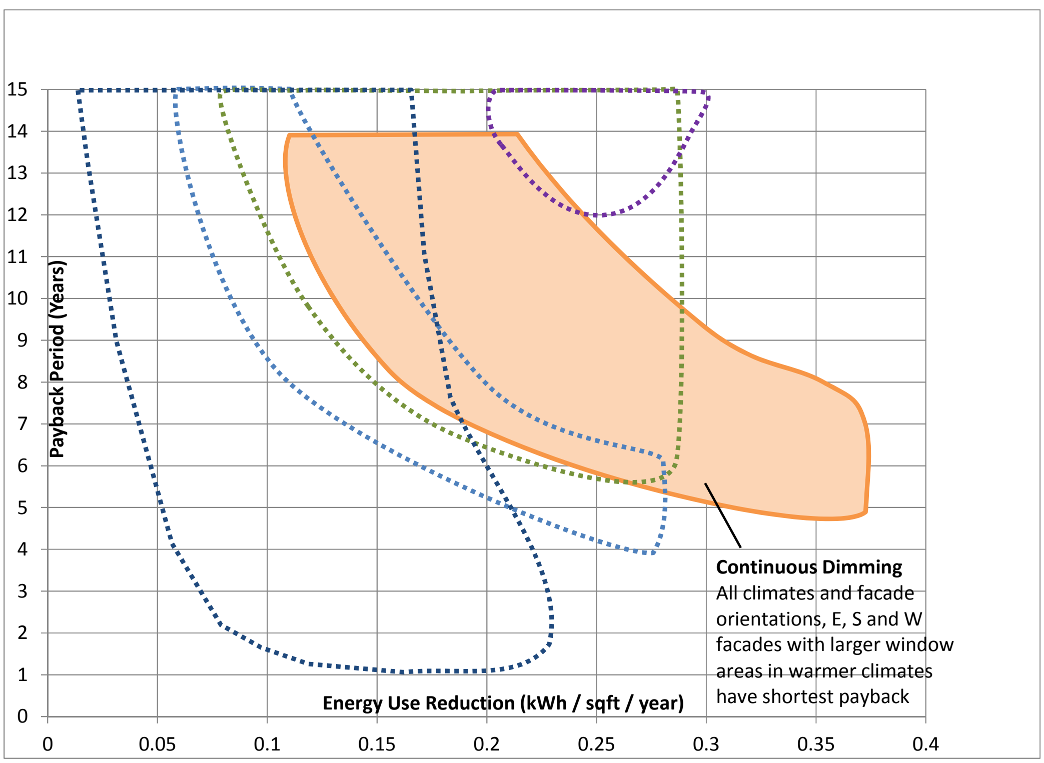
[5] If the simple payback is longer than 15 years, assessment under the life-cycle cost methodology is more appropriate.

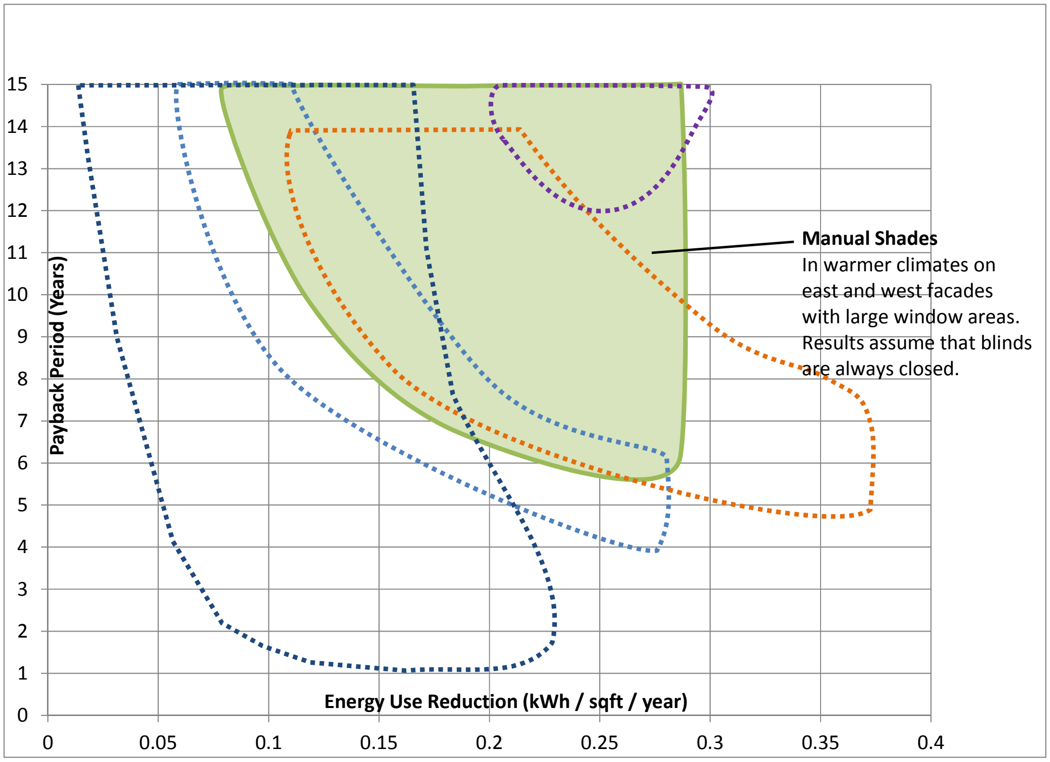
shaped figure that characterizes most systems occurs because the "payback" includes the savings figure from the horizontal axis. Imagine a technology that costs $xx/sf to purchase and install. In one application with certain energy savings it has a 5-year payback; in another it saves only half that, and so will have a 10-year payback; and in a third saves only one quarter, and so would result in simple paybacks of 20 years—thus producing the characteristic "L" shape.

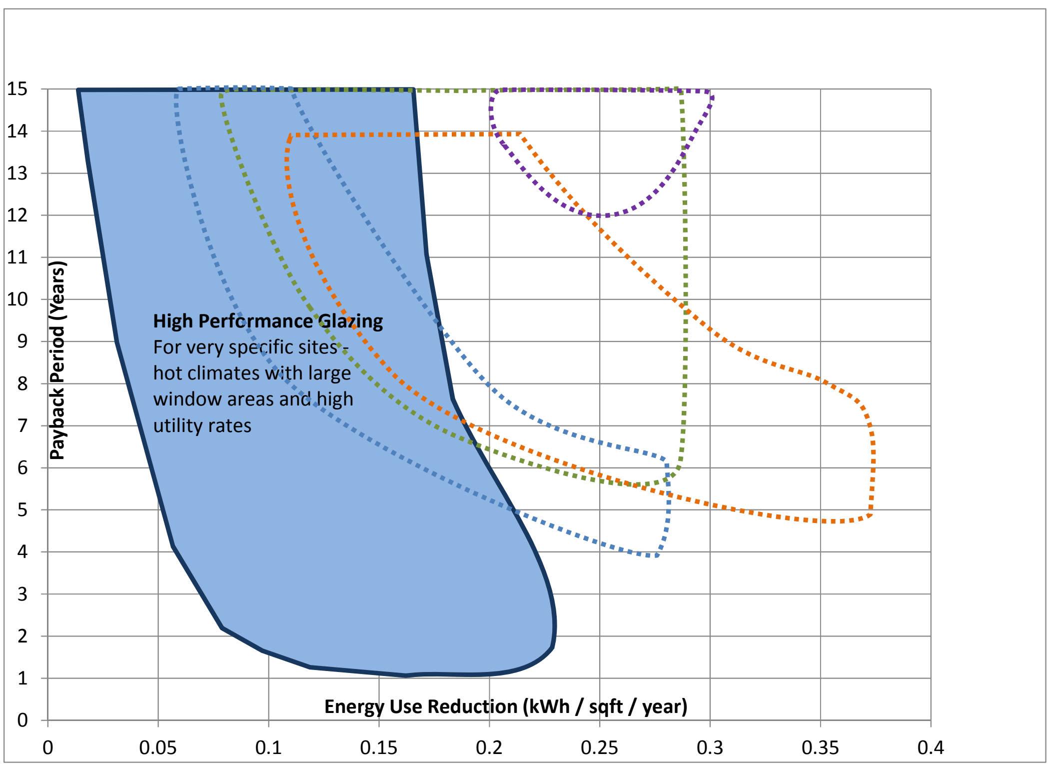
Notes on each map indicate the best scenarios in which to include each system, in terms of climate type, building facade orientation, and window size.

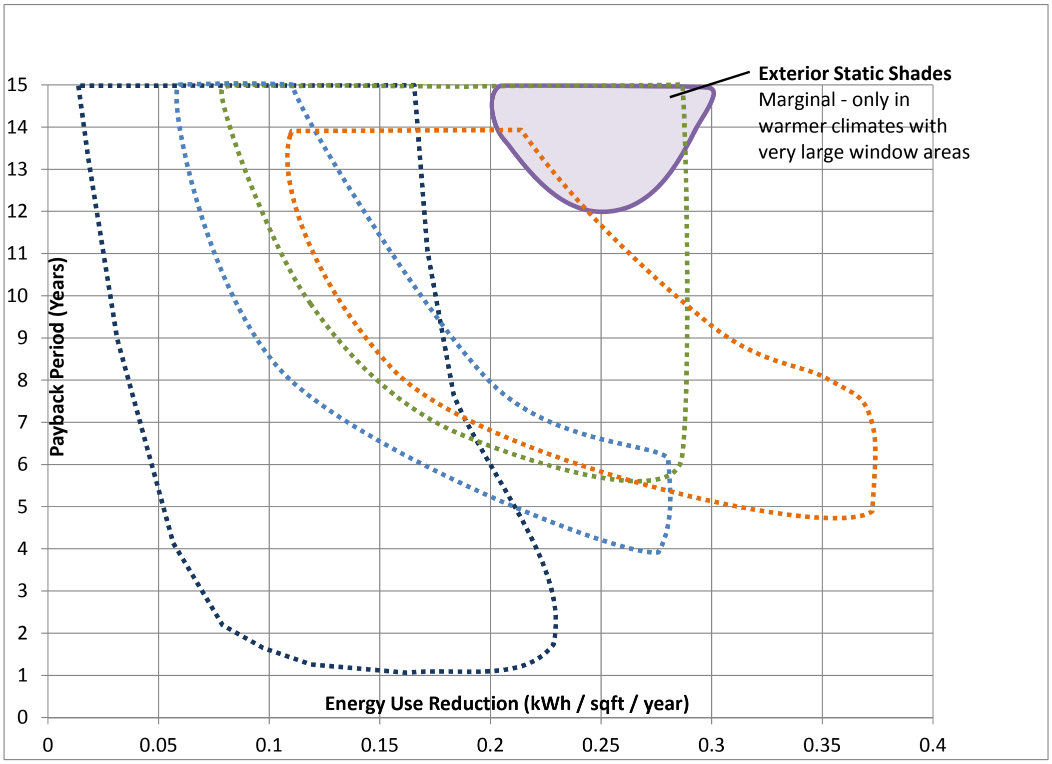
Simple Cost and Energy Performance Mapping – Daylighting in New Construction Projects






15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Payback Period (Years)
Manual Shades
In warmer climates on east and west facades with large window areas. Results assume that blinds are always closed.
Energy Use Reduction (kWh / sqft / year)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4


15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Payback Period (Years)
High Performance Glazing
For very specific sites - hot climates with large window areas and high utility rates
Energy Use Reduction (kWh / sqft / year)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4


Exterior Static Shades
Marginal - only in warmer climates with very large window areas
Payback Period (Years)
Energy Use Reduction (kWh / sqft / year)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4

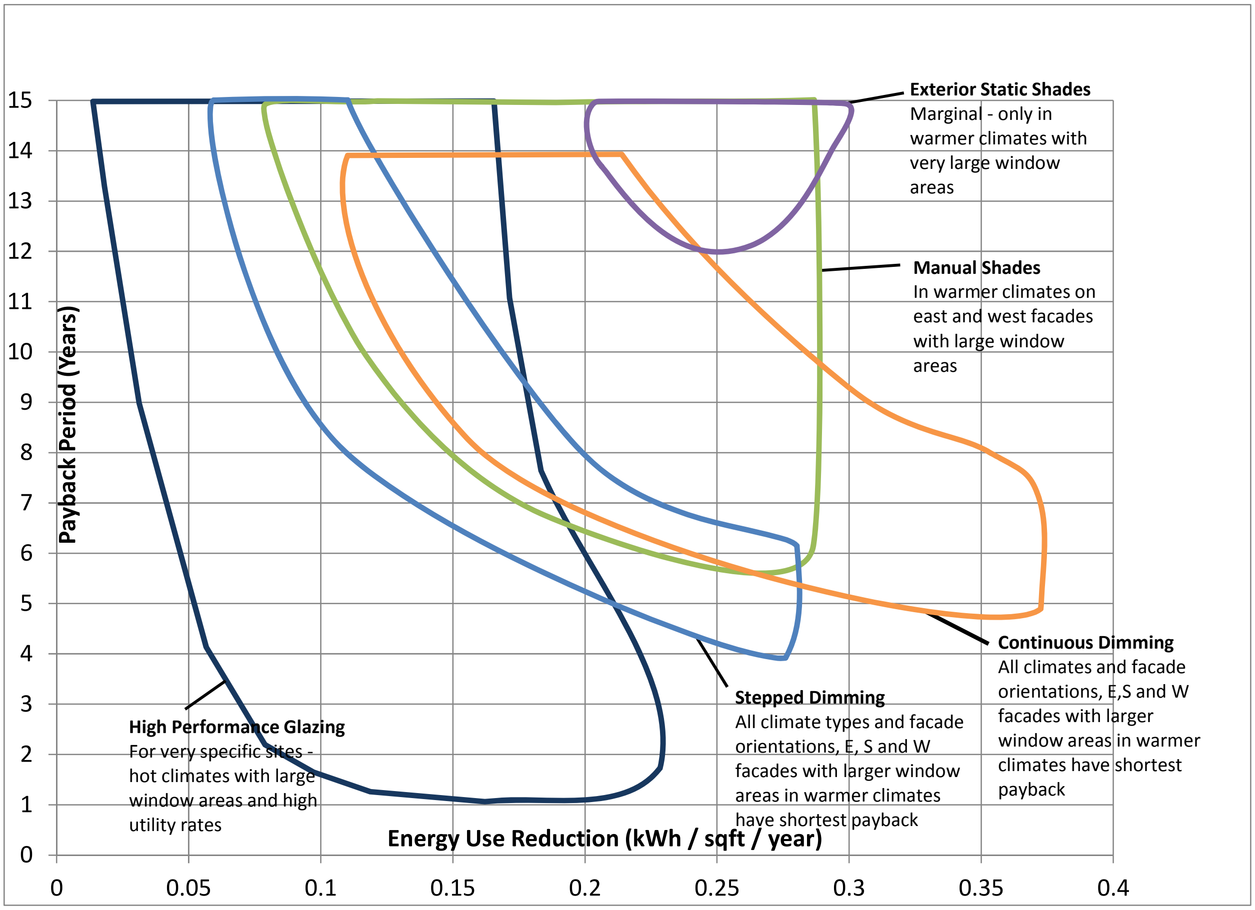
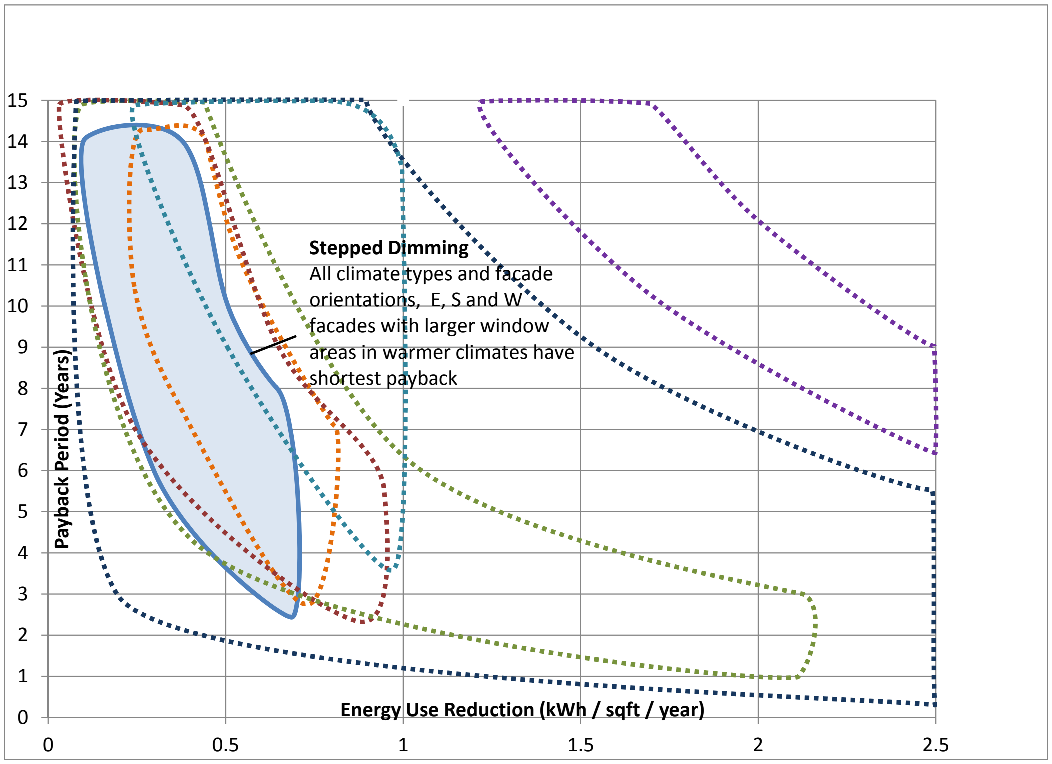
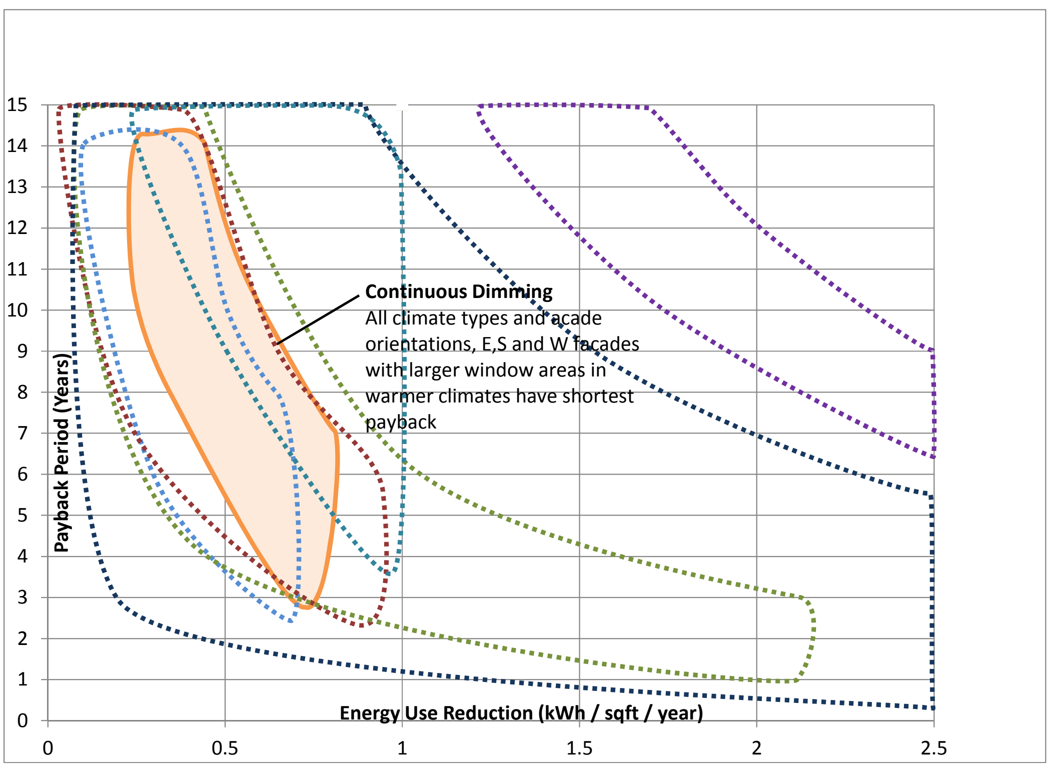


Figure 35: Payback period and energy use reductions for energy-efficient daylighting systems in new construction projects

*Note: The operation of manually operated blinds / shades by building occupants is varied and unpredictable; the results presented assume that they are always closed. The longer payback periods for electrically operated shading systems (interior and exterior) for new construction projects means they are not plotted here. They provide critical value for glare control and thermal comfort, but this is not assessed economically here.

Simple Payback Mapping – Daylighting in Retrofit Projects





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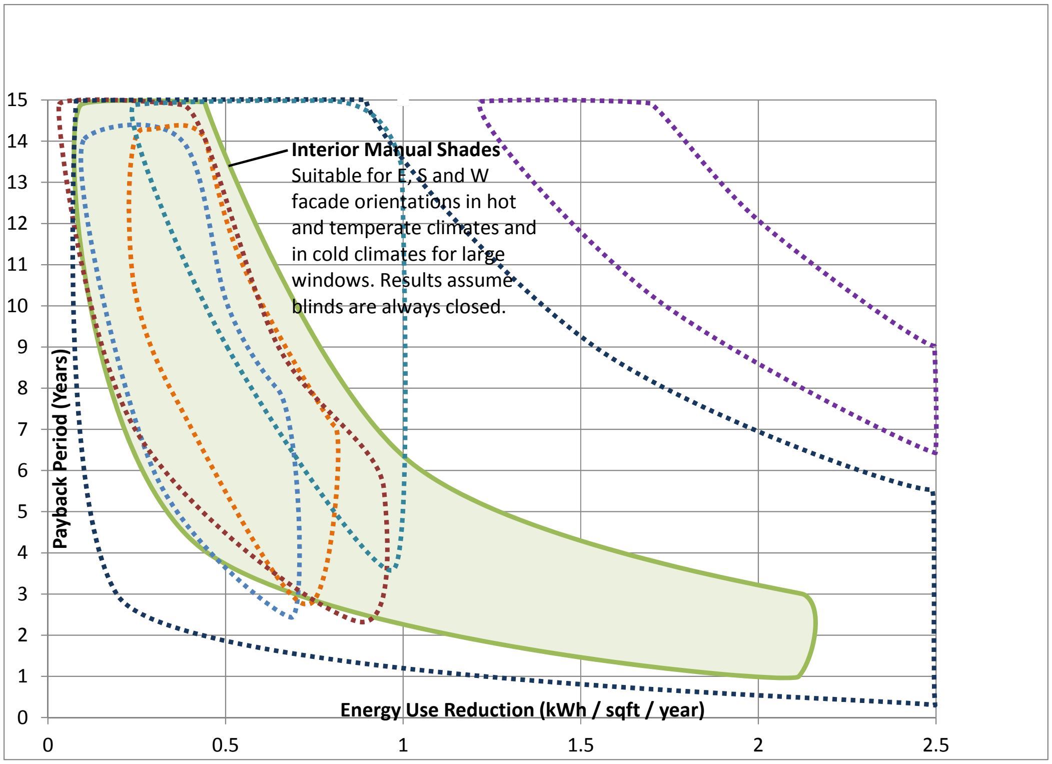
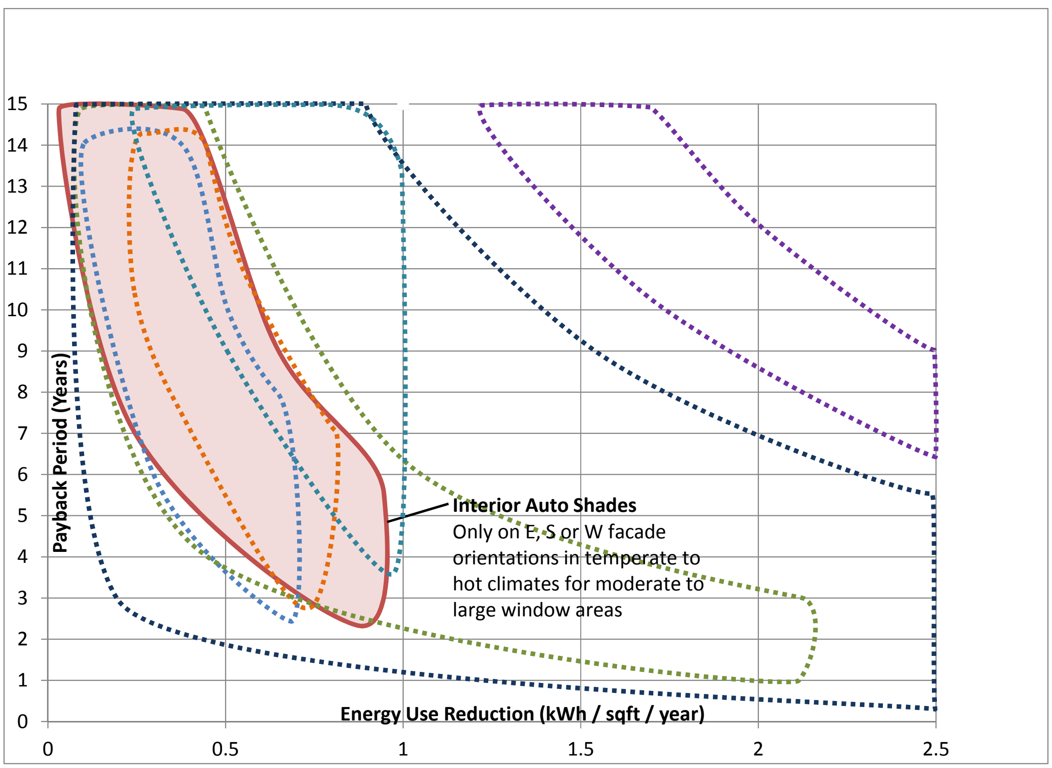
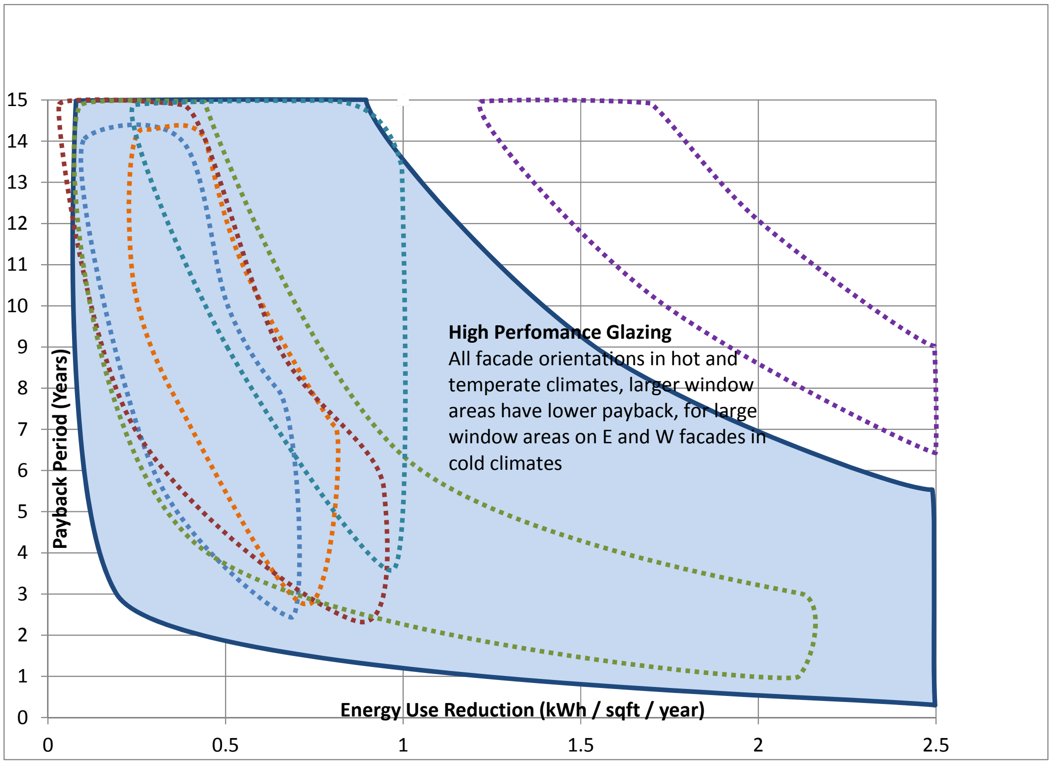
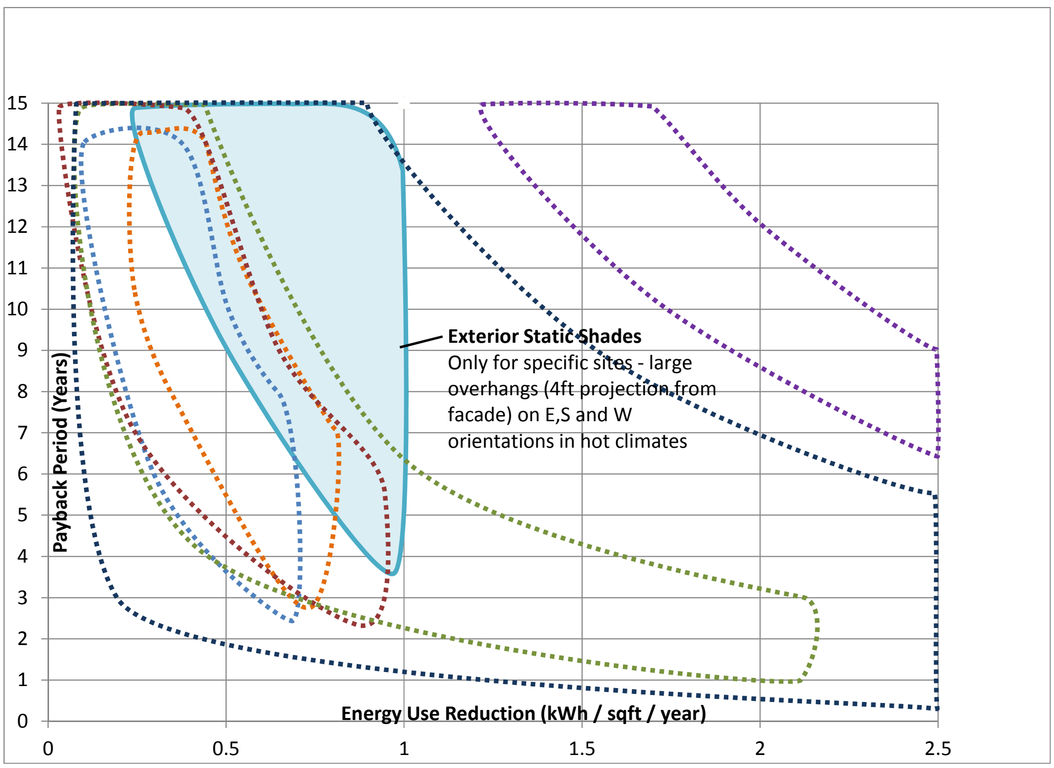

Interior Manual Shades
Suitable for E, S and W facade orientations in hot and temperate climates and in cold climates for large windows. Results assume blinds are always closed.
Payback Period (Years)
Energy Use Reduction (kWh / sqft / year)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
0
0.5
1
1.5
2
2.5


Interior Auto Shades
Only on E, S or W facade orientations in temperate to hot climates for moderate to large window areas
Payback Period (Years)
Energy Use Reduction (kWh / sqft / year)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
0
0.5
1
1.5
2
2.5





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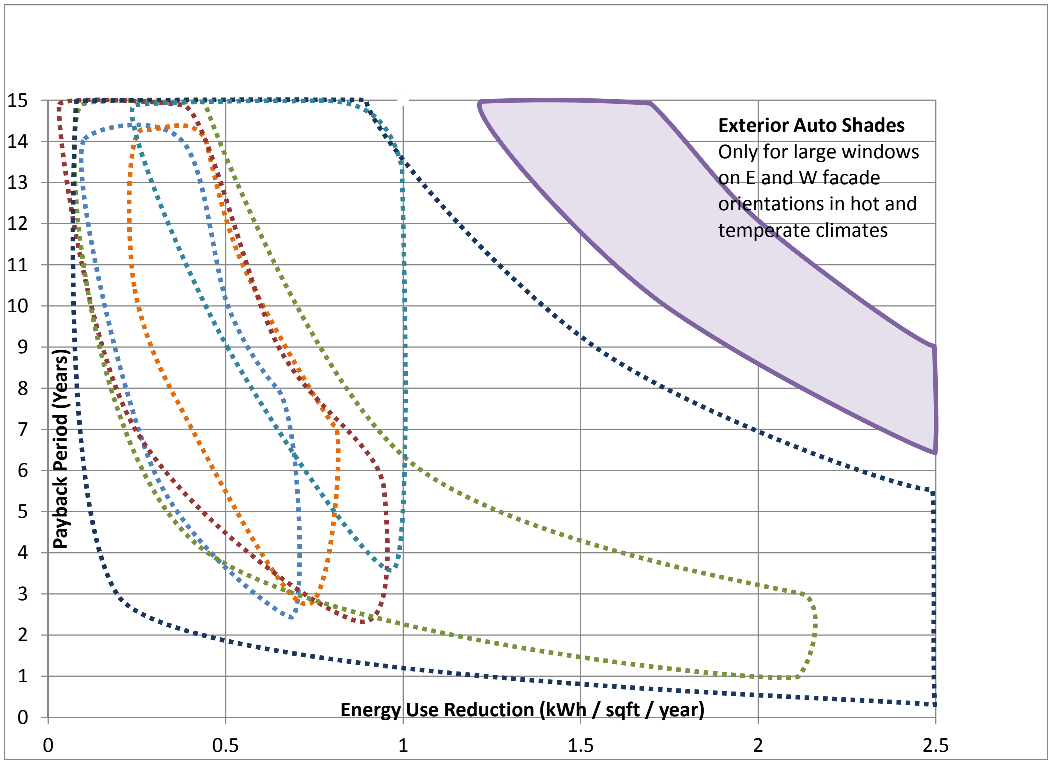

Exterior Auto Shades
Only for large windows on E and W facade orientations in hot and temperate climates
Payback Period (Years)
Energy Use Reduction (kWh / sqft / year)
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
0.5
1
1.5
2
2.5

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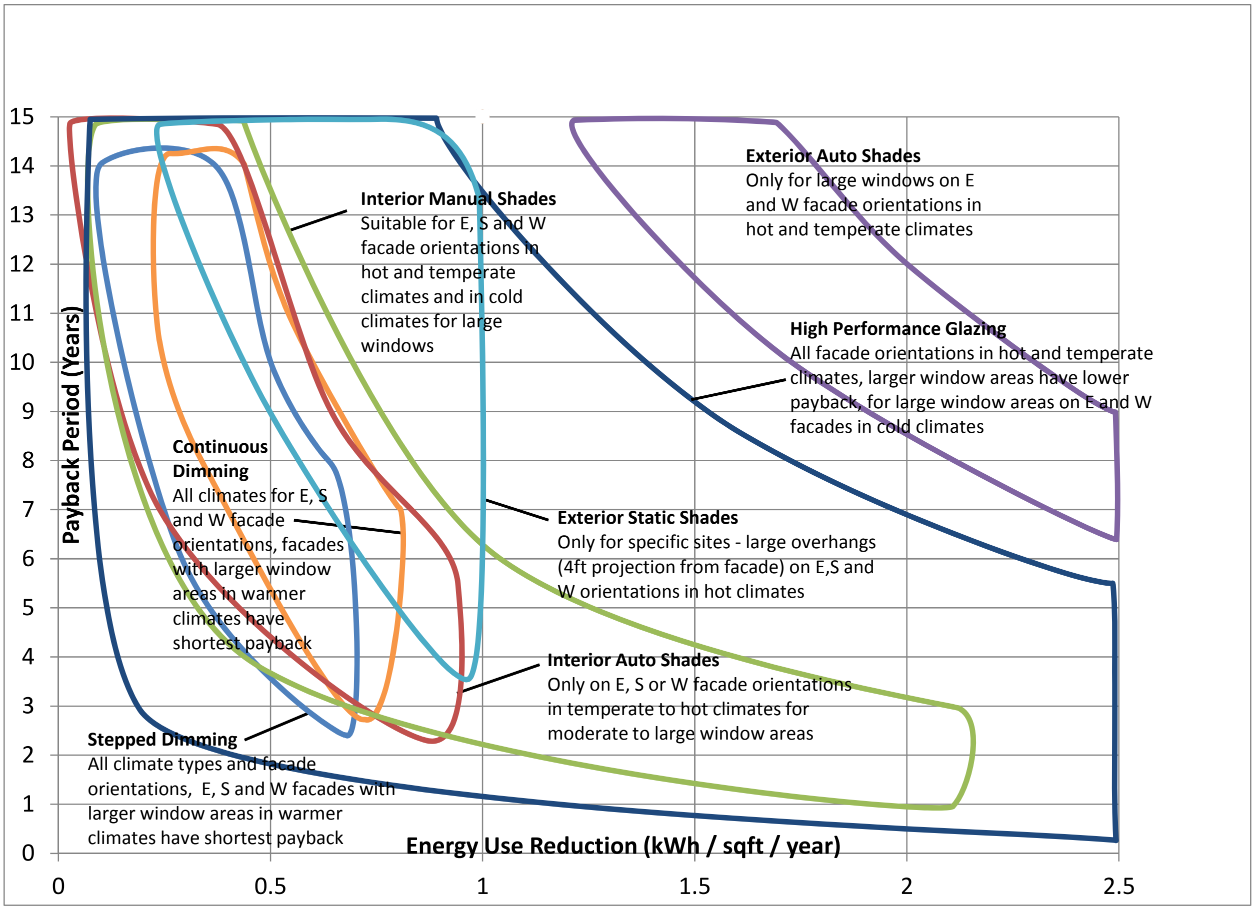

*Note: The operation of manually operated blinds / shades by building occupants is varied and unpredictable; the results presented assume that they are always closed.

There are several other methods of cost-benefit analysis, but they are better suited to specific projects due to their more nuanced concepts. Two options, the first practically quite simple, the second more involved, are summarized below:

- **Cost of Conserved Energy (CCE)** This is a quick method to assess the cost effectiveness of energy-saving options. It calculates the value of an investment in terms of an equivalent energy price and incorporates lifetime of the product/measure, annual energy savings, and the time value of money. It is calculated using the following formula:

  $$\text{CCE (\$/kWh)} = \frac{\text{First Costs (\$)}}{\text{Energy Savings (kWh)}} \times \frac{\text{Discount Rate}}{1-(1+\text{Discount Rate})^{-\text{System Lifetime}}}$$

  Where CCE is equal to or lower than the unit cost of energy currently borne by the investor, the product or measure represents a net positive investment. A full explanation can be found in The Cost of Conserved Energy as an Investment Statistic, at:

  http://repository.tamu.edu/bitstream/handle/1969.1/94751/ESL-IE-84-04-109.pdf?sequence=1.

- **Life-Cycle Cost Analysis** This is a preferred method of cost analysis for the latter stages of the project development process, because it accounts for the time value of money and is structured to indicate detailed project cash flows. It is the standard economic and financial method for assessing and comparing alternative investments. An example of this method can be found in Life-Cycle Cost Analysis (LCCA), at www.wbdg.org/resources/lcca.php. It can be summarized as:

  > *"Sum of all recurring and one-time (non-recurring) costs over the full life span or a specified period of a good, service, structure, or system. It includes purchase price, installation cost, operating costs, maintenance and upgrade costs, and remaining (residual or salvage) value at the end of ownership or its useful life." Source: Business Dictionary [online]*

For both of the approaches described, energy price and discount rate are crucial, and both may vary significantly from project to project.

For energy prices, variations between utility service territories are significant. Factoring in future energy price rises and fuel price volatility makes it more difficult to provide sound guidance due to the additional complexity this adds to an already complex picture.

Discount rate is a reflection on an investor's (1) minimum threshold for financial reward, and (2) perception of risk. It also reflects the cost of financing. Federal, state, and local public sector organizations will accept low returns on investment (using nominal hurdle rates of 5%–7% in economic appraisals is fairly typical); whereas, the private sector will use much higher rates in their analysis (10% and higher). Public-private partnerships will by definition be somewhere in between.

Additional Cost Reductions: Demand Charge Reduction

The prior analysis used only the "energy" costs of electricity. In some utility service territories building owners pay high charges for electric demand and surcharges for energy used at specific times of the day and year, e.g., time-of-use rates. The actual savings from daylight systems could be increased above those estimated in the COMFEN analysis if these demand savings were used in the overall analysis.

Table **1** highlights “typical” peak electricity savings for each of the assessed daylighting systems; this reflects a range of latitudes, altitudes, and orientations for the facades on which they are installed. The cost savings reflect a demand charge tariff of $6 per kilowatt per month, or $72 per kilowatt per year equivalent, which is in the range of tariffs applied in California. While this table provides some guidance, check with your local utility company to assess the value of savings for your particular building.

	New Construction		Retrofit	
Daylighting System	Typical Peak Saving (W/ft^2)	Associated Cost Saving ($/ft^2)	Typical Peak Saving (W/ft^2)	Associated Cost Saving ($/ft^2)
Stepped Dimming	0.6	0.05	1.4	0.1
Continuous Dimming	0.9	0.06	2.1	0.15
Interior Manual Shading	0.15	0.01	1.4	0.1
Interior Auto Shading	0.15	0.01	1.4	0.1
Glazing	0	0	1.7	0.12
Exterior Static Shading	0.3	0.02	0.8	0.06
Exterior Auto Shading	0.7	0.05	2.5	0.18

Table 1: Indicative peak and cost savings for daylighting energy efficiency measures per unit of floor area

Additional Cost Reductions: Reduction in HVAC System Capacity

New construction and retrofit projects (if HVAC systems are being updated) offer an excellent opportunity to reduce the installed cooling or heating capacity required for a building or building zone. Estimates on the expected cost reductions are highly variable, as should be expected for the numerous building designs and configurations that exist and the variations in HVAC systems.

As a guide, a reduction of a 1 watt in cooling capacity per square foot may be worth around 8 cents; whereas, a reduction of 1 watt in heating capacity may be around

2 cents.[6] For new construction projects, COMFEN outputs suggest that designers can expect to make significant first-cost savings of between 10 cents and 30 cents per square foot when installing several systems (such as continuous dimming, higher-performance glazing, and exterior automatic shading) in concert; in more extreme climates, load reductions of 3 watts per square foot of floor area appear possible. For retrofit projects, significant cost savings are also on offer: significantly greater reductions in cooling and heating demand are available (up to 13 watts per square foot in hot climates with large windows). However, cost reductions are unlikely to unlock all of that value, as an HVAC plant retrofit would likely be limited to replacement of the existing plant with smaller capacity equivalents and not include refitting infrastructure such as ducts and pipes.

Conclusion: For an accurate assessment of your design options, always conduct a thorough load analysis with skilled engineers or consultants.

Additional Cost Reductions: Utility Rebate and Equipment Installation Programs

Rebate programs for commercial buildings operate across the country and will cover a variety of equipment, depending on where you are. These initiatives can include replacement of light fixtures and installation of new control features (including daylight harvesting), and they also offer custom incentives such as a dollar amount per kilowatt-hour of energy saved, although these may be limited to a project's first year or two.

Rebates are calculated according to equipment or system type. For lamp replacement, the rebate is likely to be based on the cost of the replacement items, whereas for controls, the rebate amount may be linked to a reduction in operational lighting power density (measured power reductions in watts per square foot) or by the number of sensors and controls installed (dollars per square foot of installed controls). The rebate would normally cover a certain portion of the project cost up to a maximum percentage (as high as 70%) or up to a maximum dollar value (up to $200,000).

Your project may also qualify for discounted installation of such equipment.

Local utilities also provide energy analysis services, which can audit your current energy use and help you target specific measures to reduce it. For further details, check with your utility. For an overview of what is available in your area, visit www.dsireusa.org.

Additional Cost Reductions: Demand Response (DR)

Time-based pricing of electricity provides a strong incentive for building owners and operators to manage their consumption of electricity, in particular to limit the building electricity load during periods of peak demand. An increasingly common approach is to incorporate flexibility into building energy systems, so that demand can be reduced to a certain threshold during peak periods or during demand response "events."

[6] From the COMFEN Cost Module, at http://windows.lbl.gov/software/comfen/4.1/Cost.htm. Taken originally from 901 HVAC Downsizing (Means, 2006), where cost per ton of cooling is estimated at $940/ton and cost per kBtu-hour of heating is estimated at $21.

The economic benefits are tangible but problematic to incorporate in a cost-benefit analysis; the savings that can be realized will depend not just on the usual climate and environment variables, but also on the electrical connection capacity (which is a site-specific issue) and tariff structures applied by different utilities in different parts of the country. For this reason, an example is more helpful than trying to assess average impact. In Northern California, demand-response benefits range in value from $0.5 per kilowatt to $9 per kilowatt per event[7] for demand-response capacity reduction, and from $0.15 per kilowatt-hour to $1 per kilowatt-hour per event for demand-response energy savings. Realizing cost savings through the use of dimming controls is a real prospect for more-efficient lighting systems that can reduce demand instantaneously for DR events, for load management with time-of-use rates, and for overall energy savings over thousands of hours per year, so that savings are captured both in terms of connected energy load reductions (kilowatts) and units of energy saved (kilowatt-hours).

Unvalued Benefits of Daylight Harvesting Technologies

It is worth reiterating that other elements, such as visual comfort and productivity, could be assessed to have value applied to them. None of these benefits have been included in the economic results above. Assigning an appropriate value is always problematic, but it is inaccurate to assign a zero-value to them. Each designer/owner partnership will have different perspectives on this, so it remains a discussion between those partners (and ideally other stakeholders too).

A review of labor-cost intensity and energy-cost intensity (both per square foot) illustrates their relative cost burdens to the building owner, operator, or tenant. Commercial building energy costs are in the range of $2–$4 per square foot per year for an energy-intense building or in a utility service territory with high prices. Staff costs, including employer overhead, assuming an average U.S. office worker's salary, can be $500–$1,000 dollars per square foot of office space per year. To realize the maximum benefit associated with the labor cost, the working environment must be thermally comfortable and glare free, support relaxation and concentration, and discourage absenteeism. Comfort requirements should logically be assigned greater value, furthering the economic case for good energy-efficient daylighting design over and above savings made in energy costs. This approach should also lead to better integrated design.

The same principles apply to the preservation of health. Minimizing illness or stress-related absence is crucial in maximizing the value of investment in staff. Where a space provides good air quality and circulation, light conditions appropriate to the work task and individual preference, and the means to control one's environment, the likelihood of physical or psychological ailments and illness-related absences are greatly diminished.

The project team should attempt to value comfort-related occupant satisfaction and productivity and encourage others to think in these terms. Comfort value should be incorporated into a full and fair analysis of daylighting design, and into building design generally.

[7] The Pacific Gas and Electricity regime pays per event, so the annual value will reflect how often the building owner wishes to participate.

Conclusion

Results of the analysis suggest that many buildings offer plenty of energy-saving opportunities through implementation of daylighting design. When selecting the best systems for a building, the key is to understand the project priorities and the owner's economic goals and to maximize energy savings in ways that are consistent with those goals.

There are factors beyond energy cost savings that have not been reflected in the analysis above; for example, glare in a hot, bright summer climate will frequently drive design decisions to install high-performance glazing and exterior shading. In this case, the energy cost benefits might be viewed merely as a consequence of good design rather than as a separate target.

But with energy prices trending gradually upwards and the cost of the daylight control equipment dropping as the result of greater market competition and technological development, payback periods for building systems that focus on provision of usable, comfortable daylight will continue to fall.

INTEGRATION ISSUES

Architecture

Using good performance simulation data with a cost-benefit analysis is the only way to review HVAC/lighting/envelope trade-offs. Added envelope and lighting features for daylighting and shading may be compensated for in first-cost and operating-cost savings.

Interior

Cost-benefit analysis for daylighting design has relatively little impact on interior decisions.

HVAC

Use a cost-benefit analysis to accurately examine how reductions in heat gains from the lighting and envelope system affect HVAC first costs and operating costs.

Lighting

Many energy-efficient lighting technologies and controls have a relatively short payback period.

Savings prediction of daylighting technologies and envelope/lighting design strategies for daylight integration are not so clear cut. A life-cycle cost analysis is recommended.

Cost Effectiveness

Cost effectiveness of energy-efficient design is best derived from a life-cycle analysis. Include hard-to-quantify factors such as comfort, productivity, tenant retention, and building amenities.

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Occupant Comfort

An emphasis on low first cost often results in future occupant comfort. Discomfort is typically a long-term expense.

Uncomfortable occupants may lead to long-term increases in operating costs due to thermostat adjustments by occupants or portable heaters and fans adding to plug loads. Complaints often lead to a high rate of tenant turnover and costly mechanical or envelope retrofits. Uncomfortable occupants are less productive. Furthermore, as employee salaries are a dominating cost for employers, maintaining productivity (and the cost-effectiveness of investment in it) should be a priority.

There are real economic benefits to occupant comfort, although they are hard to quantify. Nonetheless, some recognition of comfort should be included in cost-benefit analysis.

PROVISOS

- The ability to predict cost effectiveness is limited when actual building performance calculations are not taken into account. Building performance can be assessed through measured data from comparable existing buildings or through computer modeling software that includes daylighting analysis.
- Due to the many variables, it is impossible to exactly predict the true savings. Variables such as user behavior, future modifications to the building or site, important changes during construction, changes in utility rates, and lack of proper operation and maintenance can all affect savings potential. However, it is possible to make good estimates of potential savings with uncertainties attached.

TOOLS & RESOURCES

- Cost-benefit analysis methodologies (as outlined in Key Ideas)
- Check with an appropriate expert or consult the large array of literature available on this subject. An introduction to this topic area may be found at:

  Whole-Building Design Guide – Life-Cycle Cost Analysis (LCCA)
  www.wbdg.org/resources/lcca.php

  Federal Energy Management Program – Life-Cycle Cost Analysis
  www1.eere.energy.gov/femp/program/lifecycle.html

  Online cost-benefit analysis tools are also available:

  The WBDG website also provides links to other cost analysis tools:
  www.wbdg.org/tools/tools.php

  The Energy Life-Cycle Cost Analysis (www.ga.wa.gov/eas/elcca/home.html), from the State of Washington General Administration, provides an

Integrated Approach
Feasibility
Envelope/ Room
Glazing
Shading
Mechanical Coordination
Lighting
Sensors & Controls
Calibration/ Commissioning
Maintenance
Cost-Benefit Analysis

Preparation
Pre-Design
Conceptual Design & Programming
Schematic Design/ Design Development
Construction Documents
Pre-Occupancy
Post-Occupancy

introduction to the methodology and guidance on using the assessment spreadsheet, which is available as a download.

Conducting an internet-based search will identify near-infinite resources with useful guidance on this subject.

- **Consultant** A detailed cost-benefit study requires specialized knowledge in both energy modeling and economic analysis. A consultant with experience in these areas is recommended for projects where the building owner's financial concerns are paramount.
- **Utility Company** Your local utility may provide design assistance or financial incentives. Many utilities have customer service educational centers equipped with rotating displays, seminars, and staff available to answer questions on specific projects.
- **NTIS** Many documents and guidelines are available from the National Technical Information Service at www.ntis.gov/.
- **AIA** *Guide to Building Life Cycle Assessment in Practice* (American Institute of Architects, Washington D.C. 2010) is a useful handbook. Contact your local AIA chapter for this and any other relevant AIA publications, or download the guide at www.aia.org/aiaucmp/groups/aia/documents/pdf/aiab082942.pdf.
- **BOMA** The Building Owners and Managers Association offers publications on a variety of topics, including a large selection of economic materials; visit www.boma.org/Pages/default.aspx for details.
- **Computer Tools** The Building Life-Cycle Cost program (BLCC) is available at the NTIS website address above.
- **Books** Many titles on cost-benefit analysis are available, and they cover the general topic, as well as specific applications. Consult an online bookstore for the latest offerings.

Resources for Codes and Standards

General Building Design: Applicable to Majority of Daylighting Design Disciplines

American Institute of Architects: www.aia.org/

American National Standards Institute: www.ansi.org/

American Society of Heating, Refrigeration and Air-conditioning Engineers: www.ashrae.org/

American Society for Testing and Materials: www.astm.org/

Building Code, Federal Commercial Buildings:
http://www.energycodes.gov/regulations/federal-building-standards

Building Energy Codes: search by State at energycodesocean.org/code-status-commercial

Illuminating Engineering Society of North America: www.iesna.org/

International Code Council: www.iccsafe.org

Institute of Electrical and Electronics Engineers: www.ieee.org/

International Electrotechnical Commission: www.iec.ch/

International Energy Agency: www.iea.org/

International Standards Organization: www.iso.ch/

Local and State Electrical Codes (search by location)

National Electrical Code: www.necplus.org/

National Electrical Manufacturers Association: www.nema.org/

National Fire Protection Agency: www.nfpa.org/

National Institute of Standards and Technology: www.nist.gov/index.html

Occupational Safety and Health Administration: www.osha.gov/

Building Design Integration

ASHRAE/IES/USGBC Standard 189.1: Design of High Performance Green Buildings

International Energy Conservation Code – Inspecting for the Commercial Provisions of the IECC (US DOE)

Glass and Glazing

American Architectural Manufacturers Association (AAMA) – North American Fenestration Standards/Specification for windows, doors, and skylights, **and**

American Architectural Manufacturers Association (AAMA) Voluntary Standards for Thermal Transmittance and Performance: www.aamanet.org/

National Fenestration Ratings Council Certified Products Directory, to identify certified products by purpose of use: www.nfrc.org/

Window and Door Manufacturers Association: www.wdma.com/

Shading

American Society of Civil Engineers, for guidance and specifications on appropriate means of attachment and wind load requirements: www.asce.org/

Building Seismic Safety Council, for guidance and specifications for seismic mitigation methods: www.bssconline.org/

Mechanical Systems and Integration

ASHRAE Indoor Air Quality (IAQ) Guide: Best Practices for Design, Construction and Commissioning.

ASHRAE Standards – check for latest version as updates take place every four years:

ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy.

ASHRAE Standard 62.1: Ventilation for Acceptable Indoor Air Quality.

ASHRAE 90.1: Energy Standard for Buildings (except Low-Rise Residential).

Lighting

IES Lighting Handbook: www.ies.org/handbook/

IES RP-1 - American National Standard for Office Lighting: Available from the ASHRAE website at www.techstreet.com/cgi-bin/detail?doc_no=ies|rp_1_04;product_id=1154865

Calibration and Commissioning

IES Guides for Measurement Testing and Calculation: www.ies.org/store/department/measurement-testing-calculation-guides-10008.cfm

International Performance Measurement and Verification Protocol: www.evo-world.org/

Cost Estimating

The International Cost Estimating and Analysis Association: www.sceaonline.org/

12 Tools and Resources Summary

Section	Target User Group(s)
Integrated Design	
ENERGY STAR A joint program of U.S. Environmental Protection Agency and U.S. Department of Energy that aims to promote energy-efficient products and practices. The program offers incentives for decreasing energy use through adapting energy-efficient windows and skylights. The website is a good resource for current U.S. standards and to find examples of buildings that meet energy efficient goals. www.energystar.gov/	**Building Owner/Operator, Engineer**
DesignBuilder A whole-building model that can be used also as a learning/teaching tool due to its simple operation. The software can produce daylight contour plots and daylight factor calculations based on the RADIANCE raytracing software. A feature of the program is generating reports for eligibility to various daylighting credits. The software can be integrated with EnergyPlus for more sophisticated lighting controls and energy savings calculations. For more information, visit www.designbuilder.co.uk/.	**Energy Modeler, Engineer, Lighting Designer**
Energy Plus and Simergy A whole-building energy simulation program used by researchers and professionals to model energy and water use in buildings. The tool can model lighting control, glazing, shading, and dynamic window management and daylighting effects. Learning to manipulate the program takes time, and an expert might be consulted and hired to perform the simulations. The program has the ability to optimize building features in order to reduce water and energy consumption. A new easier-to-use graphical user interface to EnergyPlus, Simergy, was released late in 2012. For more information, visit http://apps1.eere.energy.gov/buildings/energyplus/.	**Energy Modeler, Engineer**
Federal Green Construction Guide for Specifiers www.wbdg.org/ccb/	**Architect**
IES Advanced Energy Design Guides (various building types). For more information, visit www.ies.org/store/AEDG.cfm/.	**Architect, Building Owner/Operator, Engineer**
PECI Advanced Energy Retrofit Guides (various building types). For more information, visit www.peci.org/advanced-energy-retrofit-guides/.	**Architect, Building Owner/Operator, Engineer**
United States Green Building Council for details of current LEED requirements related to daylighting and seminars by your local chapter on daylighting design. Visit new.usgbc.org/.	**Architect, Building Owner/Operator, Engineer**

Daylight Feasibility	
Advanced Lighting Guidelines now online, the New Building Institute resource for guidelines on lighting for commercial buildings, visit www.algonline.org/	**Architect, Lighting Designer**
COMFEN, short for *commercial fenestration*, is a single-zone facade analysis tool that can be used to evaluate a range of facade configurations in order to understand the impact of different design variables on facade performance. After defining a building type, location, and zone properties (dimensions and loads from equipment and people and fenestration layout), several additional scenarios can be quickly created and compared side-by-side. Orientation, window-to-wall ratio (WWR), glazing type, and/or shading can easily be varied in order to assess their impact on energy use, peak loads, daylighting, and thermal and visual comfort. Some Radiance analysis can be completed from within COMFEN to assess glare. Visit http://windows.lbl.gov/software/comfen/comfen.html.	**Architect, Building Owner, Engineer**
Daylighting Pattern Guide This tool was developed by the New Buildings Institute to guide commercial building designers and professionals in planning daylit spaces. The guide consists of visual aids showing the effects of design variables to daylight distribution. Results are developed from case studies and simulation of different daylit spaces throughout the country. The key design choices compared in the guide include orientation, glazing layout, area, shading strategies, and more. For more information, visit http://patternguide.advancedbuildings.net/.	**Architect, Lighting Designer**
DAYSIM Daylighting analysis tool based on RADIANCE that can calculate the annual availability of daylight in buildings. The program considers occupant behavior and how they control the space lighting and blinds. The tool can be used to calculate savings from automated lighting controls such as occupancy sensors and daylight dimming. The tool can also calculate annual glare and useful daylight illuminance. For more information, visit www.daysim.com/.	**Architect, Lighting Designer**
ECOTECT A 3-D design tool that incorporates lighting, solar radiation, and cost analysis features developed by Autodesk. The software can interface with Radiance, EnergyPlus and other analysis tools. The software is used for whole-building analysis to model total energy and water use; in terms of daylighting the software can simulate illuminance levels, daylight factors, and incident solar radiation on building surfaces. For more information, visit http://usa.autodesk.com/ecotect-analysis/.	**Architect, Lighting Designer**
Integrated Environmental Solutions Virtual Environment An integrated building simulation program that supports whole-building modeling and also detailed focus on individual building systems. For more information, visit www.iesve.com/.	**Architect, Lighting Designer, Engineer**

IEA Task21 This technical guide and accompanying website are a excellent general resource for information and data on daylighting design and provides detailed technical guidance on controls, performance evaluation, and design tools. For more information, visit http://archive.iea-shc.org/publications/downloads/8-8-1%20Application%20Guide.pdf. **RADIANCE** A suite of programs to analyze and visualize light levels used for lighting design. It translates scene geometry, luminaire data, and material properties into radiance values. This tool can be used to simulate concept designs before construction. For more information, visit http://radsite.lbl.gov/radiance/framew.html. **SOLAR TOOL** This parametric software supports sizing and placement of exterior shading systems such as overhangs, blinds, and louvers, and is therefore a useful precursor to some of the more detailed modeling software options. For more information, visit http://apps1.eere.energy.gov/buildings/tools_directory/software.cfm/ID=376/. **VECTORWORKS** This software allows visualization of effects of direct solar radiation for any location or time of year. It also supports the understanding of daylight distribution and light levels (illuminance and luminance). For more information, visit www.vectorworks.net/.	**Architect, Lighting Designer** **Architect, Lighting Designer** **Architect, Lighting Designer** **Architect, Lighting Designer**
Envelope and Room	
Window Systems for High Performance Buildings - Facade Design Tool This tool allows the user to compare annual energy, peak demand, daylight illuminance, and other performance metrics for different design choices. Design parameters included in the tool are facade orientation, window area, daylight controls, interior shades, and window type. For more information, visit www.commercialwindows.org/fdt.php.	**Architect, Lighting Designer, Energy Modeler, Engineer**
Shading	
ParaSol A design tool to determine the effects of shading and glazing to solar radiation and to the building's energy load. The results show the total and direct solar energy per month, energy demand, and maximum heating and cooling load, which can be saved into a spreadsheet. For more information, visit www.parasol.se. **Polar Sun Chart Path Program** This website will plot the sun paths that apply to your building project. http://solardat.uoregon.edu/PolarSunChartProgram.php.	**Architect, Energy Modeler, Engineer** **Architect, Lighting Designer**

Sustainable by Design A web-based interface that shows a visual representation of external shading designs and solar design parameters. The interface is simple and can be used for quick references and to visualize the effects of common design decisions such as overhang width and height. The tool does not contain energy or cost metrics. For more information, visit www.susdesign.com/. **SketchUp** A software tool that is a simple, accessible route to creating a project design, and allows the user to incorporate all necessary architectural details relating to provision of good quality daylight through the use of shading design. For more information, visit www.sketchup.com/. **SunTools (for SketchUp)** A software plug-in that provides further support to the SketchUp software suite by allowing the user to understand the impacts of building at different latitudes, using sun path, sun position, and sun penetration algorithms. Available as a free download from several websites: search on "Sun Tools" to find the latest version.	**Architect, Lighting Designer** **Architect, Lighting Designer** **Architect, Lighting Designer**
Glazing	
Commercial Windows An online facade design tool, which allows users to pick from numerous facade options, varying window area, glass types, shading systems etc. Based on COMFEN, results are reported in terms of energy savings, peak demand, cost savings and reductions in emissions. For more information, visit www.commercialwindows.org/. **FENSIZE** A user-friendly tool that quickly calculated the thermal and solar properties of windows, skylights, and other fenestration products. The tool can be used as a quick reference to fenestration properties and to generate standard project and product reports. The tool can also target window properties that would meet building codes and Energy Star criteria. Whole-building properties are not part of the analysis. For more information, visit www.fenestration.com/index.php. **Frame Simulator** The program is used to analyzed the heat flow through the window system, glazed area and frame. The program can calculate surface temperatures which is related to condensation problems. For more information, visit www.dartwin.it/en/sw/frame-simulator/. **Optics** This software supports detailed analysis of glazing using the optical and radiative properties of specified glazing units, and other add-ons such as solar coatings or tinted treatments. For more information, visit http://windows.lbl.gov/software/optics/optics.html.	**Architect, Lighting Designer, Energy Modeler, Engineer** **Architect, Lighting Designer, Energy Modeler, Engineer** **Energy Modeler, Engineer** **Architect, Lighting Designer**

THERM A two-dimensional building model for heat-transfer for building components such as windows. The program is used to evaluate the energy efficiency of building materials and their temperature patterns. Other software use THERM as a basis for their energy models. For more information, visit http://windows.lbl.gov/software/therm/therm.html. **Window** This program calculates the thermal performance indices of windows, such as U-value, solar heat gain coefficient and visible transmittance, and can be used in the project design process of for the development of new products. For more information, visit http://windows.lbl.gov/software/window/window.html.	**Energy Modeler, Engineer** **Architect, Energy Modeler, Engineer**
Lighting Coordination	
DIALux A software program used to simulate outdoor and indoor building lighting systems. The software can import and export files to CAD programs. The software has a wide database of international regulations and standards for different countries. This program is free and easy to learn and can be used for architectural and technical lighting design. For more information, visit www.dial.de/DIAL/en/dialux-international-download.html. **NECA/IES:** Installing Indoor Commercial Lighting Systems: www.necanet.org/store/products/index.cfm/NECA%20500R-06	**Architect, Lighting Designer** **Architect, Lighting Designer**
Sensors and Controls	
IES TM-23-11 Lighting Control Protocols: this is a reference document for lighting design teams that are also specifying integrated controls on their projects. www.ies.org/PDF/Store/TM-23-11_FINAL.pdf **LCA** The Lighting Controls Association is a resource for switching and dimming controls. Leading manufacturers of control systems are members of this association. The website has up-to-date publication and information about current lighting control technology. http://lightingcontrolsassociation.org/ **Sensor Placement and Optimization Tool (SPOT)** An online tool to assist with the placement of daylight harvesting sensors according to the type of daylighting systems will be operated, selection of appropriate algorithms and control system setting, with reporting in terms of light levels and energy savings. For more information, visit www.archenergy.com/SPOT/download.html.	**Engineer, Lighting Designer** **Engineer, Lighting Designer** **Architect, Engineer, Lighting Designer**
Calibration and Commissioning	
International Energy Agency - Daylighting Buildings in the 21st Century:	**Lighting Designer**

http://archive.iea-shc.org/publications/downloads/8-8-1%20Application%20Guide.pdf. **National Electrical Contractors Association**: Guide to Commissioning Lighting Controls: www.necanet.org/files/ACF363E.pdf **International Performance Measurement and Verification Protocol**: www.evo-world.org/ **See SPOT in the Sensors and Controls section above.**	 **Engineer, Commissioning Agent** **Engineer, Commissioning Agent**

13 Glossary

Altitude The vertical angular distance of a point in the sky (usually the sun) above the horizon. Altitude is measured positively from the horizon (0˚) to the zenith (the point in the sky straight overhead, 90˚).

Ambient Lighting General illumination, typically used to define lighting requirements for non-task specific areas, e.g., circulation areas.

Azimuth The horizontal angular distance between the vertical plane containing a point in the sky (usually the sun) and true south. In other words, the angle of sun from true south as seen in plan view. In some cases, this angle is defined relative to true north.

Baffle A single opaque or translucent element used to shield a source from direct view at certain angles.

Ballast Electrical device which supplies proper voltage, current, and wave form conditions to start and operate discharge lamps (fluorescent, mercury, high-intensity discharge).

Brightness The subjective perception of luminance.

Brightness Glare Glare resulting from high luminances or insufficiently shielded light sources in the field of view. Also called direct glare.

Candela (cd) A common unit of light output from a source, a measure of luminous intensity.

Candlepower The intensity of light produced by a source, measured in candelas.

Candlepower Distribution Curve A diagram plotted on polar coordinates which represents the variations in light output of a source throughout the directions into which the source emits light. Commonly used in lighting product brochures.

Color Rendition The effect of a light source on the color appearance of objects.

Commissioning A set of activities conducted during or after the construction phase aimed at verifying that the building, or pieces of its systems, function as designed. This is a comprehensive process of reviewing design documentation, verifying installation, testing equipment and system performance, training building operators, and analyzing the operation of building systems.

Contrast Glare Glare resulting from a large brightness difference in the field of view.

Cost/Benefit Analysis Any technique intended to relate the economic benefits of a solution to the costs incurred in providing the solution.

Cut-Off Angle The critical viewing angle beyond which a source can no longer be seen because of an obstruction, such as a baffle or overhang.

Daylight Factor The ratio of daylight illuminance on a horizontal point indoors to the horizontal illuminance outdoors, expressed as a percentage. Direct sunlight is excluded.

Deadband The thermal range within which mechanical systems are not operating.

Diffuse Lighting Indirect light (the source is often not visible) that comes from a variety of angles or directions.

Diffuser Any device that disperses light from a source, e.g., translucent glass.

Discount Rate A rate used to relate present and future dollars. This is a percentage used to reduce the value of future dollars in relation to present dollars, to account for the time value of money. Discount rate may be the interest rate or the desired rate of return.

Footcandle (fc) Unit of illuminance used in the inch-pound system. The metric unit is lux.

Footlambert Unit for luminance in the inch-pound system. The metric unit is the candelas per square meter (cd/m^2).

Glare The sensation produced by brightness within the visual field that is greater than the brightness to which the eye is adapted and thus causes annoyance, discomfort, or loss in visual performance and visibility.

Illuminance (fc, lux) Roughly, the amount of light falling on a surface.

Indirect Lighting Lighting achieved by reflection, usually from wall and ceiling surfaces.

Kilowatt (kW) Unit of electric power (the rate at which energy is used). Equals 1,000 watts.

Kilowatt-Hour Unit of energy. Equals 1,000 watt-hours.

Life Cycle The period of time between a baseline date and the time horizon, over which future costs or benefits will be incurred.

Light Shelf A horizontal element positioned above eye level to reflect daylight onto the ceiling.

Load shedding The process through which peak electricity requirement is reduced, normally through turndown in plant or component operations or shut down / switch off.

Louver A series of baffles used to shield a light source from view at certain angles.

Lumen (lm) A common unit of light output from a source.

Luminaire A complete electric lighting unit including housing, lamp, electrical components, diffusers, and focusers. Also called a fixture.

Luminance (cd/m^2) Roughly, the amount of light coming from a surface in a single direction; in other words, how bright it is.

Luminance Ratio Ratio between different brightnesses in the visual field.

Lux The metric unit for illuminance. The inch-pound unit is the footcandle.

Minimum Attractive Rate of Return The effective annual rate of return on an investment which just meets the investor's threshold of acceptability. It reflects the cost of using resources as well as the potential risk involved with the project.

Payback Period Time required for an investment to return its value to the investor.

Photometer/photosensor An instrument for measuring light.

Present Worth (or Value) The current value of an amount. Typically used to represent the value today of a future amount, by discounting the future amount to current dollars.

Rate of Return on Investment An interest rate which represents a measure of profit from an investment.

Reflectance The ratio of energy (light) bouncing away from a surface to the amount striking it, expressed as a percentage.

Reflected Glare Glare resulting from mirror-like reflections off of shiny surfaces.

Stationpoint The preferred location for placement of sensors and meters on the basis of their access to natural and artificial light.

Task Lighting Light provided for a specific task, versus general or ambient lighting.

Transmittance The ratio of energy (light) passing through a surface to the amount striking it, expressed as a percentage.

Thermal comfort criteria/standards The thermal range within which a person wearing a "normal" amount of clothing is neither too hot nor too cold.

U-value The metric by which heat flow through a material is measured; lower values indicate lower rates of transmission.

Veiling Reflection A condition where light reflected from a surface masks the details of that surface. A common occurrence when glossy magazines are read under bright, direct lighting.

Visual Acuity A measure of the eye's ability to distinguish fine details.

Visual Comfort Probability Rating of a lighting system expressed as a percentage of the people who will find it free of discomfort glare.

Visual Field What can be seen when head and eyes are kept fixed.

Visual Performance The quantitative assessment of a visual task, taking into consideration speed and accuracy.

Watt Metric unit of power.

Watt-hour Unit of energy corresponding to exerting one watt of power during one hour.

Workplane The plane at which work is performed, usually taken as horizontal and at desk height (30") above the floor.

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15 Appendix A

First Cost and Energy Savings

Costs units: $/sqft	New Construction						Retrofit					
Energy units: $ /sqft /yr	Minimum		Typical		Maximum		Minimum		Typical		Maximum	
Energy Efficiency Measure	Eqmt Cost ($/sqft)	Labor Cost ($/sqft)	Eqmt Cost ($/sqft)	Labor Cost ($/sqft)	Eqmt Cost ($/sqft)	Labor Cost ($/sqft)	Eqmt Cost ($/sqft)	Labor Cost ($/sqft)	Eqmt Cost ($/sqft)	Labor Cost ($/sqft)	Eqmt Cost ($/sqft)	Labor Cost ($/sqft)
	Total Installed Cost ($/sqft)		Total Installed Cost ($/sqft)		Total Installed Cost ($/sqft)		Total Installed Cost ($/sqft)		Total Installed Cost ($/sqft)		Total Installed Cost ($/sqft)	
	Energy Saving ($/sqft/yr)		Energy Saving ($/sqft/yr)		Energy Saving ($/sqft/yr)		Energy Saving ($/sqft/yr)		Energy Saving ($/sqft/yr)		Energy Saving ($/sqft/yr)	
Stepped Dimming	0.63	0.25	0.86	0.38	1.09	0.50	0.63	1.08	0.86	2.17	1.09	4.33
	0.88		1.23		1.59		1.71		3.02		5.42	
	0.85		0.56		0.51		0.85		0.56		0.51	
Continuous Dimming	1.10	0.50	1.50	0.75	1.90	1.00	1.10	1.08	1.50	2.17	1.90	4.33
	1.60		2.25		2.90		2.18		3.67		6.23	
	0.98		0.62		0.27		0.98		0.62		0.27	
Internal Manual Shading	1.68	0.00	2.64	0.00	6.00	0.00	1.68	0.00	2.64	0.00	6.00	0.00
	1.68		2.64		6.00		1.68		2.64		6.00	
	0.79		0.19		0.01		0.79		0.19		0.01	
Internal Adaptive Shading	6.48	0.00	6.96	0.00	7.44	0.00	6.48	0.00	6.96	0.00	7.44	0.00
	6.48		6.96		7.44		6.48		6.96		7.44	
	0.23		0.09		0.06		0.23		0.09		0.06	
High Performance Glazing	0.24	0.00	3.42	0.00	9.97	0.00	0.66	0.00	4.63	0.00	13.87	0.00
	0.24		3.42		9.97		0.66		4.63		13.87	
	0.68		0.17		0.01		0.68		0.17		0.01	
External Static Shading	1.39	2.40	5.60	2.40	11.20	2.40	1.39	2.40	5.60	2.40	11.20	2.40
	3.79		8.00		13.60		3.79		8.00		13.60	
	0.88		0.26		0.02		0.88		0.26		0.02	
External Auto / Motorized Shading	13.33	4.90	16.67	4.90	20.00	4.90	13.33	4.90	16.67	4.90	20.00	4.90
	18.23		21.57		24.90		18.23		21.57		24.90	
	2.48		0.68		0.05		2.48		0.68		0.05	

Year of material and labor cost data: 2011, indicative labor cost from California (which has generally higher commercial equipment / plant installation labor rates than elsewhere in the United States[8]). Cost data is on $ / square foot, energy savings quoted in $ / square foot / year for three climate zones (reference locations, Phoenix; Washington, D.C.; and

[8] U.S. Bureau of Labor Statistics. www.bls.gov/oes/current/oessrcst.htm.

Minneapolis), cardinal point facade orientations and a range of window sizes. Maximum and minimum energy savings reflect performance in extreme climates, with “typical" being a calculation of the mean across all three climate zones. Energy savings estimates include impacts on electricity use for lighting and cooling and on gas use for heating.

Table A-1: Equipment and Labor Costs and Energy Savings by System Type

Table A-1 highlights costs and energy savings associated with each of the listed EEMs. Costs are quoted in dollars per square foot of serviced floor area and include equipment and labor (including installation) costs separately and in total. Energy savings are quoted in dollars per square foot per year. So for instance, for Stepped Dimming in New Construction (red highlighted numbers), the total typical installed cost is estimated at $1.23 per square foot ($0.85 for equipment and $0.38 for labor), and the typical energy cost savings are estimated at $0.56 per square foot. For that example, the simple payback would be less than 2.5 years.