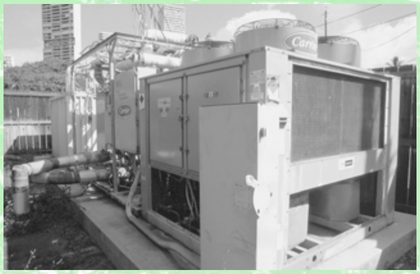
Hawaii Commercial Building Guidelines for Energy Efficiency



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PREFACE

Introduction to Energy Efficiency Guidelines

The *Hawaii Commercial Building Guidelines for Energy Efficiency* promote the design of energy-efficient buildings that are also healthy and pleasing places to spend time in. These guidelines address new construction as well as major renovation of commercial buildings.

This document is written for architects, engineers, lighting designers, contractors, building owners, and others making decisions about the design of buildings and their systems. Building professionals often have a hard time obtaining information about the relative efficiency and costs of design alternatives, especially when they are working under a tight schedule. These guidelines are intended to make that information readily accessible.

While these guidelines cover a wide range of topics, they are not intended to be comprehensive. Other energy efficiency strategies not included here may be appropriate as well.

These guidelines cover the following topics, with a separate chapter dedicated to each topic:

1. Whole Building Design
2. Natural Ventilation
3. Daylighting
4. Electric Lighting and Controls
5. Energy-Efficient Windows
6. Cool Roof Systems
7. Dehumidification
8. HVAC and Water Heating
9. Building Heating, Cooling and Power Systems

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1. WHOLE BUILDING DESIGN

Overview of Whole Building Design

Hawaii's climate presents unique challenges and opportunities to designers of commercial buildings. In most of the United States it is taken for granted that heating and/or cooling systems will be installed. But in Hawaii designers often have a choice of using either air conditioning or natural ventilation in a building. There are many successful examples of both strategies.

Whether a building is naturally ventilated or air conditioned, the odds of success improve dramatically if the project team employs an integrated design — or *whole building design* — approach. This is especially true when considering a building's energy efficiency. The operating costs of energy-consuming systems such as lighting and air conditioning are highly dependent on the architectural design. For example, a well-shaded building will not only consume less energy but will likely have a smaller and less expensive cooling system. With adequate attention to cross-ventilation design, the building may need no cooling at all. In addition, a well-designed fenestration system will reduce the need for electric lighting and save large amounts of energy.

From an energy efficiency perspective, the following design issues should be addressed at the same time and as early as possible in the design process:

- Solar control strategy
- Daylighting and visual comfort strategy
- Thermal comfort strategy
- Special indoor environment requirements
- Air quality strategy

Sometimes design strategies may seem to be in conflict with one another. For example, using reflective glass for solar control limits the amount of visible light available for daylighting. Natural ventilation for thermal comfort may not always maintain the indoor temperature and humidity necessary for special equipment. But if these issues are considered early in the design process, then conflicts can be resolved and energy-efficient design options can be developed.

These general design strategies influence many specific design decisions, including:

- Siting and orientation (although there is not always much choice in Hawaii because land is scarce and views are a high priority)
- Building form (shape, number of stories)
- Fenestration design (glass type, window area, shading design, operability)
- Roof construction and surface type
- Lighting system design (luminaire type, controls)
- Mechanical system type (including ceiling fans)
- Interior space zoning
- Material selection (moisture resistance, light color, thermal mass)

The remaining sections of this chapter discuss important whole building design issues and describe design alternatives and recommendations.

Whole Building Design and Construction Process

In the traditional design process, lack of communication among the designers sometimes leads to lost savings opportunities. In some cases, efficient HVAC equipment cannot be accommodated unless considered early in the schematic design phase (or even earlier, in the budgeting phase). Sometimes there is not enough design time budgeted at the beginning of the project to evaluate design alternatives.

While there is no single “best” design process, several steps can help ensure a successful project.

Energy Efficiency Budget

In the planning process, provide a budget for design coordination and evaluation of energy efficiency alternatives. Depending on the project’s size, this could range from $5,000 to $50,000. In addition, the inspections and functional testing required for proper building commissioning cost roughly $0.25 per square foot of floor area.

Integrated Design Meeting #1

At the beginning of schematic design, hold a meeting between the architect, mechanical designer, electrical designer, lighting designer, owner/tenant, and other consultants. Consider including utility personnel to take advantage of their expertise and incentive programs.

At this meeting discuss design strategies for energy efficiency. The list of design issues in this chapter (for example, solar control strategy, daylighting and visual comfort strategy, etc.) could serve as a framework for the meeting.

The meeting should result in a list of potential strategies and design goals. Some issues will require further evaluation.

Evaluation of Alternatives

Following the initial meeting, evaluate design alternatives. A little extra investment at this point can save a lot later on. This step may involve simulations or engineering calculations. Thermal simulations can predict the performance of building form options or air conditioning system choices. Daylighting simulation can predict illumination levels. Rough cost estimating is important to determine the lifecycle cost of design alternatives.

Integrated Design Meeting #2

Hold a second integrated design meeting before finalizing the schematic design. This meeting can be used to select design alternatives and to communicate the design approach and important features to the whole team.

Design Development Review

Arrange for a plan and specification review before the end of design development to ensure that the design strategies are implemented properly. The project manager or construction manager should formally track the status of energy efficiency measures.

Construction Documents Review

Review construction documents to ensure that the plans and specs clearly state the contractors' responsibilities for installation and testing of efficiency measures.

Submittals Review

During the construction phase, review contractor submittals to ensure proper performance of efficiency measures. This step is critical because some substitutions may not be equal in ways that are not immediately obvious (for example, the substituted equipment may not be compatible with other controls).

Construction Inspection

Inspection is an obvious step and is a normal part of any construction project. However, specific inspection of energy-efficient equipment does not always occur. Conduct an inspection to confirm that controls are installed as specified and that sensors are located so they will give accurate readings.

Functional Performance Testing

A formal testing process is extremely valuable. When buildings are first occupied, the building systems seldom function as their designers' intended. Using the building's maintenance staff to debug problems and address occupant complaints can be very costly. Many of these problems could be eliminated by testing system performance before occupancy.

Solar Control Strategy

To achieve a comfortable and energy-efficient building in Hawaii, controlling the amount of sunlight and heat from the sun that enters the building is key. Good solar control offers several benefits:

- Lower energy cost
- Smaller and less expensive cooling system
- Greater occupant comfort because of cooler interior surfaces
- More usable interior space because of improved comfort near windows

Effective solar control is not always easy or inexpensive. Fortunately, several strategies work well. This section provides an overview of alternatives and discusses some whole building design implications. **More details on many of these strategies may be found in the specific guidelines in this document.**

Orientation

Proper orientation is the most important strategy. Whenever possible, limit the amount of window and wall area on the east and west facades. Sunlight is easier to control on the north and south sides of a building.

Fixed Shades

The best strategy for solar control in Hawaii is to keep direct sunlight off the windows. Overhangs are typically the best choice and are especially effective on the north and south facades. The combination of overhangs and vertical fins can nearly eliminate direct solar gain for most of the year. See the Energy-Efficient Windows Guidelines for details.

Operable Shades

Automatic or manually controlled operable shades can replace or supplement fixed shades. When the sun is obscured by clouds or is on the other side of the building, operable shades can be adjusted to allow more light into the space and to give occupants a better view. However, operable shades are less likely to provide full long-term energy efficiency benefits compared to fixed shades because operable shades require more maintenance and their effectiveness depends on occupant behavior.

Exterior shades provide greater solar control because they block more heat from entering the building. However, interior shades may last longer, especially in areas close to the ocean or subject to harsh weather.

Windows

Windows are critical in the battle against the sun. A designer's first choice should be to minimize the amount of direct solar radiation that reaches the windows. If direct sunlight can be kept off the windows, then inexpensive clear or lightly tinted glass can be used. However, if it is not possible to completely shade the windows from direct sunlight, then solar-control glazing should be specified.

The most important glazing characteristic for windows in Hawaii is solar heat gain coefficient (SHGC). A low SHGC can be provided through several different technologies:

- *Heat-absorbing tints.* These tints are available in a range of colors. Some tints, typically blue or green in color, offer better visible light transmittance while providing equal or better solar control than gray or bronze tints. Consider using these blue or green tints in daylighting designs. All heat-absorbing tints get hot in direct sunlight — an important consideration for buildings where occupants sit close to windows.
- *Heat-reflecting coatings.* Several types of coatings are available. Some appear reflective; others are designed to reflect as much heat as possible while also appearing as clear as possible. The latter type of coating is called "spectrally selective" and is the best choice for simultaneously providing daylight and solar control.
- *Laminates.* These consist of plastic films sandwiched between two sheets of glass. Both heat-absorbing and heat-reflecting films are available. Heat-absorbing glass can be used to create the laminated glass sheet, providing further solar control.
- *Films.* Plastic films similar to those used to create laminated glass can be applied to the surface of the glass after the window is installed. This should be considered only as a retrofit measure because the exposed film is not as durable as glass.

In colder parts of the world, U-factor (an indicator of insulating performance) is often considered the most important feature of a window. Low U-factor is achieved using measures like multi-pane windows, infrared reflecting coatings and inert gas fill in glazing cavities. In Hawaii, where the difference between outdoor and indoor temperatures is small, U-factor is not an important issue.

Cool Roof

After windows, the roof is the next most significant path for solar heat to enter a building. As with windows, several effective solar control strategies are available. The first is to prevent solar heat from ever being absorbed by the roof surface. A "cool roof" surface is typically a white material that reflects solar radiation (high reflectance) and reradiates heat to the cool sky (high emissivity). Cool roof materials include white single-ply membranes, white liquid-applied coatings and white painted metal or tile.

A second solar control option is a radiant barrier, a reflective sheet with a low-emissivity surface that prevents radiant heat transfer between a hot roof and the surfaces below. For details, see the Cool Roofs Guidelines.

Finally, insulation also reduces heat gain through the roof. Foam board and fiberglass batts are two common materials. Cellulose spray-in insulation is also effective; many spray-in cellulose products are made primarily from recycled paper, an added environmental benefit.

Walls

As with windows, the first choice for controlling heat gain through a wall is shading. If shading is not possible, consider a light-colored exterior wall, radiant barrier, insulation and/or thermal mass to reduce heat flow. As with windows, the primary source of cooling load through walls in Hawaii is not high outdoor temperature. Rather it is solar radiation hitting the wall and heating the wall's surface. Therefore, a white uninsulated wall can be as effective as a dark wall with insulation.

Landscaping

Landscaping can provide excellent solar control. Place trees and shrubs in strategic locations, especially on the east or west sides where they can block morning and afternoon sun. But even if plants do not directly shade a building, they can help keep the local environment cooler. Pay special attention to shading asphalt roads and parking lots.

Integrated Design Conflicts

Designing for good solar control involves several tradeoffs and potential synergies. These are a few of the potential conflicts to consider when choosing an appropriate strategy.

Solar Control vs. Daylighting

Providing more daylight can conflict with the goal of reducing solar heat gain. However, well-designed shades can block much solar gain while also improving daylight penetration into the building. In addition, spectrally selective glazings can provide a low SHGC while also offering good visible light transmittance.

Solar Control vs. Hurricane Safety

Window overhangs or vertical fins might increase wind pressure on building walls during a storm. Extra structural measures may be necessary.

Solar Control vs. Allowable Building Floor Area

Overhangs or lanais are sometimes counted toward the allowable floor area of a building, thereby reducing the amount of interior floor area allowed.

Solar Control vs. Maintenance

Exterior shades should be designed to allow access for window washing. Measures to discourage roosting birds might also be considered.

Integrated Design Benefits

Good solar control provides benefits that affect many aspects of the building's design and operations, including:

Air Conditioning Zoning

Fewer air conditioning zones may be necessary if windows are effectively shaded because cooling loads will vary less between orientations.

Air Conditioning Capacity

An important benefit to solar control is smaller cooling loads and smaller and less expensive cooling equipment.

Dehumidification Performance

Typically, air conditioning equipment must be sized to meet peak solar loads through windows. If the windows are well shaded, then the equipment can be smaller and run at a more constant load. Not only does the equipment run more efficiently, but it also provides better dehumidification performance and better comfort.

Occupant Comfort

Hot surfaces cause comfort problems for occupants. Therefore, solar control at the roof, walls and windows improves occupant comfort.

Daylighting and Visual Comfort Strategy

Lighting accounts for about 40% of the energy cost for commercial buildings in Hawaii, and most of that lighting energy is consumed during daylight hours. Therefore, buildings designed to take advantage of daylight provide dramatic energy savings.

Several daylighting strategies are available, and more than one may be applied in a single project. Two broad categories of daylighting design are toplighting and sidelighting. Toplighting employs skylights or roof monitors to illuminate a space from above. Sidelighting designs use daylight from windows.

To be effective, a daylighting design must consider visual comfort. If glare is excessive, occupants may resort to using window shades, which may reduce the energy savings of the daylighting design.

To take advantage of the potential energy savings, the designers must develop a daylighting strategy early in the design process. Once decisions such as the number of stories and basic floor plan are made, many daylighting options may be eliminated.

Design team collaboration is critical to successful daylighting design. The architect, lighting designer and electrical engineer all play important roles and need to work together.

The success of a daylighting design often lies in the design details. Analysis tools such as physical models or computer simulations are very useful for selecting window size, shading configurations and space layouts. These tools can predict illumination levels and identify glare or daylight distribution problems.

Building Form

The most basic design decisions have a big impact on daylighting potential. Single-story buildings have the greatest number of options: they can take advantage of toplighting, sidelighting or both. Multi-story buildings can achieve nearly complete daylighting through several means. A narrow floor plan, like that of many high-rise hotels, allows most indoor space to be illuminated by sidelighting. A courtyard or atrium can also allow daylight to reach interior zones of lower floors.

Space planning should account for uses that benefit from daylighting and those that don't. Most general office, medical examination, retail and educational spaces benefit from daylight access. Seldom-occupied spaces, such as storage rooms, can be given lower priority. Some types of work that are best performed with lower illumination levels will receive less benefit from daylighting. However, with careful design, even spaces with critical computer-intensive tasks can successfully employ daylighting.

Orientation

Orientation has an impact on daylighting effectiveness. As with solar shading design, daylight is more easily controlled on the north and south sides of a building. Whenever possible, the long sides of a building should face north and south, minimizing the east and west exposures. Good daylighting design is more difficult on the east and west sides because of glare created by direct sunlight in the morning and afternoon.

Skylights

Overhead skylights can be a very cost-effective means of providing pleasant and even illumination to an interior space. And in a single-story building, skylights can meet all the daytime lighting needs. Skylights are common in large spaces such as warehouses and factories, but they have also been used with great success in smaller spaces such as offices and classrooms. See the Daylighting Guidelines for details.

Windows

It's usually desirable to provide separate vision fenestration (windows that provide views) and daylighting fenestration (glass that provides daylighting). Vision glass should have lower light transmission to reduce glare and maintain the visual comfort of occupants close to the window. Daylighting glass, positioned higher on the wall, should transmit more visible light to provide better daylight penetration for occupants further from the window. Refer to the Daylighting Guidelines for more information.

Lightshelves and Other Shading Devices

Lightshelves or similar shading devices help improve the daylighting performance of windows. A good shade design serves two purposes: it blocks direct sunlight penetration and reflects diffuse light deeper into the room. See the Daylighting Guidelines for more information.

Controls

For a daylighting design to save energy, some form of electric lighting control is necessary. There are several control options; the best choice depends on the space type, the size of the space, and the type of lamp being controlled. See the Daylighting Guidelines.

Manual control is the simplest approach. However, occupant control is unlikely to achieve consistent and lasting savings, especially in larger buildings. Small, owner-occupied buildings are the best candidates for manual lighting control.

Automatic dimming control is the most desirable option for continuously occupied spaces such as offices. Dimming controls are least distracting and are therefore most likely to be accepted by occupants.

Automatic On/Off or multiple-step control is the best choice for spaces that are intermittently occupied, such as warehouses, workshops or similar spaces. Automatic On/Off control provides good energy savings while being relatively inexpensive.

Costs and Benefits

Some daylighting design options can add significant cost to the project, but daylighting's many benefits should be considered before rejecting daylighting based solely on first-cost concerns. For example, a design that allows daylight to reach all parts of the building may result in less floor area than a square floor plan that fills up the lot and has large interior spaces. But that extra cost could be worth the additional benefits. Besides saving lighting energy, a building designed for daylighting may also be able to save energy by employing natural ventilation because occupied spaces are likely to be close to openings. Even without natural ventilation, daylighting can lead to cooling energy savings because of the reduced heat gain from lights. And tenants often favor daylit spaces, increasing the value of the building.

Productivity can also be a powerful — and perhaps the most valuable — benefit to good daylighting design. The value of a mere 1% increase in occupant productivity far outweighs the investment cost for better daylighting and controls. Recent studies have shown that schoolchildren learn faster in a daylit environment.[1] Other studies seem to show improved sales in daylit retail stores; further studies are underway to verify this effect.[2] These study results indicate that energy savings are just a small part of the total benefits of good daylighting design.

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[1] Heschong Mahone Group, *Daylighting in Schools,* and *Skylighting and Retail Sales* (Pacific Gas & Electric Company, 1999). Available at www.pge.com/pec/daylight.

[2] *Productivity and Interior Environments* studies now being conducted by Heschong Mahone Group for the New Buildings Institute's *Integrated Energy Systems: Productivity & Building Science* program, a project of the State of California PIER Program. For more information, go to www.newbuildings.org/pier.

Thermal Comfort Strategy

Thermal comfort depends on several factors, including air temperature, relative humidity, air movement and the temperature of surrounding surfaces. Therefore, several approaches to maintaining comfort are possible.

Natural Ventilation

From an energy efficiency and air quality perspective, natural ventilation is usually the best choice. Natural ventilation should be considered in all spaces without special indoor environment constraints (see Special Indoor Environment Requirements section). Of course, the feasibility of natural ventilation also depends on the building location.

For a successful naturally ventilated building, designers need to pay greater attention to the surroundings. Obstructions, landscaping and microclimate issues are important. Nearby sources of noise or dust can also be a constraint.

The Natural Ventilation Guidelines discuss thermal comfort and natural ventilation strategies.

Ceiling Fans

Ceiling fans are an effective way to provide comfort through air movement. See the Natural Ventilation Guidelines for ceiling fan design guidelines.

Mechanical Cooling

Mechanical cooling and dehumidification can ensure comfort for the majority of occupants. But no single condition is acceptable to all people, so even a well-designed mechanical system will not provide perfect comfort.

If choosing air conditioning for all or a portion of a building, consider the following:

- *Low supply air temperature.* By operating at a lower supply air temperature — closer to 50°F rather than 55°F leaving the cooling coil — dehumidification performance improves. And if humidity control is required, then less reheat energy will be necessary. Use a low approach coil (typically larger) to achieve the lower supply air temperature without necessarily reducing chilled water temperature.
- *Dual-path air handler.* Condition outside ventilation air (where much of the system's latent moisture-load comes from) separately from return air. Cool the outside air as low as is feasible to extract as much moisture as possible. Then provide additional cooling to the relatively dry return air if more cooling is necessary. See the Dehumidification Guidelines for details.

- *Humidity control.* Use measures such as heat pipes and run-around coils to avoid using a reheat coil. See the Dehumidification Guidelines.
- *Careful load calculation and equipment sizing.* If specifying packaged, direct expansion cooling equipment (as opposed to chilled water cooling), be especially careful not to oversize the cooling capacity. In addition, consider a unit with a refrigerant subcooling option to improve the dehumidification capacity. See the HVAC Guidelines for recommendations regarding packaged air conditioners.

Hybrid Design

Many successful designs employ natural ventilation and air conditioning in separate portions of the same building. For example, spaces with very high equipment loads or occupant density can be mechanically cooled, while areas such as open offices, private offices, corridors and lobbies can be naturally ventilated. A good hybrid design requires careful space planning from the start.

Building Envelope

Regardless of the choice of natural or mechanical ventilation, the building shell should be designed to prevent the occupants from being exposed to hot interior surfaces. Insulation reduces the interior wall and ceiling temperatures. Window shading, coated glass or both help keep windows cool. Avoid tinted glass where it will be exposed to direct sunlight. Tinted glass absorbs solar radiation and can reach very high temperatures, causing discomfort for people close to the windows.

Special Indoor Environment Requirements

The choice between natural ventilation and air conditioning depends in part on whether natural ventilation can provide acceptable indoor conditions. One important consideration is human comfort, but another is the environment necessary for the operation of equipment or for other indoor space functions.

Office Equipment

Electronic equipment is designed for operation within certain temperature and humidity limits. Some electronic devices will malfunction if they get hot. Therefore it is important to make sure that any equipment located in a naturally ventilated space will tolerate temperatures of 80°F to 90°F.

Natural ventilation is not a problem for typical personal computers; they are rated to operate in temperatures as high as 95°F and relative humidity as high as 90%.

Table 1-1. Operating temperature and relative humidity (RH) range for selected office equipment. Source: Manufacturers' product literature.

Product	Temperature Range °F	RH Range (non-condensing) %RH
Desktop Computers		
Power Mac G4	50 – 95	5 – 95%
iMac	50 – 95	5 – 95%
Power Mac G4 Cube	50 – 95	5 – 95%
HP Desktop (Brio)	41 – 95	15 – 85%
HP Desktop (Vectis)	41 – 95	8 – 85%
Laptop Computers		
IBook	50 – 95	20 – 80%
PowerBook G4	50 – 95	20 – 80%
Dell Inspiron	41 – 95	10 – 90%
Printers		
HP Copyjet	59 – 95	30 – 80%
HP Deskjet	59 – 95	20 – 80%
Xerox Desktop Laser	50 – 90	15 – 85%
IBM Laser	60 – 90	20 – 80%
Epson Inkjet	50 – 95	20 – 80%
Copy Machines		
Xerox 2510	60 – 90	15 – 85%

Some paper may curl at high humidity and affect printer or copier performance. These problems may be minimal if the paper is not subject to changing conditions. For copiers and printers located in naturally ventilated spaces, store the paper under the same conditions.

Refrigerated equipment may develop condensation on its surface if it is not well insulated. Water coolers, refrigerators and vending machines could be affected.

Medical Facilities

Some spaces within hospitals and other medical facilities may require pressurization controls to prevent contamination between rooms. Mechanical ventilation and cooling may be required for those areas, limiting the potential application of natural ventilation.

Medical electronics may be sensitive to temperature and humidity. Manufacturer specifications should be checked when natural ventilation is considered.

Laboratories

Some laboratories require exhaust systems to remove potential contaminants. The changing pressure due to natural ventilation could interfere with the safe operation of fume hoods.

Libraries & Museums

Some materials such as books and other paper documents require low humidity to prevent damage. Art and artifacts may also require conditions not attainable through natural ventilation.

Retail Spaces

Spaces with many refrigerated cases are not good candidates for natural ventilation because the humidity can create condensation problems.

Indoor Air Quality Strategy

Good indoor air quality is best achieved through a system approach that considers:

- ventilation,
- moisture control,
- reduction of indoor pollution sources, and
- monitoring and maintenance.

Ventilation

For naturally ventilated buildings the most important issue is the location of nearby exterior pollution sources. Obvious sources include roads, parking lots, dusty fields, agricultural areas and some commercial or industrial activities.

Ventilation is traditionally employed as an indoor air quality solution for air-conditioned buildings. However, ventilation alone cannot guarantee a healthy building, and high ventilation rates raise energy costs.

Moisture Control

Good moisture control in the roof, walls and floors is important to prevent mold growth. Careful design of the air conditioning system can also improve dehumidification to inhibit mold growth.

Indoor Pollution

To improve indoor air quality, reducing indoor pollution sources is critical. Choose furniture and finishings with low emission rates of toxic chemicals. Ensure that air from storage spaces for chemicals and cleaning materials is directly exhausted to the outside. It is also a good idea to exhaust air from areas with photocopiers or printers.

Monitoring & Maintenance

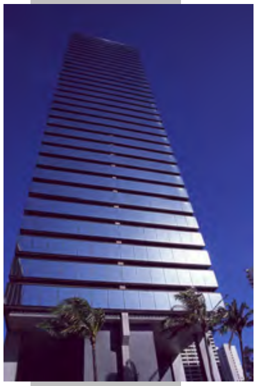
Regular cleaning and maintenance of air conditioning equipment is essential. Cooling coils are nearly always host to mold growth in Hawaii, and can be sources of odor and health problems. Maintenance options include thoroughly cleaning the coils (preferably twice each year), or installing ultraviolet lamps in the air handlers to inhibit mold growth. See the HVAC Guidelines.

Specific Building Type Issues

Different building types present different opportunities for energy efficiency. This section highlights important issues for a number of commercial and institutional building types.

Office Buildings

Solar Control



Windows are the critical element in office solar control. Proper orientation and exterior shading are the preferred approach. Otherwise, glazing with low solar transmission is appropriate (but also remember light transmission for daylighting). See the Energy-Efficient Windows Guidelines for recommendations.

The roof is also important, especially for low-rise offices. See the Cool Roofs Guidelines.

Daylighting and Visual Comfort

Daylighting is ideal for offices, saving both lighting and cooling energy. Both sidelighting (through windows and clerestories) and toplighting (via skylights) are applicable. See the Daylighting Guidelines.

Wherever possible, try to keep the building depth narrow (under 40 feet) to allow for good daylighting and improve natural ventilation opportunities. A relatively high ceiling — 10 to 12 feet — will also improve daylight penetration and natural ventilation.

Lighting design also offers an excellent savings opportunity for offices. Consider suspended direct/indirect fixtures and appropriate (low) ambient illumination. See the Electric Lighting Guidelines.

Use occupancy sensors for lighting control.

Thermal Comfort

Natural ventilation works for offices in Hawaii, especially if supplemented with ceiling fans. If there's critical equipment or materials that require special environmental conditions, consider designing the building with a small air-conditioned room in the

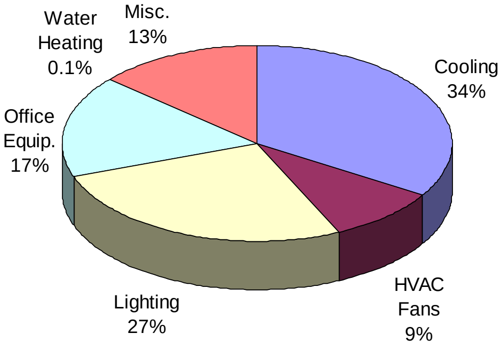


Figure 1-1. Energy consumption for typical Hawaii office building; total 23 kWh/yr-ft^2.

building core instead of conditioning the whole building. See the Natural Ventilation Guidelines.

Otherwise use a variable-air-volume air conditioning system to provide fan power savings and superior dehumidification performance compared to a constant-air-volume system. In addition, consider a dual-path system that cools ventilation air separately from return air and further improves dehumidification. See the HVAC and Dehumidification Guidelines.

Indoor Air Quality

Natural ventilation can often provide excellent indoor air quality. Otherwise, consider a demand-controlled ventilation system that varies the amount of outside ventilation air depending on the number of occupants. Also consider UV lamps in air handlers to inhibit mold growth. See the HVAC Guidelines.

Retail Buildings

Solar Control

For many retail buildings, especially “big box” stores, the roof is the main path for solar heat to enter the building. See the Cool Roofs Guidelines for recommendations.

Daylighting and Visual Comfort

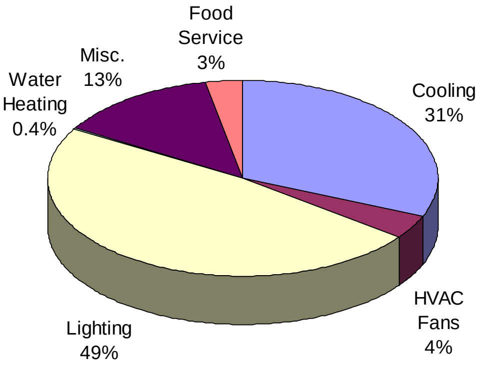
Lighting is usually the biggest energy consumer in retail buildings (except for grocery stores, where refrigeration is also significant). Therefore, special attention to lighting design is critical. Minimize the use of incandescent lamps, using them only for accent lighting. See the Electric Lighting Guidelines.

Skylights are a great choice for many retail spaces, providing lighting savings as well as excellent color rendition. See the Daylighting Guidelines for recommendations.

Thermal Comfort

If air conditioning is necessary, then a dual-path system may be appropriate, especially for spaces with refrigerated cases because the lower humidity will help prevent condensation.

Also consider variable-air-volume controls to minimize fan energy and improve dehumidification.



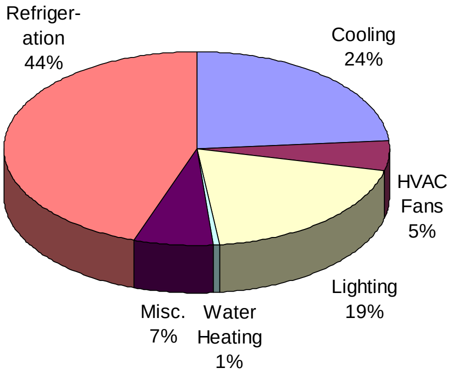


Figure 1-2 (left). Energy consumption for typical Hawaii retail facility (excluding grocery); total 26 kWh/yr-ft^2.

Figure 1-3 (right). Energy consumption for typical Hawaii grocery building; total 53 kWh/yr-ft^2.

Indoor Air Quality

Consider UV lamps in air handlers to inhibit mold growth on cooling coils.

Other Savings Opportunities

Recover heat rejected from refrigeration and air conditioning systems for water heating.

School Buildings

Solar Control

School buildings in Hawaii are typically naturally ventilated. Therefore, solar control is critical for comfort. Proper orientation is important, and window shading is common and highly desirable. In addition, a cool roof—such as a white roof combined with a radiant barrier—is necessary to help keep the classrooms cool and comfortable.

Daylighting and Visual Comfort

Daylight has been shown to improve learning performance. Therefore, classrooms, gyms and multipurpose rooms are excellent candidates for daylighting design using windows and skylights. See the Daylighting Guidelines for details.

Lighting design is another big savings opportunity in schools. A high ceiling provides multiple benefits, allowing pendant-mounted direct/indirect lighting and improving daylight distribution and thermal comfort. See the Electric Lighting Guidelines for design and lighting control recommendations.

Thermal Comfort

Natural ventilation should be the first choice for classroom comfort. Otherwise, if outdoor noise or pollution don't allow the windows to stay open, then a dual-path air conditioning system is an excellent choice because classrooms have high outside air ventilation rate requirements due to high occupant density. See the Dehumidification Guidelines for more information.

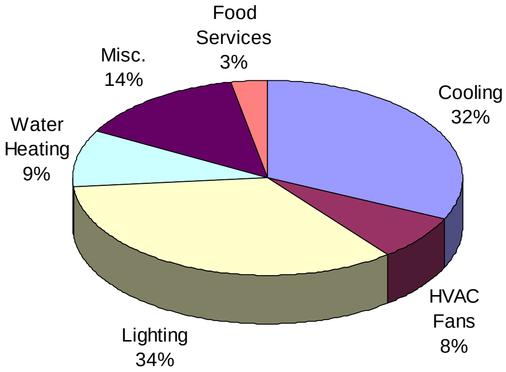


Figure 1-4. Energy consumption for typical Hawaii school; total 9 kWh/yr-ft^2.

Indoor Air Quality

Natural ventilation is the best choice, assuming that outdoor air quality is reasonable. If air conditioning is installed, then humidity control is important. The system should be carefully designed so that it is not any larger than necessary. An oversized system cycles on and off more frequently and dehumidification performance degrades.

Health Care Buildings

Solar Control

Health care buildings often have less window area than other commercial building types, but high performance windows are still likely to be cost effective for solar control, especially if windows have little exterior shading.

Daylighting and Visual Comfort

Many parts of health care facilities can be effective illuminated using daylight, with task lighting used for critical tasks. Lighting controls should include occupancy sensors in private office spaces and exam rooms.

Thermal Comfort

Cooling is a major energy consumer in many health care facilities because many spaces use 100% outside air for ventilation (no recirculated air). In addition, some spaces such as operating rooms also require humidity control. The Dehumidification Guidelines provide recommendations for energy-saving systems such as heat pipes and run-around coils.

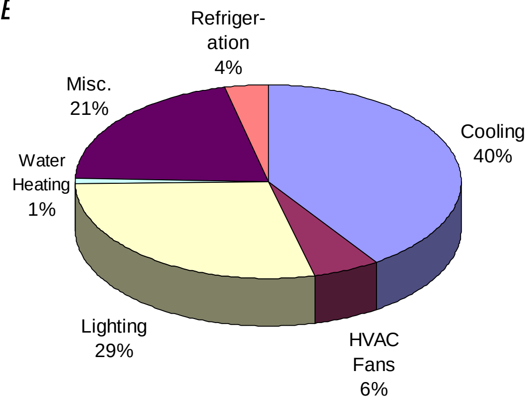


Figure 1-5. Energy consumption for typical Hawaii health care building; total 25 kWh/yr-ft^2.

Indoor Air Quality

Humidity control is important for good indoor air quality. It’s especially challenging in facilities that operate 24 hours per day, as do many health care buildings. The problem is that moisture must be removed from the ventilation air even at night when the air temperature is relatively low and cooling requirements inside the building are lower. In a conventional system the ventilation air is cooled to low temperature, perhaps 50°F to 55°F, to remove moisture and then reheated to avoid overcooling the building. The process of cooling and reheating can be energy intensive. Therefore, it is important to consider the energy-saving dehumidification techniques described in the Dehumidification Guidelines.

Another source of air quality problems can be mold growing on the damp cooling coils. UV lamps inside the air handlers can help keep coils clean. More intense levels of UV light can be used to kill microbes in the air as it flows through the air handler to help prevent the spread of diseases such as tuberculosis.

Hotels

Solar Control

The main challenge for solar control in hotels is providing complete window shading while also maintaining views. As much as possible, windows should be facing north or south. And balconies should be designed to keep the sun off the windows at all times (which is very difficult for east and west-facing windows). If complete shading is not possible, then consider high performance low-e windows that have low solar transmission while maintaining good views. See the Energy-Efficient Windows Guidelines for details.

Daylighting and Visual Comfort

Hotel guest rooms typically have adequate window area for daylighting illumination. To optimize light distribution within the room, use light-colored interior surfaces. For low-rise hotels, consider small skylights in bathrooms.

Avoid the use of energy-intensive incandescent lighting. Modern compact fluorescent fixtures can provide good color rendition, lower energy consumption, and much longer life.

Thermal Comfort

Design for natural ventilation, allowing the guests to easily shut off cooling and rely on cross ventilation and ceiling fans for comfort. If air conditioning is installed, use magnetic switches on balcony doors to shut off cooling to a room when the door is open. Also consider an energy management system that reduces cooling demand by automatically raising the temperature in vacant rooms.

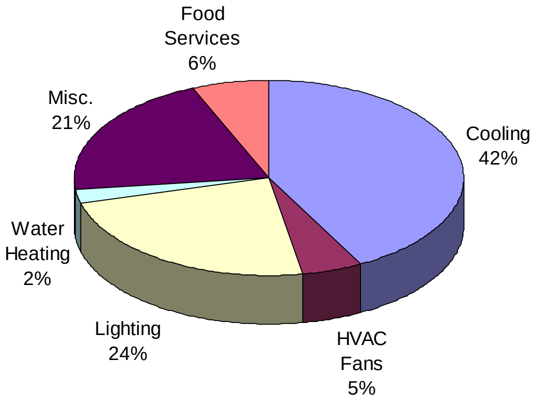


Figure 1-6. Energy consumption for typical Hawaii hotel; total 16 kWh/yr-ft^2.

For ballrooms and meeting rooms, use controls to vary the amount of outdoor air ventilation depending on occupancy. See the HVAC Guidelines.

Indoor Air Quality

Moisture control is the primary air quality issue in hotels. Ventilation air delivered to guest rooms should be dehumidified.

Other Savings Opportunities

Hotels are an excellent application for using heat recovered from the cooling system to heat water. Heat rejected by water chilling equipment can be very effectively recovered using heat pump water heaters.

Restaurants

Solar Control

As with most other building types, attention to the windows and the roof is important for solar control. Consider operable exterior shades for east- or west-facing glazing.

Daylighting and Visual Comfort

For general ambient light, use full-size or compact fluorescent lighting. Limit the use of incandescent (including halogen) lamps to accent lighting.

Thermal Comfort

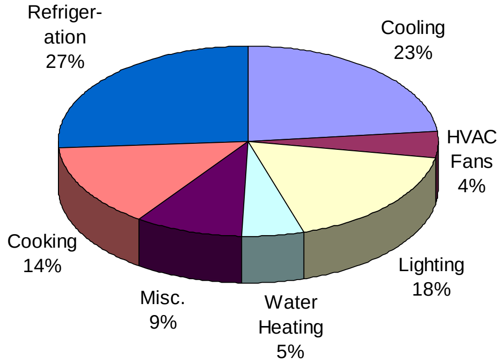


Figure 1-7. Energy consumption for typical Hawaii restaurant; total 53 kWh/yr-ft^2.

In many cases, cross ventilation and ceiling fans can provide comfort in dining rooms and cooling should not be necessary. Otherwise, it is important to pay attention to air conditioner sizing. A restaurant can have highly variable cooling loads because the number of occupants varies over the day. Therefore, good comfort requires that the system operate over a wide range of cooling loads while still providing good humidity control. Consider a dual-path system for humidity control and demand control for outside air volume. See the Dehumidification and HVAC Guidelines.

Kitchen comfort can be a significant energy issue. Providing air conditioning to the kitchen can be very costly due to the large heat sources and the large volume of exhaust air. Before providing air conditioning to the kitchen, it is important to carefully design the exhaust system so that the majority of air that is exhausted is drawn directly from outdoors and introduced to the space directly in front of the range hoods. See the Kitchen Exhaust Makeup section of the HVAC Guidelines.

Indoor Air Quality

Design and commission the kitchen exhaust system to ensure that the kitchen is negatively pressurized relative to the dining room. And, as described in the proceeding discussion of thermal comfort, design the cooling system to operate over a wide range of cooling conditions.

Other Savings Opportunities

Heat recovery from the cooling system or refrigeration system for water heating may be cost effective.

Commissioning

Increasingly, building owners are recognizing that building commissioning is an important strategy for achieving lasting energy savings. Commissioning is a type of quality assurance program used to verify that building systems work together efficiently, effectively and as intended in the design specifications. Commissioning can give the building owner confidence that the designers and contractors have done the work the owner hired them to do. Without a formal commissioning process, building owners may find themselves dealing with costly and frustrating system problems well after construction is complete and the building contractors have moved on to other projects.

Not only does commissioning help ensure that a new building is performing optimally when delivered to the owner, it also improves the chances that the building will continue to operate as intended.

Commissioning Agent

The commissioning process starts with a commissioning agent (CA), who is engaged by the building owner to manage the commissioning and to act as an advocate for the owner. It’s important that the CA be independent and under direct contract to the owner, not under contract to other members of the design and construction team.

The owner should hire a commissioning agent as early as possible in the project. Part of the CA’s job is to identify the commissioning responsibilities of each member of the design and construction team so that this information can be included in each team member’s contract.

Commissioning Plan

In a written commissioning plan, the CA identifies the systems to be commissioned, describes the scope of the commissioning process, lays out a commissioning schedule, and defines the testing and reporting procedures that are integral to the commissioning process.

Most commissioning plans include the following important elements:

- *Installation checks.* Ensure that specified equipment and accessories are installed.
- *Performance checks.* Verify and document that systems are performing as intended, and that sensors and other control devices are properly calibrated.
- *Documentation.* Ensure that all required documentation has been provided, such as a statement of the design intent and operating protocols for all building systems.
- *Manuals and training.* Prepare operation and maintenance (O&M) manuals and provide training to the building operations staff.

- *Monitoring.* Conduct ongoing monitoring after the building is occupied to ensure that equipment and systems continue to perform as expected.

Verification and Testing

Although any building system can be commissioned, the most important systems that should be commissioned are the mechanical, electrical and life safety systems. Throughout the construction process, the CA verifies that the systems are being installed as specified, identifies any problems related to that particular system or its interaction with other systems, and makes recommendations to the owner for correcting those problems.

Functional tests, a key part of commissioning, help ensure that systems are working together as intended. The CA develops written protocols for these tests, ensures that they are properly conducted, documents the results, and reports the findings to the building owner.

Commissioning Report

The Building Commissioning Association recommends that every commissioning process be thoroughly documented with a commissioning report that includes:

- An assessment of the systems’ operating condition when the functional tests are conducted;
- Problems discovered and the steps taken to correct them;
- Uncorrected operational problems that the owner decided to accept;
- Functional test procedures and results;
- Reports documenting all commissioning activities as they progress; and
- A description and estimated schedule of any deferred testing.

Properly implemented, commissioning will ensure that a new building starts its life at the highest performance level possible.

Resources

For more information about building commissioning:

U.S. Department of Energy, Office of Building Technology, State and Community Programs, www.eren.doe.gov/buildings/comm_energyeff.html

Building Commissioning Association, www.bcxa.org

2. NATURAL VENTILATION GUIDELINES

Overview

From energy efficiency, indoor air quality and occupant comfort perspectives, natural ventilation is usually a better choice than air conditioning in a climate like Hawaii's. Natural ventilation can save substantial energy by decreasing or eliminating the need for mechanical cooling. It may also improve the building's indoor air quality, provided that dust and other pollutants in the air outside the building aren't a problem. And buildings with well-designed natural ventilation systems often provide very comfortable and pleasant environments for the occupants. People may even work more productively when they can open and close windows and vary the airflow in their workspaces.

For a successful naturally ventilated building, designers need to pay greater attention to the building's immediate surroundings. Obstructions, landscaping, nearby sources of noise or dust, and microclimate issues must all be considered.

Thermal Comfort

The choice between natural ventilation and air conditioning depends on whether natural ventilation can provide acceptable indoor conditions. One important consideration is occupant comfort.

The traditional definition of comfort published in ANSI/ASHRAE Standard 55–1992 (Thermal Environmental Conditions for Human Occupancy) does not distinguish between spaces with and without natural ventilation. But recent research by Gail Brager of the University of California–Berkeley shows that in naturally ventilated buildings, people adapt to changes in mean outdoor temperature and are comfortable in — and may even prefer — a broader range of thermal conditions. People in air-conditioned buildings, on the other hand, expect even and cool temperatures, and are quickly dissatisfied if thermal conditions differ from what they expect.

This difference in comfort expectations is partly the result of behavioral adaptations: people in naturally ventilated buildings wear appropriate clothes and open or close windows to adjust the airflow. Some of the difference may also be due to physiological factors, as the body's thermal expectations change over the course of a year.

An adaptive model of thermal comfort, instead of the narrow model recommended by ASHRAE Standard 55, allows buildings to be designed and operated to optimize thermal comfort and reduce energy use. Brager's research is at the heart of changes to ASHRAE Standard 55 that are currently under consideration.

For Hawaii, Brager's model means that people in naturally ventilated buildings can be comfortable at higher indoor temperatures as the outdoor air temperature increases[1] (see Figure 2-1). Based on this proposed new thermal comfort model, buildings in Honolulu can be naturally ventilated for most hours between the months of November through April (Figure 2-2). In Hilo natural ventilation can be adequate all year (Figure 2-3).

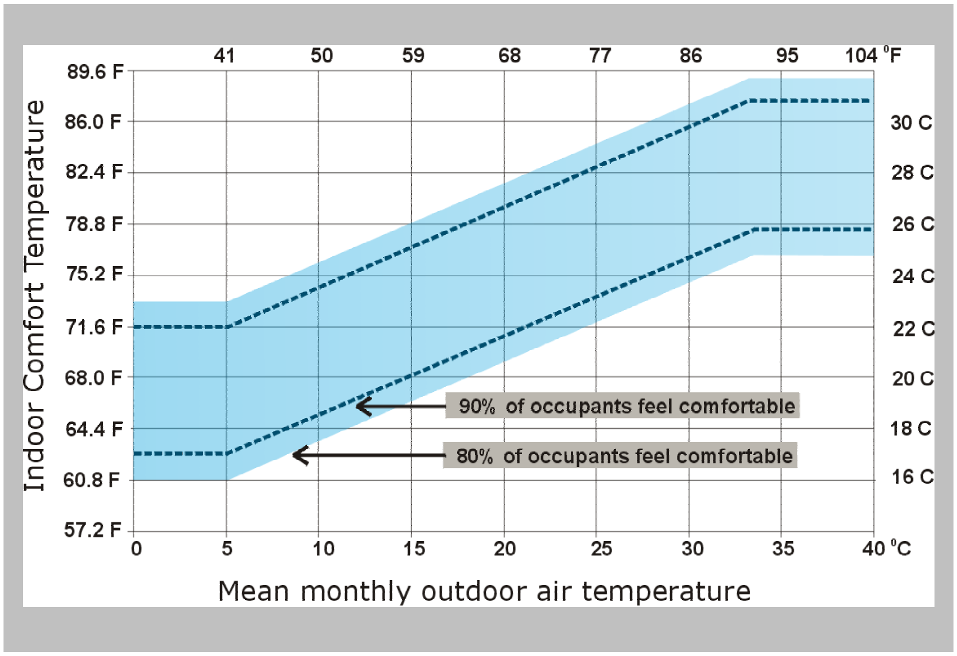


Figure 2-1. Thermal comfort model proposed by Gail Brager. The shaded area shows indoor temperatures at which 80% of occupants feel comfortable as outdoor temperature varies. The area between the dotted lines shows the indoor temperatures at which 90% of occupants feel comfortable.

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[1] Gail Schiller Brager and Richard de Dear, "A Field-Based Thermal Comfort Standard for Naturally Ventilated Buildings," *Collaborative for High Performance Schools (CHPS) Best Practices Manual, Appendix C* (Eley Associates, 2001). Available at www.chps.net. Also, Gail Schiller Brager and Richard de Dear, "A Standard for Natural Ventilation," *ASHRAE Journal,* vol. 42, no. 10 (October 2000), p. 21-28.

Figure 2-2. Indoor comfort range in naturally ventilated buildings in Honolulu (based on comfort model shown in Figure 2-1).

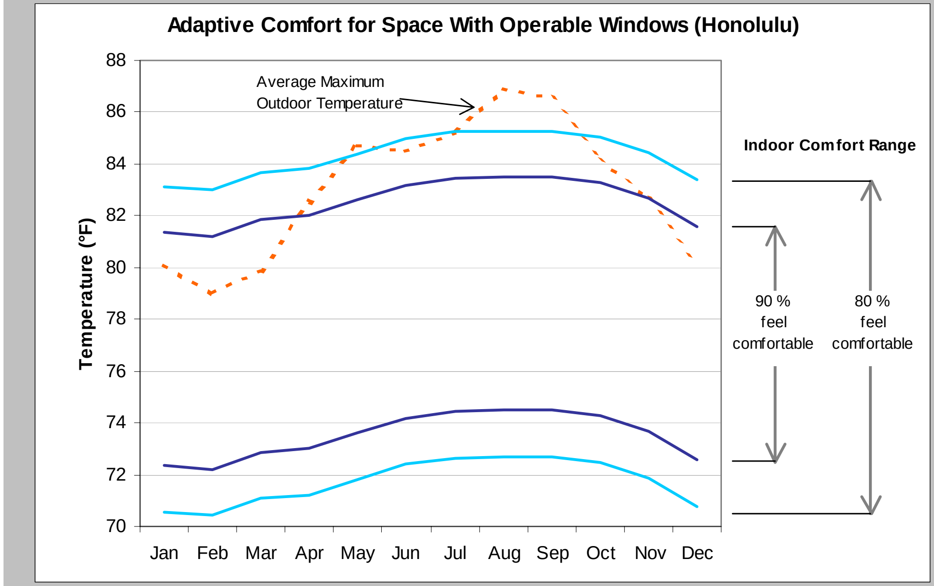

Figure 2-3. Indoor comfort range in naturally ventilated buildings in Hilo (based on comfort model shown in Figure 2-1).

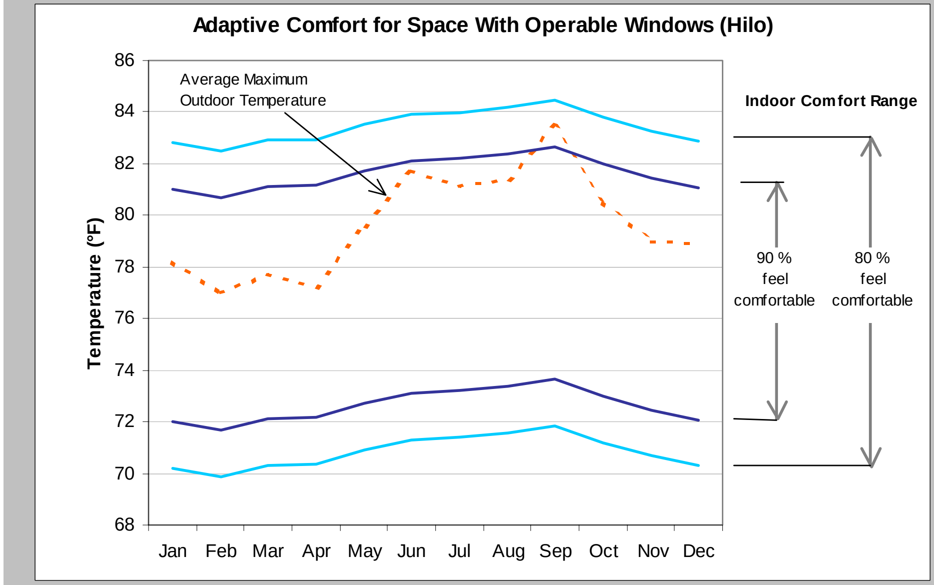

Table 2-1 and Table 2-2 show average hourly outdoor temperatures for Honolulu and Hilo and identify the times of year when outdoor air satisfies indoor comfort requirements. Table 2-1 shows that the majority of working hours fall within the comfort range, but that in Honolulu there are portions of the day in May through October that exceed the 90% comfort limit (outlined in the table with a dotted line). The less stringent 80% limit is exceeded only in August and September (indicated by shading in the table). Commercial buildings in warmer regions of Oahu might need measures like ceiling fans to provide air movement (see next section) and/or careful use of building mass and landscaping to reduce heat loads.

Table 2-1. Average outdoor hourly temperatures (°F) for Honolulu. Dotted line marks the hours when outdoor temperature exceeds indoor comfort limits in naturally ventilated buildings for 10% of occupants. Source of temperature data: Typical Meteorological Year Data, U.S. National Climatic Data Center.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
HOUR													
1	69.3	68.2	70.2	71.1	72.7	75.4	75.4	77.2	76.4	75.6	72.9	69.7	**72.9**
2	68.8	67.9	69.6	70.8	72.3	75.1	74.9	77.1	76.0	75.1	72.4	69.4	**72.5**
3	68.4	67.6	69.1	70.1	71.8	74.7	74.5	76.7	75.6	74.9	72.1	69.4	**72.1**
4	68.1	67.6	68.8	69.9	71.4	74.3	74.3	76.3	75.3	74.4	71.9	69.2	**71.8**
5	67.8	67.3	68.2	69.9	70.8	74.0	73.9	76.1	74.9	74.2	71.7	69.2	**71.5**
6	67.6	66.6	69.3	69.6	70.5	74.0	75.3	75.8	76.1	75.3	71.8	69.4	**71.8**
7	67.3	66.5	70.4	70.5	73.4	75.1	76.8	76.6	77.4	76.3	71.7	69.6	**72.7**
8	69.1	67.5	71.5	73.9	77.0	77.5	78.2	78.5	78.6	77.5	74.1	69.8	**74.5**
9	73.3	71.2	73.6	76.1	79.3	79.3	80.0	80.4	80.6	79.2	77.2	72.7	**76.9**
10	76.3	73.7	75.9	78.5	81.3	80.9	81.7	82.5	82.8	80.9	79.6	75.4	**79.2**
11	77.7	75.9	78.0	79.9	82.5	82.4	83.5	83.8	84.8	82.6	80.7	78.3	**80.9**
12	78.5	77.1	78.5	81.0	83.3	82.9	83.9	85.4	85.2	82.8	81.4	78.7	**81.6**
13	78.7	77.5	79.3	81.4	84.0	83.5	84.2	85.7	85.9	83.5	81.6	79.2	**82.1**
14	79.0	77.9	79.9	81.0	83.4	83.5	84.6	86.2	86.3	83.7	81.7	79.6	**82.2**
15	78.1	77.5	79.2	80.9	82.8	83.4	83.7	85.6	85.4	82.9	81.1	78.8	**81.6**
16	77.3	76.3	78.6	80.5	81.5	82.7	83.0	84.4	84.3	81.9	79.7	78.0	**80.7**
17	75.6	75.4	77.9	78.5	79.8	81.6	82.1	83.4	83.4	81.1	78.2	77.2	**79.5**
18	73.5	73.9	76.5	76.2	78.0	80.0	80.4	81.2	81.8	79.9	76.0	75.8	**77.8**
19	72.2	72.2	75.1	73.6	75.9	78.4	78.9	79.5	80.1	78.6	75.2	74.5	**76.2**
20	71.5	71.5	73.6	72.7	74.9	77.2	77.3	78.7	78.5	77.5	74.3	73.1	**75.1**
21	71.2	70.5	72.9	72.6	74.5	76.9	77.0	78.3	78.3	77.2	74.2	72.2	**74.7**
22	70.5	69.5	72.2	72.3	74.1	76.7	76.5	78.1	77.6	76.8	73.6	71.4	**74.1**
23	69.9	69.0	71.6	71.8	73.9	76.4	76.3	77.8	77.4	76.5	73.4	70.5	**73.7**
24	69.7	68.7	71.0	71.4	73.6	75.8	75.8	77.7	77.0	76.0	73.1	70.2	**73.4**
Avg. Outdoor Temperature (Dry bulb)	72.1	71.7	73.8	74.3	76.1	78	78.8	78.9	78.9	78.2	76.3	72.9	75.8
AVG. DAILY MAX. TEMP.	80.1	79	79.9	82.5	84.7	84.5	85.2	86.9	86.5	84.2	82.6	80.1	83
AVG. DAILY MIN. TEMP.	66.1	65.4	67.7	68.8	70.2	73.5	73.7	75.5	74.8	73.8	70.8	67.5	70.7

⬚ 10% feel uncomfortable

☐ Typical occupied hours (7 am - 6 pm)

🟦 20% feel uncomfortable

Table 2-2 shows that temperatures in Hilo are a bit lower than in Honolulu and that average temperatures fall within the comfort range all year. Therefore, year-round natural ventilation should be feasible in Hilo and similar climates.

Table 2-2. Average outdoor hourly temperatures (°F) for Hilo. Ninety percent of occupants will be comfortable in a naturally ventilated building during typical occupied hours. Source of temperature data: Typical Meteorological Year Data, U.S. National Climatic Data Center.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
HOUR													
1	67.4	66.4	67.7	68.3	69.2	69.8	71.2	71.3	72.1	71.0	69.2	67.4	**69.3**
2	67.0	65.8	67.3	67.7	68.7	69.4	70.6	70.6	71.4	70.8	68.6	66.9	**68.7**
3	66.6	65.5	67.0	67.2	68.4	69.1	70.4	70.3	71.1	70.2	68.4	66.7	**68.4**
4	66.1	65.2	66.7	66.8	68.0	68.8	70.3	70.1	70.8	69.5	68.1	66.2	**68.1**
5	65.8	65.0	66.3	66.3	67.6	68.5	69.9	69.8	70.5	69.2	67.9	65.9	**67.7**
6	66.4	65.7	67.1	67.8	69.7	70.5	69.9	71.5	72.2	68.9	68.8	66.6	**68.8**
7	66.9	66.3	67.8	69.4	71.8	72.7	70.9	73.4	73.9	69.7	69.6	67.3	**70.0**
8	67.5	67.1	68.7	70.9	73.8	74.8	74.1	75.1	75.7	73.5	70.6	68.0	**71.7**
9	70.7	69.7	71.3	72.6	75.3	76.5	76.2	76.6	78.0	77.0	72.9	71.3	**74.0**
10	73.9	72.4	73.7	74.3	76.9	77.9	78.0	78.5	80.3	78.1	75.1	74.5	**76.2**
11	77.1	75.0	76.3	76.0	78.4	79.7	79.3	80.1	82.6	78.6	77.5	77.7	**78.2**
12	77.1	75.6	76.6	76.0	78.4	80.3	79.9	80.4	82.4	79.0	77.8	77.9	**78.5**
13	77.1	76.1	77.1	76.5	78.5	80.9	80.0	80.7	82.4	79.1	78.2	78.2	**78.8**
14	77.1	76.6	77.5	76.5	78.5	81.5	80.2	80.9	82.2	79.3	78.6	78.5	**79.0**
15	76.1	75.6	76.8	75.8	77.9	80.5	79.9	80.2	81.3	79.0	77.5	77.1	**78.2**
16	75.2	74.7	76.0	75.0	77.4	79.4	79.1	79.7	80.3	77.9	76.3	75.9	**77.3**
17	74.2	73.7	75.3	74.4	76.8	78.4	78.1	79.0	79.4	76.6	75.2	74.5	**76.3**
18	73.1	72.2	73.9	73.2	75.4	76.7	76.8	77.5	78.0	75.6	74.1	73.1	**75.0**
19	71.8	70.8	72.3	72.1	73.7	74.8	75.1	76.1	76.6	74.5	73.1	71.8	**73.6**
20	70.7	69.2	70.9	71.0	72.3	73.1	74.0	74.6	75.2	73.6	72.0	70.3	**72.3**
21	69.9	68.7	70.1	70.5	71.6	72.3	73.6	74.1	74.7	73.1	71.3	69.6	**71.6**
22	69.2	68.0	69.5	69.9	70.8	71.4	72.9	73.4	73.9	72.4	70.7	68.8	**70.9**
23	68.4	67.5	68.7	69.4	70.2	70.6	72.4	72.8	73.3	71.8	70.1	68.1	**70.3**
24	67.9	66.9	68.3	68.8	69.6	70.3	71.8	72.1	72.6	71.5	69.5	67.6	**69.8**
Avg. Outdoor Temperature (Dry bulb)	71.0	70.0	71.4	71.5	73.3	74.5	74.8	75.4	76.3	74.2	72.5	71.3	73.0
AVG. DAILY MAX. TEMP.	78.2	77.0	77.7	77.2	79.6	81.7	81.1	81.4	83.4	80.5	79.0	78.9	79.7
AVG. DAILY MIN. TEMP.	65.0	64.2	65.9	66.0	67.3	68.1	69.4	69.5	70.2	68.3	67.4	65.3	67.2

All hours fall within 90% comfort range

☐ Typical occupied hours (7 am - 6 pm)

Air Movement

Air movement from open windows and fans also affects comfort. Air speeds up to 100 fpm are comfortable for most people, while air speeds between 100 and 200 fpm are often acceptable even though people will be aware of the air movement (Table 2-3). However, at 160 fpm, hair, loose paper and light objects may start to blow around and annoy people. Avoid velocities over 200 fpm because they create drafts and can be a nuisance.

Table 2-3. Impact of air velocity on occupants.[2]

Air velocity (feet per minute)	**Probable impact on occupants**
Up to 50 fpm	Unnoticed
50 to 100	Pleasant
100 to 200	Generally pleasant but causing a constant awareness of air movement
200 to 300	From slightly to annoyingly drafty
Above 300	Requires corrective measures if comfort and productivity are to be maintained

Utility Programs

The utilities that serve Oahu, Maui, Molokai, Lanai and the Big Island (HECO, MECO and HELCO) have a rebate program called the Commercial and Industrial Customized Rebate (CICR) program. Under this program innovative technologies that save energy and demand would qualify for a rebate based on $125/kW of peak demand reduction and $0.05/kWh for a year of energy savings. Rebates are based on engineering estimates of energy and demand savings. In the case of unproven technologies the rebate may be paid over a period of five years based on metered savings.

Resources

G.Z. Brown, *Sun, Wind and Light* (New York: John Wiley & Sons, 1986).

Jeffrey Cook (editor), *Passive Cooling* (Cambridge, MA: MIT Press, 1989).

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[2] Source: Victor Olgyay, *Design with Climate: Bioclimatic Approach to Architectural Regionalism* (Princeton, NJ: Princeton University Press, 1963).

Cross Ventilation

Recommendation

Provide equal area of operable openings on the windward and leeward side. Ensure that the windward side is well shaded to provide cool air intake. Locate the openings on the windward side at the occupied level.

Description

Wind-driven ventilation — or cross ventilation — is one of two methods of providing natural ventilation. (The other method, stack ventilation, is discussed in the next guideline.) All natural ventilation strategies rely on the movement of air through space to equalize pressure. When wind blows against a building, it is deflected around and above the building. The air pressure on the windward side rises above atmospheric pressure, creating a high pressure zone. The pressure on the leeward side drops, creating pressure stratification across the building. To equalize pressure, outdoor air will enter through available openings on the windward side and eventually be exhausted through the leeward side.

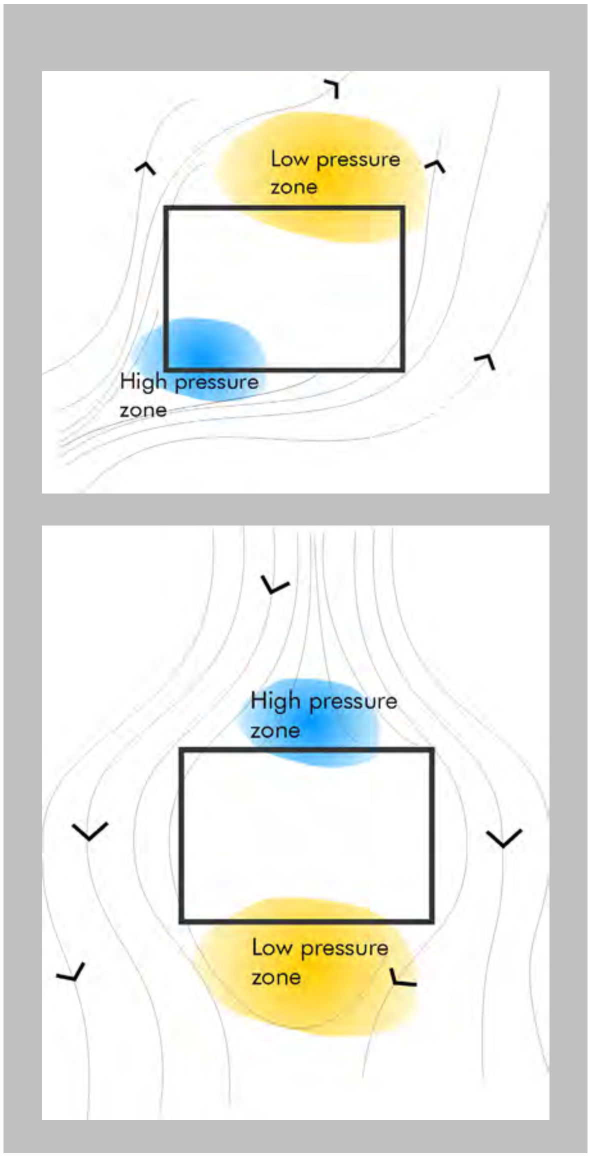

Figure 2-4. Wind blowing against a building creates a high pressure zone on the windward side and a low pressure zone on the leeward side.

Pressure is not uniformly distributed over the entire windward face, but diminishes outward from the pressure zone. The pressure difference between any two points on the building envelope will determine the potential for ventilation if openings were provided at these two points. The airflow is directly proportional to the effective area of inlet openings, wind speed and wind direction.

Applicability

In Hawaii, a carefully designed cross ventilation system may eliminate the need for a mechanical cooling system. But in some spaces where special humidity control is required, cross ventilation cannot replace the moisture-removing capabilities of air conditioning.

Cross ventilation depends chiefly on two factors that may change continuously: wind availability and wind direction. Consequently, it is a somewhat unreliable source for providing thermal comfort. It may be necessary to supplement cross ventilation with ceiling fans to make the spaces more comfortable for people. Also, natural ventilation may not be applicable in locations where dirt, dust or noise is a problem.

Codes and Standards

The Hawaii Model Energy Code, Section 8.3(e), sets air leakage and comfort ventilation requirements. Comfort ventilation is required in hotel guest rooms; unconditioned commercial spaces must either comply with the same comfort ventilation requirements or must be sealed to prevent air leakage. Comfort ventilation requirements call for either minimum opening areas equal to at least 12% of the floor area or wiring for ceiling fans.

Integrated Design Implications

Design phase: Cross ventilation can (or should) very strongly influence building aesthetics and site planning. To maximize the effectiveness of openings, a building’s long facade should be perpendicular to the prevailing wind direction. Narrow plans and other designs with more surfaces exposed to the outside will work better than bulky plans with concentrated volumes. Single-loaded corridors will provide better airflow than double-loaded ones. An open building plan with plenty of surface area exposed to the outside works well for cross ventilation. Architectural elements like fins, wing walls, parapets and balconies enhance wind speeds and should be an integral part of cross-ventilation design.

Integration with daylighting and view windows: The apertures for cross ventilation can also serve as view windows and can provide sidelighting. All architectural elements intended to enhance one strategy should also work for the other. However, an orientation that works for ventilation (openings on the windward side) may not be the ideal direction for bringing in daylight. For daylight, north- and south-facing windows are usually best. But for cross ventilation in Hawaii, windows ideally would be located to take advantage of the trade winds that typically come from the northeast. Prioritize the needs of the space based on function and climate.

Integration with HVAC: Natural ventilation may replace air conditioning entirely or may coexist with mechanical systems in a hybrid mode. For buildings that require air conditioning in some areas, the best solution is to divide the building into separate zones for natural ventilation and mechanical ventilation. The next best solution is a changeover system in which windows are shut when the air conditioning is on. Changeover controls should be used to automatically shut off the air conditioning if windows are open. Hybrid systems in which the air conditioning is on when windows are open are not recommended in Hawaii due to the humidity load from outside air. For information on air conditioning system selection, see the HVAC Guidelines.

Costs

Costs for cross ventilation are low to moderate. Buildings that use natural ventilation may have higher initial costs because operable windows typically cost 5% to 10% more than fixed glazing, but the savings from not using air conditioning will offset this added cost. Crossover systems will be more expensive because of the higher cost for operable windows and interlock controls for the HVAC system.

Benefits

Benefits vary significantly depending on climatic conditions and the natural ventilation design.

- In Hawaii, wind-driven ventilation can meet the cooling loads much of the time. In many cases, it can offset the need for an air conditioning system, eliminating the cost of the equipment and energy used to operate it. This will result in huge savings that will offset the cost of installing operable windows. The simple payback period may be as short as to 1 to 4 years.
- Cross ventilation can quickly exhaust odors and contaminants from indoor sources.
- Increased airflow in a space may result in higher thermal comfort levels and increased productivity.
- Operable openings at the occupied level give the occupants a sense of individual control over the indoor environment.
- An intangible benefit of natural ventilation is that it establishes a connection with the outdoors (both visual and tactile), weather patterns, and seasonal changes. This results in higher tolerances for variations in temperature and humidity levels.
- Natural ventilation systems are simple to install and require little maintenance.

Design Tools

Opening areas may be derived from simple spreadsheet-based calculations. These estimates use approximation techniques but are good numbers to start with. The following algorithm shows the rate of wind-induced airflow through inlet openings:

$$Q = C_4 C_v A V$$

where,

Q = airflow rate, cfm
C_v = effectiveness of openings (C_v is assumed to be 0.5–0.6 for perpendicular winds and 0.25 to 0.35 for diagonal winds)
A = free area of inlet openings
V = wind speed, mph
C_4 = unit conversion factor = 88.0

The following algorithm calculates the required airflow rate for removal of a given amount of heat from a space. (To estimate the amount of heat to be removed, see the information about load calculations in the Sizing AC Systems section of the HVAC Guidelines.)

$$Q = \frac{60q}{c_p \rho (t_i - t_o)}$$

where,

Q = airflow rate required to remove heat, cfm
q = rate of heat removal, Btu/h
C_p = specific heat of air Btu/lb°F (about 0.24)
ρ = air density, lb_m/ft^3 (about 0.075)
t_i-t_o = indoor-outdoor temperature difference, °F

Many computer software programs are available for predicting ventilation patterns. Programs that employ the zonal method may be used to predict ventilation rates (mechanical and natural), magnitude and direction of airflow through openings, air infiltration rates as a function of climate and building air leakage, pattern of airflow between zones, internal room pressures, pollutant concentration, and backdrafting and cross-contamination risks. These models take the form of a flow network in which zones or rooms of differing pressure are interconnected by a set of flow paths. This network is approximated by a series of equations that represent the flow characteristics of each opening and the forces driving the airflow process. Widely available codes include BREEZE and COMIS.

A Computational Fluid Dynamics (CFD) program is a more accurate and complex tool for modeling airflow through a space based on pressure and temperature differentials. These programs can simulate and predict room airflow, airflow in large enclosures (atria, shopping malls, airports, exhibitions centers, etc.), air change efficiency, pollutant removal effectiveness, temperature distribution, air velocity distribution, turbulence distribution, pressure distribution, and airflow around buildings.

- Fluent, Inc. is the largest provider of CFD code. Fluent is a sophisticated analysis technique that can, among other things, model and/or predict fluid flow behavior, transfer of heat, and behavior of mass.
- Flomerics authors the software Flovent, designed to calculate airflow, heat transfer, and contamination distribution for built environments. This software is particularly geared toward ventilation calculations, including natural and forced convection currents. It also accurately calculates air density as a function of temperature and predicts the resulting buoyancy forces that can give rise to important thermal stratification effects. Important outputs from Flovent are user variables such as the comfort indices of Predicted Mean Vote (PMV), Percentage of People Dissatisfied (PPD), Mean Radiant Temperature (MRT), Dry Resultant Temperature and Percentage Saturation, including a visualization of their variation through space. A summary of minimum, maximum, mean and standard deviation for all calculated variables is also available.

Design Details

An effective cross-ventilation design starts with limiting space sizes to facilitate inward flow of air from one face and outward flow from the other. Architectural elements can be used to harness prevailing winds.

- Orient the building to maximize surface exposure to prevailing winds.
- Provide the inlets on the windward side (pressure zone) and the outlets on the leeward side (suction zone).
- Use architectural features like wing walls and parapets to create positive and negative pressure areas to induce cross ventilation.
- Air speed inside a space varies significantly depending on the location of openings. The most effective strategy is to provide openings on opposite walls. Using single-loaded corridors makes it easier to provide openings on opposite walls. Limit room widths to 15 to 20 feet if openings cannot be provided on two walls.

- For small spaces where it's not possible to have openings on opposite walls, placing windows on adjacent walls may provide some cross ventilation. This should be limited to smaller spaces (less than 15 ft x 15 ft).
- Consider designing cross-ventilation openings that are secure enough to be left open at night, so that natural ventilation can provide additional nighttime cooling benefits.
- The openings must be easily accessible to and operable by the occupants.
- Equal inlet and outlet areas maximize airflow whereas outlets that are 25% larger than inlets produce higher air velocities.
- The inlet location affects airflow patterns far more significantly than outlet location. Inlet location should be a higher priority (if faced with a choice) as a high inlet will direct air toward the ceiling and may bypass the occupied level. Provide inlets for cross-ventilation openings at the occupied level.
- Stagger the outlet openings both vertically and horizontally by a few feet to achieve longer air paths. Concentrate ventilation openings in spaces most likely to require cooling.
- For natural ventilation to function properly, minimize solar gain. Direct sunlight penetration may make it difficult or impossible to achieve comfortable conditions with natural ventilation alone. Use shading devices like overhangs, awnings and fins to control solar gain. For details, see the Energy-Efficient Windows Guidelines.

- Use good site planning, landscaping and planting strategies to cool the incoming air. If a body of water is planned for the site, place it on the windward side to precool the incoming air through evaporative cooling. Planting tall deciduous trees on the windward side will lower the temperature of the inflow and shade the openings. Avoid locating large asphalt parking lots or other ground surface treatments that get hot on the upwind side of naturally ventilated buildings.

Figure 2-5. The effectiveness of natural ventilation is reduced when a ground surface that heats the outside air — such as a parking lot — is located upwind of a cross-ventilated building. Photo: Erik Kolderup, Eley Associates.

- Ground cover plantings can help prevent loose dirt and dust from blowing in through the windows. If excessive wind is a problem on the site, shrubs, trees or other landscaping can be situated to help reduce wind speed.
- Provide windows with sections or shutters that can be opened individually. This allows the occupants to vary the inlet and outlet areas according to seasonal variations.
- Use features like overhangs, awning windows, eaves and porches to protect the openings from rain. Awning windows work very well for cross ventilation because they provide more airflow than double-hung windows for the same glazed area and also provide protection from rain. Casement windows provide maximum airflow in both perpendicular and oblique wind conditions.
- Ensure that vents and windows are accessible and easy to use. Avoid blocking windows with exterior objects such as shrubs and fences, but do not eliminate shading.
- Ensure that openings can be tightly sealed when using an air conditioner.

- HVAC systems should be designed to work in harmony with natural ventilation. The objective of a concurrent natural ventilation system is to meet the outside air requirement using the smallest possible opening area. The objective of a changeover natural ventilation system is to meet the outside air requirement as well as provide cooling. The HVAC and natural ventilation system are mutually dependent.

Operation and Maintenance Issues

Cross ventilation is largely dependent on manual operation for its success. Automated operation may make sense for very large commercial buildings.

- Encourage occupants to open and close openings as needed to create more comfortable conditions.
- The mechanisms for operable inlets and outlets should be well maintained and clean.
- Periodically clean windowsills, panes, fins and louvers to ensure healthy air intake for the space.
- Make sure that openings are shut when the mechanical system is operating, unless the HVAC and natural ventilation are designed to work concurrently.

Case Study

Most schools in Hawaii are naturally ventilated. The Pearlridge Elementary School's (Oahu) new administration building, for example, uses cross ventilation supplemented with ceiling fans in some spaces. The building is reported to be comfortable in winter, but a little hot in the summer.

Stack Ventilation

Recommendation

Use inlets and outlets of equal area and maximize the vertical distance between these two sets of apertures. Place inlets close to or in the floor or at the occupied level. Locate the outlets closer to the ceiling on the opposite wall.

Description

Stack ventilation is one of two methods of providing natural ventilation (the other — cross ventilation — is described in the previous guideline). Stack ventilation utilizes air density differences to provide air movement across a space. At least two ventilation apertures need to be provided — one closer to the floor and the other high in the space.

Warmed by internal loads (people, lights and equipment), the indoor air rises. This creates a vertical pressure gradient within the enclosed space. If an aperture is available near the ceiling, the warmer air at the upper levels will escape as the cool outside air is drawn in through the lower aperture.

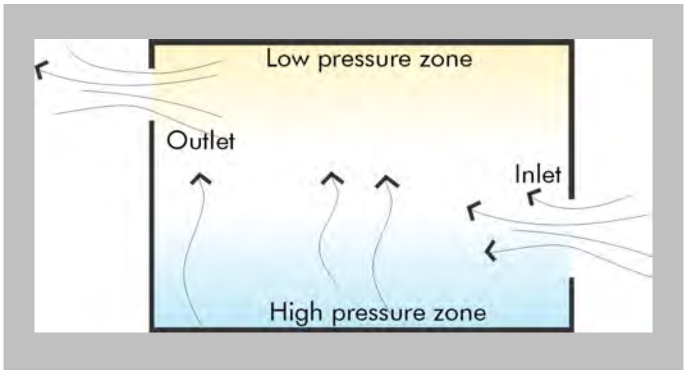

Figure 2-6. Stack ventilation requires two ventilation apertures, one closer to the floor and the other high in the space.

In places like Hawaii, stack ventilation can be a challenge because the indoor temperature must be higher than the outdoor temperature for the stack ventilation to occur. Higher indoor temperatures cause a pressure difference so that the upper openings act as the outlet and cool air intake is induced at the lower opening.

The airflow induced by thermal force is directly proportional to the inlet-outlet height differential, the effective area of the aperture, and the inside-outside temperature differential.

Applicability

To get any cooling benefit from stack ventilation, you need access to cool outdoor air. The cool air may be drawn from a shaded or landscaped space or from over a body of water. Stack ventilation works best in spaces with high ceilings and where cross ventilation is not feasible because of security, privacy, noise or other reasons.

Codes and Standards

Stack ventilation can be used to meet the Hawaii Model Energy Code's comfort ventilation requirements, Section 8.3(e), using the exception for innovative ventilation design.

Integrated Design Implications

Design phase: Using the stack effect for ventilation requires an integrated design approach. Stack ventilation will affect building mass and aesthetics. Vertical airshafts for providing stack ventilation also need to be considered early in the design phase.

Integration with daylighting and view windows: Apertures for stack ventilation need to be located close to the floor and ceiling for best results. The high apertures can work as clerestories for sidelighting. The benefits of daylighting and natural ventilation need to be considered in conjunction with each other to arrive at the ideal location and size for the openings.

Integration with HVAC: Stack ventilation can be used to meet the outside air requirement in most climates other than hot-dry (where stack ventilation will also be used for nighttime cooling).

Carefully integrating this strategy with HVAC system selection and operation will maximize its benefits.

Costs

Costs are low to moderate. Stack ventilation may not add to overall costs significantly if it is integrated with view windows, high sidelighting, and other daylighting strategies. However, an additional cost of $\$2/ft^2$ may be associated with ensuring that all openings are operable. Adjustable frame intake louvers may cost up to $\$25/ft^2$ (this includes installation costs). Additional cost of installing windows high in the space will range from $\$15–\$30/ft^2$.

Benefits

The benefits of stack ventilation are low to moderate, depending largely on weather conditions (indoor-outdoor temperature differential) and the design of openings.

- Stack ventilation apertures can double as sidelighting.
- Stack ventilation effectively removes contaminants and pollutants from a space.
- Compared to cross ventilation, it's easier to design stack ventilation openings so that they are secure from intruders and less susceptible to noise and dust infiltration.

Design Tools

The airflow (cfm) required can be reasonably estimated using spreadsheet-based calculations. The following algorithm defines the airflow as it varies with the area of openings, indoor temperature, outdoor temperature, and location of the inlet and outlet:

$$Q = 60C_D A\sqrt{2g\Delta H_{NPL}(T_i - T_o)/T_i}$$

Q = airflow rate, cfm
C_D = discharge coefficient for opening
ΔH_{NPL} = height from mid-point of lower opening to NPL, ft
T_i = indoor temperature, °R
T_o = outdoor temperature, °R

Use this algorithm to estimate the aperture area for a particular hour of a day (with Q equal to 15 cfm).

A number of computer tools are available for simulating pressure driven airflow. Refer to the Cross Ventilation Guideline in this chapter for details.

Design Details

An effective stack ventilation design starts with inlet and outlet openings of equal area. Architectural elements can be used to harness prevailing winds and exhaust indoor air.

- Provide equal inlet and outlet areas to maximize airflow. If they are not equal, then airflow will be dictated by the smaller of the inlet or outlet areas.
- The width-to-height ratio of openings should be more than 1, as far as possible (in other words, orient the openings horizontally).
- Allow for at least a 5 ft (center-to-center) height difference between the inlet and the outlet. Increasing the height differential further will produce better airflow.
- Provide adequate apertures in stairwells or other continuous vertical elements so that they can work as stack wells. Such spaces may be used to ventilate adjacent spaces because their stack height allows them to displace large volumes of air.
- Carefully control and minimize solar gains. For details, see the Energy-Efficient Windows Guidelines.
- Use louvers on inlets to channel air intake. Use architectural features like solar chimneys to effectively exhaust the hot indoor air.
- HVAC systems should be designed to work in harmony with stack ventilation. Consider a displacement ventilation design for the air conditioning system to supplement the stack ventilation during hot periods.
- For buildings with crawl spaces, consider using inlet openings in the floor to draw air from the cool space below.

Operation and Maintenance Issues

This strategy is largely dependent on manual operation for its success.

- Openings should be appropriately operated according to indoor-outdoor temperature differentials.
- The mechanisms for operable inlets and outlets should be well maintained and clean.
- Periodically clean windowsills, fins and louvers to ensure healthy air intake for the space.
- Make sure that openings remain shut when the mechanical system is operating.

Commissioning

During construction, ensure that the airflow meets the design intentions. Before applying interior finishes, check the cross ventilation to determine if the opening areas provide the expected level of ventilation. If they don't, it may be necessary to increase or decrease the opening areas.

Case Study

Stack ventilation is less commonly used than cross ventilation in Hawaii. However, there are some successful stack ventilation projects. The office of Dr. Lee-Ching in Hilo employs low inlets and uses vented skylights as outlets for stack ventilation. More information about this building and other stack ventilation designs by architect Virginia Macdonald, FAIA, can be found in the *Guide to Resource-Efficient Building in Hawaii* (First Edition, Revision B, June 2000), produced by the Hawaii Advanced Building Technologies Training Program.

Ceiling Fans

Recommendation

Use ceiling fans instead of air conditioners to make occupants more comfortable by increasing the air velocity in a space.

Description

A ceiling fan is a permanent fixture mounted on the ceiling and operated by a switch or a pull string. In warm climates, ceiling fans are used to move interior air, which cools people and makes them feel more comfortable by increasing the evaporation of moisture from their skin. As long as there is some air movement, people can generally tolerate higher temperatures. Generally, for speeds above 30 fpm, most people will perceive a 15 fpm increase in air to be equal to 1°F decrease in temperature (this is commonly called "chill factor").

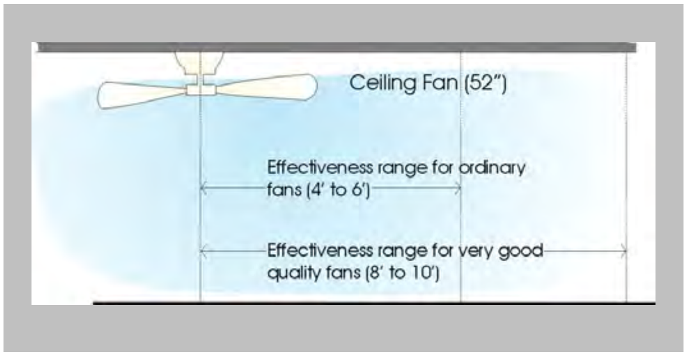

Figure 2-7. Ceiling fans increase air velocity to provide greater comfort for occupants.

A ceiling fan can be used to draw outside air into a space when the air cannot enter the space on its own because it's either too humid or too hot. A fan can also recirculate air within a space.

The interior air motion cause by ceiling fans varies as a function of fan position, power, blade speed (measured in rpm), blade size, and the number of fans within the space. Moreover, air speeds within a space vary significantly at different distances from the fan.

The normal current draw will range from approximately 15 W at low speed to 115 W at high speed.

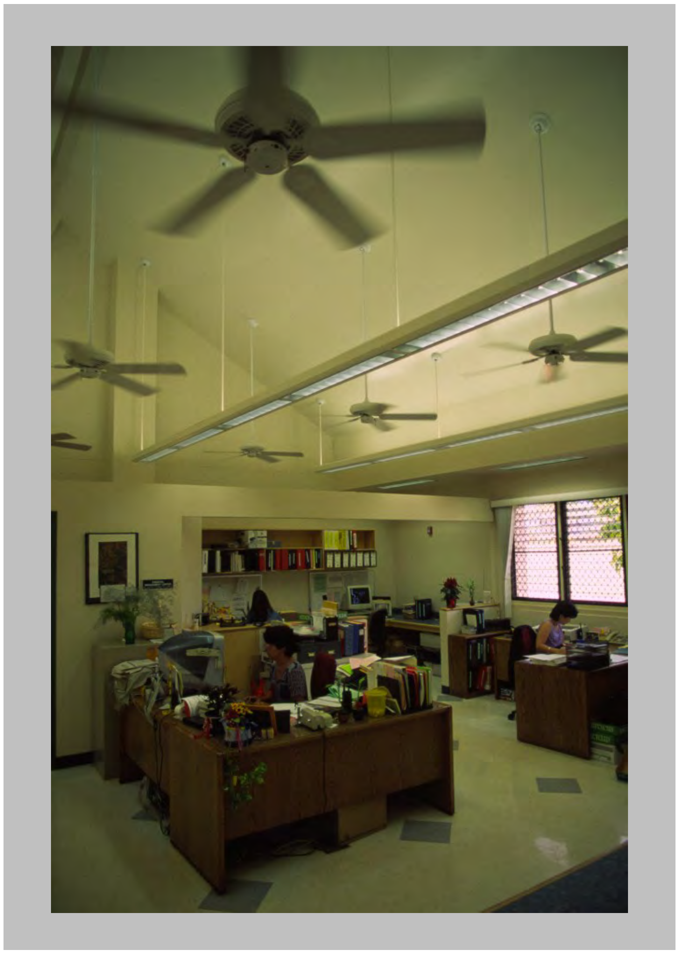

Figure 2-8. Ceiling fans cool people, not spaces. They enhance comfort by increasing the evaporation of moisture from skin. Photo: Erik Kolderup, Eley Associates.

Applicability

Ceiling fans are appropriate for many types of spaces, including offices and classrooms. They may not be appropriate small spaces such as restrooms. Noise produced by ceiling fans may be an issue in auditoriums.

Ceiling fans are suitable for most climates that require cooling. Combined with other natural ventilation strategies they may eliminate the need for air conditioning.

They may not be applicable in spaces where the air movement may cause problems or spaces where you want temperature stratification to occur (such as when using stack ventilation).

Codes and Standards

In the Hawaii Model Energy Code, the comfort ventilation requirements in Section 8.3(e) can be met by supplying wiring for ceiling fans as an alternative to providing cross-ventilation openings.

Integrated Design Implications

Ceiling fans need to be integrated with the lighting system design.

A minimum ceiling height of 9 ft must be provided to accommodate a fan so that its blades are at least 8 ft from the floor and 1 ft from the ceiling.

Ceiling fans should be combined with natural ventilation strategies for best results.

Costs

Ceiling fans cost between $75 and $200. The typical cost with professional installation is about $250. Fans with features such as light fixtures, reverse or multiple speed settings, and extended warranties may cost more. Ceiling fans are economical to operate because they consume very little energy.

Benefits

Moving air extends the comfort range and allows occupants to feel comfortable at higher temperatures. It also helps occupants feel dry.

When ceiling fans are used, air conditioners can be set at a higher temperature. The resulting energy savings will more than offset the fans' energy consumption. According to the Texas Energy Extension Service, for a 3-ton cooling system costing $550 per season, raising the thermostat from 75°F to 80°F can reduce the operating cost by $151. Operating a ceiling fan 10 hours a day or more may cost less than $3 per month. A typical fan operating at high speed, for example, uses approximately 100 watts of power. If the fan is operated 5 hours per day with an energy cost of $0.08/kWh, the operating cost will be $0.04/day. At lower speeds this operating cost will be even less. This low operating cost, combined with the potential reduction in HVAC costs, makes the ceiling fan one of the better energy-saving devices on the market.

As a rule of thumb, each degree rise in a thermostat setting (beyond 78°F) results in a 3–5% saving on cooling energy. If the ceiling fan is supplementing air conditioning, the thermostat of the AC unit may be raised a full 4°F above the standard 78°F setting while still maintaining comfortable space conditions.

Design Tools

Use the following charts to size ceiling fans according to the largest room dimension and room area:

Table 2-4. Fan diameter selection based on space dimensions.

Largest Dimension of Room	Minimum Fan Diameter
12 ft or less	36 in.
12 – 16 ft	48 in.
16 – 17.5 ft	52 in.
17.5 – 18.5 ft	56 in.
18.5 ft or more	2 fans needed

Table 2-5. Fan diameter selection based on space area.

Room Area	Minimum Fan Diameter
100 ft^2	36 in.
150 ft^2	42 in.
225 ft^2	48 in.
375 ft^2	52 in.
400+ ft^2	2 fans needed

Source: *Consumer Guide to Home Energy Saving,* American Council for an Energy Efficient Economy (1995).

Design Details

Ceiling fans should be considered in the design development stage due to electrical wiring issues, although adding fans to existing spaces is also feasible.

- Use ceiling fans in frequently occupied spaces. Fans should be on only when the space is occupied; otherwise the movement of the motor in introducing heat in the room without any cooling benefits. Remember that ceiling fans cool people, not spaces. Consider using an occupancy sensor to control the fans.
- A larger fan provides a greater range of airflow settings and ventilates a larger area at lower velocities, with less noise, and only slightly more power than similar smaller units.
- Ceiling fans work best when the blades are 8 ft to 9 ft above the floor and 10 in. to 12 in. below the ceiling. Placing fans so the blades are closer than 8 in. to the ceiling can decrease the efficiency by 40%. Fans also require at least 18 in. of clearance between the blade tips and walls.

- Two types of mountings are available for ceiling fans: rod and hugger. In rod fans, the motor housing is suspended from the mounting bracket by a rod. With hugger fans, the motor housing is mounted directly to the ceiling box. Hugger fans are not as efficient as rod fans in the down motion, especially at higher speeds. The blades will starve themselves for air when they are too close to the ceiling.
- Generally speaking, the larger the blades of the fan, the greater the air movement (also such fans are less noisy). Use larger blade pitches (note that as the pitch or blade surface increases, the motor size must be increased or the rpm of the motor will drop). A good ceiling fan should create enough air movement to make the occupant comfortable at 82°F with 80% relative humidity.
- Select a fan with at least a 2-speed control for better regulation of air movement.

Operation and Maintenance Issues

Operation and maintenance issues for ceiling fans include:

- Ensure that all blades are screwed firmly into the blade holder and that all blade holders are tightly secured at the fan. This should be checked from time to time (once a year).
- Periodically clean the fan because the blades tend to accumulate dust on the upper side. An anti-static agent can be used for cleaning but don’t use cleaning agents that can damage the finish. Never saturate a cloth with water to clean a ceiling fan; water introduces the possibility of electrical shock.
- For a fan to perform efficiently it is very important that the blade be flat throughout. Most manufacturers have programs to keep warpage to a minimum. “Balanced” blades — that is, blades that are electronically matched at the factory — are sold as a balanced four- or five-blade set depending on the design of the fan. For this reason, never interchange blades between fans.

Commissioning

Specify durable fans with longer warranties. Use fans with metal motor housings; these may require annual oiling (while plastic motor housings will not) but may have better warranties and be worth the added maintenance. During building commissioning, ensure that the specified equipment is what actually gets installed.

Resources

ASHRAE Standard 62—Ventilation for Acceptable Indoor Air Quality. Web site: www.ashrae.org.

Oikos/Green Construction Source (Eugene, OR: Iris Communications). Features REDI, an online directory of products, including ventilation fans, devices and controls. Web site: http://oikos.com.

3. DAYLIGHTING GUIDELINES

Overview

Description

Daylighting is the use of transparent or translucent panels located in the building envelope to let natural light into interior spaces. To provide balanced, glare-free illumination, daylight can be diffused in a variety of ways, such as by using louvers or translucent glazing panels, designing apertures to bounce daylight into the space, and using shading devices to block direct sun penetration.

There are two forms of daylighting: toplighting and sidelighting. With toplighting, the daylighting openings — or *apertures* — are located in the ceiling plane to provide uniform, glare-free illumination. Daylight is diffused using translucent glazing, reflective fixed or operable baffles, or deep skylight wells. Several configurations — such as vertical and splayed skylight wells, clerestory windows, light boxes and sawtooth roof monitors — can be used successfully in toplighting designs. Daylight levels are highest directly under the aperture and drop off as you move away from it. The spacing of the daylight aperture depends on the ceiling height.

Sidelighting allows daylight to enter through windows in vertical walls. With sidelighting, uniform illuminance is more difficult to provide, as there is always more light next to the window. Glare is also more difficult to control. But there are design techniques that can substantially reduce problems associated with sidelighting.

Benefits of Daylighting

Daylighting is at the heart of sustainable design for most buildings. A well-designed daylighting system can significantly reduce or even eliminate the need for electric lighting during the day, which can save a substantial amount of lighting energy and air conditioning energy.

Energy savings are only one aspect of the benefits of good daylighting. Productivity can be another compelling benefit. Recent studies have shown improved learning rates in schoolchildren in daylit classrooms and improved sales in daylit retail stores.[1] Further studies are underway to verify these findings.[2] In commercial buildings in industrialized countries where labor costs are high, the investment cost for better daylighting design and controls can typically be readily offset by the value of likely increases in occupant productivity. Even if better daylighting were to result in a mere 1% increase in employee productivity, the value of that increase would far outweigh the added costs for the daylighting and controls.

Daylight affects us in both obvious and subtle ways: it provides light to see our environment, go about our lives and do our work; it determines the cycles of our days and seasons; and on a biological level it stimulates hormones that regulate our body systems and moods. Daylight also affects certain physiological functions. For example, it stimulates the assimilation of Vitamin D, which is important for healthy bone formation, and it affects sleep cycles.

Daylighting Strategies

Daylighting uses natural light to provide adequate interior illumination for doing various tasks. Illumination may be provided completely through daylighting or through a combination of daylight and electric light.

Daylighting can be provided through an opening in the wall, roof or ceiling via transparent or translucent panels such as windows, glazed doors, skylights and other sources. These glazed apertures are referred to as fenestration.

The availability of sunlight depends primarily on the daily and seasonal path of the sun, while the intensity of daylight depends on the presence of clouds and moisture in the air. To successfully daylight a building it's important to understand the basic principles of solar orientation, climatic conditions and shading systems.

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[1] Heschong Mahone Group, "Daylighting in Schools," and "Skylighting and Retail Sales," (Pacific Gas & Electric Company, 1999). Available at www.pge.com/pec/daylight.

[2] "Productivity and Interior Environments" studies now being conducted by Heschong Mahone Group for the New Buildings Institute's Integrated Energy Systems: Productivity & Building Science Program, a project of the State of California PIER Program. For more information, go to www.newbuildings.org/pier.

These Daylighting Guidelines provide an overview of daylighting and fenestration design, including basic principles for good daylighting design and general and specific guidelines for toplighting and sidelighting strategies. For more information about optimum glazing areas, choice of glazing types and thermal comfort issues, see the Energy-Efficient Windows Guidelines. For information about energy-efficient electric lighting systems, refer to the Electric Lighting and Controls Guidelines.

The daylighting strategies listed here are discussed in detail in the subsequent Guidelines in this chapter:

- Provide uniform illumination using **GOOD DAYLIGHT DESIGN**
- Provide access to exterior views through **VIEW WINDOWS**
- Use **CLERESTORIES** for deeper daylight penetration
- Add **LIGHTSHELVES TO CLERESTORIES** to improve daylight distribution
- Balance daylight from window walls with **WALL-WASH TOPLIGHTING**
- Provide even daylight with **CENTRAL TOPLIGHTING**
- Use **PATTERNED TOPLIGHTING** to provide even illumination across a large area
- Use **LINEAR TOPLIGHTING** to direct movement or provide visual orientation in a linear space
- Employ **TUBULAR SKYLIGHTS** for toplighting areas with deep roof cavities and for low-cost retrofits

These daylighting strategies each have their own advantages and disadvantages, as shown in Table 3-1. Most spaces will need to include more than one daylighting strategy if they are to be fully daylit.

Table 3-1. Selection criteria for daylighting strategies.

Design Criteria	**View Windows**	**High Sidelighting**	**Wall-wash Toplighting**	**Central & Patterned Toplighting**	**Linear Toplighting**	**Tubular Skylights**
View	+	-	-	-	-	-
Uniform Light Distribution	-	+ / -	+	+ +	*	*
Low Glare	-	+	+	+	+	+ / -
Reduced Energy Costs	-	+	+	+ +	+	+
Cost Effectiveness	+	+	+	+	+	+ +
Safety/ Security Concerns	-	+ / -	+	+	+	+ +
Low Maintenance	-	+	+	+	+	+

Notes: **+** Good application. **-** Poor application. ***** Depends on space layout and number and distribution of daylight apertures.
Source: Eley Associates. *Collaborative for High Performance Schools Best Practices Manual, Vol. II — Design,* 2001. Web site: www.chps.net.

General Principles for Daylighting Design

Recommendation

Provide daylighting for uniform and low glare illumination wherever possible. In locations that have predominantly clear days, provide daylight using vertical glazing. In locations with predominantly cloudy days, use horizontal glazing to provide daylight.

Provide toplighting in single-story structures or in the top floor of multistory buildings. Use sidelighting to provide illumination in areas near the walls and to provide views. Use high sidelighting to deliver daylight deeper into the space.

Description

Daylighting provides uniform interior illumination through transparent or translucent panels located in the building envelope that let in natural light. Daylight can be diffused by using louvers or translucent glazing panels or by articulating the aperture.

Applicability

Daylighting can provide uniform illumination in many types of spaces — including classrooms, offices, restaurants, retail stores, cafeterias, corridors, multipurpose spaces, hospitals, assembly areas, warehouses, and light industrial spaces — to save lighting energy, reduce cooling loads and increase productivity.

Codes and Standards

The Hawaii Model Energy Code does not require that view windows or skylights be installed.

The code limits the maximum Relative Solar Heat Gain factor (RSHG) for various window-wall ratios for vertical glazing for windows (there are different limits for north-facing and non-north facing windows). The RSHG factor is a function of the shading coefficient of the glazing and exterior shade screens and/or louvers, interior shading devices, overhangs and fins. Individual windows may exceed the maximum RSHG limit as long as the area-weighted average RSHGs for both north and the combined east, west and south orientations are less than or equal to the maximum limit. Most buildings require window shading or tinted glass.

The skylight shading coefficient limits the skylight area. The maximum effective aperture (which is defined as a product of the horizontal glazing area and the fraction of the roof area covered by skylights) cannot exceed 0.025.

Benefits

Energy Savings

Turning off or dimming electric lights in response to the amount of available daylight can result in electric light savings of 40% to 80% during daylight hours. However, if the total glazing area is not optimized, these savings can be offset by increased solar gain. The Electric Lighting and Controls Guidelines address the design of supplementary electric lighting systems and controls, while the Energy-Efficient Windows Guidelines address solar control.

Indoor Air Quality

When the outside temperature is within a comfortable range — which is a considerable portion of the time in Hawaii — operable skylights, clerestories or roof monitor glazing can be used to naturally ventilate a space by drawing fresh air in through a lower aperture and exhausting it through the upper aperture. This can save energy by eliminating or reducing the need for mechanical ventilation, and may help improve indoor air quality by increasing the fresh air supply.

In addition to energy benefits, natural ventilation may help improve productivity. Studies have shown a positive correlation between higher student scores on standardized tests and an increase in natural ventilation.[3]

Refer to the Natural Ventilation Guidelines for more about natural ventilation strategies.

Indirect Impacts on HVAC

The appropriate sizing of daylighting apertures and the appropriate design of shading and glazing can minimize cooling loads because daylight contributes less heat to a space than electric lighting does for the same illumination level. (See the Energy-Efficient Windows Guidelines for optimum aperture sizes for different glazing types.) Lower cooling loads may potentially reduce investment costs for air conditioning equipment by reducing equipment size. And lower cooling loads may also provide the opportunity to increase the allowable window head height if smaller air conditioning ducts can be used in the ceiling plenum.

Using operable fenestration systems to naturally ventilate the building also reduces HVAC energy consumption by reducing the number of hours during which the HVAC system operates. In Hawaii, a carefully designed natural ventilation system may eliminate the need for a mechanical cooling system (see the Natural Ventilation Guidelines for details).

The building energy simulation tools mentioned in the section on Whole Building Energy Simulation Software later in this chapter can aid in evaluating overall loads and performance.

Other Benefits

There are additional benefits to daylighting, including increased employee productivity. With good diffusion, toplighting effectively provides even, balanced and glare-free illumination across the space. This has been correlated with higher standardized test scores for students. However, uncontrolled toplighting with direct sun penetration in classrooms has been associated with lower standardized test scores.[4]

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[3] Heschong Mahone Group, "Daylighting in Schools." Also, Norris and Tillett, "Daylight and productivity: Is there a causal link?", *Glass Processing Days Conference,* (Tampere, Finland, Sept. 1997).

[4] Heschong Mahone Group, "Daylighting in Schools."

Windows serve a range of important functions including providing views, opportunities for social communication and connections with nature.

Additional benefits of daylighting include:

- Providing better color rendition for visual tasks than electric lighting;
- Making a space look brighter and larger; and
- Producing a positive impact on people, and perhaps indirectly increasing their productivity.

Integrated Design Implications

Design phase: Daylighting design is integral to a building's architecture and is best started early in the design phase. It can be difficult and expensive to add apertures for daylighting once the building is built. Orientation is a critical factor for determining the placement of toplighting, view windows and clerestories.

Horizontal vs. vertical glazing: The glazing may be either horizontal or vertical depending on the orientation of the aperture, sky conditions, and cost considerations. Use vertical glazing for south and north orientations with predominantly clear skies. Use horizontal glazing for locations with predominantly cloudy skies that generally have east or west orientations. Horizontal glazing is typically cheaper than vertical glazing and is recommended for projects with greater budget constraints. See the Energy-Efficient Windows Guidelines for a lifecycle cost analysis of various window orientations, window-wall ratios and glazing types.

Integration with electric lighting: For the same level of illumination, daylight has a lower impact on cooling loads than electric lighting. To maximize the energy benefits of daylighting, circuit and control the electric lighting so that the lights can be turned off in areas where there is adequate daylight and kept on where daylight is insufficient.

Integration with structural system: The size and location of skylights and roof monitors are limited by the roof diaphragm and the structural system, and must be coordinated with the building's structural system to maintain strength and integrity.

Coordinate the size and location of windows with the location of columns and studs. Clerestory sidelighting requires ceiling heights of 9.5 ft or more at the window wall. This extra ceiling height may be accomplished with minimal increase of the floor-to-floor height by careful integration of the structural system, HVAC ducts and electric lighting in the plenum.

Integration with HVAC: Coordinate the placement of daylighting apertures and their associated lightshelves or light wells with the location of rooftop HVAC equipment and interior ducts.

View windows can decrease cooling loads on the building if they are oriented, glazed and shaded correctly. Toplighting and high sidelighting glazing is vulnerable to solar gains during the cooling season; appropriate orientation, size, glazing materials, shading and photocontrol of electric lights can reduce the overall HVAC loads and potentially reduce HVAC system size and first costs.

To maximize lighting and HVAC energy benefits, conduct a whole building simulation to evaluate the total glazing area used for daylighting before finalizing a daylight scheme (see Design Analysis Tools later in this section).

Integration with natural ventilation: If the building has operable high sidelighting or toplighting fenestration, it can be used in combination with operable windows to naturally ventilate the space when the outside air temperature falls within a comfortable range, which is a significant portion of the time in Hawaii. Natural ventilation can have a positive impact on indoor air quality and can eliminate or significantly reduce the need for mechanical ventilation for a significant portion of the time in Hawaii.

For more information, see the Natural Ventilation Guidelines.

Design Details

The following principles, which are discussed in detail below, are fundamental elements of good daylighting design.

- Prevent direct beams of sunlight from penetrating the space
- Provide uniform illumination
- Avoid glare
- Provide methods of controlling daylight
- Integrate daylight with electric lighting
- Lay out the interior spaces so that they benefit from daylighting opportunities
- Optimize the aperture size
- Consider safety and security issues when designing daylighting apertures

Prevent Direct Sunlight Penetration

Direct sunlight can make people uncomfortable because it is so bright — up to 10,000 footcandles — and hot. Daylight that is diffused and reflected by, for example, clouds, moisture and other particulate matter, is much gentler. When properly utilized, daylight can provide excellent illumination without causing thermal or visual discomfort.

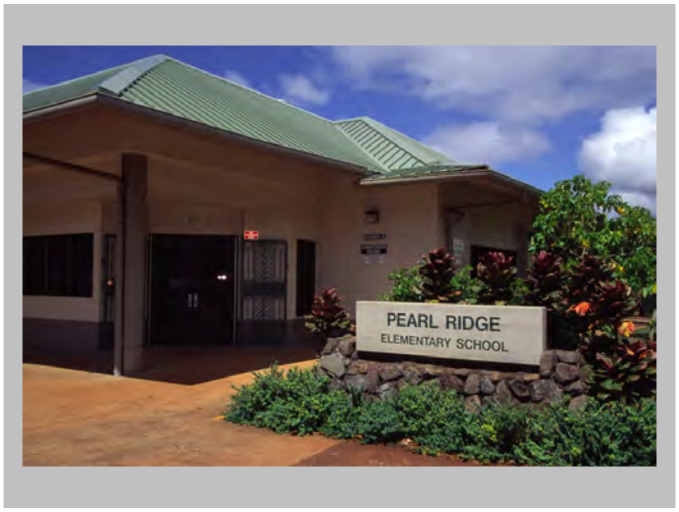

Figure 3-1. Overhangs help control direct sun penetration. To maximize daylight availability and reduce direct sun penetration, it's critical to properly orient the building. Photo: Erik Kolderup, Eley Associates.

Here are some recommendations for maximizing the use of daylight and minimizing the penetration of direct beam sunlight:

- Use sunlight in small quantities to introduce brightness and accents in non-task dominant zones, such as lobbies and cafes.
- Begin daylight design early in the design process. A building's orientation is critical for maximizing the use of diffused daylight and reducing direct solar penetration. The best orientation for daylight sources is north, since the sun strikes a north-facing window only early in the morning and late evening during midsummer. South-facing windows are the next best option. The high angle of the south sun is easy to control with a horizontal overhang.
- Avoid east- and west-facing windows for daylighting. The low angle of the sun makes it difficult to control direct sunlight penetration via overhangs or other fixed shading devices. Any window orientation more than 15 degrees off of true north or south requires careful assessment to avoid unwanted sun penetration.
- The ideal orientation may not be possible in urban situations where plot sizes may be constrained. In such cases increase the surface area of exposure toward the south and north. This may be done by using light shafts, light wells or light courts such that the west- and east-facing walls are shaded and receive diffused light.

- For toplighting, use glazing that diffuses the sunlight, or use baffles, louvers or light well walls to reflect it.

Provide Uniform Illumination

Evenly diffused daylight provides maximum energy savings and the most comfortable visual environment. Daylight can be used to provide a base level of illumination throughout a space, referred to as the ambient illumination. This is often on the order of 20 to 30 footcandles. Electric task lights can be used in specific work areas to bring the illumination levels to higher task level requirements, such as 50 or 75 footcandles. Here are some strategies for providing uniform illumination with daylighting (see the guidelines for specific daylighting strategies in this chapter for details):

- Use repetitive toplighting strategies, such as a uniform distribution of unit skylights.
- If uniform toplighting is not possible, use a combination of view windows and high sidelighting to provide daylight from two sides of a space.
- Use a combination of sidelighting and toplighting in areas where only one wall has windows.
- Paint walls, ceilings and other reflective surfaces white or a very light color. Even pastel colors absorb 50% of the light falling on the surface, reducing the amount of light reflected back into the room. Use saturated colors only in small quantities for accents or special effects.
- Exterior elements such as walkways and overhangs near the apertures also help to reflect daylight into the space. These are most effective when they are light colored.
- A series of reflective or refractive surfaces (such as mini-louvers) built into the glazing itself can redirect sunlight onto the space’s ceiling.
- Use lightshelves to bounce daylight deeper in the space (see High Sidelighting with Lightshelves Guideline).
- Baffles, fins or other reflective surfaces next to the daylight aperture can be used to distribute light uniformly through the space. Due to variations in sun angles, the best design solution for each orientation is unique. For example, a space may have lightshelves on the south side of the building, but none on the north.

Avoid Glare

Direct glare (the presence of an extremely bright surface or light source in the field of view) and reflected glare (light hitting a reflective surface) can make people uncomfortable and can make it difficult for them to perform certain tasks. Glare reflecting off a computer screen, for example, may make it difficult or impossible to view the images on the screen. The following are some strategies for reducing or eliminating glare caused by daylighting:

- Use devices such as blinds, louvers, reflectors or overhangs to block views of bright daylight sources and bright surfaces.

Figure 3-2. An overhang shades south windows from direct sun, while daylight reflects into the space from the light-colored concrete walkway and overhang. North windows are large and unshaded. Photo: Lisa Heschong.

- Place daylight apertures next to reflective (light-colored) surfaces to distribute daylight more uniformly and to brighten interior surfaces, reducing their contrast with the bright glazing surface.
- Use blinds or drapes to control brightness at the windows, diffuse the light and reduce glare.
- Avoid punched windows, which are simple holes in the middle of a wall or ceiling. Splay window reveals and skylight wells to reduce glare.
- Orient extremely shiny surfaces such as computer screens or white boards so that glare is avoided, or redesign the daylighting apertures to eliminate reflections on those surfaces.

- Locate computer screens so that the screen viewing orientation is parallel to or 45 degrees to the windows. Reflected glare will then pose less of a problem and, if present, can usually be reduced by using polarizing filters or meshes attached directly to the screen.

Figure 3-3. Deeply coffered ceiling helps to diffuse light from skylights. White ceilings and walls help reflect light into the space. Photo: SunOptics.

Provide Control of Daylight

The quantity and quality of daylight varies through the day and year, making it challenging to design an ideal aperture that provides adequate illumination for the maximum number of hours with minimal impact on cooling load. The most practical method of daylighting control is to provide shades or blinds on the apertures. Here are some guidelines:

- Provide shades or blinds inside or outside the window that are easily accessible to the occupants. These systems should be durable, easy to use, and economic to maintain.
- Manually operated controls are slightly less convenient than automatic controls but they are also less expensive and less likely to need repairs.

- Moveable exterior shades are exposed to weather conditions that may damage them over time. Use fixed exterior shades instead. Make sure that fixed exterior shades are sloped slightly so that water drains off them.

Figure 3-4. Horizontal blinds allow control of brightness from lower view windows. Note that high clerestory windows have no blinds so that daylight can reach deep into the space. Photo: Barbara Erwine.

- Skylights with clear glazing should use some form of shading device. Exterior shading devices for skylights are available, but not recommended because of maintenance problems. Rooftop devices are usually exposed to more severe weather, dust and debris. Sturdy, dependable performance is essential. If possible, position shading or operable equipment for skylights below at least the first layer of skylight glazing.
- Some skylight manufactures offer fixed or operable louver options for sun and daylight control, to reduce both solar gain and excessive daylight. Others offer movable insulation devices that can be operated, either manually or automatically, to reduce both solar gain and nighttime heat losses.

Integrate with Electric Lighting Design

Daylighting is thermally more efficient than electric lighting. For the same level of illumination the cooling load created by daylighting illumination is much lower than that created by electric lighting. Substituting daylighting for electric lighting where possible reduces both cooling and lighting costs. But these energy savings can be achieved only if the electric lights are turned off or dimmed in response to the daylight, using either manual or automatic controls.

The Design and Analysis Tools section below discusses tools to help visualize the overall light distribution in the space. Also the see the Electric Lighting and Controls Guidelines for more information. Here are some general guidelines for integrating daylighting with electric lighting design:

- Align the lighting fixtures with the daylight apertures so as to avoid blocking daylight penetration or casting undesirable shadows in the workspace.
- The light well connecting the toplighting aperture with the space below may intersect electric lighting layouts and fire sprinkler systems. Careful coordination will ensure compatibility among these systems.
- Daylight provides “bluer” light than most electric lighting. When combining electric light and daylight in a space, consider using fluorescent lamps with a color temperature of 3500°K to 4100°K or higher. (Color temperature describes a light source’s relative blueness or yellowness.)

- Automatic daylighting controls, which use photosensors to respond to light levels, cost more than manual controls but ensure savings. If using manual controls, make sure that they are accessible and well labeled so that they are easy to use. See the Electric Lighting and Controls Guidelines for more information.

Plan the Layout of Interior Spaces

Daylight can be provided through toplighting or sidelighting. Sidelighting can be used on all floors, but the extent of daylight penetration is limited because the illumination level drops off sharply as the distance from the window increases. Daylight penetration is roughly equal to twice the window head height.[5]

Here are some general guidelines for designing the interior space to best take advantage of daylighting opportunities:

- Since daylighting illuminance can vary considerably within the space, especially with sidelighting, locate work areas where there is adequate daylighting most of the time.
- To provide uniform illumination, balance the daylight from one side by providing apertures on the opposite side of the space. Where this is not possible, the space should ideally be only as wide as the daylight can penetrate, if daylight is to be provided in the entire space. If the space needs to be deeper than the extent of daylight penetration, balance the natural light by providing electric lights with controls to maintain the desired illumination level.
- Locate areas for predominantly visual tasks — such computer screens — to reduce the probability of glare. Orient these work areas so that daylighting is available from the side or from above. Facing a window may introduce direct glare into the visual field, while facing away from a window may produce shadows or reflected glare.
- Unlike sidelighting, where the width of the space is an issue, toplighting can be used to provide uniform daylight in a large space, but it can only be used in single-story buildings or on the top floor of a multistory building. Locate large spaces that require daylighting on the top floor. Spaces that are less deep, such as classrooms, conference rooms and private offices, can be located on the periphery of the building envelope to take advantage of daylight through sidelighting strategies.

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[5] The window head height is the height from the floor level to the top of the aperture.

- At the space planning stage, allot functions that would benefit most from daylighting — such as spaces with maximum operating hours during the day — to the areas that can have some toplighting. Tasks that make use of self-illuminating sources (such as computer rooms) can be located in those areas of the building where you may not be able to provide daylighting.

Optimize Aperture Size

The optimum size of the daylighting aperture depends on a number of factors, including the aperture pattern (lightshelves, sawtooth roof monitor, etc.), the desired illuminance level of the space that is being daylit, and the type of glazing material used.

For a given daylighting pattern, glazing material, occupancy pattern, lighting level, electric lighting control system, and climate, the total operating costs can be calculated and plotted for various window areas. As the glazing area increases, the energy use for lighting is steadily reduced until the window area is about 25% of the exterior wall. After that, daylight saturation is achieved for much of the time, and lighting energy savings are much smaller with increased window area. However, both cooling load and fan energy increase steadily throughout the entire range of window-wall ratios.

For more information about sizing daylighting apertures, see the Energy-Efficient Windows Guidelines.

Design for Safety and Security

Design operable apertures to minimize security risks such as intruders entering a building.

In hurricane-prone areas, there is a risk of damage to glazed panels. Exposed toplighting devices such as skylights may need to meet impact standards. A perforated metal panel or metal grill could be installed below the skylight to provide protection, although this may reduce the amount of daylight penetration To compensate, increase the number of skylights or the visible transmittance of the skylight’s glass. Another alternative is to use laminated glass. Check with local building department officials and your insurance company for current requirements on hurricane safety.

Design and Analysis Tools

Daylighting designs can be evaluated with physical models, lighting computer simulation software or whole building energy simulation software.

Physical Scale Models

Physical scale models accurately illustrate the daylighting conditions and lighting quality issues created by any given design, and help to understand why one design might work better than another. The interior of physical models can be photographed to record the lighting impacts of various design options, including issues such as uniformity and glare.

Daylighting models can be tested outdoors under real sky conditions or in simulators constructed to reproduce overcast sky and direct sun conditions. Photocells can be used to record light levels within the model. These sun simulators — which are called heliodons — can be set to correspond to the actual sun angle at specific times of the day for a particular site's latitude, and are used to study shading patterns during a typical day. A heliodon is available at the University of Hawaii at Manoa campus.[6] Daylighting textbooks provide information about constructing and testing daylighting models.

Lighting Simulation Software

Electric lighting and daylighting software can generate light level values and gradients for electric light and daylight from windows and skylights in a space. Simulation programs include Desktop Radiance, Lightscape, LumenMicro and Superlite. Because these programs produce results for a single point in time, numerous simulations must be performed to study daylight distribution for varying sun and sky conditions.

Setting up the basic computer model can take more time than constructing a physical model, but once the basic model exists, simulating various design options can be quicker and easier than with a physical model. Some of these programs have another advantage: they generate realistic renderings of the lighting in the space, which can be linked together to simulate the changes in daylighting over the course of a day. These programs vary in their ease of use, the time required to create a model, and in the range of materials and room shapes they can simulate.

Whole Building Energy Simulation Software

Unlike lighting simulation programs, which just model electric lighting and daylighting conditions, whole building energy simulation programs help to evaluate the effects of daylighting on

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[6] For more information, contact Steve Meder: smeder@hawaii.edu.

whole building energy use. Programs such as BLAST, DOE-2.1E, Energy 10 and EnergyPlus take into account the impact of daylighting fenestration on issues such as solar gain, HVAC equipment size, and reduced electric lighting energy use. Programs that interface with these whole building simulation tools have been developed to make it easier to create models and analyze results. To accurately evaluate complex daylighting designs, it may be necessary to use one of the lighting simulation program discussed above in conjunction with a whole building energy simulation tool.

Operations and Maintenance

Horizontal glazing needs more frequent cleaning than vertical glazing in areas and times of the year with low rainfall, and must be on a cleaning schedule for maximum daylight benefit.

The mechanisms for operable louvers and blackout shades should be robust, accessible to the occupant and easily repairable.

Horizontal reflecting members such as lightshelves should also be on a cleaning schedule.

Daily janitorial service should check all operable windows and skylights to make sure that they are closed when appropriate.

Commissioning

Check that operable louvers and shades are working. Set angles of adjustable louvers to eliminate direct sun penetration.

It's critical to test and adjust automatic lighting controls to ensure that expected energy savings are achieved with daylighting systems. For a daylighting system with automatic controls to work properly, several commissioning steps are important:

- Clearly specify the intended control operation;
- Carefully specify the control equipment to ensure that the installed equipment has the necessary capabilities;
- Provide the contractor with a detailed testing protocol; and
- Require that the contractor certify proper operation.

See the Electric Lighting and Controls chapter for more information about commissioning daylighting controls.

Utility Programs

To take advantage of any existing opportunities for daylighting design incentives, contact your utility company representative as early as possible in the design process.

Products

Refer to the Energy-Efficient Windows Guidelines for information about glazing characteristics and high performance glazing products.

Resources

Advanced Lighting Guidelines. White Salmon, OR: New Buildings Institute, 2001. Web site: www.newbuildings.org.

Ander, Gregg. *Daylighting Performance and Design.* NY: John Wiley & Sons, Inc., 1997.

Daylighting Initiative Case Studies and Project Reports. San Francisco: Pacific Gas & Electric Company, 1999. Web site: www.pge.com/pec/daylight.

IESNA Lighting Handbook, 9th edition. NY: Illuminating Engineering Society of North America (IESNA), 2000. Web site: www.iesna.org.

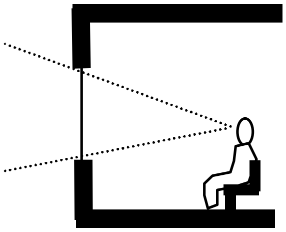
SkyCalc. A Microsoft Excel-based spreadsheet used to determine the optimum skylighting strategy for a building. Available from www.energydesignresources.com.

Skylighting Guidelines. California: Energy Design Resources. Web site: www.energydesignresources.com.

View Windows

Recommendation

Provide access to exterior views through view windows for all interior spaces where occupants are present for extended periods of time.[7]



Description

A view window is vertical glazing at eye level that provides a view to the exterior or interior adjacent spaces.

Applicability

Use view windows in all spaces except those requiring visual privacy. They should be planned for in the schematic design phase.

Codes and Standards

See Codes and Standards section in General Principles for Daylighting Design, above.

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[7] Cross-section drawings in this and subsequent Daylighting Guidelines are courtesy of *CHPS Best Practices Manual* (Eley Associates, 2001).

Benefits

In addition to providing daylight, view windows offer many other benefits, including providing building occupants with connections to outdoor conditions and to nature, and allowing people outside of a space to view what's taking place inside the space.

Stimulating views may increase occupant productivity and may help to reduce stress. Access to views can also promote eye health: optometrists encourage people who spend much time on close-up activities such as computer work to frequently shift their focus to a longer view.

If view windows are operable, they can allow for emergency egress and natural ventilation.

Also, north-facing view windows can provide enough daylight to reduce electric lighting loads, if manual controls or photocontrols are provided. But view windows on the other orientations will often have to have their blinds or curtains drawn to reduce glare, and so should not be counted on to provide adequate daylight or to predictably reduce a space's electric lighting use.

Integrated Design Implications

Design phase: Identify the location and design objectives of view windows early in the schematic design phase. View windows need to be at eye level, they should not produce glare, and they should be oriented and designed to reduce building energy loads.

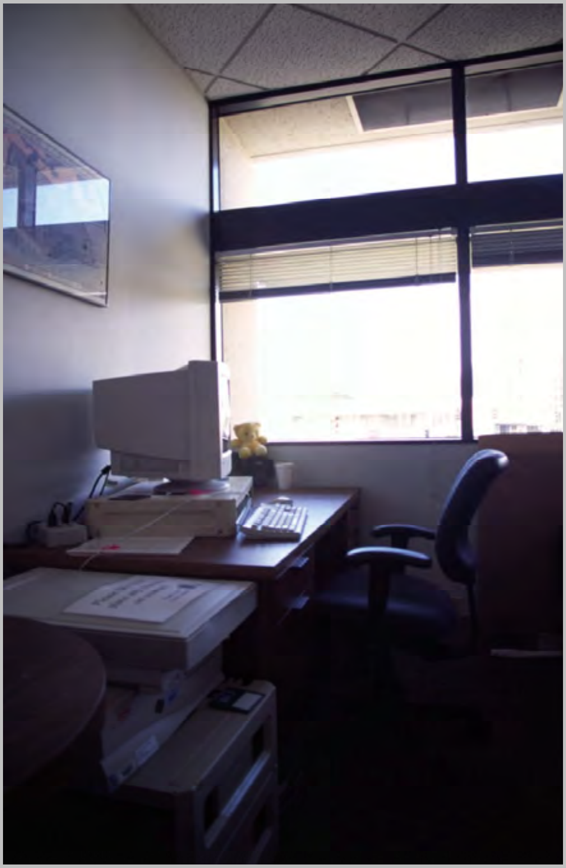


Figure 3-5. The light-colored wall perpendicular to the windows helps to reduce contrast and reflect daylight into the space. Blinds provide control over brightness and direct sunlight penetration. Photo: Erik Kolderup, Eley Associates.

Interior layout of space: If some view windows cannot be optimally oriented, it may be possible to allot time-specific activities to certain spaces to make best use of the window orientation. For example, a space with a west-facing view window can be comfortably used from morning to early afternoon, but will need to be protected from direct solar penetration with blinds in the late afternoon. Activities that require daylight in the late afternoon should be avoided in this space.

Orient view windows relative to the location of stationary tasks, such as desks, computer workspaces and reading areas. Avoid reflected glare from windows in computer screens or surfaces such as whiteboards.

Balance with other daylighting strategies: Although view windows offer many benefits, they are not the most effective daylight delivery system. For better daylight delivery, combine view windows with high sidelighting, toplighting or both.

Integration with electric lighting: See the General Principles for Daylighting Design Guideline for an overview of integrating daylighting with electric lighting.

If view windows are the only daylight apertures in a space, and they appear on only one wall of the space, balance their brightness by washing other interior walls with electric light.

With view windows the illuminance level quickly drops off as we move away from the windows (see Figure 3-6). They do not significantly lower electric lighting energy consumption unless integrated with other daylighting strategies such as high sidelighting or balancing daylight from two or more directions. To maximize the energy benefits of daylighting, circuit and control the electric lighting so that at least one row of lights can be turned off near the view windows and the rest of the rows can be left on away from the windows where there is less daylight.

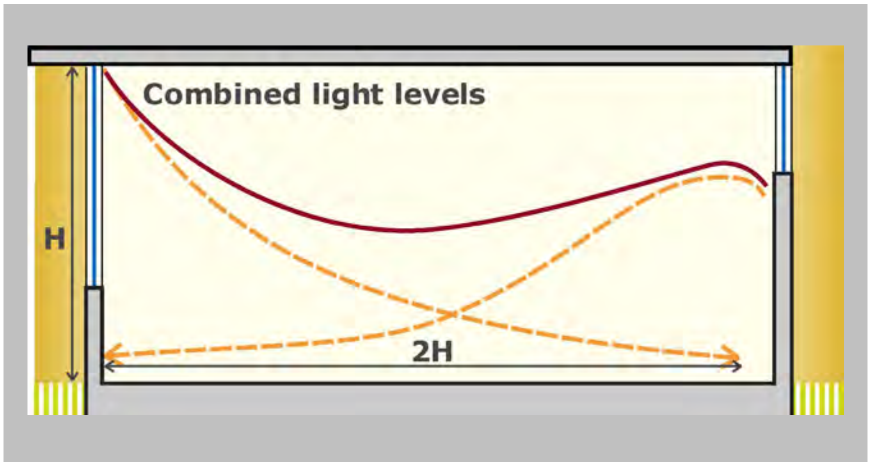


Figure 3-6. Daylight levels drop rapidly as you move away from a window. Daylight penetration is approximately two times the window head height. The solid line represents combined light levels from the two windows shown here.

Integration with structural system: Coordinate the size and location of windows with the location of columns and studs.

Integration with HVAC: If they are oriented, glazed and shaded appropriately, view windows can reduce a building's overall heating and cooling loads, which in turn can reduce the required size of the HVAC system and yearly energy costs.

Integration with natural ventilation: Operable view windows in combination with operable skylights, or operable windows in combination with high sidelighting apertures located on the opposite wall, can be used to naturally ventilate the space when the outside air temperature falls within a comfortable range. This can eliminate or significantly reduce mechanical ventilation needs for a significant portion of the time in Hawaii. Evaluate prevailing wind conditions to assess the feasibility of this approach. See the Natural Ventilation Guidelines for details.

Design Details

Orientation: Orient view windows toward the north or south to avoid the low-angle east and west sun. See the Energy-Efficient Windows Guidelines for information about the impact of window orientation on building energy performance.

Figure 3-7. Exterior fins help to reduce brightness and direct sun penetration. Photo: Erik Kolderup, Eley Associates.

Diffusion: Since view windows are within the occupants' normal field of view, the contrast between the bright window area and other interior surfaces can create glare. Use exterior shading devices such as overhangs or fins, or use landscaping, to eliminate direct sun penetration and reduce brightness. Deeply splayed walls or mullions will also reduce glare.

On south, east and west orientations, an interior shade such as a shade screen, blinds or drapes, will provide control over brightness and sun penetration.

Blackout capability: If blackout capability is required, add louvers.

Glazing area: Refer to the Energy-Efficient Windows Guidelines for information about appropriately sizing the glazing areas.

Visible transmittance: If it is not possible to use a shading device to cut off direct solar penetration, use a lower transmission glazing according to the aperture's orientation. If tinted glazing is used, evaluate its effect on color distortion with both overcast and clear skies. See the Energy-Efficient Windows Guidelines for details.

Reflectance: Paint all surfaces near windows white or off-white to reduce contrast between the brightness of the window and its surrounding wall. Place view windows adjacent to a perpendicular surface that can reflect daylight onto adjacent surfaces. Avoid windows that are merely punched holes in walls, as these create glare.

Exterior reflective surfaces: Reflective surfaces outside the view window may create glare. Reflected sun off a car windshield, for example, can create annoying glare, as can light-colored exterior walls that are within view. Landscaping such as hedges or trees can help reduce glare from these outdoor sources.

Computer screen location: Orient computers at a 45-degree angle from view windows to avoid glare from reflections of the window in the computer screen. Flat-screen computers and adjustable-angle LED screens also help to reduce glare.

Safety and security: There are safety and security issues associated with view windows, especially those located on the first floor. Operable interior shades, laminated glass, or both can make view windows more secure.

Noise transmission: If noise is expected to be a problem, use double-glazing or laminated glass to reduce noise transmission.

Design and Analysis Tools

The physical models or daylight simulation tools noted in the General Principles for Daylighting Design Guideline can be used to evaluate the potential daylight levels of a particular design that includes view windows. The energy simulation programs can be used to understand the building energy use associated with a particular design.

In spaces where a particular view is a critical element of the design, use scaled drawings or a scale physical model to evaluate views and view angles from various positions in the space, or use simulation programs such as Desktop Radiance or Lightscape. A “lipstick”-type video camera head can be used inside a physical model to record the views from various positions.

Costs

Costs for view windows are typically low. The incremental cost of energy-efficient glazing can vary widely, from $0.70 to $12 per square foot of glass.

Cost Effectiveness

Although there are many excellent reasons for including view windows in buildings, it is difficult to place a value on view windows in terms of cost effectiveness. Where view windows are used, it is often cost effective to use energy-efficient glazing to reduce cooling loads and increase occupant comfort.

Operation and Maintenance Issues

Wash view windows on a regular schedule. Clean, repair and replace as necessary any shading devices such as blinds, louvers, drapes and shades. Use shading devices with mechanisms that are sturdy, easy for the occupants to operate, and easy to repair.

Make sure that operable windows are designed to prevent physical entry and water penetration.

Commissioning

View windows typically do not require commissioning.

Utility Program

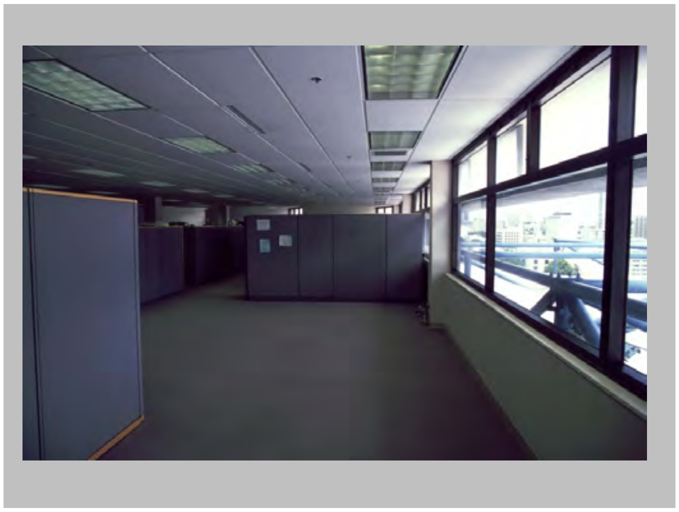
Energy-efficient windows that exceed the Hawaii Model Energy Code requirements may be eligible for customized incentives. Contact your utility company representative as early as possible in the design process.

Case Study

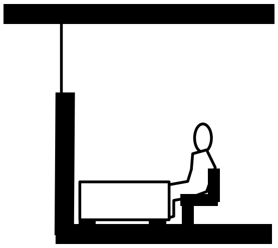
The HMSA Building in Honolulu uses lightshelves to shade view windows and bounce daylight deeper into the space. In some spaces, the glazing below the lightshelf is tinted to reduce glare, while the glazing above the lightshelf is clear. In other areas, the view windows have clear glazing, but the exterior lightshelves shade the windows.

Figure 3-8. HMSA Building. Windows provide occupants with views and daylight. Lightshelves shade the view windows. Photos: Erik Kolderup, Eley Associates.

Figure 3-9. HMSA Building. Exterior lightshelves shade the view windows and bounce light onto the ceiling.



High Sidelighting — Clerestory



Recommendation

Use high sidelighting clerestories in perimeter walls to deliver daylight deeper in spaces such as offices, classrooms, warehouses, industrial spaces, gymnasiums, and many other building types.

Description

High sidelighting is characterized by vertical glazing in an exterior wall above eye level, typically above 7 ft. The penetration of usable daylight into a space from vertical glazing is roughly 1.5 to 2.5 times the window head height. Therefore, placing the window higher on the wall increases daylight penetration in the space.

For all orientations except perhaps north, clerestories generally require some type of shading to prevent the direct penetration of sunlight. The Design Details section of this Guideline lists various shading options, while lightshelves and louvers are discussed in depth in the next Guideline, High Sidelighting — Clerestory with Lightshelves or Louvers.

Applicability

High clerestory windows can be used in many types of commercial buildings to provide deep penetration of daylight.

Codes and Standards

See Codes and Standards section in General Principles for Daylighting Design, above.

Benefits

Refer to the General Principles for Daylighting Design Guideline in this chapter for a discussion of the energy saving, productivity and visual comfort benefits of daylighting.

Clerestory sidelighting can save energy by reducing electric lighting energy use, assuming that appropriate manual or automatic controls are used for the space's electric lighting system. Clerestory sidelighting improves lighting quality by distributing daylight more uniformly across the space.

Integrated Design Implications

Design phase: High sidelighting must be planned for in the schematic design phase. High ceilings and perimeter walls are required. The best orientations for high sidelighting are north and south (if shaded). East and west orientations may be acceptable if diffusing glazing is used, or if low-angle sun penetration will not be a problem in the space.

Interior layout of space: An open-plan interior layout works best with high sidelighting because it doesn't obstruct daylight penetration.

Balance with other daylighting strategies: Used on one wall, this approach creates a decreasing gradient of useable daylight of roughly 1.5 to 2.5 times the clerestory head height into the space. For spaces 20 to 40 ft wide, balance high sidelighting with a daylighting scheme on the opposite wall to distribute daylight evenly across the space.

When combining view windows and high sidelighting in a space, the clerestories should be continuous along the whole area to be daylit, but view windows can be selectively spaced as needed.

Figure 3-10. Clear glazing on the high sidelighting and tinted glazing on the view windows. HMSA building, Honolulu. Photo: Erik Kolderup, Eley Associates.

Integration with electric lighting: Circuit electric lighting parallel to the linear zones of daylighting created by high sidelighting. Use manual controls or photocontrols to regulate electric light in response to daylighting conditions.

See the General Principles for Daylighting Design Guideline for an overview of integrating daylighting with electric lighting.

Integration with ceiling plenum: Clerestory sidelighting requires ceiling heights of at least 9.5 ft at the window wall. There are a variety of ways to achieve this extra ceiling height without significantly increasing the building's floor-to-floor height. For example, the ceiling can be sloped or stepped upward at the perimeter, as shown in Figure 3-11, which reduces the plenum near the window wall. A careful integration of the structural system, HVAC ducts and electric lighting in the plenum can also provide additional perimeter ceiling height. In spaces with HVAC ducts in the ceilings, the ducts should be located away from perimeter walls.

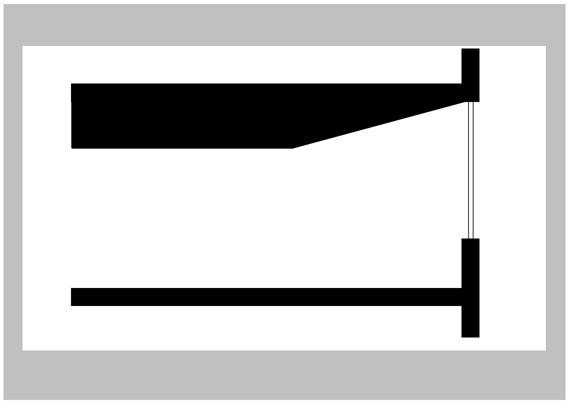


Figure 3-11. Sloped ceiling at perimeter increases window head height by reducing the plenum height.

Integration with HVAC: High sidelighting can affect a building’s overall HVAC loads because it is susceptible to solar gain in the cooling season and heat loss in the heating season. Reduce HVAC loads by correctly orienting the glazing, designing appropriately sized windows, selecting appropriate glazing materials, providing shading, and controlling the electric lighting system. In addition to saving energy, these measures may help to reduce the size and first cost of the HVAC equipment.

Locate ductwork away from clerestory windows to avoid blocking daylight.

Integration with natural ventilation: Operable clerestories that allow warm air to escape near the ceiling level can be part of a natural ventilation scheme (see the Stack Ventilation Guideline in the Natural Ventilation chapter for details). Locate operable clerestory windows on a building’s leeward side for more effective natural ventilation.

Design Details

Orientation: Clerestories are most effective on south and north orientations. For east and west orientations, evaluate the design to reduce low sun angle penetration. With east, west and south orientations, reduce solar gain by shading the glazing with an overhang or use a selective low-e coating (SHGC less than .45).

Glazing materials: There are some new glazing materials that can help deliver daylight deeper into the space by redirecting it from the clerestory window to the ceiling. These include prismatic, lensed, holographic and laser-cut acrylic materials. Before selecting these glazing materials, test them to see if they will result in excessive bright spots or glare.

Visible transmittance: Refer to the Energy-Efficient Windows Guidelines for details about the appropriate visible transmittance of glazing in Hawaii.

Reflectance: Surfaces near the clerestories should be white or off-white to reduce contrast between the brightness of the windows and their adjacent walls. The adjacent ceiling should have a white or off-white surface with a reflectance of 70% or more to help direct daylight into the space. High-reflectance ceiling tiles may be an option if the budget allows.

Ceiling design: For high sidelighting designs, a minimum perimeter ceiling height of 9.5 ft is recommended. Generally, the higher the ceiling height, the better.

The wall area directly below a clerestory may be darker than other nearby surfaces. In a multistory building, the ceiling can be stepped so that reflected daylight from the clerestory brightens the perimeter wall area, as shown in Figure 3-12.

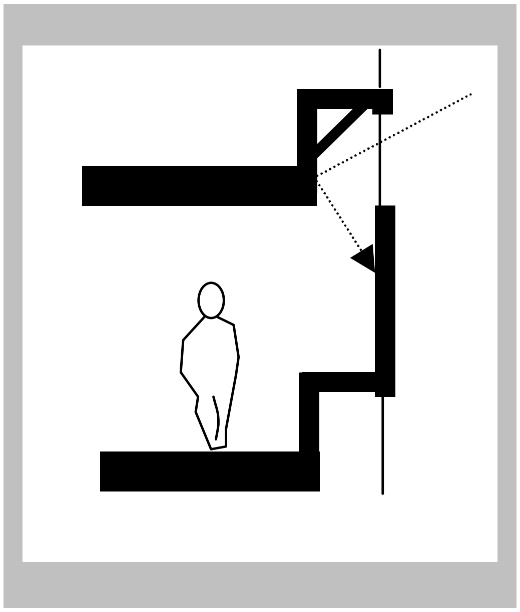


Figure 3-12. Clerestories in multistory buildings can redirect daylight onto the perimeter wall to brighten it.

Shading devices: Use exterior shading devices, diffusing glazing, operable blinds, lightshelves or louvers to reduce or eliminate direct sun penetration. The following guideline, High Sidelighting — Clerestory with Lightshelf or Louvers, discusses the lightshelf and louver strategies. The Energy-Efficient Windows Guidelines provide information about the appropriate depth of exterior shading devices.

Dedicated blinds or shades for clerestory and view windows allow them to be controlled separately for glare. One low-maintenance option is a product that has miniblinds positioned between the panes of glass in a double-glazed window. Blackout shades may be necessary in certain spaces.

Design and Analysis Tools

See the General Principles for Daylighting Design Guideline for information about design tools that can be used to evaluate daylight distribution and calculate energy savings.

For high sidelighting designs that include sloped surfaces, make sure that the simulation program can accommodate them. Evaluate daylight levels in the space under both clear and overcast sky conditions. It's important to assess sun penetration through the clerestory glazing for the lowest anticipated sun angles, because occupants may block a window if they are annoyed by even occasional glare.

Costs

Costs for high sidelighting are low to moderate. A balance of view and clerestory windows can be provided with minimal increase to the overall glazed area.

Refer to the Energy-Efficient Windows Guidelines for information about the relative costs of different types of glazing. As long as the clerestories are properly shaded, it is generally not necessary to use more expensive high-performance glazing.

For information about the costs of daylighting controls, see the Electric Lighting and Controls Guidelines.

Cost Effectiveness

Clerestories are generally more cost effective than view windows because they can be substantially smaller and yet they do a better job of providing daylight.

Operation and Maintenance Issues

Wash clerestory windows on a regular schedule. Clean, repair and replace as necessary any shading devices such as blinds, louvers and shades. Use shading devices with mechanisms that are sturdy, easy for the occupants to operate, and easy to repair.

Make sure that operable clerestory windows are designed to prevent water penetration.

Commissioning

Set adjustable louvers at their correct seasonal angle to eliminate direct sun penetration.

Utility Programs

Energy-efficient sidelighting that exceeds the Hawaii Model Energy Code requirements may be eligible for customized incentives. Contact your utility company representative as early as possible in the design process.

Case Study[8]

At the Ross Middle School in Ross, California, clerestories bring daylight into the classrooms and can be opened to provide natural ventilation. View windows on the opposite side of the room provide additional daylight, and have miniblinds for glare control when needed. White ceilings and walls help to reflect daylight deeper into the space.

The direct/indirect pendant luminaires include two fluorescent lamps that can be switched separately by the teacher to control light levels. This system uses only 1 W/ft² of electricity. In addition, the electric lighting system includes dimming ballasts and photocontrols, which can reduce lighting energy use by up to 60%.

Occupancy sensors are used in some area to shut off lights when the space is not occupied, and building-level automatic controls turn off lights when the building is not in use.

Figure 3-13. Ross Middle School, Ross, CA. The clerestories on the right allow daylight into the classroom, while white ceilings and walls reflect the daylight deeper into the space. Photo: Eley Associates.

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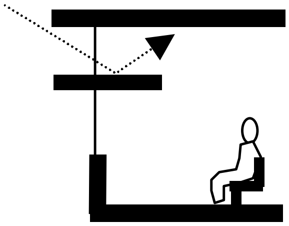
[8] Source: Eley Associates. *Collaborative for High Performance Schools Best Practices Manual, Vol. I — Planning,* 2001. Web site: www.chps.net.

High Sidelighting — Clerestory with Lightshelves or Louvers

Recommendation



Use lightshelves or louvers with high clerestory glazing to improve daylight distribution, reduce glare and prevent direct sun penetration.

(Note: The previous Guideline, High Sidelighting — Clerestories, discusses clerestories in general. You may wish to familiarize yourself with that material before continuing with this Guideline.)

Description

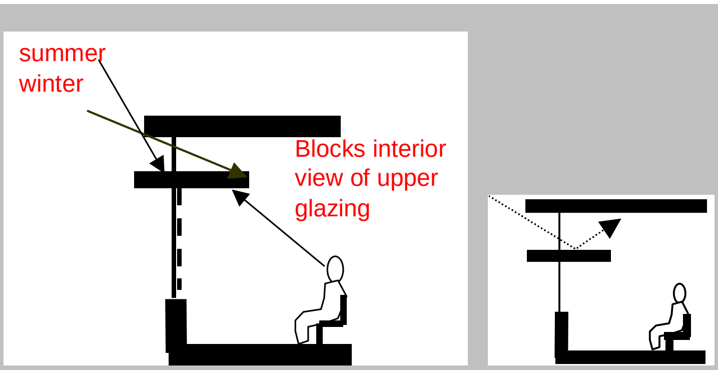
A lightshelf is a horizontal panel separating a high clerestory window from a lower view window. Daylight reflects off the top of the lightshelf or louver onto the ceiling, improving light distribution.

A series of smaller horizontal louvers can replace a large lightshelf. Performance will be reduced slightly with louvers, but they may provide better illumination on the wall directly beneath the clerestory. Larger louvers deliver daylight deeper into the space. Louvers can either be fixed or adjustable. If louvers are used instead of lightshelves, they should be designed with the same cutoff angle as the lightshelf. In Hawaii, because louvers help to reduce the size of exterior shading devices, a larger floor area may be allowed.

Lightshelves and louvers can be located on the exterior of a building, the interior or both. Exterior lightshelves (see Figure 3-14) bounce the high-angle summer sun into the space, and also shade the lower window, which helps to stop solar heat gain before it enters the building. Interior lightshelves reflect the low-angle winter sun into the space, block direct sun penetration, and reduce glare from the upper glazing. Figure 3-15 shows the effect of interior and exterior lightshelves.

Figure 3-14. Exterior lightshelves improve light distribution and help stop heat gain before it enters the building. Photo: Erik Kolderup, Eley Associates.

Figure 3-15. Exterior lightshelves shade lower window and reflect summer sun into room. Interior shelves reflect winter sun while reducing glare.



Applicability

High clerestory windows with lightshelves or louvers can be used in many types of commercial buildings to provide deep penetration of daylight.

Codes and Standards

See Codes and Standards section in General Principles for Daylighting Design, above.

Benefits

For general information about the benefits of daylighting, see the General Principles for Daylighting Design Guideline earlier in this chapter.

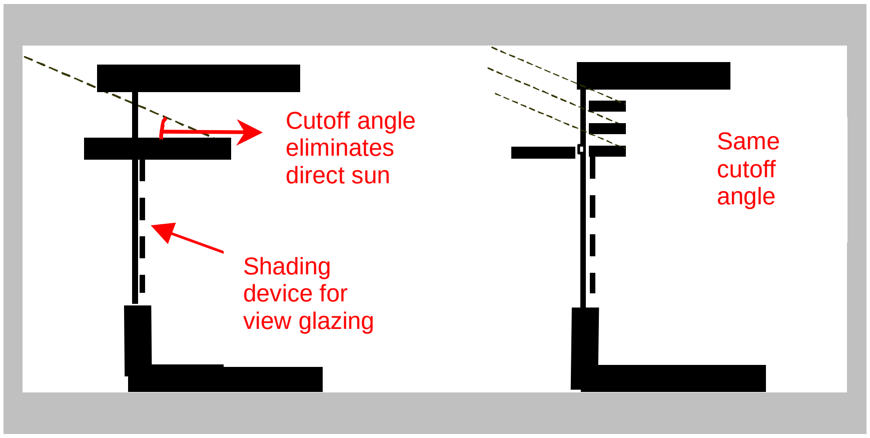
Clerestories with lightshelves or louvers provide numerous benefits. They can save energy by both reducing solar heat gain through shading and by reducing lighting energy use.

They also improve lighting quality by delivering daylight deeper into the space and distributing daylight more evenly. Interior lightshelves and louvers reduce or eliminate glare by blocking the occupants' view of the bright upper glazing.

Integrated Design Implications

Design phase: High sidelighting with lightshelves or louvers should be planned for early in the schematic design phase. High ceilings and perimeter walls are required. Clerestories with lightshelves are most effective with a south-facing orientation. The size and cutoff angles of the lightshelf or louver system must be carefully calculated. See the Energy-Efficient Windows Guidelines for information about interior and exterior shading devices.

Figure 3-16. Set the cutoff angle of lightshelves or louvers to eliminate direct sun penetration during normal operating hours.



Interior layout of space: An open-plan interior layout works best with high sidelighting because it doesn't obstruct daylight penetration.

Balance with other daylighting strategies: Used on one wall, this approach creates a decreasing gradient of useable daylight of roughly 2.5 times the clerestory head height into the space. For spaces that are 20 to 50 ft wide, balance high sidelighting with a daylighting scheme on the opposite wall to distribute daylight evenly across the space.

When combining view windows and high sidelighting in a space, the clerestories should be continuous along the whole area to be daylit, but view windows can be selectively spaced as needed.

Integration with electric lighting: Circuit electric lighting parallel to the linear zones of daylighting created by high sidelighting. Use manual controls or photocontrols to regulate electric light in response to daylighting conditions.

Lightshelves and louvers work well when combined with a direct/indirect pendant electric lighting system. The first row of electric lighting is sometimes incorporated into the lightshelf itself.

Integration with ceiling plenum: Clerestories with lightshelves require ceiling heights of at least 9.5 ft at the window wall. There are a variety of ways to achieve this extra ceiling height without significantly increasing the building's floor-to-floor height. For example, the ceiling can be sloped or stepped upward at the perimeter, as shown in Figure 3-11, which reduces the plenum height near the window wall. A careful integration of the structural system, HVAC ducts and electric lighting in the plenum can also provide additional perimeter ceiling height. In spaces with HVAC ducts in the ceilings, the ducts should be located away from perimeter walls.

Integration with HVAC: Glazing above a lightshelf can affect a building's overall HVAC loads because it is susceptible to solar gain in the cooling season and heat loss in the heating season. Reduce HVAC loads by correctly orienting the glazing, designing appropriately sized windows, selecting appropriate glazing materials, providing shading, and controlling the electric lighting system. In addition to saving energy, these measures may help to reduce size and first cost of the HVAC equipment.

Design lightshelves so they don't interfere with air circulation from the HVAC system. Locate ductwork away from clerestory windows to avoid blocking daylight.

For spaces with the potential to be naturally ventilated, consider using operable clerestories. See the Natural Ventilation Guidelines.

Integration with other mechanical systems: Design lightshelves so they don't interfere with the fire sprinkler system operation.

Design Details

Orientation: Lightshelves are most effective on south orientations. For north orientations, they are occasionally useful for reduce glare from the upper glazing. Avoid them on east and west orientations.

Materials: Lightshelves can be made of wood, metal, glass-fiber reinforced concrete (GFRC), plastic, fabric or acoustic ceiling materials. Issues to consider when selecting an appropriate material include reflectivity, structural strength, cost, maintenance requirements and durability. Some curtain wall or window manufacturers provide assistance with the design of lightshelves.

The top surface of casework along a perimeter wall can also be used as a lightshelf if its reflectivity and size are appropriate. The top should be sloped so that it won't be used for storage, which would interfere with its ability to reflect daylight into the space.

Opaque vs. translucent shelves: Lightshelves and louvers may be opaque or translucent. If opaque lightshelves are not combined with a lower view window, there may be a dark space on the wall directly under them. To address this, leave a gap between the lightshelf and the wall or use electric lighting to brighten this wall. Translucent shelves provide a soft light under them but must be designed carefully so that occupants with a view of their underside aren't bothered by glare. See Figure 3-17.

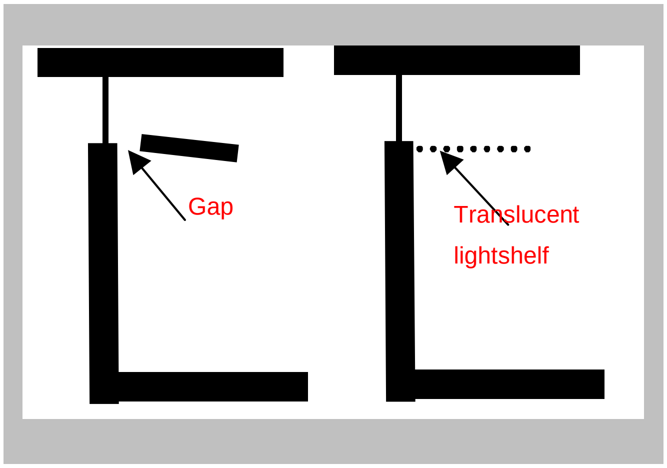


Figure 3-17. A gap between an opaque lightshelf and the perimeter wall beneath creates a wall wash. A translucent lightshelf provides a soft light.

Visible transmittance: Refer to the Energy-Efficient Windows Guidelines for details about the appropriate visible transmittance of glazing in Hawaii.

Reflectance: The top surface of the lightshelf or louvers should have a reflectance of greater than 80%, with a diffuse, not mirrored, surface. Surfaces near the clerestories should be white or off-white to reduce contrast between the brightness of the windows and their adjacent walls. The adjacent ceiling should have a white or off-white surface with a reflectance of greater than 70% to help direct the maximum amount of daylight into the space. High-reflectance ceiling tiles may be an option if the budget allows.

Ceiling design: For high sidelighting designs, a minimum perimeter ceiling height of 9.5 ft is recommended. Generally, the higher the ceiling height, the better. Position the lightshelf at 7 ft or more above the floor. Coordinate shelf position with pendant electric lighting, door headers, shelving, fire sprinklers and other interior features.

Cutoff angle: Set the cutoff angle of the lightshelf or louvers (see Figure 3-16) to eliminate direct sun penetration during normal operating hours. See the Energy-Efficient Windows Guidelines for details about shading devices.

Sloped shelves: Slope exterior lightshelves at least ¼ inch per foot so that rain can wash dirt off the shelves and so that water won’t pool on them. Slope interior shelves (or use fabric lightshelves) so they are not used for storage.

Maintenance: Design the lightshelves or louver systems so it is easy to clean the glass above them, both inside and outside. Large lightshelves may need to be positioned away from the window by about 6 in. so that window-cleaning equipment can be inserted from below the shelf.

Design and Analysis Tools

See the General Principles for Daylighting Design Guideline for information about design tools that can be used to evaluate daylight distribution and calculate energy savings.

For high sidelighting designs that include sloped surfaces, make sure that the simulation program can accommodate them. Evaluate daylight levels in the space under both clear and overcast sky conditions. It’s important to assess sun penetration through the clerestory glazing for the lowest anticipated sun angles, because occupants may block a window if they are annoyed by even occasional glare.

Costs

Lightshelves or louvers are an added expense, but some of this cost may be offset if the building’s cooling load can be reduced and the HVAC system downsized.

For information about the costs of daylighting controls, see the Electric Lighting and Controls Guidelines.

Cost Effectiveness

Energy savings from reduced lighting and cooling energy are adequate to recover the initial investment in about 8 to 12 years. Also, high sidelighting with lightshelves and louvers helps provide a better indoor environment, and may even increase occupant productivity by enhancing visual comfort. For many tenants and building owners, the value of any increase in productivity would be an even more attractive benefit than the long-term energy savings.

Operation and Maintenance Issues

Glazing, lightshelves and louvers must be kept clean to provide maximum daylight to the space. Clean the top surface of the shelf or louvers each time the windows are washed. Make sure lightshelves or louvers are detailed correctly to allow easy window cleaning. For operable louvers, it is preferable to have preset angles that can be seasonally adjusted by the building maintenance staff so the louvers are not inadvertently left at a non-optimal angle.

Commissioning

Unless the lightshelf or louvers are moveable, commissioning should not be necessary. Set adjustable louvers at their correct seasonal angle to eliminate direct sun penetration.

Utility Programs

Energy-efficient sidelighting that exceeds the Hawaii Model Energy Code requirements may be eligible for customized incentives. Contact your utility company representative as early as possible in the design process.

Case Study

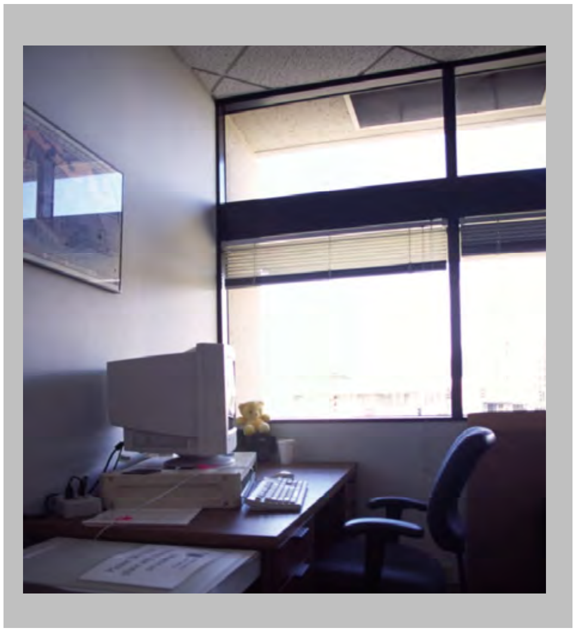
Overhangs and lightshelves shade the windows of the Kaiser Permanente Honolulu building pictured here. Windows on the east façade are angled southeast (a sawtooth pattern in plan view) to provide additional shading. Because the exterior surfaces are buff colored, they do not reflect as well as white surfaces would.

Interior miniblinds below the lightshelves provide some glare control (Figure 3-20), but the high sidelighting above the lightshelf is a potential source of glare because the lightshelves do not extend inside the building. The glass is tinted a neutral color.

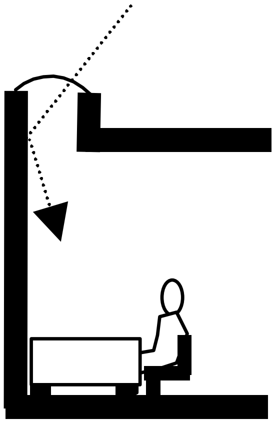
Figure 3-18. Kaiser Permanente, Honolulu Clinic. Photos: Erik Kolderup, Eley Associates.

Figure 3-19. Exterior detail.

Figure 3-20. Interior detail.



Wall-wash Toplighting



Recommendation

Use wall-wash toplighting for interior walls to balance daylight from window walls, brighten interior rooms and make them seem more spacious.

Description

Linear skylights or roof monitors located above an interior wall brighten a space by providing a "wash" of daylight across the wall surface. Skylight and roof monitor wells obscure the occupants' direct view of the bright glazing, thus minimizing uncomfortable glare. Diffusing glazing, baffles and reflective, matte light well and interior wall surfaces help diffuse the daylight.

Applicability

Toplighting is appropriate in single-story buildings or the top floor of multistory buildings. Many types of spaces may benefit from wall-wash toplighting, including private offices, meeting rooms, open plan offices, retail stores, classrooms, circulation areas and multipurpose spaces.

Codes and Standards

See Codes and Standards section in General Principles for Daylighting Design, above.

Benefits

Wall-wash toplighting reflects glare-free daylight into the space, making it appear larger and brighter. This is approach, when combined with another wall-wash or a sidelighting strategy that increases daylight on the opposite side of the room, is an excellent way to create balanced daylight across an entire space.

This strategy can save energy if the first row or two of electric lights adjacent to the wall wash are controlled in response to daylight conditions. During daylight hours, savings for controlled fixtures can range from 40% to 80%.

If the wall-wash toplighting scheme uses operable rooftop fenestration, it can be used to provide natural ventilation, which may increase occupant productivity. See the Natural Ventilation Guidelines for more information.

Integrated Design Implications

Design phase: Wall-wash toplighting must be planned for in the schematic design phase. The glazing for wall-wash toplighting may be either horizontal or vertical. Vertical glazing may face north, east, south or west. Compared to roof monitors, skylights can offer an advantage of lower construction costs.

Interior layout of space: When designing a space, take into account that this daylighting scheme will draw attention to the wall that is being “washed” with daylight. It may be possible to eliminate task lighting for work areas that are located closer to the wall-wash toplighting. But to avoid glare, do not position work areas directly under the wall-wash toplighting.

Balance with other daylighting strategies: Balance wall-wash toplighting with a daylighting scheme on the opposite wall to supply uniform lighting across the whole space.

Integration with electric lighting: An electric lighting wall-wash luminaire can wash the wall with light at night or during very cloudy conditions. The electric light should be photocontrolled to respond to daylight conditions.

See the General Principles for Daylighting Design Guideline for an overview of integrating daylighting with electric lighting.

Integration with structural system: Coordinate the location and size of skylights and roof monitors with the structural system and roof diaphragm to maintain the building’s strength and integrity.

Integration with HVAC: Coordinate the location of skylights, roof monitors and their light wells with the location of rooftop HVAC equipment and interior ductwork. Toplighting that is properly oriented, glazed, shaded and integrated with electric lighting controls, should decrease a building’s heating and cooling loads, which in turn can reduce the size and first costs of the HVAC system as well as yearly energy costs.

Integration with natural ventilation: Operable rooftop fenestration can be used to naturally ventilate the space. See the Natural Ventilation Guidelines for information.

Design Details

Skylights: Skylights perform better in a predominantly overcast sky condition and non-north/south orientations.

A pyramid or arch-shaped diffusing skylight is more effective at collecting daylight during the very low sun angles of early morning or late afternoon. Horizontal glazing is more effective when the sun is high in the sky and associated with higher solar gains.

Roof monitors: A roof monitor with glazing oriented north or south will be more expensive, but may perform better than a skylight in areas with predominantly sunny conditions. North- or south-facing monitors exhibit less variation of daylight levels than east- or west-facing monitors. They are also easier to design for good energy performance. To reduce solar heat gain with south-facing vertical glazing, use an overhang or a spectrally selective low-e coating with an SHGC of less than .45, along with baffles or diffusing glazing to eliminate direct sun. East- or west-facing roof monitors may show more variation in daylight levels and quality. If an east or west orientation is required, consider a skylight instead of a roof monitor.

Diffusion: To provide gentle, attractive light and to avoid bright spots of direct sun, the daylight needs to be diffused before it washes the wall. Use diffusing glazing, baffles or a deep light well. A diffusing material like prismatic acrylic will increase a skylight's light transmission while reducing bright spots. Baffles used with clear glazing should be adjustable or should be designed so that all anticipated sun angles are cut off.

Visible transmittance: Refer to the Energy-Efficient Windows Guidelines for details about the appropriate visible transmittance of glazing in Hawaii.

Light wells: A light well brings daylight through the roof and the ceiling plane. Light well walls should be light in color — with a reflectance of greater than 80% — to reflect more light down into the space. Avoid dark well walls. Avoid dark well walls. Flat, bright white paint performs best. Diffusely reflecting light wells should be less than 8 ft deep. For deeper wells, mirrored reflecting wells can be used.

Surface colors: The top of the wall below the skylight or roof monitor should be white or off-white with a reflectance of greater than 70% to better reflect daylight into the space.

Insulation: Ideally, the roof should be appropriately insulated. But if the insulation is located at the ceiling, then it is also necessary to insulate the light well walls to prevent heat gain into the space.

Task and accent lighting: Wall-wash toplighting can be used to light corridors and other circulation spaces, and can provide task and accent lighting on a wall.

Safety and security: Toplighting designs can present safety and security concerns, especially on flat roofs. Make sure that any operable fenestration is designed to prevent physical entry. A safety/security grating can be placed in the light well under the toplight glazing (make sure this grating does not create an undesirable shadow on the wall). Louvers and baffles can also provide security.

Leakage: There are leakage risks with all roof penetrations. Use well-tested curb design details and flashing kits provided by the manufacturer. Make sure that operable fenestration is designed to prevent rain penetration.

Design and Analysis Tools

See the General Principles for Daylighting Design Guideline for information about design tools that can be used to evaluate daylight distribution and calculate energy savings. For designs that include sloped surfaces, make sure that the simulation program can handle them. The SkyCalc program, available at www.energydesignresources.com, can be used to quickly optimize the size of the daylighting aperture ratio for most simple skylight schemes.

Costs

Costs for wall-wash toplighting are moderate to high, depending on design. Commercial, single-glazed skylights are usually the least expensive approach.

For information about the costs of daylighting controls, see the Electric Lighting and Controls Guidelines.

Cost Effectiveness

In general, wall-wash toplighting is a less cost-effective daylighting strategy than patterned or central toplighting. Wall-wash toplighting may be most appropriate when it is necessary to balance daylight from view windows on the opposite side of space or to provide special emphasis on a wall.

Operation and Maintenance Issues

To provide maximum daylight to the space, glazing needs to be cleaned on a regular schedule. In climates with low rainfall, horizontal glazing will require more frequent cleaning.

Educate occupants so that they understand how the wall-wash toplighting delivers daylight to the space, and discourage them from hanging dark-colored items such as artwork on the washed wall.

Operable louvers and blackout shades should be durable, accessible to the occupants and easy to repair. The building maintenance staff should check operable fenestration daily to ensure that it is closed when appropriate.

Commissioning

Check that operable louvers and shades are working. Set angles of adjustable louvers to eliminate direct sun penetration.

Utility Programs

Energy-efficient toplighting that exceeds the Hawaii Model Energy Code requirements may be eligible for customized incentives. Contact your utility company representative as early as possible in the design process.

Case Study[9]

At the Oakridge High School in El Dorado Hills, California, diffusing skylights provide wall-wash toplighting in classrooms. The 4 ft by 4 ft double-glazed prismatic domes line both sides of an interior wall shared between classrooms, and bring diffuse, glare-free daylight into the spaces. Four-foot deep rectangular light wells are painted white, as are the walls, to better reflect daylight into the classrooms. The teaching wall is located perpendicular to the skylit wall to avoid glare problems.

Teachers can manually operate louvers in the light wells to adjust light levels and darken the room during video presentations. View windows and clerestories on the opposite side of the classroom from the wall-wash toplighting help to balance the daylight. South-facing windows are shaded with roof overhangs and shaded walkways to reduce direct sun penetration in the summer.

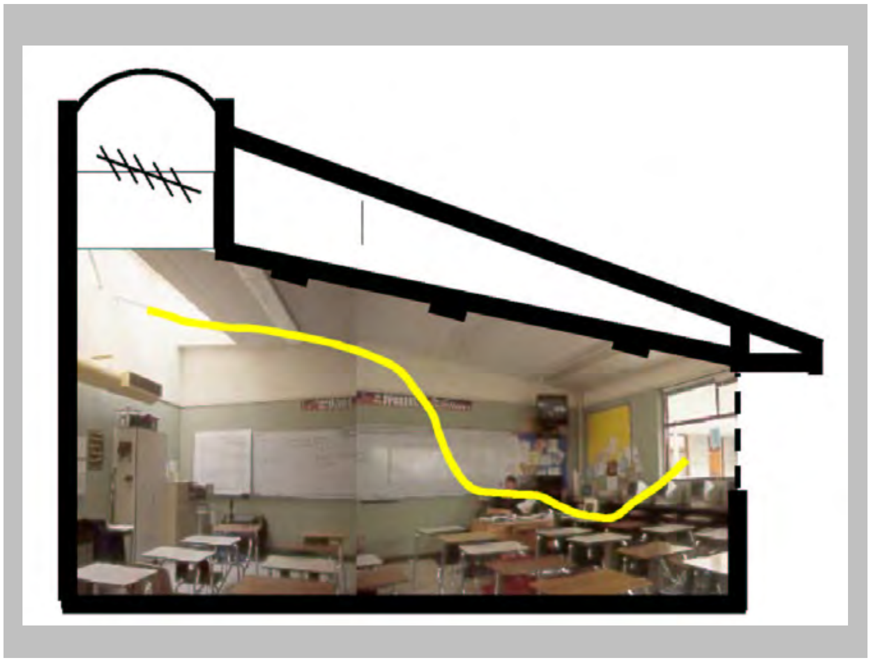


Figure 3-21. Oakridge High School, El Dorado Hills, CA. Wall-wash toplighting from diffusing skylights on the left is balanced with daylight from view windows and clerestories on the right. Photo: Lisa Heschong.

Electric lights are circuited parallel to the view windows and toplit walls, and were originally designed with automatic daylight dimming controls. However, over the years many of these controls

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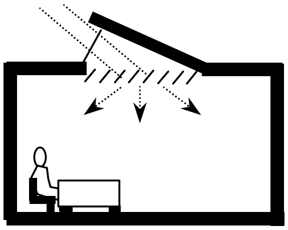
[9] Source: Eley Associates. *Collaborative for High Performance Schools Best Practices Manual, Vol. I — Planning,* 2001. Web site: www.chps.net.

have been disabled and are now working in only about 20% of the classrooms. Many teachers use the wall switch to turn off the electric lights when there is sufficient daylight.

Central Toplighting



Recommendation

Use central toplighting in single-story buildings or the top floor of multistory buildings to provide even, balanced daylight across the entire space.

Description

With central toplighting, a central roof monitor, a skylight or a group of skylights delivers daylight evenly across a space. Diffusing glazing materials or baffles that are fixed or operable diffuse the daylight. Daylight levels are highest directly under the toplighting aperture and gradually reduce toward the space's perimeter.

Figure 3-22. Central sawtooth roof monitor provides even illumination across desktops in this classroom. Photo: Barbara Erwine.

Applicability

Central toplighting is appropriate for single-story buildings or top floor spaces, including offices, warehouses, assembly and light industrial spaces, retail stores, and classrooms.

Codes and Standards

See Codes and Standards section in General Principles for Daylighting Design, above.

Benefits

When used with appropriate diffusion techniques, central toplighting creates uniform, balanced daylight across the space.

This approach saves electric lighting energy if the electric lights are controlled in response to daylight levels. Electric lighting energy savings may range from 40% to 80% during daylight hours.

Operable skylights or operable roof monitors can be used as part of a natural ventilation strategy. See the Natural Ventilation Guidelines for details.

Integrated Design Implications

Design phase: Toplighting schemes apply to single-story buildings or the top floor of multistory buildings. Toplighting should be considered during the programmatic, schematic and design development phases of a building project. Central toplighting may employ either horizontal glazing or vertical glazing that faces north, east, south or west.

Balance with other daylighting strategies: Central toplighting may be combined with view windows. Since the toplighting can provide most of the ambient daylight, smaller view windows can be judiciously spaced in perimeter walls, which frees up wall space for other needs.

Integration with electric lighting: With central toplighting, the daylight levels may be lower near the perimeter walls. Electric lighting wall-wash luminaires can provide supplemental light. If the light well is visible, pendant uplight luminaires can help prevent the light well from appearing to be a dark hole in the ceiling at night. Use photocontrols on the electric lights to respond to daylight conditions.

Integration with structural system: Coordinate the location and size of skylights and roof monitors with the structural system and roof diaphragm to maintain the building’s strength and integrity.

Integration with HVAC: Coordinate the location of skylights, roof monitors and their light wells with the location of rooftop HVAC equipment and interior ductwork. Toplighting that is properly oriented, glazed, shaded and integrated with electric lighting controls, should decrease a building’s heating and cooling loads, which in turn can reduce the size and first costs of the HVAC system as well as yearly energy costs.

Integration with natural ventilation: Operable rooftop fenestration can be used to naturally ventilate the space. See the Natural Ventilation Guidelines for information.

Design Details

Orientation: Skylights perform better than roof monitors in a predominantly overcast sky condition or non-north/south orientations. A roof monitor with glazing oriented north or south will be more expensive, but may perform better than a skylight in areas with predominantly sunny conditions.

Glazing area: Refer to the Energy-Efficient Windows Guidelines for information about appropriately sizing the glazing areas.

Roof monitors: North- or south-facing sawtooth roof monitors exhibit less variation of daylight levels than east- or west-facing monitors. They are also easier to design for good energy performance. To reduce solar heat gain with south-facing monitors, use an overhang or a spectrally selective low-e coating with an SHGC of less than .45. Don’t use east- or west-facing sawtooth monitors because they will produce large variations in light level and quantity from morning to afternoon, and will have poor thermal performance.

Diffusion: To provide gentle, attractive light and to avoid bright spots of direct sun, use diffusing glazing or baffles. Use adjustable baffles or make sure that baffles are designed to cut off all anticipated sun angles. Avoid placing diffusing glazing within the occupant’s normal field of view, as it will cause excessive glare.

Visible transmittance: Refer to the Energy-Efficient Windows Guidelines for details about the appropriate visible transmittance of glazing in Hawaii.

Light wells: A light well brings daylight through the roof and the ceiling plane. Light well walls should be light in color — with a reflectance of greater than 80% — to reflect more light down into the space. Avoid dark well walls. Flat, bright white paint performs best. Diffusely reflecting light wells should be less than 8 ft deep. For deeper wells, mirrored reflecting wells can be used.

To reduce glare and spread daylight more effectively, splay the light well walls. A 45- to 60-degree angle is recommended.

Reflectors: Reflectors located below the light well can help wash the ceiling or walls with daylight, making the room appear brighter and more spacious. Options include mirrored or matte reflective surfaces that can be flat or curved. Reflectors may also be made from partially translucent materials like fabric, plastic or perforated metal. Reflector devices require additional floor-to-ceiling height. Their daylight distribution performance should be evaluated with a daylight analysis tool such as a physical scale model or simulation program.

Insulation: Ideally, the roof should be appropriately insulated. But if the insulation is located at the ceiling, then it is also necessary to insulate the light well walls to prevent heat gain into the space.

Safety and security: Toplighting designs can present safety and security concerns, especially on flat roofs. Make sure that any operable fenestration is designed to prevent physical entry. A safety/security grating can be placed in the light well under the toplight glazing (make sure this grating does not create an undesirable shadow on the wall). Louvers and baffles can also provide security.

Leakage: There are leakage risks with all roof penetrations. Use well-tested curb design details and flashing kits provided by the manufacturer. Make sure that operable fenestration is designed to prevent rain penetration.

Design and Analysis Tools

See the General Principles for Daylighting Design Guideline for information about design tools that can be used to evaluate daylight distribution and calculate energy savings. For designs that include sloped surfaces, make sure that the simulation program can handle them. The SkyCalc program, available at www.energydesignresources.com, can be used to quickly optimize the size of the daylighting aperture ratio for most simple skylight schemes.

Costs

Costs for central toplighting are medium to high, depending on design. Unit skylights will be the least expensive. Site-built monitors with vertical or sloped glazing will cost more.

For information about the costs of daylighting controls, see the Electric Lighting and Controls Guidelines.

Operation and Maintenance

To provide maximum daylight to the space, glazing needs to be cleaned on a regular schedule. In climates with low rainfall, horizontal glazing will require more frequent cleaning.

Operable louvers and blackout shades should be durable, accessible to the occupants and easy to repair. The building maintenance staff should check operable fenestration daily to ensure that it is closed when appropriate.

Commissioning

Check that operable louvers and shades are working. Set angles of adjustable louvers to eliminate direct sun penetration.

Utility Programs

Energy-efficient toplighting that exceeds the Hawaii Model Energy Code requirements may be eligible for customized incentives. Contact your utility company representative as early as possible in the design process.

Case Study

An operable central skylight in the Honolulu Hale provides natural ventilation and fills the building's interior with daylight.

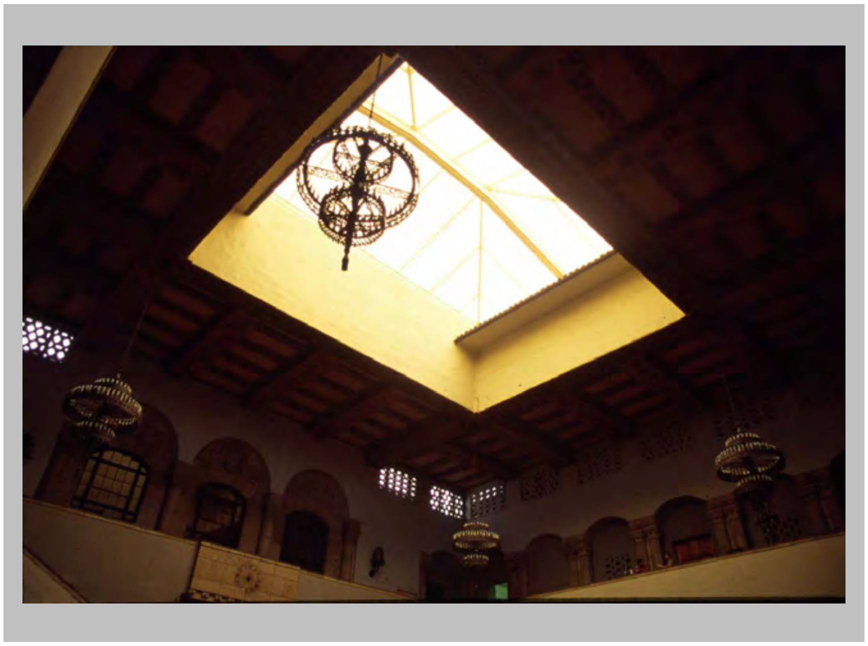
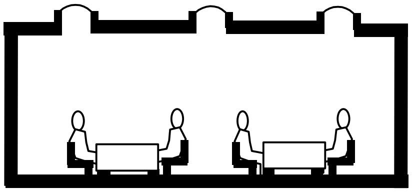


Figure 3-23. Central skylight, Honolulu Hale. Photo: Erik Kolderup, Eley Associates.

Patterned Toplighting

Recommendation

Use patterned toplighting in large spaces that need uniform, low-glare illumination.



Description

Patterned toplighting uses a grid of skylights or rows of sawtooth or square roof monitors to provide glare-free daylight across a large space. The spacing of the pattern depends on the ceiling height.

Applicability

Patterned toplighting is appropriate for providing even daylight levels to large areas such as grocery stores, big-box retail stores, gymnasiums, cafeterias, warehouses, and light industrial and assembly spaces. Since this is a toplighting scheme, it applies to single-story buildings or the top floor of multistory buildings.

Codes and Standards

See Codes and Standards section in General Principles for Daylighting Design, above.

Benefits

Patterned toplighting creates balanced, glare-free daylight across large spaces. If electric lighting systems are controlled in response to daylight levels, energy savings may range from 40% to 80% during daylight hours.

Daylight levels can be varied by using operable louvers. Natural ventilation can be provided if the skylights or roof monitors are operable (see the Natural Ventilation Guidelines for information).

Integrated Design Implications

Design phase: Patterned toplighting should be planned for during the programmatic, schematic and design development phases.

Interior layout: In spaces with tall shelves, such as grocery stores, big-box retail stores and warehouses, the toplighting design needs to be coordinated with the shelving layout.

Balance with other daylighting strategies: Balance the amount of glazing in a patterned toplighting scheme with the need for view windows and other apertures in the space. Since the toplighting provides most of the ambient daylight, smaller view windows can be judiciously spaced in perimeter walls, which frees up wall space for other needs.

Integration with electric lighting: To maximize the energy benefits of daylighting, circuit and control the electric lighting so that the lights can be turned off in areas where there is adequate daylight and kept on where daylight is insufficient.

See the General Principles for Daylighting Design Guideline for an overview of integrating daylighting with electric lighting.

Integration with structural system: Coordinate the location and size of skylights and roof monitors with the structural system and roof diaphragm to maintain the building’s strength and integrity.

Integration with HVAC: Coordinate the location of skylights, roof monitors and their light wells with the location of rooftop HVAC equipment and interior ductwork. Toplighting that is properly oriented, glazed, shaded and integrated with electric lighting controls, should decrease a building’s heating and cooling loads, which in turn can reduce the size and first costs of the HVAC system as well as yearly energy costs.

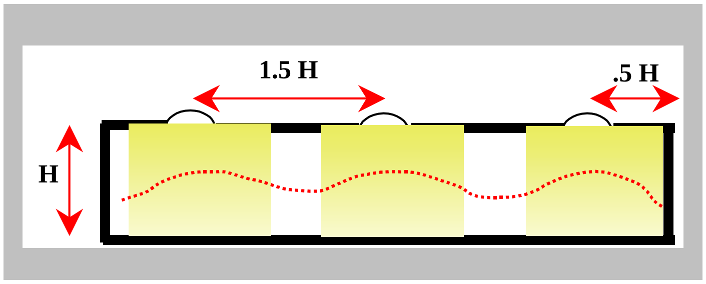
Integration with natural ventilation: If the rooftop fenestration is operable, it can be used to naturally ventilate the space. See the Natural Ventilation Guidelines for information.

Design Details

Orientation: The glazing for patterned toplighting may be either horizontal or vertical. Skylights perform better than roof monitors in a predominantly overcast sky condition or non-north/south orientations. A monitor with glazing oriented north or south will be more expensive, but may perform better than a skylight in areas with predominantly sunny conditions.

Skylights: As a rule of thumb, skylights used in a patterned toplighting scheme should be spaced roughly 1.5 times the floor-to-ceiling height (H in Figure 3-24). Their glazing should be about 3% to 12% of the floor area to be lighted. (The SkyCalc program, available at www.energydesignresources.com, can be used to optimize the design.)

Figure 3-24. Skylight grid spacing.



Roof monitors: North- or south-facing sawtooth roof monitors exhibit less variation of daylight levels than east- or west-facing monitors. They are also easier to design for good energy performance. To reduce solar heat gain with south-facing roof monitors, use an overhang or a spectrally selective low-e coating with an SHGC of less than .45. Don't use east- or west-facing sawtooth monitors because they will produce large variations in light level and quantity from morning to afternoon, and will have poor thermal performance.

Diffusion: To provide gentle, attractive light and to avoid bright spots of direct sun, use diffusing glazing or baffles. Use adjustable baffles or make sure that baffles are designed to cut off all anticipated sun angles. Avoid placing diffusing glazing within the occupant's normal field of view, as it will cause excessive glare.

Visible transmittance: Refer to the Energy-Efficient Windows Guidelines for details about the appropriate visible transmittance of glazing in Hawaii.

Light wells: A light well brings daylight through the roof and the ceiling plane. Light well walls should be light in color — with a reflectance of greater than 80% — to reflect more light down into the space. Avoid dark well walls. Flat, bright white paint performs best. Diffusely reflecting light wells should be less than 8 ft deep. For deeper wells, mirrored reflecting wells can be used.

To reduce glare and spread daylight more effectively, splay the light well walls. A 45- to 60-degree angle is recommended.

Insulation: Ideally, the roof should be appropriately insulated. But if the insulation is located at the ceiling, then it is also necessary to insulate the light well walls to prevent heat gain into the space.

Safety and security: Toplighting designs can present safety and security concerns, especially on flat roofs. Make sure that any operable fenestration is designed to prevent physical entry. A safety/security grating can be placed in the light well under the toplight glazing (make sure this grating does not create an undesirable shadow on the wall). Louvers and baffles can also provide security.

Leakage: There are leakage risks with all roof penetrations. Use well-tested curb design details and flashing kits provided by the manufacturer. Make sure that operable fenestration is designed to prevent rain penetration.

Design and Analysis Tools

See the General Principles for Daylighting Design Guideline for information about design tools that can be used to evaluate daylight distribution and calculate energy savings. For designs that include sloped surfaces, make sure that the simulation program can handle them. The SkyCalc program, available at www.energydesignresources.com, can be used to quickly optimize the size of the toplighting designs.

Costs

Costs for patterned toplighting range from low to high, depending on design. Costs to consider include the expense of the skylight or roof monitor device, rooftop installation, curbs and waterproofing, interior well construction and finish, and electric lighting controls to switch or dim in response to daylight.

A grid of skylights without light wells will be the least expensive — roughly $1,000 each installed. Roof monitors with reflecting devices will be much more expensive. Packaged skylights with integrated light wells and electric lighting cost closer to $3,000 each including installation.

For information about the costs of daylighting controls, see the Electric Lighting and Controls Guidelines.

Cost Effectiveness

Patterned toplighting is the most cost-effective form of daylighting, provided that it is feasible for a given space. Compared to other daylighting strategies, it requires less aperture area to achieve the needed illumination.

Operation and Maintenance

To provide maximum daylight to the space, glazing needs to be cleaned on a regular schedule. In climates with low rainfall, horizontal glazing will require more frequent cleaning.

Operable louvers and blackout shades should be durable, accessible to the occupants and easy to repair. The building maintenance staff should check operable fenestration daily to ensure that it is closed when appropriate.

Commissioning

Check that operable louvers and shades are working. Set angles of adjustable louvers to eliminate direct sun penetration.

It's critical to test and adjust automatic lighting controls to ensure that expected energy savings are achieved with daylighting systems. For a daylighting system with automatic controls to work properly, several commissioning steps are important:

- Clearly specify the intended control operation;
- Carefully specify the control equipment to ensure that the installed equipment has the necessary capabilities;
- Provide the contractor with a detailed testing protocol; and
- Require that the contractor certify proper operation.

Utility Programs

Energy-efficient toplighting that exceeds the Hawaii Model Energy Code requirements may be eligible for customized incentives. Contact your utility company representative as early as possible in the design process.

Case Study

At the Foodland store in Ewa on Oahu (Figure 3-25), the patterned toplighting design uses a specialized skylight with an integral light well and a diffuser at the bottom. The electric lighting is automatically controlled in response to daylight levels.

Figure 3-25. Foodland, Ewa, Oahu. Skylights and integrated light wells with diffusers (inset) at the ceiling. Photos: Erik Kolderup, Eley Associates.

The Better Brands warehouse on Oahu employs a similar skylight system with integrated light wells, which also includes electric lighting. These units contain six 4-ft T-5 fluorescent lamps mounted behind the diffuser at the bottom of the light well. These lamps can be controlled in several steps to supplement daylight or provide nighttime illumination.

Figure 3-26. Better Brands warehouse, Oahu. Skylights with integrated light wells, fluorescent lighting, and diffusers (inset). Photos: Erik Kolderup, Eley Associates.

Linear Toplighting

Recommendation

Use linear toplighting to direct movement or establish visual orientation in a long, linear space such as a hallway. Use linear toplighting on two sides of a space to define separate tasks or activities, to define edges in a larger space, or to downlight the space from two directions.

Description

Linear toplighting provides a line of high intensity daylight directly under it. As you move away from this line of daylight, its intensity drops. Used bilaterally (from two sides), it can frame a larger space.

Applicability

Since this is a toplighting scheme, it applies to single-story buildings or the top floor of multistory buildings. Use linear toplighting in corridors or linear walkways within a larger space. Linear toplighting can also be used bilaterally to frame larger areas like gymnasiums, shopping malls, convention centers and multipurpose areas. Linear toplighting may also be used in covered outdoor walkways to reduce shadows, especially in covered walkways next to spaces with sidelighting.

Codes and Standards

See Codes and Standards section in General Principles for Daylighting Design, at the beginning of this chapter.

Benefits

Linear toplighting creates bright corridors that provide important visual orientation for circulation during daylight hours. In a bilateral design, it can provide daylighting that graduates in intensity from a bright perimeter to a more moderate light level between the two linear toplights.

If electric lighting systems are controlled in response to daylight levels, energy savings may range from 40% to 80% during daylight hours.

Daylight levels can be varied by using operable louvers. Natural ventilation can be provided if the skylights or roof monitors are operable (see the Natural Ventilation Guidelines for information).

Integrated Design Implications

Design phase: Linear toplighting should be planned for during the programmatic, schematic and design development phases.

Interior layout: When applicable, coordinate linear toplighting with major circulation areas in the building. Consider increasing light levels at major intersections and at the ends of hallways.

Balance with other daylighting strategies: The amount of glazing in a linear toplighting scheme should be balanced with the need for view windows and other apertures in the space.

Integration with electric lighting: Electric lighting should be aligned with the toplighting without blocking it and causing annoying shadows. To maximize the energy benefits of daylighting, circuit and control the electric lighting so that the lights can be turned off in areas where there is adequate daylight and kept on where daylight is insufficient.

See the General Principles for Daylighting Design Guideline for an overview of integrating daylighting with electric lighting.

Integration with structural system: Coordinate the location and size of skylights and roof monitors with the structural system and roof diaphragm to maintain the building's strength and integrity.

Integration with HVAC: Coordinate the location of the linear toplights and their light wells with the location of rooftop HVAC equipment and interior ductwork. Interruptions in the toplighting design's linear run may be required to accommodate HVAC and duct requirements. Arrange these interruptions in a regular manner to avoid creating random patterns of light and dark.

Integration with natural ventilation: Operable rooftop fenestration can be used to naturally ventilate the space. See the Natural Ventilation Guidelines for information.

Design Details

Orientation: The glazing for patterned toplighting may be either horizontal or vertical. Skylights perform better than roof monitors in a predominantly overcast sky condition or non-north/south orientations. A monitor with glazing oriented north or south will be more expensive, but may perform better than a skylight in areas with predominantly sunny conditions.

Diffusion: In circulation areas, diffuse daylight can be used to provide balanced light in the space, while areas of direct sun can brighten intersections and circulation spines. To diffuse daylight, use translucent glazing or baffles. For smaller areas of direct sun, use transparent glazing.

Visible transmittance: Refer to the Energy-Efficient Windows Guidelines for details about the appropriate visible transmittance of glazing in Hawaii.

Glazing area: Refer to the Energy-Efficient Windows Guidelines for information about appropriately sizing the glazing areas.

Shared daylighting: Diffuse corridor daylight can be shared with adjacent spaces by glazing the upper portion of the adjoining wall. Avoid this if acoustic separation is an issue. In multistory buildings, daylight from the top floor corridor can be shared with the lower floor by periodically cutting light wells to the lower level.

Light wells: For diffusing skylights with deeper, narrow light wells, a splayed light well spreads the daylight more effectively and reduces glare. A 45- to 60-degree angle is recommended.

Insulation: Ideally, the roof should be appropriately insulated. But if the insulation is located at the ceiling, then it is also necessary to insulate the light well walls to prevent heat gain into the space.

Safety and security: Toplighting designs can present safety and security concerns, especially on flat roofs. Make sure that any operable fenestration is designed to prevent physical entry. A safety/security grating can be placed in the light well under the toplight glazing (make sure this grating does not create an undesirable shadow on the wall). Louvers and baffles can also provide security.

Leakage: There are leakage risks with all roof penetrations. Use well-tested curb design details and flashing kits provided by the manufacturer. Make sure that operable fenestration is designed to prevent rain penetration.

Design and Analysis Tools

See the General Principles for Daylighting Design Guideline for information about design tools that can be used to evaluate daylight distribution and calculate energy savings. For designs that include sloped surfaces, make sure that the simulation program can handle them. The SkyCalc program, available at www.energydesignresources.com, can be used to quickly optimize the size of the toplighting designs.

Costs

Costs for linear toplighting range from moderate to high, depending on design. A linear row of skylights will be the least expensive; roof monitors with reflecting devices will be more expensive. Costs include the expense of the skylight or monitor device, rooftop installation, curbs and waterproofing, interior well construction and finish, and electric lighting controls to switch or dim in response to daylight.

For information about the costs of daylighting controls, see the Electric Lighting and Controls Guidelines.

Cost Effectiveness

In most cases, linear toplighting is typically less cost effective than patterned toplighting. Patterned toplighting is generally more effective at providing even daylighting coverage, while linear toplighting is often chosen more for architectural and aesthetic reasons than specifically for providing daylight.

Operation and Maintenance

Clean glazing on a regular schedule. Horizontal glazing and clear glazing need more frequent cleaning in climates with low rainfall.

Commissioning

Check that operable louvers and shades are working. Set angles of adjustable louvers to eliminate direct sun penetration.

Utility Programs

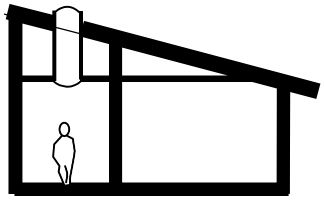
Energy-efficient toplighting that exceeds the Hawaii Model Energy Code requirements may be eligible for customized incentives. Contact your utility company representative as early as possible in the design process.

Case Study

In the Cameron Park Library (California), 8 ft x 4 ft x 4 ft ridge skylights help to establish visual orientation and guide circulation in the space. White ceilings and walls help to spread the daylight in the space. This photograph was taken before the electric light fixtures had been installed, but the skylights provided enough daylight that the library was able to open for business.

Figure 3-27. Linear skylights in Cameron Park Library, Cameron Park, CA. Photo: SunOptics.

Tubular Skylights



Recommendation

Use tubular skylights to bring daylight into spaces with deep roof cavities and for low-cost retrofits to existing spaces.

Description

Tubular skylights are small, domed skylights with clear glazing. They are connected to the space's ceiling with mirrored reflective ducts. An interior diffuser at the ceiling plane distributes daylight in the space. Some tubular skylights have electric lighting in the duct or a diffuser that is controlled in response to daylight levels.

Applicability

Tubular skylights are especially good for small spaces including restrooms, kitchens, interior corridors, enclosed work areas and other interior spaces that are intermittently occupied. They are also recommended for retrofits in existing spaces that would benefit from additional daylight.

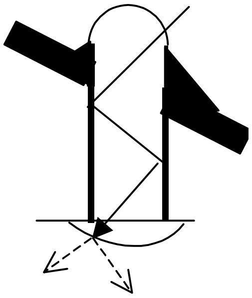


Figure 3-28. Tubular skylight's mirrored duct reflects daylight into small spaces.

Because they depend on multiple reflections to deliver daylight to the space, tubular skylights perform significantly better in clear sky conditions than in overcast climates. The longer the duct, the less daylight is delivered; so their use is limited to spaces with roof cavities of 8 ft or less.

Codes and Standards

See Codes and Standards section in General Principles for Daylighting Design, above.

Benefits

If arranged in a grid, tubular skylights can provide balanced daylight across a space, although daylight levels will fluctuate as conditions change from direct sun and to overcast skies.

They are a good low-cost retrofit option for existing spaces.

Tubular skylights can save electric lighting energy if the electric lights are controlled in response to the daylight levels. Savings may range from 20% to 60% during daylight hours.

Integrated Design Implications

Design phase: Since this is a toplighting scheme, it applies to single-story buildings or the top floor of multistory buildings. It should be planned for during schematic design, but can also be retrofitted in existing buildings.

Balance with other daylighting strategies: The amount of glazing in a linear toplighting scheme should be balanced with the need for view windows and other apertures in the space.

Figure 3-29. Tubular skylight in reception area. Photo: Solatube International, Inc.

Integration with electric lighting: Consider a system that incorporates a fluorescent — not an incandescent — light in the duct or ceiling plane diffuser to minimize ceiling luminaires. These units should have photocontrols so that they can be dimmed or switched in response to available daylight. Make sure the electric lamp does not block transmission of daylight.

Integration with HVAC: Coordinate the location of tubular skylights with the location of rooftop HVAC equipment and interior ducts. Although the tubular skylight’s reflective duct can jog somewhat to avoid barriers in the ceiling plenum, each change in direction decreases the efficiency of daylight delivery.

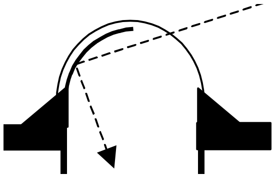
Integration with structural system: The small diameter of tubular skylights reduces their impact on the structural system compared to larger framed skylights.

Design Details

Sizing: An 8 in. tubular skylight can supply daylight to an area of about 100 ft². A 13 in. tubular skylight can serve daylight to an area of about 150 ft².

Reflective ducts: Use a product with a highly reflective cylindrical duct. (Don’t use a corrugated duct; the corrugations trap light.) Minimize the length and minimize the bends in the reflective duct.

Figure 3-30. Tubular skylight with reflective half-dome.



Half dome vs. full dome: In regions where clear skies predominate, use a tubular skylight with a south-facing, reflective half-dome under the skylight bubble to increase the reflection of low-angle winter sun into the skylight (see Figure 3-30). In predominantly overcast regions, use a full clear dome.

Diffusers: Some tubular skylights have a flat bottom diffuser that fits into a standard 2 ft x 2 ft or 2 ft x 4 ft dropped ceiling grid. These diffusers may have electric lighting in them or they may be alternated in a grid with recessed fluorescent luminaires.

Safety and security: Unless these skylights are larger than 16 in. square, they shouldn't pose a safety or security liability.

Leakage: There are leakage risks with all roof penetrations. Use well-tested curb design details and flashing kits provided by the manufacturer.

Design and Analysis Tools

It is difficult to simulate the performance of tubular skylights with physical scale models or computer programs. Some manufacturers provide estimating tools for evaluating performance. Note, however, that some manufacturers of tubular skylights have made exaggerated claims about the daylight delivery and R-value of their products.

Figure 3-31. Cross section of tubular skylight. Photo: Solatube International, Inc.

U-factor and solar heat gain coefficient data is typically not available for tubular skylights. Once this information is readily available, hourly building energy evaluation programs like DOE-2.1E and Energy 10 could be used to evaluate energy impacts.

Costs

Costs for tubular skylights are low relative to standard unit skylights because they don't require construction of a separate light well and because the small opening may not require structural reinforcement.

For information about the costs of daylighting controls, see the Electric Lighting and Controls Guidelines.

Cost Effectiveness

For small spaces with attics, tubular skylights may be the most cost-effective daylighting option.

Operation and Maintenance

Clean glazing on a schedule. Horizontal glazing needs more frequent cleaning in climates with low rainfall.

Utility Programs

To take advantage of any existing opportunities for daylighting design incentives, contact your utility company representative as early as possible in the design process.

4. ELECTRIC LIGHTING AND CONTROLS GUIDELINES

Overview

Lighting accounts for between 15% and 45% of the total electricity used in commercial buildings in Hawaii. Dramatic energy savings can be achieved through the use of energy-efficient luminaires and light sources, intelligently designed controls, and integrated daylighting design.

Efficient electric lighting systems also reduce internal heat gain, which can save air-conditioning energy, increase the potential for natural ventilation, and improve thermal comfort. And good electric lighting design improves visual performance and visual comfort by providing appropriate illumination and contrast while controlling reflectance and glare.

This chapter provides general guidelines for energy-efficient lighting systems and more detailed guidelines for three types of lighting systems: pendant-mounted lighting, recessed lighting and surface-mounted lighting. The Lighting Controls Guideline discusses various types of lighting control systems, including switches and dimmers, occupancy sensors and daylighting controls.

The final section of this chapter describes a number of energy-efficient lighting designs for typical commercial building spaces, including private and open-plan offices, grocery stores, big-box retail stores, small retail stores, classrooms, corridors, hotel guestrooms and warehouses.

General Lighting Guidelines

Recommendation

Design lighting systems carefully, using efficient equipment and effective controls, to achieve a high level of energy savings while meeting the occupants' needs for visual comfort, security and productivity. Pay particular attention to integrating the building's electric lighting systems with available daylight.

The cost of electricity to operate lighting is easily the largest expense related to lighting system ownership. In the long-term, therefore, the lowest-cost lighting system will be one that is effective and energy efficient.

Description

Electric lighting systems consist of various components, including:

- Luminaires (for example, recessed, suspended indirect or direct/indirect, and surface-mounted);
- Light sources (for example, incandescent, halogen, linear fluorescent, compact fluorescent, high-intensity discharge lamps, and LEDs);
- Ballasts; and
- Lighting controls.

These components are discussed in detail later in this guideline.

When designing electric lighting systems, designers need to consider numerous critical issues, including vertical and horizontal illumination, glare control, lighting uniformity, color rendering, and integration with daylight. These issues are discussed later in this section.

Applicability

Energy-efficient electric lighting systems should be a feature of all new and renovated commercial buildings.

Codes and Standards

Hawaii developed a Model Energy Code (MEC) to ensure that efficient, energy-saving lighting technologies are used in renovations and new construction. This code, based on ASHRAE 90.1–1989 and the more stringent Federal version of the standard, has been adopted, with various modifications, by all counties except Maui. For the latest details about the code, see www.hawaii.gov/dbedt/ert/model_ec.html or contact the local building department.

The MEC includes a lighting compliance computer program called Hilight that can be downloaded at www.hawaii.gov/dbedt/ert/mec/app-b.html.

Disposal requirements. Hawaii has accepted U.S. EPA universal waste regulations for lighting materials that contain more than trivial amounts of mercury. This means that fluorescent and HID lamps not meeting EPA TCLP (Toxicity Characteristic Leaching Procedure) requirements need to be treated as typical hazardous waste in many cases. See the Operations and Maintenance section below for more information about disposing of lamps that contain mercury.

Benefits

Some of the many potential benefits of effectively designed, installed and controlled electric lighting systems include: dramatic energy savings, improved visual comfort and satisfaction for occupants, improved productivity, reduced operating and maintenance costs, reduced environmental impacts, and greater flexibility for building owners and tenants.

Integrated Design Implications

Integration with daylighting. To achieve energy savings in daylit spaces, electric lighting must be integrated with daylighting. At a minimum, circuit the luminaires to match the dispersion of daylight into the space. Circuit the luminaires closest to windows or skylights separately from other electric lighting in the space. This saves energy by allowing luminaires in daylit zones to be switched off during most daylight hours.

For a lighting system that maximizes energy savings and flexibility, consider using dimming ballasts with manual or automatic dimmers for additional flexibility. See the Lighting Controls Guideline for details.

Resource Efficiency

Although lighting’s environmental impacts primarily relate to energy performance and indoor environmental quality, resource efficiency is also an environmental consideration.

Metal components of luminaires can sometimes be recycled, and the metal components of some luminaires may include recycled content. Intact luminaires can sometimes be salvaged during building deconstruction, and then refurbished and reused. However, paint and other optical materials deteriorate, and new lighting technologies perform much better than old ones, so reuse isn’t always the most effective strategy.

Design Details

Quality of Light

Providing appropriate visibility is one of the most important goals of good quality lighting. Lighting quality also has a significant impact on many other human needs, including visual comfort, health and safety, social communication, mood, and the ability to perform tasks.

IESNA illuminance recommendations. In the past, the Illuminating Engineering Society of North America (IESNA) provided illuminance recommendations for specific spaces. But the new lighting design procedure in the ninth edition of the *IESNA Lighting Handbook* has been enhanced to address lighting *quality* as well as lighting *quantity*. This new procedure emphasizes the relative importance of numerous design issues for specific applications. These design issues include color appearance, daylighting integration and control, luminances of room surfaces, reflected glare, and many other issues. Chapter 10 of the *IESNA Lighting Handbook* discusses these issues in detail and provides a Lighting Design Guide that illustrates the relative importance of these lighting quality issues for specific space types.

Table 4-1 provides information about the relative importance of some lighting quality issues for some sample commercial building spaces. The IESNA Lighting Design Guide lists these space types plus hundreds more.

Table 4-1. Importance of a few lighting quality issues for sample building spaces.

	Private Office	Meeting Room	Class-room (General)	Hotel Guest Room (General)	Food Court	Super-market Shelving	Industrial Simple Assem-bly
Appearance of space and luminaires	⦿	●	○	●	●	⦿	○
Color appearance	⦿	⦿	○	⦿	●	●	○
Daylight integration and control	●	○	⦿		●		⦿
Control of direct glare	●	●	⦿		⦿	●	○
Light distribution on task plane (uniformity)	⦿	⦿	⦿		○	●	○
Luminance of room surfaces	●	⦿	⦿	●	○	○	●
Control of shadows	⦿	○	○		⦿	●	●

● Very Important ⦿ Important ○ Somewhat Important *Blank* Not important

Source: *IESNA Lighting Handbook, 9th edition,* chapter 10.

While illuminance is not the sole design criteria, IESNA's lighting design procedure does provide recommended illuminance levels for seven categories, which are organized into three groups of visual tasks. These are shown in Table 4-2.

Table 4-2. IESNA recommended illuminance levels

Category	Description	Recommended Illuminance (fc)
Orientation and simple visual tasks	Public spaces	3
	Simple orientation for short visits	5
	Work spaces where simple visual tasks are performed	10
Common visual tasks	Performance of visual tasks of high contrast and large size	30
	Performance of visual tasks of high contrast and small size, or visual tasks of low contrast and large size	50
	Performance of visual tasks of low contrast and small size	100
Special visual tasks	Performance of critical visual tasks with very small or very low contrast elements	300–1000

Source: *IESNA Lighting Handbook, 9th edition,* chapter 10, p. 13.

Vertical illumination. Lighting should be designed to achieve adequate vertical illumination. Our perception of what comprises lighting quality is strongly influenced by vertical illumination. For example, proper wall illumination is critical for uniformly lit spaces such as offices and classrooms. Similarly, in very low ambient conditions, such as outside at night, vertical illumination that promotes facial recognition is important for creating a sense of security.

Glare control. To avoid causing discomfort or disabling glare, carefully control all sources of light, including daylight. Direct glare can occur when a bright light source is in the occupant's field of vision. Reflected glare occurs when bright light reflects on surfaces such as glossy paper or a computer screen. Both types of glare can impair visual performance by reducing task visibility and causing visual fatigue. Common glare problems include overhead glare from direct distribution luminaires, reflections of luminaires on computer screens, and direct glare from uncontrolled windows or skylights.

Lighting uniformity. Few lighting systems provide completely uniform illumination. Although the IESNA provides target illuminance levels, it's important for designers to understand that these targets are not minimum levels; rather, the illuminance levels can vary within a certain range. A design that combines task and ambient illumination will help avoid over- or under-illumination.

Avoid shadows or sharp patterns of light and dark in spaces that are used for tasks requiring concentration (such as office spaces, libraries and classrooms). In such spaces, the luminance contrast ratios between the visual task and its immediate surroundings should not exceed 3:1, and the contrast between the brightest surfaces in the visual field and the visual task should not exceed 5:1. However, some shadows and light patterns may be suited for areas such as lobbies or lunchrooms to create a cheerful atmosphere. Higher ratios contribute to fatigue, because the eye will constantly adapt to differing light levels.

Avoid shadow patterns in spaces that are used primarily for "heads-up" visual tasks. For example, luminaires that use parabolic louvers may require supplemental wall-wash lighting to eliminate upper wall shadows. Use very bright visible sources, such as T-5 and T-5HO lamps, only in high spaces like gyms, or in cove lighting or in indirect luminaires.

Maximize lighting uniformity by providing light for vertical surfaces as well as the ceiling whenever possible. Use light-colored diffuse surface materials to help optimize lighting uniformity.

Color rendering. Light sources that render color well enhance the visual environment. Light sources should have a minimum color-rendering index (CRI) of 75 for most interior spaces. For areas where accurate color rendering is more critical (retail spaces, art rooms, exhibition spaces), select a source with a CRI of at least 80. The latest, more efficient "second-generation" or "premium" T-8 lamps, T-5 lamps and most compact fluorescent lamps have CRI in the range of 82–86.

Light Sources

Light source selection critically affects the space's appearance, as well as visual performance and comfort. This section outlines the different types of sources available.

Incandescent Lamps (Including Halogen)

Incandescent lamps represent the oldest of electric lighting technologies. Advantages of incandescent technology include point source control, high color rendering, instant starting, and easy and inexpensive dimming. Disadvantages include low efficacy, short lamp life, high energy and maintenance costs, and a narrow range of color choices (mostly in warm, yellow tones).

To save lighting costs, avoid incandescent sources in most spaces except in very limited and special accent lighting circumstances. Examples include dimming applications where color rendering, beam control or dramatic effect is critical, such as in teleconference rooms or theaters or for highlighting artwork. In most of these cases, halogen sources—which offer longer life, better point source control, and crisper color performance—are superior to standard incandescent lamps.

Fluorescent Lamps

Fluorescent lamps can and should be used to light most types of spaces. They offer long life, high efficacy, good color performance, and low operating and maintenance costs. There are no inherent disadvantages to fluorescent technology; however, dimming fluorescent lamps requires special electronic ballasts that cost more. Past problems with fluorescent lamps, such as flicker, buzzing and greenish color, no longer exist with electronic ballasts and modern phosphor choices.

Figure 4-1. New small diameter T-5 fluorescent lamps shown next to an older, conventional T-12 fluorescent lamp.[1]

Several different types of fluorescent lamps are worth noting. These are described in Table 4-3.

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[1] Except where otherwise noted, photographs and other images in this chapter are provided courtesy of the High Performance Schools *Best Practices Manual,* available at www.chps.net.

Table 4-3. Summary of fluorescent lamp technology.

Type of Lamp	Advantages & Disadvantages	Applications
T-12	Relatively antiquated technology. Supplanted by newer technologies.	Some low temperature applications, such as food storage or display areas.
T-8	Advantages include higher efficacy, more design options, better color rendering than T-12s. Newly available “premium” T-8 lamps offer higher color rendition, higher maintained lumens, and a 20% increase in lamp life over standard T-8s; very cost effective.	Most general lighting applications, including classrooms, offices, libraries, outdoor and industrial spaces.
T-5	Similar performance to T-8 lamps, but more compact lamp envelope (5/8-in. vs. 1-in. diameter). T-5 luminaires should be well shielded to minimize glare. Electronic ballasts are necessary to achieve expected lamp life and performance.	Smaller profile luminaires. Especially effective in indirect luminaires, cove lighting systems, and wall washers.
T-5 High Output (T-5HO)	One T-5HO lamp produces nearly the equivalent light as two standard T-8 lamps, but somewhat less efficiently. May allow designer to increase the spacing between direct/indirect luminaire rows, compared to a typical T-8 design, which allows use of fewer lamps and/or fewer luminaires, reducing lighting costs. Currently more expensive than T-8 designs.	Like standard T-5 lamps, but may allow even smaller luminaires or better optical control and projection.

Fluorescent ballasts. Electronic high frequency ballasts are now standard equipment for most fluorescent sources. In addition to their efficiency advantages, electronic ballasts reduce flicker and noise, and are available in a variety of ballast factor ratings, allowing the designer to "tune" light levels based on the ballast specification.

Here are some recommendations for fluorescent ballasts:

- Consider using reduced light output (RLO) electronic ballasts in building spaces where lower light levels will suffice. RLO ballasts have ballast factors of approximately 75% of rated light output (compared to about 88% for normal electronic ballasts and 93% for old magnetic ballasts). Applicable spaces might include corridors, restrooms, storage areas and similar spaces. The reduction in light output corresponds to lower input wattage, thus reducing lighting demand and energy use.

Figure 4-2.
Electronic ballast.

- Electronic ballasts for most fluorescent lamps employ one of two methods to start the lamps: rapid-start and instant-start. For maximum energy performance, use instant-start ballasts (for T-8 lamps only) in areas where the lights are unlikely to be switched frequently.
- In areas with more frequent switching, rapid-start ballasts maximize lamp life. "Programmed rapid-start" ballasts are the best type of rapid-start design, and are optimized for use with occupancy sensors or other frequent switching applications. They allow T-5 lamps to achieve rated lamp life, so they are the only type of T-5 ballast recommended.
- Dimming ballasts for fluorescent lamps require an additional investment, but increase lighting system performance by optimizing space appearance, occupant satisfaction, system flexibility and energy efficiency. Dimming fluorescent ballasts should be considered in all cases requiring maximum energy performance and light level control. They are particularly effective in medium to large daylit spaces, computer classrooms, audiovisual (AV) rooms, conference rooms and similar spaces.

Compact fluorescent lamps. Compact fluorescent lamps (CFLs) can be used in most applications that traditionally employed incandescent sources. CFLs offer excellent color rendering and quick starting. A large palette of different lamp configurations enhances design flexibility. Principal advantages of CFLs over incandescent sources include higher efficacy, color selection and longer lamp life. Dimming CFL ballasts are available for many CFL types, but they may be expensive.

Figure 4-3. Compact fluorescent lamps. Photo: NREL.

Use CFL lamps extensively in task and accent lighting applications, including wall washing, supplementary task lighting, and portable task lighting in computer environments. They are also valuable for medium- to low-level general illumination in spaces such as lobbies, corridors, restrooms, storage rooms and closets. They are quite suitable for outdoor corridors, step lighting, and lighting over doorways. High-wattage long CFLs can be used for general space illumination in recessed lay-in troffers (see the Luminaires section below), in wall-wash luminaires, and in more decorative luminaires for office lobbies, libraries and other spaces requiring a more "high-end" look.

High-Intensity Discharge Lamps (HID)

HID lamps provide high efficacy in a wide variety of lamp wattages and configurations. In addition, they offer relatively long lamp life. There are basic types of high-efficacy HID lamps: metal halide (MH) and high-pressure sodium (HPS). The principal disadvantages to HID sources are that they start slowly, take time to warm up to full brilliance and suffer from significant lamp lumen depreciation. This makes them difficult to use in many automatic lighting control scenarios. In some applications, such as warehouses and vehicle maintenance areas, two-level dimming systems may be cost effective when evaluated from a

Figure 4-4. High intensity discharge lamps.

lifecycle cost perspective, but be prepared for reduced color performance and lamp life. Continuous dimming of HID lamps is expensive and generally not recommended.

Some of the traditional drawbacks to Metal Halide HID lamps are reduced with newer pulse-start technology and lamps with ceramic (or formed quartz) arc tubes. The pulse-start lamps reach full brightness more quickly, have longer life and are somewhat more efficient. The lamps with ceramic arc tubes may have better color stability.

Light-Emitting Diodes (LEDs)

LEDs are semiconductor devices that generate a monochromatic light. Commercially viable white LED sources are available today, using a phosphor-coated LED or by combining three primary-colored LEDs. The efficiency of the white light source is much higher than the tiny incandescent lamps that produce the same amount of light, but no better than a good tungsten halogen lamp. The principal advantages of LEDs over other lamps are their extremely long life and efficiency in producing colored light. As a result, they are cost effective in exit signs, traffic signals and other signaling devices.

LEDs are highly recommended for use in exit signs. The green and red LEDs used for exit signs offer high efficacy and very low maintenance costs when compared with either incandescent or fluorescent exit signs, and are available in most of the popular exit sign configurations. A two-sided LED exit sign can usually be illuminated with less than 5 watts, and may not require maintenance for 10 or more years.

Decorative lighting applications can make good use of LEDs, thanks to their vibrant color, low voltage, low maintenance and outstanding controllability. Some landscape or outdoor pathway lighting, with very low lighting levels, can also benefit. The very cool color of white LEDs can suggest moonlight, often desirable in outdoor hospitality applications.

Energy-Efficient Choices

Lamps convert electricity (watts) to light energy (lumens), and most modern lamps require a ballast to start the lamp and regulate power flow into the lamp. The efficacy of the conversion is measured in lumens of light output divided by watts of electric power input (L/W). The input watts include both the lamp and the ballast. In general, it is best to use the system with the highest possible efficacy that is suited for the project.

Most electric lamps emit less light as they age; this is called *lumen depreciation.* The lumen depreciation of certain lamp types has improved significantly. New metal halide lamps, for example, use pulse start to improve lumen depreciation, and the best fluorescent lamps depreciate only slightly. Lamp ratings for mean lumens are at 40% of rated lamp life, and reflect the typical light output over life.

Table 4-4 gives the mean lumens per watt (MLPW) for a variety of lamp/ballast systems and may be used to select light sources. Be careful to follow it closely to get the best value. For instance, "premium" T-8 lamps are the best overall choice for most applications, and you can use 835 (neutral color), 830 (warm color) or 841 lamps (cool color) and get the same efficacy. But if you substitute 735 color (which costs less initially), the MLPW drops significantly.

In terms of efficiency, MLPW is a good indicator of average performance. But when choosing lamps to provide a specific illumination, it’s important to consider the "design lumens." Design lumens are rated at 75% of lamp life, the usual economic point for group relamping. Since owners will replace lamps at this point, design lumens are the practical minimum output that an owner will encounter and therefore the best lamp lumen rating to establish minimum light levels. Consult manufacturers’ literature to determine design lumens.

Table 4-4. Lamp application guidelines.

MLPW	Lamp Type	CRI	Ballast	Good Applications	Limitations
92	T-5 standard 4-ft lamps (F28T5/835)	86	Electronic and electronic dimming	Specialty lighting such as valances, undercabinet, coves, wall washing.	Not for troffers or other direct viewing.
90	T-8 premium 4-ft lamps (F32T8/835)	86	Electronic and electronic dimming	General lighting. The lowest cost system available, especially with low ballast-factor ballasts.	Larger than T-5 lamps.
87	T-8 premium 8-ft lamps (F96T8/835)	86	Electronic	General commercial and institutional lighting, especially for retrofits.	4-foot lamp system may cost less.
81	T-5HO high output 4-ft lamps (F54T5/835)	86	Electronic and electronic dimming	Indirect office ltg; high ceiling industrial ltg; specialty applications: coves, wall washing.	Very bright lamps should not be visible unless mounted very high.
79	T-8 premium "U"-bent lamps (F32T8/U/835)	86	Electronic and electronic dimming	Recessed 2 ft x 2 ft commercial lighting.	More expensive than straight lamps.
78	T-5 twin tube ("biax") 40–50W (FT40T5/835)	82	Electronic and electronic dimming	Track-mounted wallwashing and display lighting.	More expensive than straight lamps. Can be too bright in open luminaires.
78	Metal halide lamps, pulse start, 450-watt class	65	Magnetic CWA (constant wattage auto-transformer)	General high-bay lighting for gyms, stores, and other applications to about 30 ft; parking lots.	Long warm up and restrike times; poor lumen maintenance.

Continued --->

MLPW	Lamp Type	CRI	Ballast	Good Applications	Limitations
75	T-8 premium 2-ft lamps (F17T8/835)	86	Electronic and electronic dimming	General commercial lighting; 2-ft luminaires.	Cost more than 4-ft lamps; not as efficient.
67	Metal halide lamps, pulse start, M137 (175W class)	65	Magnetic CWA	Parking lots, outdoors, roadway lighting.	Long warm up and restrike times prevent rapid switching.
63	Metal halide lamps, pulse start, ED-17 M140 (100W class) high CRI	85	Electronic or magnetic HX (high reactance) or CWA	Recessed and track-mounted display lighting.	May not be suitable for general illumination due to lamp cost; long warm up and restrike times prevent rapid switching.
62	Compact fluorescent 18–42W triple	82	Electronic and electronic dimming	Downlights, sconces, wall washers, pendants and other compact lamp locations; can also be used outdoors in most climates.	More costly than some other fluorescent lamps.
20	Halogen infrared reflecting lamps in PAR-30, PAR-38, MR16 and T-3 shapes	100	None required	Localized accent ltg and where full range dimming is required such as fine restaurants, hotels, high-end retail.	Halogen lamps should be used only in limited amounts. Halogen IR lamps can be cost effective compared to standard halogen lamps.

Notes: MLPW = mean lumens per watt

Luminaires

Luminaires — or light fixtures — generally consist of lamps, lamp holders or sockets, ballasts or transformers (where applicable), reflectors to direct light into the task area, and/or shielding or diffusing media to reduce glare and distribute the light uniformly. There is an enormous variety of luminaire configurations. This section briefly outlines some of the more important types for commercial building lighting design.

Recessed luminaires. Recessed luminaires represent a large segment of the overall luminaire market. There are two basic variations: lay-in troffers and downlights. Lay-in troffers replace some tiles in a dropped ceiling, and are primarily used as a direct general light source. Downlights are relatively compact luminaires used for wall washing, accent lighting, and supplemental general or task illumination, as well as for lower levels of ambient illumination.

Suspended luminaires. Suspended indirect or direct/indirect luminaires are the preferred luminaires for lighting classrooms, offices, administrative areas, library reading areas, computer work areas and other spaces with taller ceilings. Typically these luminaires employ T-8, T-5 or T-5HO lamps, and often mount in continuous row configurations. See the Pendant-Mounted Lighting Guideline later in this chapter. Low ceilings may preclude this design.

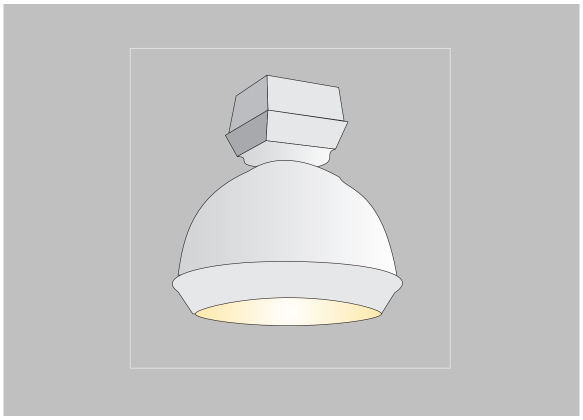

Figure 4-5. Low-bay HID luminaire.

Suspended high-ceiling luminaires. Both fluorescent and HID suspended luminaires are useful for illuminating building spaces with high ceilings. HID luminaires can be classified as either high bay (>25 ft mounting height) or low bay. Multi-lamp fluorescent luminaires employ up to eight lamps to approximate the light output of an HID luminaire, while allowing for additional control flexibility. Linear hooded industrial fluorescent luminaires can be extremely effective at lighting high ceiling spaces.

Surface-mounted luminaires. Surface-mounted fluorescent, compact fluorescent and HID luminaires are valuable for wall and ceiling mounting situations, particularly when ceiling access is a problem.

Specialty luminaires. Several specialty luminaires are available for specific lighting applications. These include wall-washing luminaires to accent or brighten walls and features; task lighting luminaires to supplement general illumination; damp or wet location luminaires for exterior areas open to the elements; and high-abuse luminaires designed to withstand vandalism in institutional environments.

Exit signs. Numerous exit sign configurations are available. LED exit signs offer the best value for minimizing energy use and maintenance. However, compact fluorescent exit signs may be preferable when an additional downlight component is desired.

Design and Analysis Tools

Several high quality analysis tools exist to help professionals design lighting systems. The simplest of these programs provide rudimentary zonal cavity calculations to predict average horizontal footcandles, while the most sophisticated tools can handle advanced calculations and produce realistic renderings.

Many of the major luminaire manufacturers offer standard computational software that can predict the performance of their (or other manufacturers') luminaires in typical lighting designs. Usually these programs can calculate horizontal and vertical illuminance for a number of points within the space. Some can produce renderings as well. Most can export output to AutoCAD.

Companies that specialize in lighting software offer the most sophisticated lighting software packages. These products are typically more robust than the manufacturer-provided packages, and can handle more complex problems, such as surface luminances, daylight effects, irregularly shaped rooms, and high resolution rendering.

Lighting software products include: AGI (Lighting Analysts); LitePro (Columbia Lighting); Genesys (Lightolier); Lightscape (Autodesk); Visual (Lithonia); and LumenMicro (Lighting Technologies).

Operations and Maintenance

Appropriate maintenance is critical to the performance, lighting quality, and energy efficiency of lighting systems. Establishing proper maintenance procedures is as much a responsibility of the lighting designer as it is of the person who changes spent lamps. A good lighting maintenance plan should be included with the building specifications.

Luminaire Cleaning and Troubleshooting

Thoroughly clean luminaires at regular intervals. Regular maintenance ensures that the lighting system will continue to perform as designed, thereby maximizing lighting quality and space appearance. When cleaning luminaires, maintenance personnel should also check for and replace any broken or malfunctioning equipment, such as lenses, louvers and ballasts.

Group Relamping

Lighting systems perform best when they are maintained at regular intervals. Group relamping is a maintenance strategy aimed at maximizing lighting system performance and economy by changing out all lamps at regular intervals, just before the start of the highest failure period. While some spot relamping is usually required to maintain appearance and illumination due to occasional early lamp failures, spot relamping by itself is normally labor intensive and therefore expensive. In the long run, group relamping reduces the cost of lighting system components through simple economies of scale. Furthermore, relamping luminaires at regular intervals maintains light levels and lighting quality according to design intent. For best economy, group relamping should usually be combined with luminaire cleaning and troubleshooting.

Specifications

Lighting designers have a number of specification tools available to promote proper maintenance and reduce maintenance costs. For example:

- Specify premium T-8 lamps whenever possible to extend lamp life by 20%.
- Limit the number of different lamp types specified. This will simplify maintenance and allow for reduced backup inventory.
- Include specification language that requires the builder to supply the owner with manuals for occupancy sensors and other automatic control hardware.
- Include a maintenance manual (see below) in the lighting specification.

Maintenance Manual

Include a detailed maintenance package with the building specifications. At a minimum the package should contain the following:

- As-built plans showing the installed lighting systems
- Luminaire schedule that includes detailed lamp and ballast information
- Luminaire cut sheets
- Lamp inventory list, including recommended stocking quantities

- Manufacturer data for all lighting controls, including operating documentation and tuning procedures
- Procedures and schedule for maintaining lighting controls
- Luminaire cleaning and troubleshooting procedures
- Group relamping procedure and schedule
- Lamp recycling plan and contacts

Lamp Disposal and Recycling

Mercury is a toxic element and there are significant concerns about mercury being emitted into the atmosphere or released into groundwater when fluorescent lamps are improperly discarded. On average, fluorescent lamps manufactured in 2001 contain 8.3 milligrams of mercury per 4-ft lamp. This is a considerable reduction from about 40 milligrams a decade ago but still a potential health hazard.

The U.S. Environmental Protection Agency has declared that used lamps containing mercury are hazardous materials, requiring special handling in many cases. This applies to linear and compact fluorescent lamps, and in many cases may also apply to high-intensity discharge (HID) lamps. Exceptions to the EPA standards are lamps that have been tested through the Toxic Characteristic Leaching Procedure (TCLP) to show that they do not exceed specific contamination limits when discarded in a landfill.

Small users that dispose of less than 100 kilograms total of hazardous waste per month are exempt from EPA disposal regulations; their spent lamps may be disposed of in landfills, although it is much more ecologically responsible to recycle them. Current costs for recycling fluorescent lamps average about $0.06 per linear foot (when shipped to the recycling facility). When preparing a maintenance plan for a lighting system, it is advisable to include lamp recycling.

For demolition and renovation projects, lamps should be recycled where local recycling options are available. Contact the Hawaii Department of Health, Solid and Hazardous Waste Branch, tel. 808-586-4226, for details.

We recommend using lamps that pass the EPA TCLP test to minimize the use of mercury. Also, we recommend recycling all lighting products that contain mercury in order to minimize the mercury that enters our environment. Some old lighting ballasts may contain toxic PCBs; these need proper disposal.

Note that lamp disposal requirements are subject to change, and it is always a good idea to check on current regulations.

Commissioning

For information about commissioning lighting systems, see the Lighting Controls Guideline.

Utility Programs

Incentives may be available for specific lighting equipment or systems. Contact your local utility as early as possible in the design process to take advantage of existing incentive programs.

Resources

Advanced Lighting Guidelines, 2001, New Buildings Institute. Web site: www.newbuildings.org.

High Performance Schools Best Practices Manual, 2002, Coalition for High Performance Schools (CHPS). Web site: www.chps.net.

Daylighting Design: Smart and Simple, 1997, by R.A. Rundquist, T. McDougal, Palo Alto, CA: Electric Power Research Institute (EPRI). EPRI report #TR109720. Web site: www.epri.com.

IESNA Lighting Handbook, 9th edition, Illuminating Engineering Society of North America. Web site: www.iesna.org.

Lighting Controls: Patterns for Design, 1996, by R.A. Rundquist, T. McDougal, J. Benya. Palo Alto, CA: Electric Power Research Institute (EPRI). EPRI report #TR107230. Web site: www.epri.com.

Pendant-Mounted Lighting

Recommendation

In rooms having a ceiling at least 9.5-ft high, consider suspended fluorescent lighting having either:

- A semi-indirect or indirect distribution and at least 85% luminaire efficiency, using T-8 premium or T-5 lamps and electronic ballasts and a connected lighting power of 0.8 to 1.3 W/ft²; or
- Direct/indirect distribution and at least 75% luminaire efficiency, using T-8 premium or T-5 lamps and electronic ballasts and a connected lighting power of 0.8 to 1.1 W/ft².

Description

There are several types of suspended fluorescent luminaires, which are classified according to the amount of uplight and downlight they provide.

- Direct/indirect luminaires can provide relatively even illumination on ceiling, walls and floors by adding a little direct light to the indirect component.

- Indirect luminaires illuminate a space by reflecting light from the ceiling.

With a direct/indirect luminaire, a light-colored ceiling is preferred to take advantage of the uplight. The suspension length for direct/indirect lighting is less critical than for indirect lighting.

In an indirect luminaire, the amount of uplight is at least 90% of the total light output. The downlight is generally intended to create a sense of luminance, but most of the illumination in the room is caused by reflected light from the ceiling. Indirect lighting requires a high reflectance ceiling and a minimum suspension length of 12 in., with 18 in. or more strongly preferred.

In both cases, affordable luminaires may have steel bodies and steel or plastic louvers. More sophisticated luminaires employ extruded aluminum housings, but this generally costs significantly more. Likewise, T-5 and T-5HO lighting systems will cost more than T-8, and these very bright lamps may create glare when used in any direct lighting component.

Applicability

Pendant-mounted lighting is appropriate for offices, classrooms, libraries, multi-purpose spaces, lobbies, and administration spaces that have a high enough ceiling.

Codes and Standards

See the Codes and Standards section of the General Lighting Guidelines above.

Benefits

Direct/indirect lighting systems often offer a combination of efficiency and visual comfort, and make excellent use of the low-cost, widely used T-8 lamp system. Systems operating at about 1.0 W/ft² (with a very reflective ceiling) will generate between 40 and 50 footcandles, maintained average, with excellent uniformity. Indirect lighting systems are generally less efficient, requiring 1.1–1.2 W/ft² to achieve 40 to 50 footcandles.

Integrated Design Implications

Suspended lighting systems can work well with almost all ceilings that are at least 9.5 ft high. However, avoid dark ceilings such as stained wood or highly colored paint, or areas with many ducts or louvers that can absorb large amounts of light. For direct/indirect luminaires, ceilings should be light colored. For indirect luminaires, ceilings must be high-reflectance white or off-white, as should be upper walls. If the room has an extremely high ceiling, such as with a sawtooth clerestory, use a direct/indirect luminaire with a greater percentage of downlight (50% or more).

Design Details

Pendant-mounted lighting provides good general lighting throughout a room. Some types of direct/indirect lighting are optimized for computer screen work, although they tend to be expensive. It may be necessary to provide separate wall-wash lighting for display areas or separate chalkboard illumination in classrooms, especially if the suspended lighting system is manually dimmed. For T-8 lamps, be certain to use premium types with 835 or 841 color, rated 24,000 hours. For non-dimming applications, luminaire light and power can be tuned through choice of ballast factor.

Design and Analysis Tools

Although minimally acceptable results will be obtained using the zonal cavity (lumen) method, a modern point-by-point computer program will provide much more information and confidence. See the General Lighting Guidelines above for more about design and analysis tools.

Costs

Suspended lighting systems costs are shown in Table 4-5.

Table 4-5. Pendant-mounted lighting system costs.

Lighting System Type	Cost per Lineal Foot, Installed*
Steel indirect luminaires, 90%+ uplight, T-8 lamps, non-dimming	$42
Steel direct/indirect luminaires, plastic louvers, 65% uplight, T-8 lamps, non-dimming	$48
Steel direct/indirect luminaires, steel louvers, 50% uplight, T-8 lamps, non-dimming	$54
Extruded aluminum luminaires, parabolic louvers, 75% uplight, T-8 lamps, non-dimming	$60
Add for dimming ballasts using standard 0–10 volt type	$14–18

*Approximate cost to owner, including labor, materials (luminaires, lamps and suspension hardware) and costs of construction. Includes connecting luminaire to branch circuit. Controls and branch circuit costs not included. Based on July 2000 mainland prices, marked up by 20% to account for additional shipping costs to Hawaii. Costs vary depending on market conditions.

Cost Effectiveness

Suspended lighting systems are highly cost effective in most applications. Non-dimming, indirect steel luminaires are the lowest cost, but optimum solutions are generally steel luminaires with steel or plastic louvers with 35% to 50% downlight.

Operations and Maintenance

These lighting systems rarely need extra maintenance. As with all fluorescent systems, lamps should be group-replaced at approximately 18,000 to 21,000 hours of operation (based on a 24,000-hour life rating). Luminaires should be cleaned annually. Open-louvered luminaires, especially using plastic louvers, require less cleaning and are more tolerant of poor maintenance and abuse.

Commissioning

None, other than preconditioning lamps in dimming applications. Controls, such as dimming or occupancy sensors, need to be commissioned. See the commissioning section of the Lighting Controls Guideline.

Utility Programs

Incentives may be available for specific lighting equipment or systems. Contact your local utility as early as possible in the design process to take advantage of existing incentive programs.

Case Study

The office at Pearlridge Elementary School uses pendant-mounted fixtures to complement the high ceiling and create a bright and open feeling. The direct/indirect luminaires provide good task light while also illuminating the ceiling. The result is very even illumination that improves visual performance compared to a direct lighting design with the same lighting level. Installed lighting power is less than 1.0 watt per square foot.

Figure 4-6. Direct/indirect luminaires at Pearlridge Elementary School office. Photo: Erik Kolderup, Eley Associates.

Recessed Lighting

Recommendation

Use recessed lighting in low-ceiling spaces where pendant-mounted lighting is inappropriate or when the budget is limited. Use fluorescent lens troffers with at least 78% luminaire efficiency, T-8 premium lamps and electronic ballasts, and a connected lighting power of 0.9 to 1.1 W/ft².

Description

Luminaires recessed into the ceiling provide ambient lighting. While recessed luminaires may include incandescent, compact fluorescent and metal-halide lamps, the most common type of recessed lighting in commercial buildings is the fluorescent troffer.

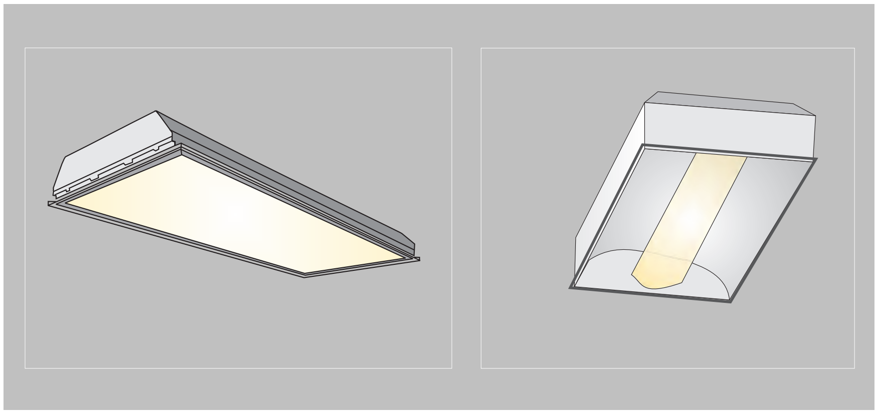

Figure 4-7. Lensed recessed troffer (left) and industrial recessed troffer (right).

Fluorescent troffers are designed to “lay-in” in place of an acoustical tile in suspended T-bar ceiling systems. The most common and cost-effective size is 2 ft x 4 ft. Less common sizes include 2 ft x 2 ft and 1 ft x 4 ft. The luminaire typically contains two T-8 lamps (some contain three, four or six lamps, but the two-lamp version is more efficient and allows better uniformity, especially with low ceilings). The interior reflector should be either high-reflectance white paint or specular (highly polished) silver coating or aluminum. Silver, special aluminum and the best white paint all reflect approximately 95% of incident light on internal optical surfaces, increasing room illumination without using more energy.

The lens may be an industry standard “Pattern 12” prismatic acrylic lens, with a minimum lens thickness of .125 in. to provide durability and to prevent glare-inducing lens sag. For specific applications, other lenses, good louvers or both may provide better luminance control. The luminaires can be configured in rows, although in spaces such as classrooms many architects prefer a “donut” configuration.

There are a number of variations among troffers. These include:

- *Quality or price class.* A “specification grade” troffer is generally deeper, heavier gauge metal, includes better hardware and costs more. A basic troffer may work just as well, but it is flimsier and may use a lower performance reflector and other materials.
- *Door type.* Recessed troffers without doors may be difficult to maintain, adding labor costs. A flat steel door with butt joints costs the least; a regressed aluminum door with mitered corners costs quite a bit more. The regress may provide some glare relief.
- *Static,* meaning that the luminaire is basic and enclosed; *heat extraction*, meaning the luminaire is designed to draw air through the luminaire and heat into the ceiling plenum above; and *air handling*, in which the luminaire can be connected to special HVAC supply or return devices. The cost of HVAC attachments is high, and they do not eliminate the need for conventional HVAC diffusers and grilles. Careful heat extraction design can optimize lamp and ballast temperature and therefore luminaire output. But since electronic ballasts and efficient lamps generate much less heat than old magnetic ballasts and T-12 lamps, there may no longer be a need for heat extraction.

Lens troffers do not illuminate the ceiling and upper walls well, and may not provide appropriate lighting quality for some tasks. They are also essentially the same luminaire style as used in many institutional buildings, contributing to an ordinary, cheap-looking appearance. Premium lenses can improve both appearance and performance, but better luminaire selection can result in even more improvement for a similar cost.

Applicability

Recessed lighting is appropriate for offices, classrooms, libraries, multi-purpose spaces, administration spaces, and some retail, storage and industrial applications.

Codes and Standards

See the Codes and Standards section in the General Lighting Guidelines above.

Benefits

Recessed troffer lighting systems generally offer excellent efficiency, but usually with some loss of visual comfort. They make excellent use of the low-cost, widely available T-8 lamps. Systems operating at about 1.0 W/ft^2 will generate between 50 to 60 footcandles maintained average, with very good uniformity.

Integrated Design Implications

This type of lighting is primarily used in flat acoustic tile ceilings, and then only when ceiling height and/or budget precludes other options.

Design Details

Recessed fluorescent troffers provide general downlighting throughout a room. However, lens troffers may cause problems for computer workspaces due to reflections on computer screens. Employ premium T-8 lamps with 835 or 841 color, rated 24,000 hours.

For non-dimming applications, luminaire light and power can be varied through careful choice of ballast factor.

Design and Analysis Tools

A modern lighting point-by-point calculation program should be used. However, minimally acceptable results may be obtained using the zonal cavity calculation method. For more about design and analysis tools, see the General Lighting Guidelines.

Costs

Recessed lighting systems will cost about $140 per luminaire[2] for basic, white reflector luminaires with #12 lens, two premium T-8 lamps, and electronic ballast. A dimming ballast will add about $45–$55 to each luminaire.

Cost Effectiveness

Lens troffer lighting systems are extremely low cost, but their inexpensive appearance can be a drawback.

Operations and Maintenance

These lighting systems rarely need extra maintenance. As with all fluorescent systems, lamps should be replaced at approximately 18,000 to 21,000 hours of operation (based on 24,000-hour lamp rating). Luminaires should be cleaned annually. Lensed luminaires require periodic cleaning and occasional lens replacement (acrylic lenses last far longer than styrene).

Commissioning

None, other than preconditioning lamps in dimming applications. Lighting controls used with recessed luminaires need commissioning; see the commissioning section of the Lighting Controls Guideline.

Utility Programs

Incentives may be available for specific lighting equipment or systems. Contact your local utility as early as possible in the design process to take advantage of existing incentive programs.

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[2] Approximate cost to owner, including labor, materials (luminaires, lamps, and suspension hardware) and costs of construction. Includes connecting luminaire to branch circuit. Controls and branch circuit costs not included. Based on July 2000 mainland prices, marked up by 20% to account for shipping costs to Hawaii. Costs vary depending on market conditions.

Surface-Mounted Lighting

Recommendation

Use surface-mounted lighting in rooms that do not have recessed or suspended lighting systems. There are several possible circumstances:

- Ceiling height is 8.5 ft or less, preventing use of suspended luminaires.
- Ceiling cavity is impenetrable because of, for example, the presence of asbestos or roof insulation.
- The space design employs a hard ceiling surface, such as concrete, that is impenetrable or has only a moderate reflectance.

When using surface-mounted lighting, there are two good choices:

1. Use short stem-mounted semi-direct fluorescent luminaires having at least 65% efficiency, using T-8 premium lamps and electronic ballasts and a connected lighting power of 1.1 to 1.2 W/ft².

2. Use surface-mounted fluorescent lens troffers having at least 78% efficiency, using T-8 premium lamps and electronic ballasts and a connected lighting power of 0.9 to 1.1 W/ft².

Description

Surface-mounted semi-direct luminaires provide general downlighting in a space, as well as some uplighting of the ceiling surface. They are versions of direct/indirect luminaires designed for short stem mounting. In general, this means a luminaire that is mounted very close to the ceiling, no more than 6 in. or so from the ceiling to the lowest part of the luminaire. A small percentage of uplight illuminates the adjacent ceiling with a minimum amount of light to prevent a hot spot.

Figure 4-8. Surface-mounted troffer.

These T-8 lamp luminaires require some form of downlight shielding. Louvers and lenses are the two most likely choices.

In general, the layout of surface-mounted semi-direct luminaires will be similar to the layout for suspended lighting systems. This will result in higher light levels with a slight sacrifice in lighting quality.

Surface-mounted direct luminaires are similar to recessed troffers, but they have finished box enclosures. The most common and cost-effective size is 2 ft x 4 ft; less common sizes include 2 ft x 2 ft and 1 ft x 4 ft. As with recessed troffers, inside the box there are two T-8 lamps.

The interior reflector should be either high-reflectance white paint or specular (highly polished) silver coating or aluminum. High-reflectance materials may increase the cost considerably but they also increase luminaire efficiency. Silver, special aluminum and the best white paint all reflect approximately 95% of incident light on internal optical surfaces, increasing room illumination without using more energy.

The lens may be an industry standard “Pattern 12” prismatic acrylic lens, with a minimum lens thickness of .125 in. to provide durability and to prevent glare-inducing lens sag. For specific applications other lenses, good louvers or both may provide better luminance control. Other variations applicable to troffers — such product grade and door type — also apply.

Applicability

Surface-mounted luminaires are typically used where it isn't practical to recess a luminaire into a surface. An example of this is a cast concrete corridor, with a simple recessed electric box. The surface-mounted luminaire is connected to the box and bolted to the box or concrete surface.

Codes and Standards

See the Codes and Standards section of the General Lighting Guidelines.

Suspended luminaires need to be restrained in case of an earthquake. For short-stem luminaires, the luminaire usually cannot swing, but support independent of the ceiling system is still needed.

Benefits

Troffer lighting systems generally offer excellent efficiency, but with some loss of visual comfort. They make excellent use of the low-cost, widely used T-8 lamp system. Systems operating at about 1.0 W/ft^2 will generate between 50 to 60 footcandles maintained average, with very good uniformity.

Integrated Design Implications

Use surface-mounted lighting systems only in very specific applications. Pursue the pendant-mounted and recessed lighting strategies first; use surface-mounted luminaires only when ceiling issues preclude other options.

Design Details

Surface-mounted lighting systems provide general lighting throughout a room. However, lensed luminaires are not recommended for computer workspaces. Be certain to use premium T-8 lamps with 835 or 841 color, rated 24,000 hours.

For non-dimming applications, luminaire light and power can be varied through choice of ballast factor.

Refer to the Pendant-Mounted Lighting Guideline and the Recessed Lighting Guideline for information about using semi-direct and surface-mounted direct luminaires — the design details described there also apply to surface-mounted luminaires.

Design and Analysis Tools

A modern lighting point-by-point calculation program should be used. However, minimally acceptable results will be obtained using the zonal cavity (lumen) calculation method.

For more about design and analysis tools, see the General Lighting Guidelines.

Costs

Surface-mounted lighting systems will cost about $240 per luminaire[3] for basic, lensed, white reflector direct luminaires with .125 in. lens, two premium T-8 lamps and an electronic ballast. Aluminum surface luminaires will probably cost a bit more, perhaps $280 each. A dimming ballast will add about $45–$55 to each luminaire.

Cost Effectiveness

Surface-mounted lighting systems are relatively expensive compared to recessed troffers but may still offer a good value.

Operations and Maintenance

These lighting systems rarely need extra maintenance. As with all fluorescent systems, lamps should be replaced at approximately 18,000 to 21,000 hours of operation (based on 24,000-hour lamp rating). Luminaires should be cleaned annually. Lensed luminaires require periodic cleaning and occasional lens replacement (acrylic lenses last far longer than styrene).

Commissioning

No commissioning is needed, other than preconditioning lamps for dimming applications. See the Lighting Controls Guideline for information about commissioning lighting controls.

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[3] Approximate cost to owner, including labor, materials (luminaires, lamps, and suspension hardware), and costs of construction. Includes connecting luminaire to branch circuit. Controls and branch circuit costs not included. Based on July 2000 mainland prices, marked up by 20% to account for shipping costs to Hawaii. Costs vary depending on market conditions.

Utility Programs

Incentives may be available for specific lighting equipment or systems. Contact your local utility as early as possible in the design process to take advantage of existing incentive programs.

Lighting Controls

Recommendation

Use lighting controls to reduce lighting energy use, ensure good lighting quality and offer occupants better control of their lighted environment.

Description

Lighting controls are critical for minimizing lighting energy use and maximizing space functionality and user satisfaction. Control techniques range from simple to extremely sophisticated. Lighting control strategies are most successful when the people who use them easily understand how to operate them. Another critical factor is the proper commissioning of lighting control systems so that they operate according to design intent.

Finally, regularly scheduled maintenance of control equipment will improve the system's long-term success. Poorly designed, commissioned or maintained automatic lighting controls can actually increase lighting energy use, and will cause user dissatisfaction.

Control devices include switches and dimmers, occupancy sensors, time controls, photoelectric controls, and energy management systems. Different control devices will be appropriate depending on the specific application.

Switches. Manual switches are the simplest form of user-accessible lighting control. Manual switches are especially valuable in daylit spaces because they allow people to turn off electric lights when daylight is adequate. Manual switches should also be installed in spaces with occupancy sensors (they may be an integral part of the control). This increases the energy savings of occupancy sensor controls by allowing people to turn off the lights when they are not needed.

Manual dimmers. Next to standard wall switches, manual dimmers are the simplest of lighting control devices. Manual dimmers serve two important functions. First, dimming the lights reduces lighting demand and energy use. With incandescent and halogen sources, there is the additional benefit of extended lamp life (dimming a halogen lamp too low, however, may cause lamp blackening). Second, and more importantly, dimmers allow people to tune the lights to optimum levels for visual performance and comfort. Consider manual dimmers (combined with dimming ballasts, where applicable) for many building spaces, including classrooms, computer workrooms and office spaces.

Figure 4-9. Dual-technology occupancy sensor.

Occupancy sensors. Occupancy sensors automatically shut lights off in unoccupied spaces. The primary detection technology can be either passive infrared (PIR) or ultrasonic. Some sensors employ both passive infrared and either ultrasonic or microphonic detection.

Mounting configurations include simple wallbox sensors appropriate for small spaces such as private offices, and ceiling- or wall-mounted sensors that provide detection of areas up to 2,000 ft².

Occupancy sensors are most effective in spaces that are intermittently occupied, or where the lights are likely to be left on when unoccupied. Good applications include classrooms, private offices, conference rooms, restrooms and storage areas. Use occupancy sensors in combination with manual overrides whenever possible to maximize energy savings, space flexibility, and occupant satisfaction. Careful control specification can preclude annoying events, such as the lights turning off prematurely in a restroom.

Figure 4-10. Digital time switch.

Time controls. Time controls save energy by reducing lighting time of use through preprogrammed scheduling. Time control equipment ranges from simple devices designed to control a single electrical load to sophisticated systems that control several lighting zones. Time controls make sense in applications where the occupancy hours are predictable, and where occupancy sensor automatic control is either impractical or undesirable. Candidate building spaces include classrooms, offices, auditoriums and exteriors.

Be sure to keep a summary of the programming instructions with the time controls so that the maintenance staff doesn't need to search for the instructions when recovering from some failure.

Photoelectric controls. Photoelectric controls employ a photosensor and logic controller to control lights in daylit spaces. The logic controller processes a signal from the photosensor and sends a dimming or switching signal to the lighting circuit based on the monitored light level. Open-loop systems "see" only daylight, while closed-loop systems monitor both daylight and the light emitted by the luminaires they control. Successful use of photoelectrically controlled lighting systems requires careful design, installation and commissioning, as well as a commitment to the long-term maintenance of the system. Without these elements, energy savings are rarely sustainable.

In areas with ample daylight, such as outdoors, a simple photoelectric switch can ensure that lighting is off during daylight hours. Even though the switch is simple, it may occasionally fail or need other maintenance. Without periodic performance verification and maintenance, even a simple control problem can cause significant increases in lighting costs.

Energy management systems (EMS). Typically when lighting is controlled through an EMS it is via a time clock. However, many building operators take advantage of the built-in EMS functions to monitor lighting usage on a space-by-space basis. EMS control of lighting systems may also allow building operators to shed non-essential lighting loads during peak demand periods, or even dim some of them to reduce electric load.

Applicability

Lighting controls are recommended for a wide variety of commercial building types, including offices, warehouses, retail stores, schools, and assembly and light manufacturing facilities.

Codes and Standards

Building energy codes adopted in Oahu, Hawaii, and Kauai include minimum requirements for lighting controls. The type and number of controls required depends on the type and size of the space being lighted. In some cases multi-level switching or occupancy sensors may be required. Details are available in the Hawaii Model Energy Code Application Manual available on the Internet at http://www.hawaii.gov/dbedt/ert/model_ec.html. Software called Hilight is also available to assist with documenting lighting controls compliance and may be downloaded at http://www.hawaii.gov/dbedt/ert/mec/app-b.html.

Benefits

Lighting controls can reduce energy consumption by 50% in existing buildings and at least by 35% in new construction. As a rule of thumb, every watt saved in lighting saves an additional 1/10 to 1/4 watt in avoided HVAC energy.

In addition to saving energy, lighting controls can improve occupant satisfaction and comfort by giving people the ability to change the light levels around them in response to changing tasks, moods or other conditions. Also, today's workers move around often, changing tasks, workspaces and even jobs more frequently than they once did. A flexibly controlled lighting system can accommodate these changes with minimal disruption and expense.

Design Details

Design for flexibility. Design lighting controls to accommodate the varying nature of spaces (such as office conference rooms, auditoriums, and spaces used for multiple tasks like AV presentations, performances and meetings).

- Bi-level or multiple-level switching enables the selection of different light levels to respond to changing requirements.
- Separate circuiting of luminaires in daylit zones enhances space flexibility and energy savings.
- Control flexibility improves lighting energy performance by encouraging only the use of lights that are needed for the activity at hand.

Design for occupant satisfaction. Design lighting controls so that they are accessible and easy to understand, and so that occupants can override automatic controls where appropriate.

- In spaces such as private offices, give occupants the ability to override automatic dimming or occupancy sensor controls, so that they can switch the lights off manually when they need to.
- In multipurpose spaces, consider designing several different lighting control schemes to account for different activities. It may make sense to specify a preset dimming or switching system allowing one-button scene changing.
- Make lighting control systems easy to understand and operate. Non-intuitive control interfaces are likely to be ignored or disabled.
- With automatic controls, make sure that occupancy sensors and daylighting controls are not set so that lights shut off at inappropriate times or cycle on and off too frequently, or occupants may complain and even disable the controls.

- Be proactive about asking users if they like the controls that affect them. Respond to issues or complaints promptly.

Design and Analysis Tools

There are few useful design tools in this evolving field. Controls manufacturers and their representatives can usually provide the best information.

Costs

Manual controls cost less than automatic controls. Automatic controls typically have higher installation and maintenance costs, but can save a significant amount of energy in large buildings by ensuring that the optimum amount of illumination is provided in public spaces where manual controls may not be used effectively.

The choice of dimming versus switching can have major first-cost implications, especially in retrofit situations. Special dimming ballasts are required for fluorescent and HID lamps, but the cost of fluorescent dimming (or controllable) ballasts is about twice that of equivalent non-dimming ballasts. HID dimming ballasts can be much more expensive. Multi-level ballasts, either fluorescent or HID, are less expensive than equivalent dimming ballasts, but may not give users the feeling of total control.

Cost Effectiveness

Controls are an evolving area of building technology. At present, cost effectiveness is good, but initial costs for some types seem relatively high. Still, lighting upgrades in existing buildings are usually more cost effective than HVAC improvements. In new buildings, lighting controls can reduce the effective lighting power density so that a smaller HVAC unit can be installed, saving on first costs.

- *Manual controls* are cost effective in small spaces such as private offices.
- *Automatic controls* are more cost effective than manual controls in shared spaces such as lobbies and break rooms where an individual occupant wouldn't usually feel responsible for turning off or dimming the lights. *Switching* hardware is relatively simple and generally very cost effective.
- The cost effectiveness of *occupancy sensors* varies depending on the overall energy management skills and interests of the occupants. People who are personally careful about turning lights off when they're not needed will generally outperform occupancy sensors, but for less well-managed spaces, occupancy sensors are worthwhile.
- *Daylight sensors* and dimming ballasts are worthwhile if the daylighting is designed correctly.

Operations and Maintenance

A properly commissioned lighting control system needs only periodic maintenance to ensure optimum performance. Refer to the manufacturer's recommended recalibration and cleaning cycle for sensors.

Make sure the maintenance staff understands the control system operation, as well as commissioning, maintenance and design goals. It will be up to the maintenance staff to ensure that the system is working for the building occupants. Poorly trained staff can create more problems and resultant costs than no controls at all.

Commissioning

All automatic lighting control systems must be tuned after installation to ensure optimal performance and energy efficiency. Malfunctioning automatic control systems waste energy and will disturb occupants. Systems that work properly will be left to do their job; systems that have false tripping and other unwanted behavior will end up disconnected or bypassed.

Commissioning of occupancy sensor systems and daylighting controls is critical to their success. Here are some good rules of thumb:

- *Dimmed fluorescent lamps:* Fluorescent lamps must be seasoned for 100 hours at full light output prior to being dimmed. Dimming the lamps before completing this "burn in" period can significantly reduce lamp life.
- *Occupancy sensors:* Occupancy sensors must be adjusted to make certain that they only sense motion in the controlled space. Motion in adjoining spaces can cause false triggering or cause the lights to remain on needlessly, thereby wasting energy. Similarly, sensors must not turn lights off when spaces are occupied.

  An additional adjustment on sensors controls the time-delay period between last detection and lights off. This time-out setting is important: a setting too short may cause false cycling; a setting too long fails to save energy as well as it could. A preliminary time-out setting of 15 minutes is suggested as a compromise, but the control manufacturer can recommend good preliminary settings for each application.
- *Photosensors:* Mount photosensors designed for use in open-loop daylighting control systems so that they cannot detect the lights they control. This may require some tweaking, masking or relocating of the unit after installation. Consult the manufacturer's recommendations for proper procedures for commissioning photosensor devices.

Daylight sensor settings should be made and checked several times. If illuminance criteria are specified, use a good light meter with a silicon photodetector to verify design adjustment settings. Cheap meters can give poor results. If necessary, borrow a better meter from your local electric utility.

- *Dimming controllers:* Dimming controllers for lighting systems should be tuned so that illuminance at the high dimming range will not exceed design parameters. This is a relatively easy procedure on most dimming boards, requiring a simple adjustment.
- *Relay controllers:* If a stepped lighting control system is used for daylighting, adjust the deadband between the on and off switching thresholds so that the system does not cycle on cloudy days. Continuous on-off cycling is annoying to occupants and reduces lamp life.

Utility Programs

Incentives may be available for specific lighting equipment or systems. Contact your local utility as early as possible in the design process to take advantage of existing incentive programs.

Lighting Design Applications

This section describes a number of energy-efficient lighting designs for some typical commercial building spaces: private and open-plan offices, grocery stores, big-box retail stores, small retail stores, classrooms, corridors, hotel guestrooms and warehouses. Except in the case of corridors, hotel guestrooms and warehouses, these design recommendations are derived from the *Advanced Lighting Guidelines* (ALG), 2001 edition, which contains an entire “Applications” chapter with detailed information and diagrams of recommended advanced lighting designs. The ALG can be downloaded for free from the New Buildings Institute (www.newbuildings.org/lighting.htm) or can be purchased as a CD from IESNA (www.iesna.org).

Private Offices

Design Options

The *Advanced Lighting Guidelines* offers several task-ambient lighting design recommendations for small offices of about 104 ft². In each of these designs, the ambient light level is between 15 and 30 footcandles, average, and meets the IESNA’s *Design Guide* criteria. Task lighting is provided on the desk only. Two of the eight private office examples from the *ALG* are described here.

- **Direct.** One suggested design uses two overhead high-performance recessed luminaires that generate more than 40 footcandles in the center of the room. Each luminaire includes one F32T8 lamp and a high-light-output ballast (ballast factor > 1.1, 76W). An undercabinet task light with one 25W F25T8 lamp produces more than 70 footcandles on the desk surface. Power density is 0.97 W/ft².
- **Indirect.** A second option uses one uplight luminaire containing two F32T8 lamps (48–80W, depending on ballast factor and the resulting illuminance level for the room) and one undercabinet luminaire with one F25T8 lamp. With this design, it's particularly important to have a light-colored ceiling to reflect light down into the space. Power density is 0.81 to 1.1 W/ft².

Controls

In small offices and workrooms, provide both manual and occupancy sensor controls (sometimes the occupancy sensor integrates manual override into the control). In rooms with windows, consider providing either controls that automatically dim the lights in response to daylighting or manual dimmers so that occupants can adjust the illumination to their preference.

Open Offices

Design Options

The *ALG* shows a number of advanced lighting designs for open offices, including the two described below. As with the private office examples above, task lighting is only provided on the desk. The ambient light level is between 15 and 30 footcandles, average, and the design follows the IESNA's *Design Guide* criteria.

- **Lay-in troffers.** One suggested design uses two-lamp recessed troffers (F32T8) that are spaced 8 ft x 12 ft. For this wide spacing to be effective, a luminaire must be positioned over each workstation, and each workstation must have a task light. Wall washers with FT40 lamps (or linear T-5 lamps) provide balanced illumination in the circulation areas. The connected power of this design is 0.89 W/ft².
- **Uplighting.** In the second *ALG* example, rows of indirect suspended luminaires are spaced every 10 ft. Each luminaire contains one T-8 lamp with a high ballast factor ballast. In the circulation areas, a continuous wall slot uses a standard T-5 or T-8 lamp. This design's connected power density is 1.05 to 1.10 W/ft². Another option would be to use one T-5 lamp in the uplights, which would reduce the connected power to 0.88 W/ft², but additional task lights may then be needed.

A slightly different approach is illustrated by a lighting retrofit at the Honolulu office of Architects Hawaii. This design, which uses two-lamp luminaires and a slightly higher lighting power, may be more appropriate in retrofit applications where the occupants are accustomed to a certain light level. The office renovation involved changing work areas to an open-plan layout. Existing 2 ft x 4 ft T-8 fluorescent lay-in luminaires were replaced with suspended direct/indirect T-8 fluorescent luminaires with two lamps per luminaire and electronic ballasts.

The luminaires were suspended about 18 inches below the ceiling, both for optimal spread of light on the ceiling and to clear the fire-sprinkler heads. The lighting retrofit reduced lighting energy usage to 1.30 W/ft^2 from 2.57 W/ft^2. The evenly spread light has virtually eliminated glare reflected in the computer monitors and employees' complaints about eye strain have disappeared. In addition, many of the company's clients have commented on the attractiveness of the lighting design.

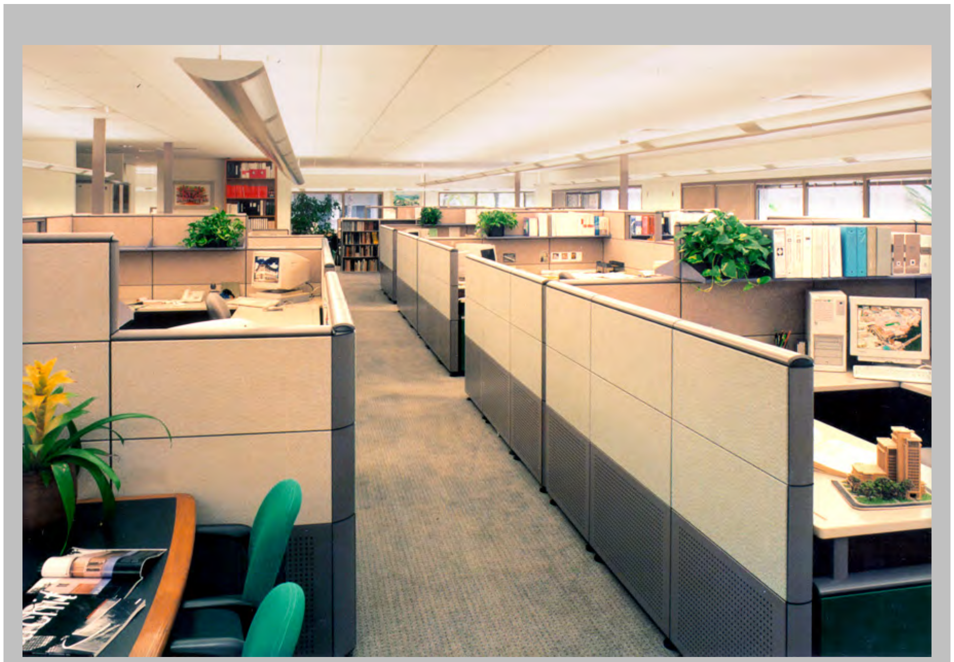


Figure 4-11. Suspended lighting at office of Architects Hawaii, Honolulu. Photo: Architects Hawaii.

Controls

In open offices, one or more local override switches are typically connected to a relay that is also controlled by a time-of-day program.

Consider providing individual dimmers for the luminaires above each workstation. Many workers, particularly those who spend a lot of time using computers, prefer to be able to control the light levels in their workspaces. Dimmers with handheld controllers can reduce costs and the need for wiring.

Provide a separate switching zone for daylit areas near windows. Using automatic daylight dimming on the luminaires nearest to the windows can save a significant amount of energy.

Plug-strip occupancy sensors can be used at each workstation to control task lights, computer monitors, printers and other equipment. Occupancy sensors can save from 10% to 30% of the energy used by these devices.

Grocery Store

Design Options

Grocery stores are a good application for skylights: daylit grocery stores can use considerably less electricity than comparable stores without daylighting. Whether or not the store is daylit, consider using T-5 task lighting integrated with shelving to reduce lighting power to 1.2 to 1.4 W/ft². The *ALG* design described below has a connected light power of about 1.4 to 1.5 W/ft², not including refrigerated case lighting.

- **General lighting.** The *ALG* provides an example of an energy-efficient grocery store lighting design that uses striplights or recessed troffers running perpendicular to the aisles with T-8 lamps and electronic ballasts. A continuous fluorescent valance or uplight illuminates the store's perimeter. (A T-5 lamp used in uplights here would permit a very small cove valance.)
- **Specialty departments.** For pendant luminaires in small specialty departments such as a bakery or flower display, consider using a 26W or 32W triple-tube CFL lamp with a shield. A 70W or 100W metal halide lamp (ceramic arc tube may be best) can illuminate larger areas.
- **Produce area.** To provide dramatic lighting in the produce area, the *ALG* design uses track lighting with metal halide lamps. Other options include suspended fluorescent direct luminaires or larger industrial luminaires with metal halide or large compact fluorescent lamps.

Controls

Consider using multilevel switching for alternating lamps or ballasts so that lower light levels can be used at night, during stocking hours, or in the case of an energy crisis. If a single lighting zone serves an area, partial dimming can ruin uniformity and create unappealing dark areas.

Big-Box Retail

Design Options

Big-box retail stores typically have 20- to 30-ft ceiling heights and display racks that are 12- to 14-ft tall. As described in the *ALG,* the metal halide industrial downlights generally used in big-box retail stores don't provide ideal lighting for the narrow aisles lined by tall racks of merchandise. The *ALG* suggests an advanced lighting design for a daylit big-box retail store that uses metal halide downlights in the open areas and fluorescent luminaires between the shelving racks.

- **Daylighting.** Big-box retail is an excellent application for skylights. In the *ALG* example, a skylit big-box store uses 100W metal halide industrial-style downlights and 100W metal halide track floodlights for general lighting. Continuous rows of single-lamp F59T8 luminaires are positioned above the aisles. Low display fixtures are illuminated with continuous rows of two-lamp F32T8s. Store windows are lit with dual 40W T-5 twin-tube floodlights, while 42W compact fluorescent pendants are used in "boutique" areas. The lighting power density is 1.5 W/ft^2.
- **High-bay T-5 high output.** Another option for big-box retail is to use high-bay T-5 high-output luminaires with reflectors that direct light downward. This option is very energy efficient, since high-output T-5s have mean lumens per watt (MLPW) of more than 80, compared to only 60–65 MLPW for small metal halide or compact fluorescents. With a nominal output of about 5,000 lumens, six T-5 HO lamps are approximately equivalent to a 400-watt MH since the mean light output is about 30,000 lumens for either option.

Controls

If the store is daylit, automatic daylight dimming controls on the fluorescent lighting could reduce the average power of the design described above by 20% to 30%, according to the *ALG.* For further savings, consider using bilevel controls on the metal halide or fluorescent luminaires before and after regular business hours, when employees stocking merchandise or doing other work may find lower light levels adequate.

Small Retail

Design Options

There are many energy-efficient options for lighting small retail stores such as specialty stores, coffee retailers or delis. It's possible to achieve 2.0 W/ft² or less in small retail stores by limiting the use of incandescents to a few halogen IR lamps for accent lighting.

- **Coffee, deli or other specialty stores.** One design shown in the *ALG* uses four large decorative pendants with compact fluorescent lamps for ambient lighting. Compact fluorescent pendants hang over the counters. In the windows, track lights have 37-watt MR-16 IR lamps. The work areas behind the counters and the menu boards are lit with F40T5 twin tubes with 0.85 BF ballasts. The connected power is 1.9 to 2.0 W/ft².
- **T-5 high output.** Another option shown in the *ALG* uses attractive suspended fluorescent luminaires containing a single T-5 high-output lamp. Thirty-two watt compact fluorescent pendants hang over the counters.
- **Small general retail or grocery.** The *ALG* shows another energy-efficient design using 2 ft x 2 ft recessed luminaires with three F17T8 lamps (or two FB32 lamps on a low ballast factor ballast). The perimeter spaces are lit with wall washers that have F40T5 twin tubes and 0.85 BF ballasts. T-5 HO wall washers may also work well, with longer lamp life.

Controls

Dimming controls can be used for adaptive compensation to save energy after dark (at night, eyes are adapted to lower outside lighting levels, so lower interior lighting levels seem more comfortable). The use of dimming during the day may be limited, since many small retail spaces only have access to daylight at the front window.

Classroom

Design Options

The *ALG* provides two lighting design examples for a typical 960-ft² classroom.

- **Direct/indirect or semi-indirect suspended luminaires.** Pendant-mounted lights are an excellent choice for classrooms because they provide balanced, glare-free illumination. The *ALG* shows an energy-efficient design with three rows of two-lamp T-8 direct/indirect or semi-indirect luminaires with normal ballast-factor ballasts. This design generates at least 50 footcandles, with a connected power of 1.16 W/ft². Independently switched chalkboard lighting with four F32T8 or F28T5 lamps could also be included; this would increase the lighting power by about 0.13 W/ft².

- **Lens troffers.** Another common classroom lighting design is the “donut” configuration, with four rows of lens troffers outlining the classroom’s perimeter (the ring of the “donut”) and a short row of luminaires in the center (the “donut hole”). The design shown in the *ALG* uses inexpensive two-lamp T-8 troffers and low ballast-factor ballasts to provide good vertical illumination on all four walls.

Controls

In classrooms, use occupancy sensors as the basic on/off lighting control. (Note: especially in lower grade classrooms, some teachers do a better job of turning off unnecessary lighting than occupancy sensors do; the higher the grade, the more need for automatic lighting controls.) Also provide manual override switches so that the teacher can turn the lights off as needed. Controls can save from 5% to 15% of lighting energy used by classrooms, according to the *ALG*. In classrooms with good daylighting design, automatic controls can save as much as 20% to 60%.

Corridor

Design Options

In corridors with tall ceilings, typical lighting includes recessed 2 ft x 2 ft troffers, recessed CFL downlights or indirect linear fluorescent (pendant or cove lighting). CFL wall sconces may also work well, and they are common in hospitality applications. While the horizontal illumination requirement for corridors is modest, vertical illumination to identify other people in the corridors is important.

Surface-mounted fluorescent luminaires may be required for some applications, but glare might be a problem without careful design. If necessary, look for louvered luminaires or prismatic luminaires with generous uplight. A larger number of luminaires with fewer or smaller lamps per luminaire will increase lighting uniformity.

Controls

Some occupancy sensors are specially designed for corridors. The less frequently a corridor is used, the more it needs an occupancy sensor. Some stairways can also benefit from occupancy sensors. For stairways, however, some of the lighting must remain on at all times, so a few luminaires should not have occupancy sensor control. Avoid preheat lamps when using occupancy sensors; their blinking upon startup may be disconcerting or in some cases unsafe.

Hotel Guestroom

Design Options

The actual design depends greatly on the room style and decoration, but fluorescent lamps and CFLs will save considerable energy. In particular, T-8 fluorescent lamps with color rendering index (CRI) above 80 in the lavatory and bath areas can provide excellent color rendering and energy efficiency. Careful luminaire and lamp selection can make this combination compatible with almost any interior decoration theme.

Recessed downlights in areas such as an entry foyer can save energy using CFLs (use programmed rapid-start ballasts to preserve lamp life). Portable luminaires should use CFLs for a combination of long lamp life and energy efficiency. Pin-based CFLs will decrease theft problems; locks for some screw-based CFLs are also available. To preserve guest satisfaction, do not use lamps with a CRI less than 80.

Some hotels have started using a new type of table lamp that has separate dimming CFLs, one for indirect uplight and another for direct downlight. Hotels save energy by using CFLs with efficient electronic ballasts, and can also save energy if users dim from full light output.

Controls

The Honolulu, Hawaii and Kauai energy codes require that all hardwired lights and switched receptacles be controlled from a switch at the entry door. Other controls, such as timers in bathrooms, can potentially save a lot of energy. Dimmers or 3-way switches in portable luminaires may save also some energy.

Warehouse

Design Options

Warehouses typically use either fluorescent or HID lamps in industrial high-bay or low-bay luminaires. While simple and generally inexpensive, industrial luminaires use key design features to optimize light distribution for task visibility, low maintenance and low energy costs. Many warehouses use aisle storage racks; these present difficulties for some HID luminaire designs, but manufacturers offer a number of them specifically intended for aisle applications. Since some warehouse areas may be infrequently occupied, controls can save significant amounts energy (see below).

Many warehouses use high-bay luminaires. Lamp selection should consider both lamp characteristics and the method of changing lamps. For example, unless the maintenance crew already has a lift that can be used for changing high-bay lamps, buying or renting a lift will add to relamping costs. A long string of fluorescent luminaires along each aisle may provide good uniformity, but if a rented lift must be raised, lowered, and then moved to relamp each luminaire in the string, the relamping project could take a while.

Some high-bay HID luminaires allow relamping access by a person on the ground using a pole; other poles types are available to change lamps in open fluorescent luminaires. Some lamps, such as T-8 fluorescent, high-pressure sodium and 400-watt metal halide offer very long lamp life, decreasing overall maintenance costs. While fluorescent lamp life may be affected by frequent starting, the overall lamp life may be longer for lamps that operate on occupancy sensors because they are on for fewer hours. HID lamps, on the other hand, are still on whenever they are controlled by an occupancy sensor, so all hours count toward lamp life.

Some warehouses utilize daylight from windows or skylights to supplement electric light. If these are combined with photocontrols to dim or switch off lamps when daylight is sufficient, the controls may save ample energy. The key to saving energy with daylighting is a well-designed daylighting system, properly integrated with the luminaires and controls.

Controls

Two-level controls (hi-lo or step) often work well with HID lamps and especially well with fluorescent lamps. These controls usually rely on a motion detector to determine that an aisle needs the higher light level. Most HID lamps will work properly with a hi-lo ballast package, but a few may cause problems; check with the ballast manufacturer for details.

Fluorescent lamps start quickly when switched on. Some industrial fluorescent lighting applications may need only 20% or less of the lamps on for safety, while the remaining lamps can turn on quickly when the occupancy sensor switches them on. With fluorescent lamps, consider the frequency that full lighting will be used; that will determine the best electronic ballast start mode. If the lamps will start many times daily, programmed rapid-start ballasts can eliminate early lamp failure. While these ballasts cost more and use slightly more energy than instant-start ballasts, the overall cost may be lower if lamps last significantly longer. T-5 lamps always use programmed rapid-start ballasts.

5. ENERGY-EFFICIENT WINDOWS

Energy-Efficient Windows Overview

Description

A window is vertical glazing located in a building to provide views, natural ventilation, daylight, or some combination of these three. Energy-efficient window design takes into account the window area, glass type, building orientation, and shading devices to maximize daylighting while minimizing solar heat gain.

Benefits

Windows serve many important functions. They can provide views, fresh air and cooling breezes, and daylight. Views of the outdoors give people a sense of connection to nature and the surrounding community, and also provide a sense of passing time and changing weather conditions. Natural ventilation and daylight can help provide more comfortable conditions for occupants, and may result in significant energy savings for the building owner or tenant.

Access to views, daylight and natural ventilation have been associated with increased employee productivity. Views through windows, for example, may improve eye health by encouraging people to occasionally shift their eyes' focus from close-up tasks to more distant sights.

Windows also provide people on the outside with views of the activities inside a building, which is quite important for many types of commercial buildings such as stores and restaurants.

General Design Considerations

While there are many powerful arguments for including windows in commercial buildings, windows also admit direct solar gain into a space. This heat gain can be a source of passive heating in colder climates, but it is not desirable in cooling-dominated climates, such as Hawaii.

In addition to affecting HVAC energy use, a window's surface temperature can make occupants in the building's peripheral zones feel uncomfortably hot or cold. In Hawaii, glazing types that tend to have high surface temperatures when exposed to direct sun are not desirable. Also, if windows are not properly located or shaded, direct sun penetration may cause uncomfortable glare for the occupants.

But by optimizing aperture size, glazing type and solar shading, it's possible to take advantage of the benefits of windows without significantly increasing the cooling load or causing thermal or visual discomfort.

Solar control — whether achieved with shading devices, window orientation or glass selection — reduces heat gain by cutting off direct solar penetration into the building. In existing buildings that are retrofitted with solar control devices such as interior or exterior shading, this results in significant savings in peak load energy and lower energy bills. In new construction, good solar shading design may also mean that the size of the air conditioning equipment can be reduced. In some cases, the savings in equipment costs will offset the cost of the shading devices.

Window Terminology

Windows have four principle performance characteristics: solar heat gain coefficient (SHGC), visible light transmittance (VLT), U-factor and efficacy. Other important window terminology includes window-wall ratio (WWR) and projection factor (PF).

- **Solar heat gain coefficient (SHGC)** is the ratio of solar heat gain entering a space through the fenestration area to the incident solar radiation. Solar heat gain includes directly transmitted solar heat and absorbed solar radiation, which then enters the space through reradiation, conduction or convection.

  A window that allows no solar gain would have an SHGC of zero, while perfectly transmissive glazing would have an SHGC of 1.0 (these extremes are both theoretical and are not possible in the real world). **In Hawaii, glazing materials should be selected with the lowest possible SHGC.** However, some glazing materials with a low SHGC (like dark gray and bronze tints) may also have a low visible light transmittance (VLT). The challenge is to identify spectrally selective low-emissivity (low-e) products and blue or green tints that combine the lowest SHGC with the highest VLT.

- **Visible light transmittance (VLT)** is the ratio of visible light transmitted through the glazing to the total amount of light that strikes the glass. Single-pane clear glass has a VLT of about 0.9, while highly reflective glass can have a VLT as low as 0.05. In general, VLT should be as high as possible to allow more daylight inside, as long as it does not create glare or other visibility problems.

- **U-factor** measures the heat flow through a window assembly due to the temperature difference between the inside and outside (U-factor = 1/R-value). The lower the U-factor, the lower the rate of heat loss and of heating energy consumption. However, U-factor is more critical in areas that have very hot summers or cold winters. **In Hawaii, where the weather is not extremely hot or extremely cold, low SHGC is more important than low U-factor.**
- **Efficacy** is the ratio of VLT to SHGC. The higher the efficacy, the better the fenestration product is at allowing daylight in and reducing solar gain.

  Glazing materials with a high efficacy are known as **"spectrally selective"** because they selectively transmit radiation in the visible portion of the spectrum while blocking solar radiation in the ultraviolet and infrared spectra. Spectrally selective products typically have a VLT to SHGC ratio greater than 1.3.
- **Window-wall ratio (WWR**) is the ratio of window area to the exterior wall area.
- **Projection factor (PF**) is the ratio of an overhang's horizontal projection to the vertical distance from the windowsill to the bottom of the overhang. The overhang projection is measured as the perpendicular distance from the window surface to the overhang's outside edge.

NFRC Rating

The National Fenestration Rating Council (NFRC) has established a rating system to evaluate the whole window performance of manufactured windows, including the frame, spacer and glazing. The whole-window SHGC, VLT and U-factor are shown on a label attached to all rated windows. Site-built windows and skylights will not have these ratings. For more information, visit the NFRC's Web site, www.nfrc.org.

Solar Control Glazing

As mentioned above, in Hawaii the most important glazing characteristic for windows is low solar heat gain coefficient. A low SHGC can be provided through several different technologies:

- **Heat-absorbing tints.** These tints are available in a range of colors. Some tints, typically blue or green, offer better visible light transmittance while providing equal or better solar control than gray or bronze tints. Consider using these blue or green tints in daylighting designs. All heat-absorbing tints get hot in direct sunlight, which is an important concern in buildings where occupants work close to windows.
- **Heat-reflecting coatings (including low-e).** Several types of coatings are available. Some appear mirrorlike, while others are designed to reflect as much heat as possible while also appearing as clear as possible. The latter type of coating is called “spectrally selective” and is a better choice for simultaneously providing daylight and solar control.

  Some — but not all — of these heat-reflecting coatings will have low-emissivity (low-e) properties. Low-e coatings reduce the radiant heat transfer between two surfaces, for example from one pane to the other in a double-pane glazing. Low-e coatings improve a window’s insulation value (lower U-factor), but in Hawaii, SHGC is a much more important concern. Therefore, when specifying a heat-reflecting window, it’s not adequate to specify a low-e window; **it’s critical to specify the desired SHGC and VLT.**

  Be aware that not all low-e windows have a low SHGC. There are several types of low-e coatings: some reduce solar gain while others allow solar gain. Low-e coatings that allow solar gain are not desirable in Hawaii.

  Often these heat-reflecting coatings are applied to one of the surfaces facing the air gap in a double-pane window. This is necessary to protect the coating from scratches that might occur if it were exposed. While it wouldn’t normally be cost effective to add a second pane of glass in Hawaii, double-pane windows are necessary if you want the performance benefits of higher performance coatings.
- **Laminates.** Either heat-absorbing or heat-reflecting plastic film can be sandwiched between two sheets of glass to create a single pane. To provide further solar control, heat-absorbing glass can be used. Laminated glazing provides stronger resistance to lateral forces and is recommended in hurricane-prone areas.
- **Retrofit films.** Plastic films similar to those used to create laminated glass can be applied to the surface of the glass. This should be considered only as a retrofit measure because the exposed film is not as durable as glass.

Glazing types and their properties

Table 5-1 compares the performance and relative costs of a range of representative glazing types, from basic single-pane clear glass to high-performance double-pane glass. Table 5-2 describes some of the advantages and disadvantages of these glazing types. All glass types in these two tables are intended as examples; they don’t refer to a particular manufacturer’s product.

Table 5-1. Glazing types and their properties. Shows typical performance values. These values may vary slightly among manufacturers.

Glass Type[a]	**SHGC**	**VLT**	**U-factor**	**Efficacy**	**Relative Cost[b] ($/ft²)**
Single Clear	0.82	0.88	1.09	1.08	---
Single Tinted (gray tint)	0.59	0.43	1.09	0.73	0.68
Single High-Performance Tinted (green or blue tint)	0.50	0.66	1.09	1.32	1.86
Single Reflective (medium reflectance)	0.55	0.39	1.09	0.71	1.69
Single Reflective (high reflectance)	0.25	0.13	0.91	0.52	3.18
High-Performance Laminated Clear	0.45	0.71	1.06	1.58	9.17
High-Performance Laminated Clear Low-e	0.38	0.63	0.71	1.66	10.67
Double Clear	0.70	0.78	0.48	1.12	5.10
Double Tinted	0.47	0.38	0.48	0.81	5.78
Double High-Performance Tinted	0.38	0.58	0.48	1.55	6.96
Standard Double Clear Low-e[c] (lowest SHGC)	0.36	0.47	0.31	1.32	8.28
Standard Double High-Performance Tinted Low-e[c] (lowest SHGC)	0.22	0.35	0.31	1.63	10.14
Premium Double Clear Low-e[c] (highest efficacy)	0.38	0.70	0.31	1.87	8.28
Premium Double High-Performance Tinted Low-e[c] (highest efficacy)	0.27	0.53	0.31	2.00	10.14

Notes:

(a) All values are COG, based on 1/4-in. thick glass. Double-pane alternatives have 1/2-in. air gap.
(b) Relative cost column shows approximate incremental increase in cost compared to single-pane clear glass.
(c) Some manufacturers offer many different types of low-e coatings, with a range of SHGC and VLT values. The four low-e glazings listed here represent two generic categories: "standard" refers to a low-e coating with very low solar heat transmission, while "premium" refers to a low-e coating with relatively low heat transmission but much higher light transmission (better efficacy).

Table 5-2. Advantages and disadvantages of representative glazing types.

Glass Type	Description	Advantages	Disadvantages
Single Clear	Single layer of glass. Recommended only for well-shaded windows.	Lack of tinting allows good color rendition.	Allows a lot of direct solar radiation into the space. Poor thermal performance (high SHGC).
Single Tinted	Single layer of tinted glass (blue, green, gray, bronze, etc.). Green and blue are preferable to gray and bronze. Not recommended for unshaded windows.	Relatively inexpensive. Can improve visual comfort by reducing glare. Green and blue tints have relatively high efficacy.	Gray and bronze tints have relatively low efficacy, so they reduce visible light more than they reduce overall heat gain. Tinted glazing is less desirable if it's important that views are not altered by tinting. Tinted glazing gets hot when the sun strikes it so may be uncomfortable for people next to it.
Single High-Performance Tinted	Some manufacturers offer higher performance blue or green tinted glazing. These are similar to standard single-pane tinted but the tint transmits more visible light and less visible heat. These high-performance tints usually range from light green to light blue.	Relatively high efficacy. Lower cooling load impact and relatively affordable price. More expensive than standard single tinted but much less expensive than double-pane low-e glass.	Views are not rendered in true color, although the tinting is lighter than with standard single-pane tinted. SHGC still somewhat higher than the best performing glazings.
Single Reflective (medium reflect-ance)	Special coating reflects much direct solar energy.	Relatively low SHGC.	Mirrorlike appearance causes excessive glare outside. Low efficacy. Low VLT makes it a poor choice for view windows or daylighting.
Single Reflective (high reflect-ance)	Similar to single reflective–medium but reflects a higher percent of incident solar radiation.	Lower SHGC than single reflective–medium.	Mirrorlike appearance causes excessive glare outside. Very low efficacy and VLT. The light-to-heat-gain ratio makes it one of the worst choices for daylighting.

Continued -->

Glass Type	Description	Advantages	Disadvantages
High-Performance Laminated Clear	Special heat-reflecting plastic film sandwiched between two sheets of clear glass to create a single pane.	High efficacy. Good daylighting performance. Can provide similar performance to high-performance tinted glass without the green or blue color cast. Provides the typical penetration resistance of standard laminated glass, with better energy performance.	Relatively expensive. Laminated glass may require more careful handling during installation to prevent cracking.
High performance Laminated Clear Low-e	Similar to high-performance laminated clear glazing but one of the panes of glass has a spectrally selective low-e coating.	Even higher efficacy and lower SHGC than the non-low-e laminated alternative (above). Very good daylighting performance.	Relatively expensive. Laminated glass may require more careful handling during installation to prevent cracking.
Double Clear	Two sheets of clear glass separated by a gap filled with air or gas (such as argon). Depth of gap typically varies from 1/8 in. to 1/2 in.	Has lower U-factor and somewhat lower SHGC than single-pane clear.	In Hawaii, the performance improvements over single-pane clear glazing are not worth the cost of adding an extra pane of glass. Lower U-factor is not a major benefit in Hawaii.
Double Tinted	Similar to double clear glazing, with one pane (typically the exterior) tinted. Generally not recommended in Hawaii.	Lower SHGC than double clear glazing.	Worse efficacy than double clear glazing.
Double High-Performance Tinted	High-performance tint on outer layer of glass. Generally not recommended in Hawaii.	High efficacy. Typically cheaper than double low-e glazing.	In Hawaii, the extra expense of adding a second pane isn't worth the improvement in performance.

continued -->

Glass Type	**Description**	**Advantages**	**Disadvantages**
Standard Double Clear Low-e[(a)] (lowest SHGC)	Double-pane glazing with a low-e coating typically on the inner surface of the outer pane. Premium low-e (see below) is typically a better choice because of its enhanced daylighting performance. But for larger glass areas, standard low-e would be a better choice than the highest efficacy low-e coating because higher VLT wouldn't be as important.	Low SHGC and high VLT.	Similar SHGC but lower efficacy than premium low-e glazing. Expensive. Sacrifices some efficacy.
Standard Double High Performance Tinted Low-e[(a)] (lowest SHGC)	Outer pane has high-performance tint and low-e coating on inner surface; separated from inner clear glass pane with 1/2-in. air gap. Different thicknesses of glass and air gap are available.	Very low SHGC. Relatively good efficacy.	May not be very cost effective.
Premium Double Clear Low-e[(a)] (highest efficacy)	Same type of glass as standard double clear low-e (lowest SHGC), but with better thermal and daylighting performance.	Excellent efficacy. In general, best daylighting performance.	For large glass areas, the standard double-clear low-e might be a better choice because it has lower SHGC and high enough VLT.
Premium Double High Performance Tinted Low-e[(a)] (highest efficacy)	Same type of glass as standard double high-performance tinted low-e, but with better thermal and daylighting performance.	Excellent efficacy. In general, best daylighting performance.	For large glass areas, the standard double high-performance tinted low-e might be a better choice because it has lower SHGC and high enough VLT.

Notes:

(a) Some manufacturers offer many different types of low-e coatings, with a range of SHGC and VLT values. The four low-e glazings listed here represent two generic categories: “standard” refers to a low-e coating with very low solar heat transmission; while “premium” refers to a low-e coating with relatively low heat transmission but much higher light transmission (better efficacy).

General Principles of Window Design

Recommendation

To achieve high-performance window design, choose a combination of building orientation, shading, window area and glass type that maximizes daylighting while minimizing heat gain.

- **Orientation.** Proper orientation is the most important strategy. Whenever possible, limit the amount of window area on the east and west facades. Sunlight is easier to control on the north and south sides of a building.
- **Exterior Shading.** A designer's first choice should be to minimize the amount of direct solar radiation that reaches the windows. If direct sunlight can be kept off the windows, then inexpensive clear or lightly tinted glass can be used.

  Overhangs are typically the best choice for keeping sunlight off the windows, and are especially effective on the north and south facades. The combination of overhangs and vertical fins can nearly eliminate direct solar gain for most of the year. See the Exterior Overhangs and Side Fins Guideline for details.

  Operable exterior shades are another option. They are particularly useful where it's difficult to provide complete shading with overhangs or fins. The operable shades could be automatically controlled in response to the sun's position or manually adjusted to shade the window at different times of the year.
- **Interior shading.** Interior shades such as blinds and drapes provide some reduction in heat gain, but are not nearly as effective as exterior shades. Consider using interior shades on east- and west-facing windows where it's difficult to provide exterior shading throughout the day. See the Design Details section later in this General Principles section for more information about interior shading.
- **Combination of size and glazing type.** There's no single best combination of window size and glazing type. The optimum design will allow enough light transmission to provide good daylighting and adequate views while admitting no more solar heat than necessary. The energy, peak cooling load and lifecycle cost graphs in this chapter can be used to evaluate designs employing various window sizes and glass types.

- **Glazing performance.** If it is not possible to completely shade the windows from direct sunlight, then solar-control glazing should be specified. In Hawaii, select glazing materials with a low solar heat gain coefficient and a high visible light transmittance. Consider "spectrally selective" low-emissivity (low-e) products and blue or green tints that combine low SHGC with high VLT. Remember that in Hawaii, high SHGC is much more important than low U-factor.

Description

Well-designed, energy-efficient windows can reduce the overall building cooling loads. They can also deliver enough dependable daylight to reduce electric lighting loads, if manual or automatic controls are used to turn off the electric lights when not needed.

Applicability

Windows are essential in most commercial buildings (except in spaces requiring visual privacy) to provide relaxing views and information about exterior natural conditions, to allow people outside of a space to view and connect with activities inside, and to allow in daylight. They should be planned for in the schematic design phase.

Codes and Standards

The Hawaii Model Energy Code does not require that view windows or skylights be installed.

The code limits the maximum Relative Solar Heat Gain factor (RSHG) for various window-wall ratios for windows. There are different limits for north-facing and non-north facing windows. The RSHG factor is a function of the shading coefficient of the glazing (shading coefficient is similar to SHGC; see the code for a definition) and the exterior shade screens and/or louvers, interior shading devices, overhangs and fins. Individual windows may exceed the maximum RSHG limit as long as the area-weighted average RSHGs for both north and the combined east, west and south orientations are less than or equal to the maximum limit. Most buildings require window shading or tinted glass in order to comply with the code.

Benefits

Energy-efficient window design reduces solar heat gain while offering high visible light transmittance to allow more daylight inside. Benefits include:

- Smaller and less expensive air conditioning equipment required
- Lower cooling energy cost
- Lower lighting energy cost

- Potentially better dehumidification performance from the air conditioning system because there is less variability in the space's cooling loads, and because the AC system can be smaller and run at a more constant capacity (See the Dehumidification Guidelines for details).

Costs

Clear single-pane glass is generally the least expensive type of glazing. Solar control options such as tints and low-e coatings typically add some cost. Approximate incremental costs are listed in Table 5-1 above.

Cost Effectiveness

The lifecycle cost of window design options is described in the Integrated Design Implications section below.

Integrated Design Implications

Energy Impact of Windows

Windows have a significant impact on energy consumption in a building's perimeter spaces. The most direct impact is on cooling and fan energy for air conditioning.

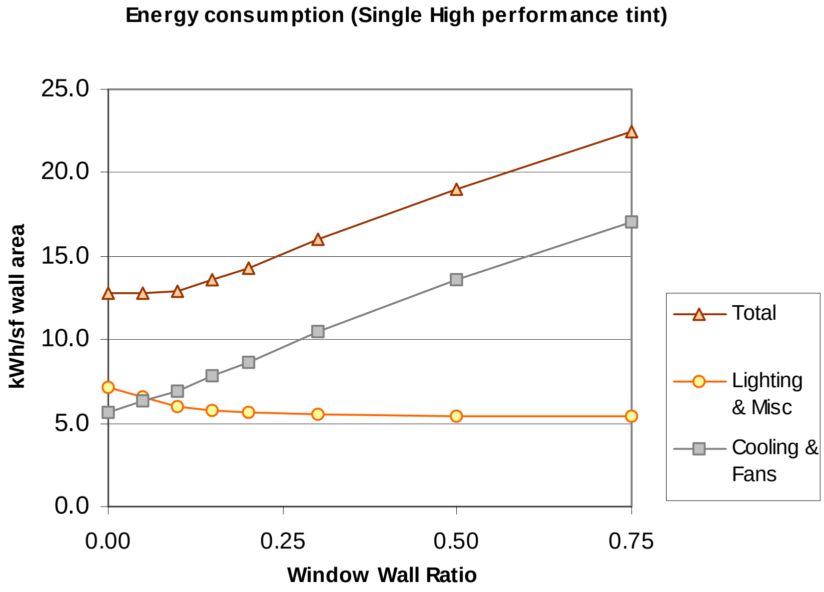
If the windows are properly designed and the lighting system is well controlled, windows can eliminate or reduce the need for lighting energy during the day by providing daylight.

The energy consumption, peak cooling load and lifecycle cost graphs in this chapter can be used to evaluate window options. They are based on a typical office building with manual or automatic daylighting controls in the perimeter spaces, operating five days a week for normal business hours (8 AM to 5 PM).

Impact of WWR on energy consumption. Figure 5-1 shows the effect of window-wall ratio on energy use for a south-facing window with high-performance tinted glazing (without any shades). In this example, as WWR increases from 0% to 75%, air conditioning energy rises steadily while lighting energy drops initially and then levels off. Total energy consumption drops slightly at first while the lighting savings dominate; then total energy use rises as lighting savings level off and air conditioning energy continues to rise.

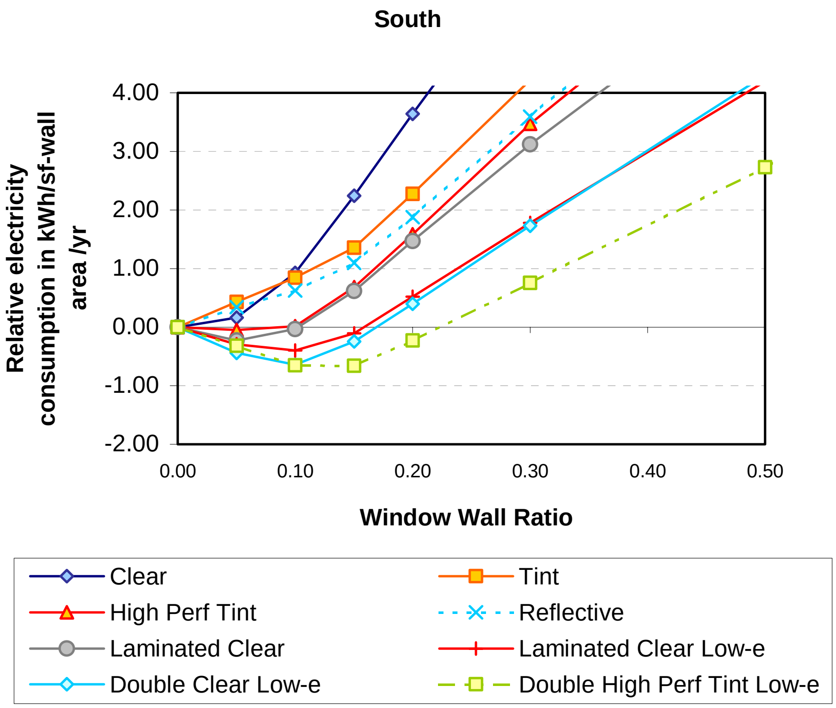
In this particular example, total energy use doesn't rise until WWR reaches about 15%. These results will vary depending on orientation and glass type; the graphs later in this section and in the Windows Performance Data section provide more information for evaluating eight different orientations and a range of glass types.

Figure 5-1. Impact of WWR on energy consumption for a south-facing window with high-performance tinted glazing.



Impact of glazing type on energy consumption. Figure 5-2 provides another perspective on the energy impact of windows: it compares the energy consumption of several types of glass for a south-facing window without interior or exterior shading devices. For a WWR of less than 10%, the lowest energy consumption occurs with double-pane clear glazing with a low-e coating. For larger window areas, the double-pane high-performance tinted low-e glazing is most efficient.

Figure 5-2. Impact of WWR on total electricity consumption for various glazing types (south-facing window). Electricity consumption is relative to having no windows at all (i.e., negative value means that electricity consumption is lower with window than without).



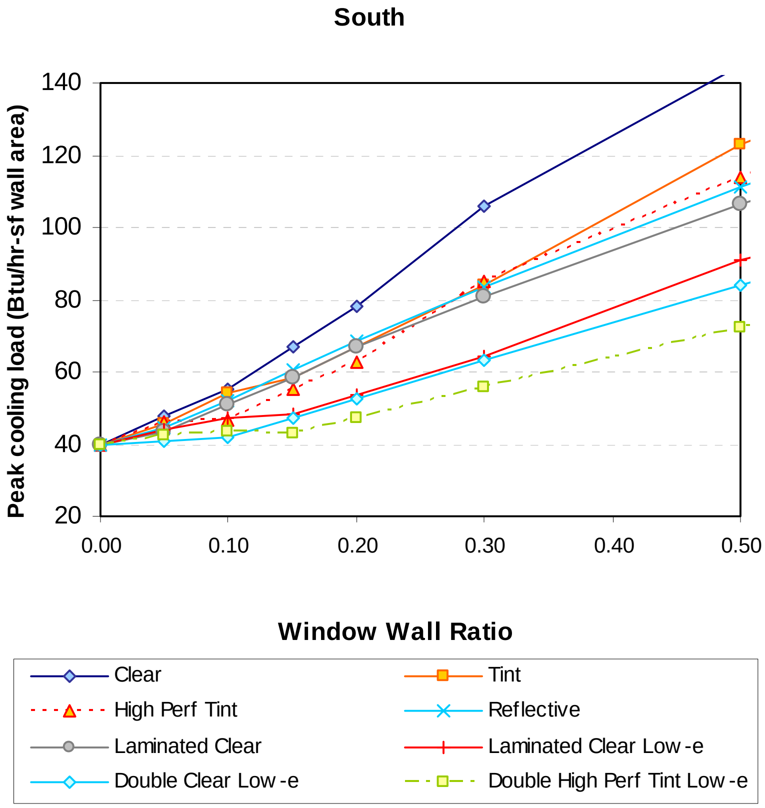
Impact of Windows on AC Sizing

Solar heat gain can account for the majority of the cooling load in perimeter spaces with windows. By using windows with solar control, it may be possible to reduce the size of the air conditioning equipment; this equipment savings, in turn, can help offset some of the additional cost of the windows.

Figure 5-3 shows how the peak cooling load in the perimeter zone increases as the window area increases. It also shows the relative impact of various glass types on peak cooling load. In general, glazing types with the lowest SHGC will have the least impact on peaking cooling load. But with small window areas, a higher VLT will be important because it allows electric lighting to be turned off, eliminating the lighting load.

Figure 5-3 shows that for a south-facing window with no interior or exterior shading devices, double-pane low-e clear glass has the lowest impact on peak load, up to a 12% WWR. Above that point, double-pane glazing with a high-performance tint and low-e coating has the least impact on peak load.

Figure 5-3. Impact of WWR on peak cooling load for various glazing types (south-facing window).



Impact of Windows on Lifecycle Cost

Window design affects both a building's construction cost and its operating cost, which makes it challenging to select the most cost-effective combination of glass type and window area.

Figure 5-4 shows the lifecycle cost (initial purchase and installation cost plus operating costs over the building's lifetime) of a single-pane, high-performance tinted window that faces south and has no interior or exterior shades. The results are presented as cost per square foot of wall area. Energy and cooling system costs apply to the corresponding indoor perimeter space. The four components of this lifecycle cost calculation are:

- **Wall & window cost.** With zero window area, the cost is assumed to be $10/ft² of wall (actual cost will vary depending on construction type). As the window area increases, glazing displaces a fraction of the wall and the cost increases proportionately because windows are assumed to cost $15/ft² for baseline clear glass. When glass accounts for 50% of wall area, the wall and window cost is $12.50 per square foot.

- **HVAC system cost.** Figure 5-4 assumes that the cooling system costs $1,200 per ton of cooling capacity. The system cost increases as window area increases.
- **Other energy.** In Figure 5-4, "other energy" refers to lighting and plug loads (but not cooling or fan energy). This cost component drops as the window area increases. The lifecycle energy cost is based assumptions of $0.12/ kWh for electricity, inflation of 3%, a discount rate of 10% and a lifetime of 25 years.
- **HVAC energy.** As shown in Figure 5-4, cooling energy increases with window area. Economic assumptions are the same as for "other energy."

Figure 5-4. Impact of WWR on lifecycle cost (south-facing window, single-pane, high-performance tinted glass).

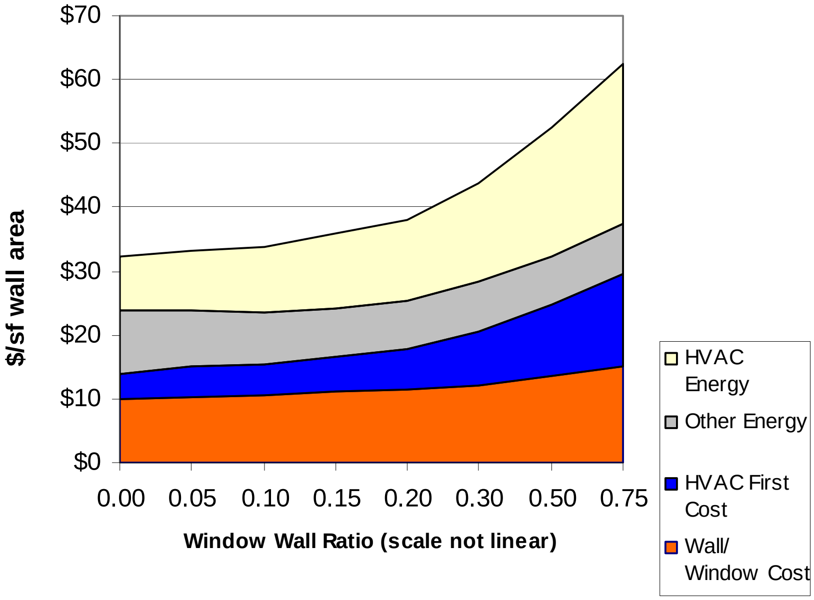


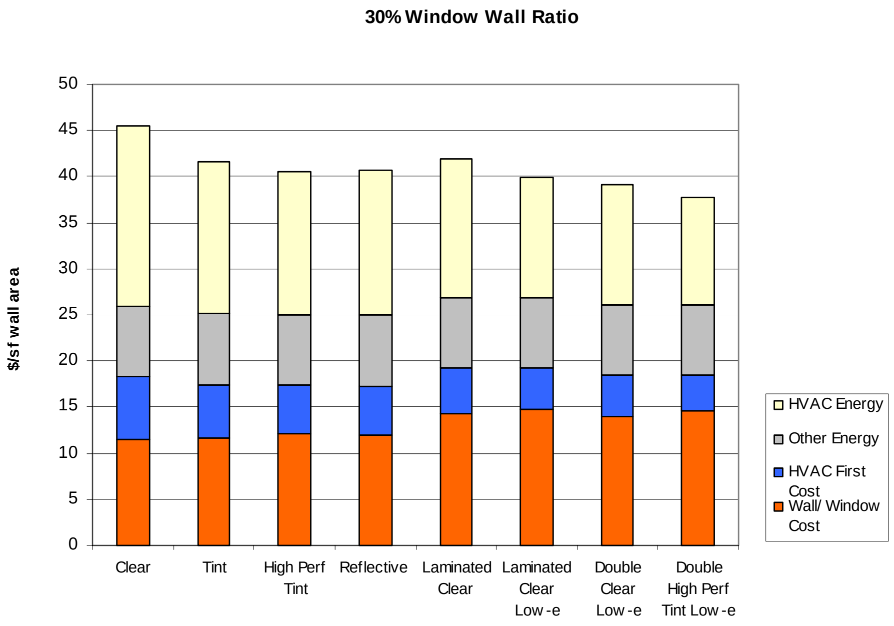
Figure 5-4 shows the lifecycle cost for one case: single-pane, high-performance tint in a south-facing window. The "other energy" decreases gradually until the WWR reaches about 0.20, while the other components of lifecycle cost increase slightly. The net result is a gradual increase in the lifecycle cost up to about 0.20 WWR.

As the WWR increases beyond this point, lighting energy levels off but cooling energy, cooling system cost, and wall and window cost all continue to increase, resulting in a substantial increase in the lifecycle cost. When the WWR reaches 0.50, the lifecycle cost is just over $50/ft² of wall area.

In this example, it appears that the most cost-effective design will have no windows at all. That will sometimes be the result when only construction and operating costs are considered. There are, of course, other factors that influence window design beyond the direct economic impacts, as discussed at the beginning of this chapter. Aesthetics, views, and the productivity and health benefits associated with daylighting are also important. The ideal design should meet aesthetic, social, comfort and other goals while also optimizing the lifecycle cost of the building.

Lifecycle costs can be used to help select the optimal glass type. Figure 5-5 plots the total lifecycle cost for several glazing options at a WWR of 0.30. In this case, for a south-facing window, double-pane, high-performance tinted, low-e glass offers the lowest lifecycle cost. But the best choice for glazing will vary with window orientation and WWR (see the Windows Performance Data section for graphs showing the lifecycle costs for other window-wall ratios and orientations).

Figure 5-5. Impact of glazing type on lifecycle cost (south-facing window, 0.30 WWR).



Integration with Natural Ventilation

Operable windows can potentially reduce the number of hours the cooling equipment operates if natural ventilation is used to cool the building when the outdoor environment is favorable. See the Natural Ventilation chapter for details.

Visual Comfort

Many aspects of window design will affect the occupants' visual comfort, including the glazing type, window location, position of the sill height relative to floor height, and the distribution of windows. Uniform illumination and lack of glare also contribute to good visual comfort. The Daylighting chapter provides guidelines for designing windows and skylights to reduce glare and achieve good visual comfort.

Resource Efficiency Issues

In addition to affecting energy use, the fenestration system — combined glazing and framing — has other environmental impacts, including resource use, indoor air quality, and pollution created during manufacturing or disposal. However, data comparing the cradle-to-grave lifecycle impacts of various fenestration systems is difficult to come by. When considering framing and sash options, the best environmental performance strategy is to select durable frame and sash options that enhance energy performance and meet programming and daylighting needs.

Table 5-3 describes some of the environmental benefits and considerations of various framing options.

Table 5-3. Strategies for selecting resource-efficient window frames and sashes.

Frame and Sash	**Strategies**	**Environmental Considerations**
Wood	Select windows produced with wood certified by Forest Stewardship Council.	Certified wood prevents degradation to forest and wildlife habitat. Wood can be high maintenance. Good energy performance.
Finishing coat	Specify factory-applied finish.	More durable than field-applied. Controlled finishing environment reduces pollution.
Wood and Plastic Composite	Durable options combine wood fiber, post-consumer waste plastic, recycled PVC scrap, virgin PVC, or recycled wood scrap.	Uses waste, stretching the wood supply. Very durable. Low maintenance. But PVC manufacturing may create pollution. Good energy performance.
Vinyl/PVC	Vinyl frames include foamed PVC insulating core.	Low maintenance. Needs no paint. PVC manufacturing may create pollution. High coefficient of thermal expansion can lead to premature failure of seal. Excellent energy performance.
Fiberglass	Pultruded fiberglass frame members have a hollow profile usually insulated with fiberglass or polyurethane foam.	Durable. Difficult to recycle. Emissions may contribute to indoor air quality problems and manufacture may create pollution. Moderately good energy performance.
Metal	Specify durable, factory-applied finishes: anodized, polyvinlidene fluoride, or siliconized polyester.	Durable. Reduces potential pollution on site. Energy-intensive production. Not the best energy performance.

Source: *GreenSpec: The Environmental Building News Product Directory and Guideline Specifications.* For specific product recommendations, see *GreenSpec* (www.buildinggreen.com) or OIKOS's *REDI Guide* (www.oikos.com).

Design Details

Energy Impact of Exterior Shading

This section provides an overview of important details to consider when designing windows with exterior shading devices. For an in-depth discussion of exterior shading, see the Exterior Overhangs and Side Fins Guideline later in this chapter.

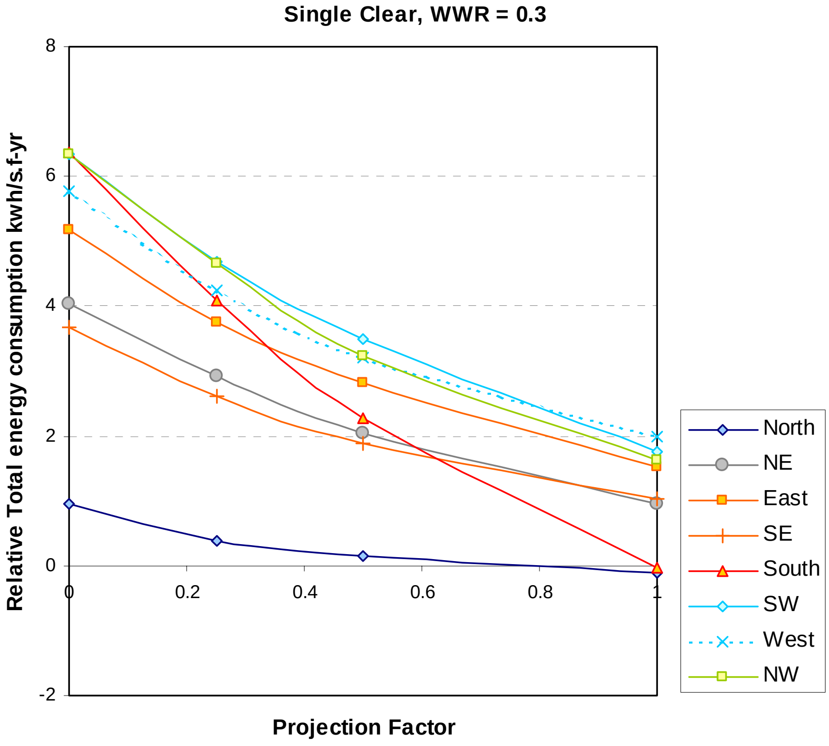
Exterior shading devices such as horizontal overhangs and vertical side fins can significantly reduce overall energy consumption and peak cooling load. For reducing solar heat gain, **overhangs are most effective on the south side of a building. On the north**

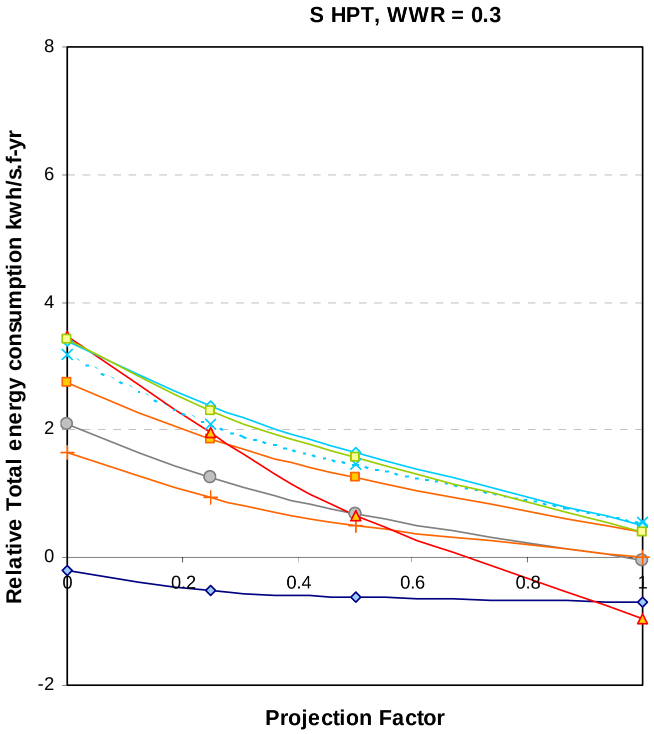
side, a small overhang combined with sidefins provides very effective shading. Overhangs have the greatest impact when used with single-pane, clear glass, and a relatively small impact when used with windows that have high-performance tint and low-e coating.

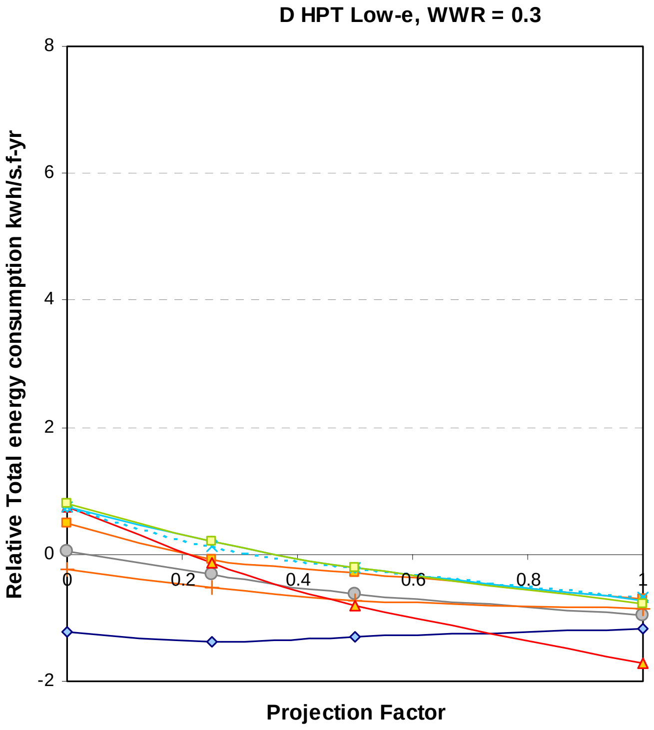
Figure 5-6 illustrates the effect that an exterior shading device's projection factor has on energy consumption for three different glazing types: single-pane clear, single-pane high-performance tinted, and double-pane high-performance tinted. The magnitude of the impact, especially on peak cooling loads, is proportional to the depth of the projection factor; in other words, the deeper the overhang, the more effective it will be at shading the window. Note that exterior shading has relatively little impact on north windows, while it can save a significant amount of energy when used with south windows.

See the Exterior Overhangs and Side Fins Guideline for details on choosing the most cost-effective glazing type by orientation and window-wall ratio.

Figure 5-6. Impact of overhangs on energy consumption for three types of glass (0.30 WWR). Zero relative energy consumption equals no windows.




S HPT, WWR = 0.3
Relative Total energy consumption kwh/s.f-yr
8
6
4
2
0
-2
0
0.2
0.4
0.6
0.8
1
Projection Factor

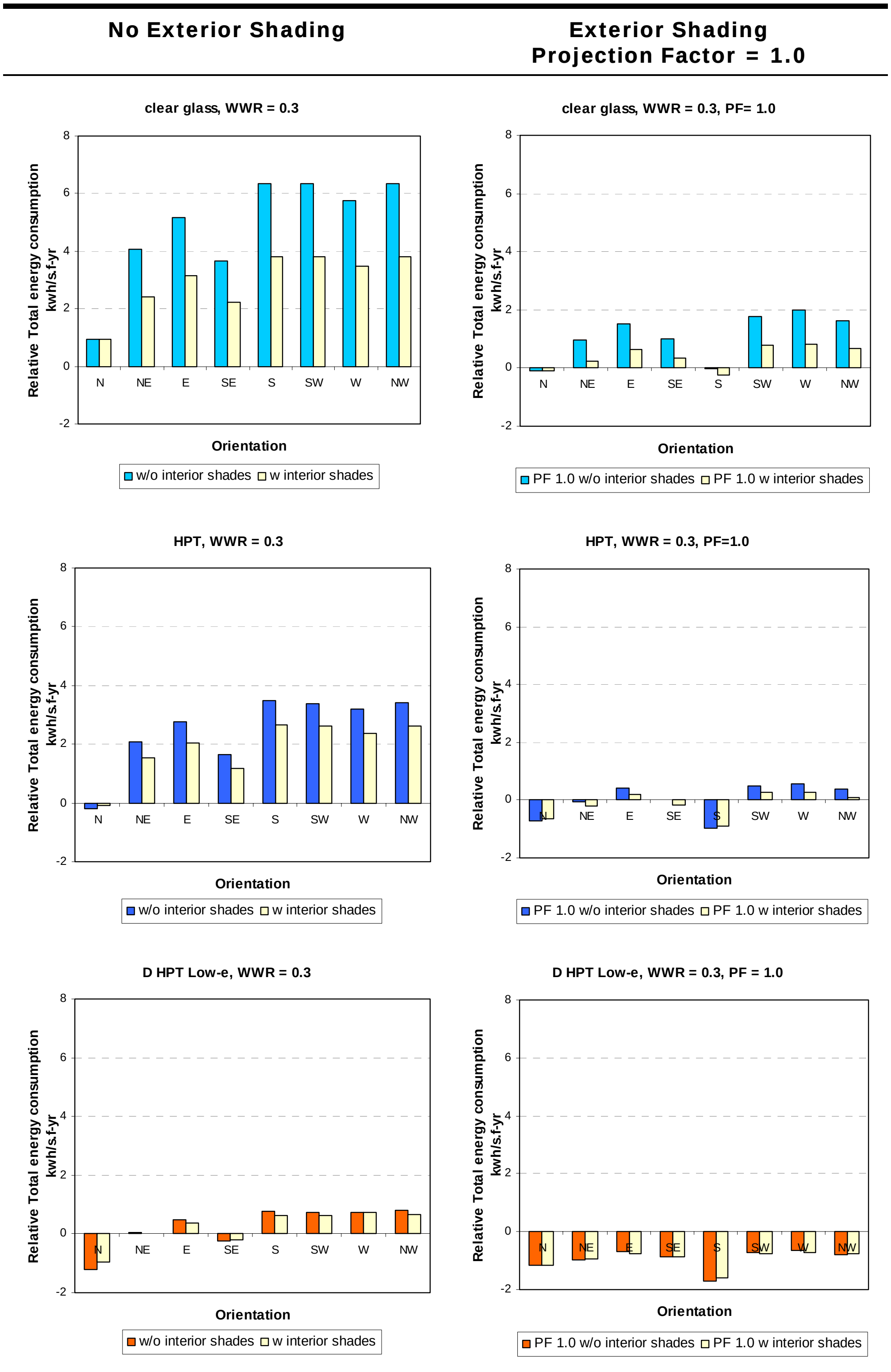

D HPT Low-e, WWR = 0.3
Relative Total energy consumption kwh/s.f-yr
8
6
4
2
0
-2
0
0.2
0.4
0.6
0.8
1
Projection Factor

Energy Impact of Interior Shading

Interior shades reduce energy consumption and peak load by blocking excess solar heat gain, although exterior shades are much more effective at blocking heat gain. Interior shades are appropriate for glare control and for east or west orientations where exterior shades may not be able to provide complete protection from the sun. Interior shades generally aren’t necessary on a building’s north side. If windows have fairly deep overhangs, interior shades don’t provide much additional protection from solar heat gain.

When low SHGC glass is used, interior shades may not be useful. As with exterior shading devices, interior shades have the greatest impact on energy consumption when single-pane clear glazing is used and less of an impact when high-performance glazing is used. Figure 5-7 and Figure 5-8 illustrate the impacts of interior shades on relative electricity consumption and peak cooling load.

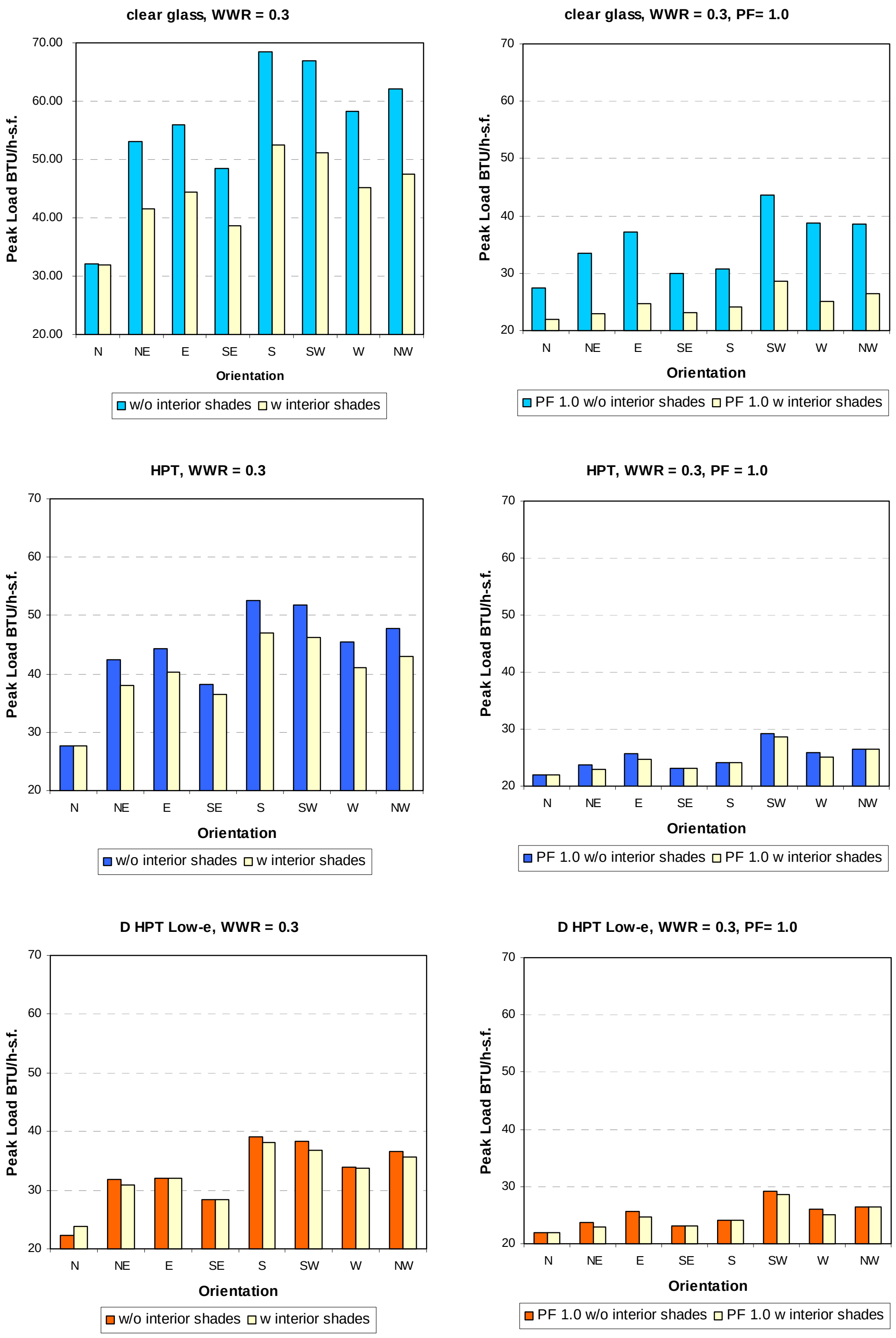
Figure 5-7. Effect of interior shades on ***electricity consumption****. WWR = 0.30. Graphs on the left show windows without exterior shading, while graphs on the right show windows that have overhangs with a projection factor of 1.0.*



Notes: **HPT** = High-performance tint.
D HPT Low-e = Double-pane, high-performance tint with low-e coating.

Figure 5-8. Effect of interior shades on ***peak cooling load.*** *WWR = 0.30. Graphs on the left show windows without exterior shading, while graphs on the right show windows that have overhangs with a projection factor of 1.0.*

No Exterior Shading | **Exterior Shading Projection Factor = 1.0**



Notes: **HPT** = High-performance tint.
D HPT Low-e = Double-pane, high-performance tint with low-e coating.

Design and Analysis Tools

Computer simulation programs such as DOE-2.1E can be used to evaluate the impact of various window designs on a building's cooling and lighting loads. Window 4.1 can be used to determine the SHGC, light transmission and surface temperatures of custom combinations of glass types.

An overhang's shadow can be cast manually with a physical scale model, or computer programs can be used to predict the shading. Lightscape and Desktop Radiance can be used to study the daylighting effects of shading devices such as overhangs and side fins. Solar-2, a free program available online, plots sunlight penetration through a window for any combination of fins and overhangs (available at www.aud.ucla.edu/energy-design-tools).

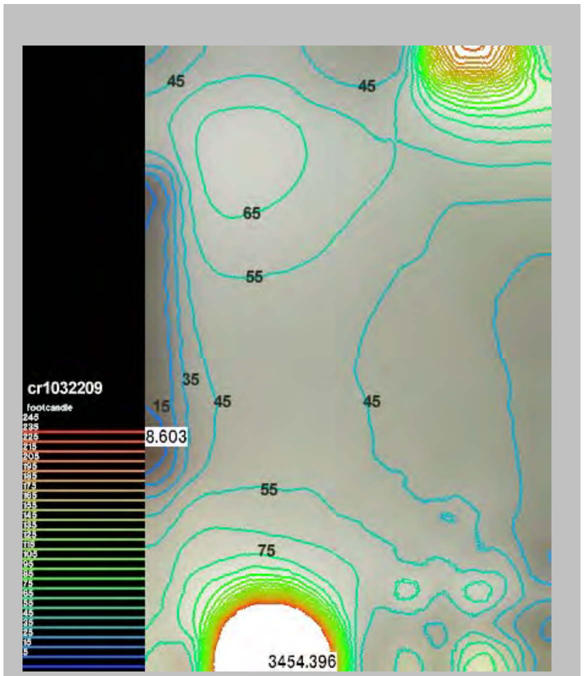


Figure 5-9. Radiance plot showing illuminance level at desk height in plan view (overhead view). Source: Eley Associates.

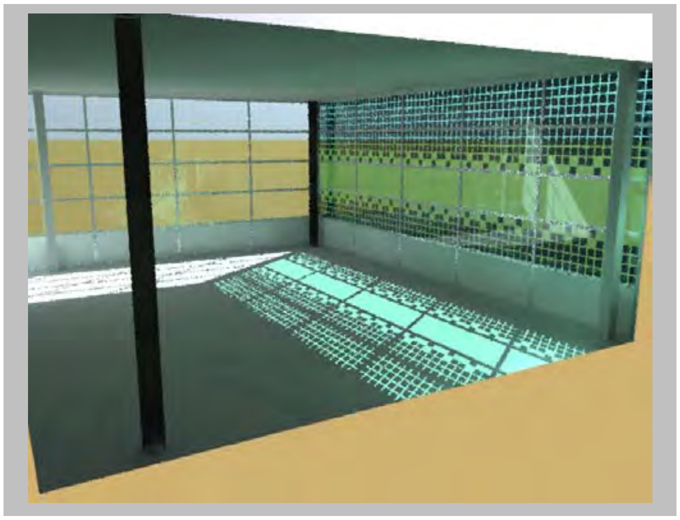
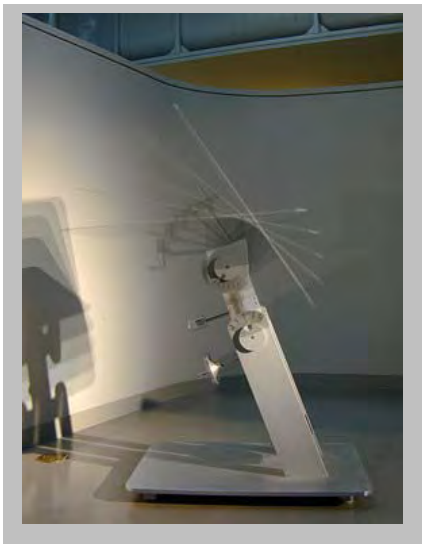


Figure 5-10. Radiance image showing three-dimensional view of corner window for a specific time and day. Source: Eley Associates.

Figure 5-11. Heliodon. Photo: Robert Marcial, Pacific Energy Center.



A heliodon can be used to simulate sunlight penetration and shading for a physical scale model of a building. A heliodon is an articulated table that can be adjusted to simulate the position of the sun at any time of the year for any latitude.

A heliodon is available at the University of Hawaii's Manoa campus.[1] For a more detailed discussion of daylighting simulation tools, see the General Principles for Daylighting Design Guideline in the Daylighting chapter.

Utility Programs

To take advantage of any existing opportunities for energy-efficient windows incentives, contact your utility company representative as early as possible in the design process.

Windows Without Exterior Shading

Recommendation

If exterior shading cannot be provided, then use glazing with good solar control. Choose the combination of window area, glass type and orientation that provides the lowest lifecycle cost while satisfying other design constraints. Use the energy consumption, peak cooling load and lifecycle cost graphs provided in this section and in the Window Performance Data section to evaluate alternative designs.

Description

For windows that don't have exterior shading devices such as overhangs or vertical side fins, other design details can be manipulated to ensure good solar control. These details include sizing and orienting the windows to minimize direct sun penetration, using interior shading devices such as blinds, and specifying glass with a low SHGC and high VLT.

Applicability

The results in the graphs below apply to most air-conditioned buildings. The analysis is based on office buildings, but results would be similar for most commercial facilities.

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[1] For more information, contact Steve Meder: smeder@hawaii.edu.

Codes and Standards

The Hawaii Model Energy Code sets maximum heat gain limits for windows in new buildings (see the Codes and Standards section in the General Principles of Window Design Guideline).

Benefits

See the General Principles of Window Design Guideline above for a description of the benefits of energy-efficient windows.

Costs

Clear glass is generally the least expensive type of glass; solar control options add some cost. Approximate incremental costs are listed in Table 5-1.

Cost Effectiveness

The lifecycle cost of window design options is described in the Design Details section below.

Integrated Design Implications

Refer to the Energy-efficient Windows Overview and the General Principles of Window Design Guideline above.

Design Details

The following graphs show the energy consumption and lifecycle cost impacts of window design options.

While these graphs may not provide a simple answer to the question of how to optimize a window design, they can be used to evaluate the relative cost impacts of various options.

If the WWR for each orientation cannot be changed, consider choosing the appropriate glazing type based on the lowest lifecycle cost from the following graphs. On the other hand, if the glazing type cannot be changed, you can use the electricity consumption graphs to determine which WWR offers the lowest energy consumption.

The window performance graphs shown in Figure 5-12 are for south-facing windows only. For other orientations, see the Windows Performance Data section.

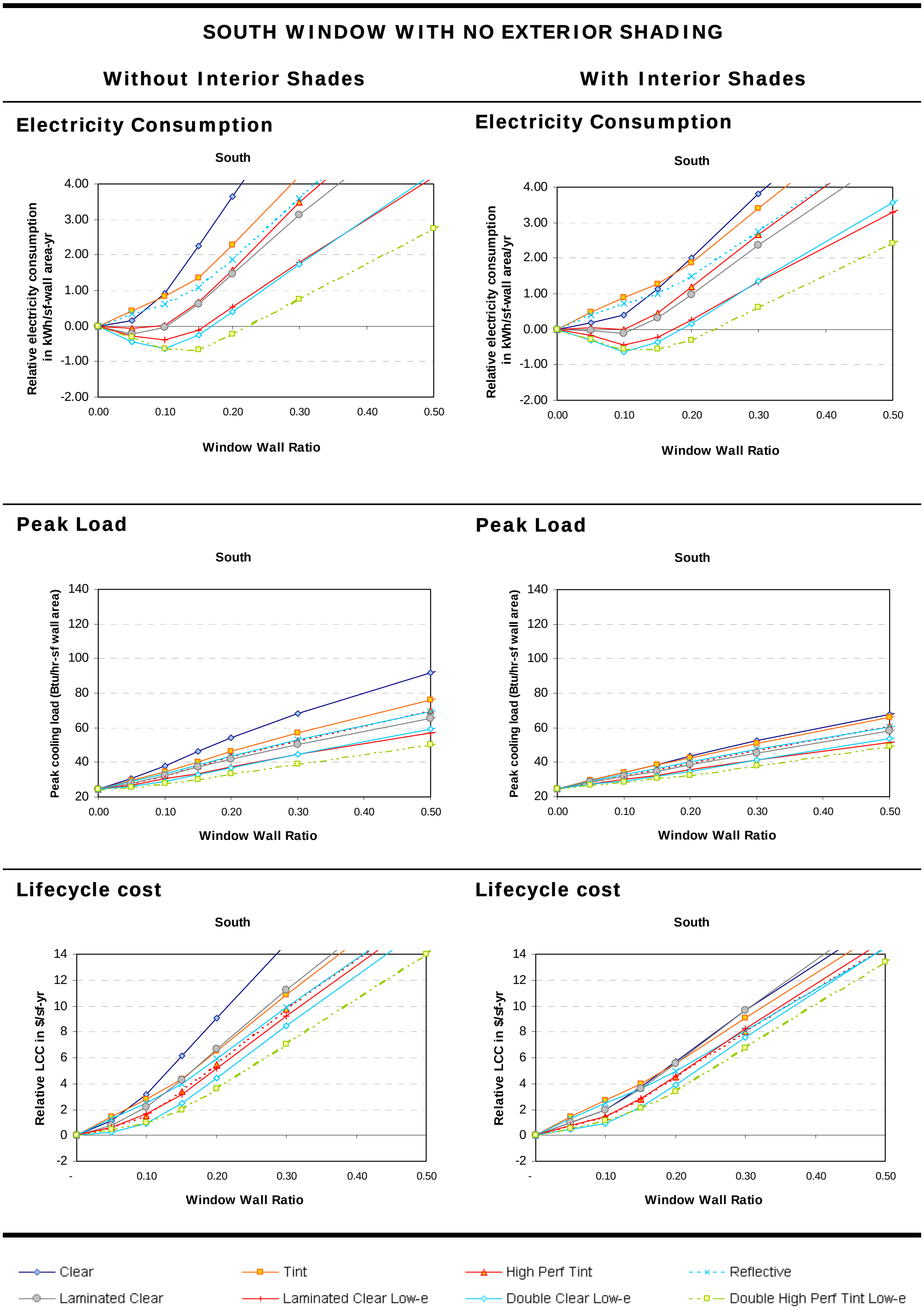


Figure 5-12. Impact of WWR on electricity consumption, peak cooling load, and lifecycle cost, for windows with and without interior shades. ***South-facing window only*** *(see the Windows Performance Data section for other orientations).*

Exterior Overhangs and Side Fins

Recommendation

Use exterior shading devices such as overhangs and side fins to block the direct penetration of sun into a space and to reduce heat gain.

- Exterior shading is most effective on the south side of a building.
- For south facades, horizontal overhangs work better than fins, while east and west facades can use horizontal overhangs, vertical fins or a combination of the two. On the north side, a small overhang combined with sidefins is very effective.
- Exterior shading makes more of a difference when used with clear glass; it has much less of an impact when used with solar-control glazing.
- Consider the daylighting impacts of exterior shading. Elements such as lightshelves can provide shading while also improving daylighting performance. See the Daylighting Guidelines for details on lightshelf design.

Description

Horizontal overhangs, vertical side fins or a combination of these two devices are recommended on the outside of buildings to shade windows and block the direct penetration of sun into a space. Other exterior shading options such as louvers may also be used. While both exterior and interior shading devices help reduce glare and improve visual comfort for the people inside a building, exterior shading devices offer the additional advantage of stopping heat gain before it enters the building.

Applicability

Exterior shading is recommended for windows on all commercial buildings. It will be most cost effective when used with low-rise buildings such as schools and offices, where roof overhangs can provide some or all of the shade. Exterior shading is typically more costly in high-rise buildings, but the same design recommendations apply.

Codes and Standards

The Hawaii Model Energy Code provides compliance credit for overhangs and side fins.

Benefits

Exterior shading devices enhance visual comfort by reducing glare inside a space. If properly designed, they can significantly reduce the cooling load by blocking the sun’s heat from entering the building, while still allowing adequate daylight penetration.

Costs

With new construction, the use of solar shading devices often means that the size of the air conditioning system can be reduced. These equipment savings may offset the cost of the shading devices. In addition, fully shaded windows may mean that less expensive glazing can be used.

Cost Effectiveness

Exterior shading may or may not be cost effective when looked at strictly in terms of energy efficiency. However, there are many other benefits, such as improved visual and thermal comfort near windows and the corresponding increase in usable interior space.

Integrated Design Implications

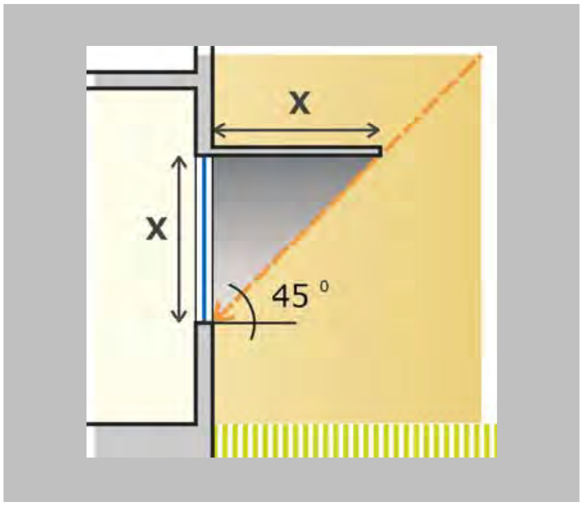
Exterior shading, window orientation and area, and glazing type need to be carefully integrated with the building design to maximize daylight while reducing solar heat gain. For more information, refer to the Integrated Design Implications section of the General Principles of Window Design Guidelines above.

Design Details

In Hawaii, exterior window shades are almost always desirable. However, it is difficult to shade east and west orientations from the early morning and late afternoon sun. In some cases, it may be preferable to use a combination of exterior and interior shades. If exterior shading devices are used with high-performance glazing, interior shades are usually not needed. Interior shades are more effective with glazing types that have a relatively high SHGC.

Cut-off angle. The cut-off angle should be designed to minimize or completely eliminate direct solar penetration. The cut-off angle is the angle formed by a straight line from the edge of the overhang to the bottom of the window (or the inner edge of the next lower overhang in the case of multiple overhangs) and the horizontal plane. In the case of side fins, it is the angle formed by the straight line connecting the outer edge of the fin to the opposite edge of the window (or the inner edge of the next fin in the case of multiple fins) and the normal to the window.

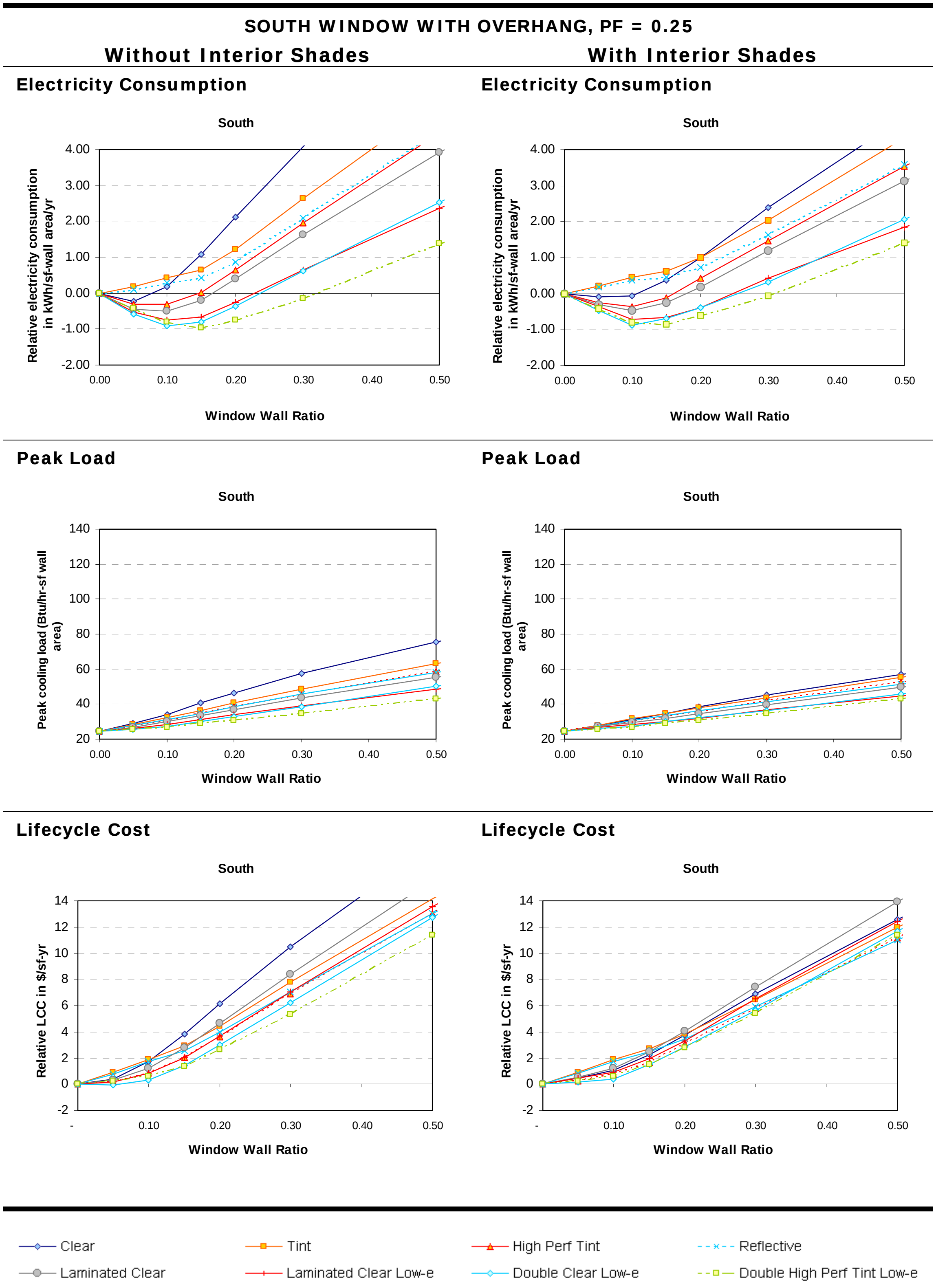
Figure 5-13. Overhang with 45-degree cut-off angle.



Selecting glass type and WWR when you have overhangs. The following sets of graphs (Figure 5-14, Figure 5-15 and Figure 5-16) show the energy and cost impacts for south-facing windows with three overhangs of different depths (projection factor = 0.25, 0.50 and 1.00). Similar graphs showing seven other orientations can be found in the Windows Performance Data section.

As with the graphs in the Windows Without Exterior Shading Guideline, the following graphs can be used to select the glass type and/or window area that minimizes energy consumption or lifecycle cost given a specific overhang size.

Figure 5-14. Impact of WWR on electricity consumption, peak load demand, and lifecycle cost. ***South-facing window. Overhang PF = 0.25.*** *(See Windows Performance Data section for other orientations.)*



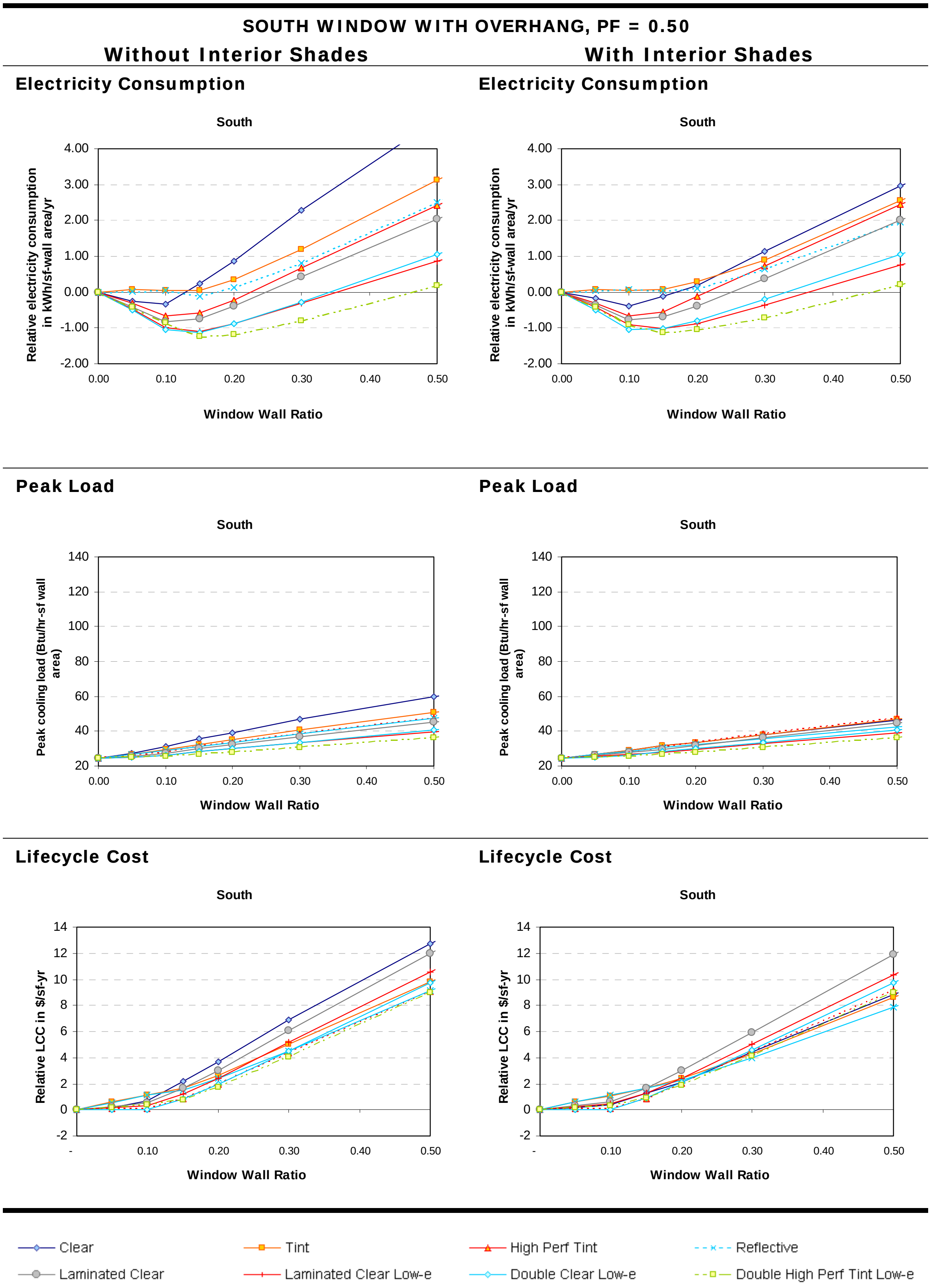
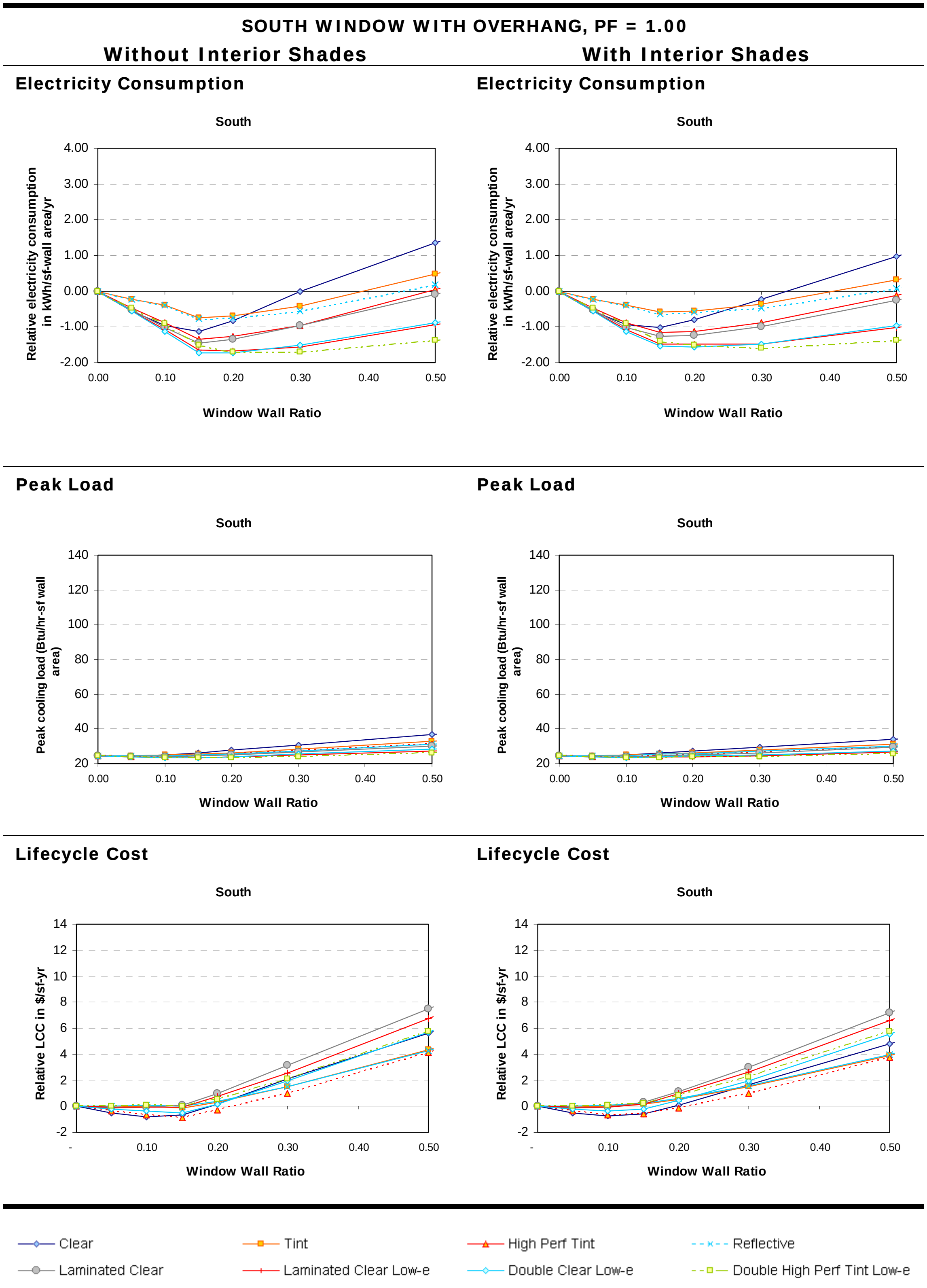


Figure 5-15. Impact of WWR on electricity consumption, peak load demand, and lifecycle cost. ***South-facing window. Overhang PF = 0.50.*** *(See Windows Performance Data section for other orientations.)*

Figure 5-16. Impact of WWR on electricity consumption, peak load demand, and lifecycle cost. ***South-facing window. Overhang PF = 1.00.*** *(See Windows Performance Data section for other orientations.)*



Sizing Overhangs and Fins for Ample Shading

To reduce solar gain and eliminate glare, windows should ideally be shaded during all daylight hours in Hawaii. However, trying to accomplish this can lead to some impractical overhang and fin designs when the sun is low in the sky, particularly for east and west orientations during the early morning and late afternoon.

The overhang and fin designs recommended in this section have been developed to balance an ideal design with one that may be more practical. The following assumptions underlie these recommended designs:

- Solar gain is less of a concern during late December and early January because daytime outdoor air temperatures are lower than at other times of the year. Exterior shade designs shown below provide only partial shade during this period.
- Interior shades can be used to eliminate glare during winter when necessary.
- Normal occupancy hours for a typical commercial building are assumed to be 8 AM to 5 PM. The exterior shade designs shown below will shade the windows completely during these hours for most of the year, except during the period described above.

Figure 5-17 shows the solar path diagram for 20 deg N latitude (for Hawaii). The altitude[2] and azimuth[3] of the sun can be determined using this solar path diagram[4]. Figure 5-18 and Figure 5-19 show shading devices that were designed based on this solar path diagram. A shading mask, indicated by dark gray shading in the solar path diagrams, marks the time of year and time of day when shading is desired (based on the assumptions described above).

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[2] The angle between the rays of the sun and a horizontal plane.

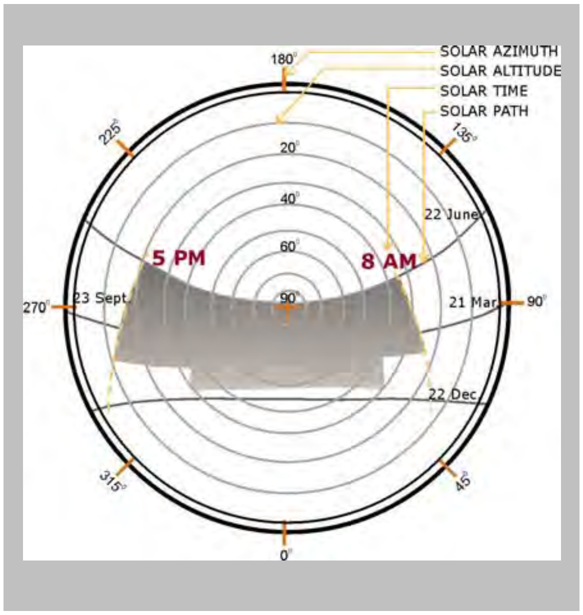
[3] The angle of the sun from true south.

[4] A solar path diagram shows the position of the sun (solar altitude and solar azimuth) for all hours through the year for a specific latitude. Solar paths are typically available for latitudes at an increment of 4 degrees. Solar path diagrams can be used to design effective shading devices.

In this example, the shading mask covers the period of 8 AM to 5 PM (solar time)[5] for most of the year, except for some early morning and late afternoon hours in the winter.

The following figures provide information on the recommended size of overhangs and fins to completely shade windows during the periods indicated in the solar path diagram. Different sizes for overhangs and fins, or a combination of exterior and interior shades, may be appropriate if the design criteria are different from the assumptions used here.

Figure 5-17. Shading mask for 20-degree north latitude.



Southwest Windows

An in-depth analysis of overhang recommendations for southwest-facing windows is provided in this section, followed by summarized recommendations for the remaining seven orientations.

As shown in Figure 5-18, a 35-degree cut-off angle (also called *profile angle*) for a horizontal overhang would provide complete shading for all southwest-facing windows in Hawaii during most of the year.

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[5] Solar time refers to the time defined by the position of the sun. Solar time varies by longitude, but in Hawaii there is not a significant difference between solar time and Hawaii Standard time.

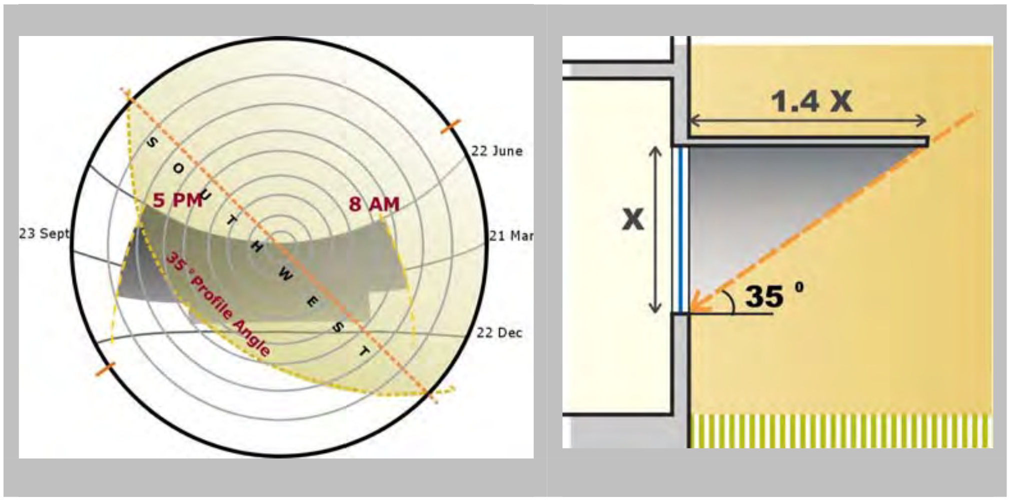

Figure 5-18. Left: An overhang with a 35-degree cut-off angle will shade a southwest window from 8 AM to 4 PM in summer, but only until about 2 PM in winter.

Right: Section through overhang with 35-degree cut-off angle.

Figure 5-19 shows when the southwest window will be shaded by vertical fins with a 15-degree cut-off angle (equal to a projection factor of 3.7).

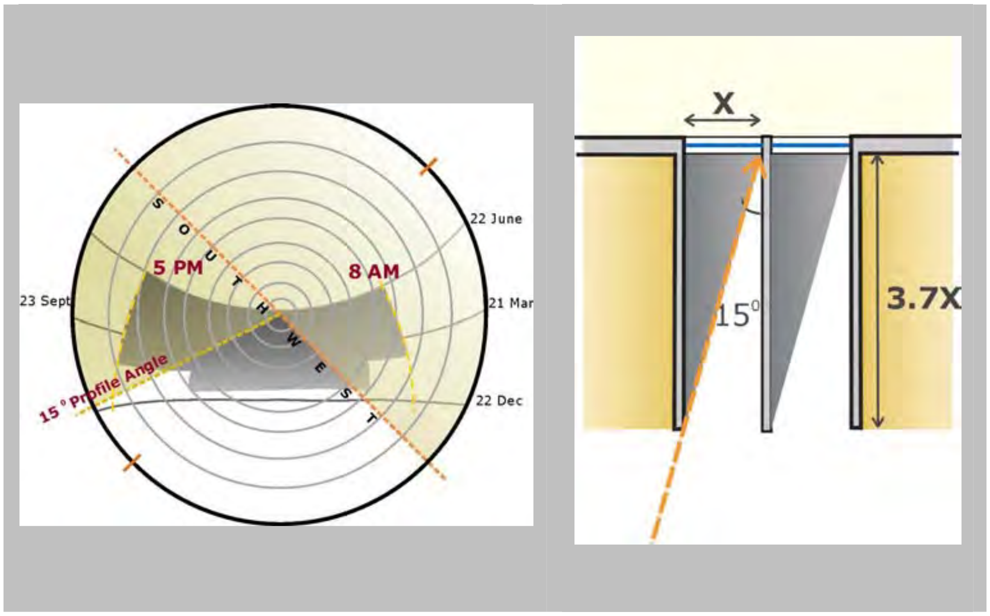

Figure 5-19. Left: Vertical fins with a 15-degree cut-off angle will shade southwest window from 8 AM to 4 PM in summer except for a few hours around midday, and not provide any shade through much of the winter.

Right: Plan view showing vertical fin with 15-degree cut-off angle.

Combining the overhang (35-degree cut-off angle) with vertical fins (15-degree cut-off angle) would provide complete shading between 8 AM and 5 PM, as shown in Figure 5-20. This combination of vertical fins and overhangs is sometimes called an "egg crate" design.

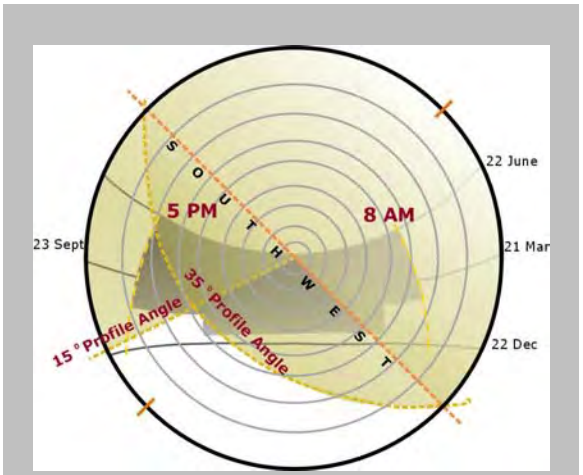

Figure 5-20. Combination of vertical side fin (15-degree cut-off) and horizontal overhang (35-degree cut-off) will shade a southwest window from 8 AM to 5 PM from mid-January to late December.

Shading devices can be designed in several ways, as long as the relationship between the window height and the depth of the shading device (the cut-off angle) does not change.

Figure 5-21 shows an example of a window with multiple overhangs, where the depth of the overhangs is different, but the ratio between the depth of the overhang and the height of the portion of the window shaded by the overhang remains unchanged. In this example of a window facing southwest, the overhang depth should be at least 1.4 times the height of the window shaded by the overhang. Compare this to Figure 5-18 where the same window is shaded by a single overhang.

An overhang or vertical fin that is this deep may not be practical to build. More practical options include dividing the overhang into a multiple louver design to maintain the same cut-off angle as described above, or sloping the overhang away from the wall by 15 degrees (see Figure 5-22). Similarly, the vertical fins can be divided into multiple fins or tilted away from the normal[6] by 45 degrees for a shorter, more practical design (see Figure 5-23).

These solutions (multiple louvers, and sloped fins and overhangs) should be considered for all orientations that have very low cut-off angles. In Hawaii, this applies to all orientations other than north and south windows.

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[6] A line perpendicular to the plane of the window.

Figure 5-21. Section through southwest window with multiple overhangs (35-degree cut-off angle).

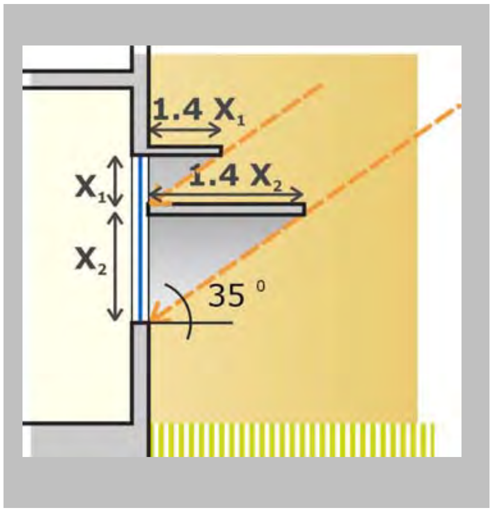


Figure 5-22. Alternative overhang sections showing multiple louvers (left) and sloped overhang (right). Note that the cut-off angle remains unchanged.

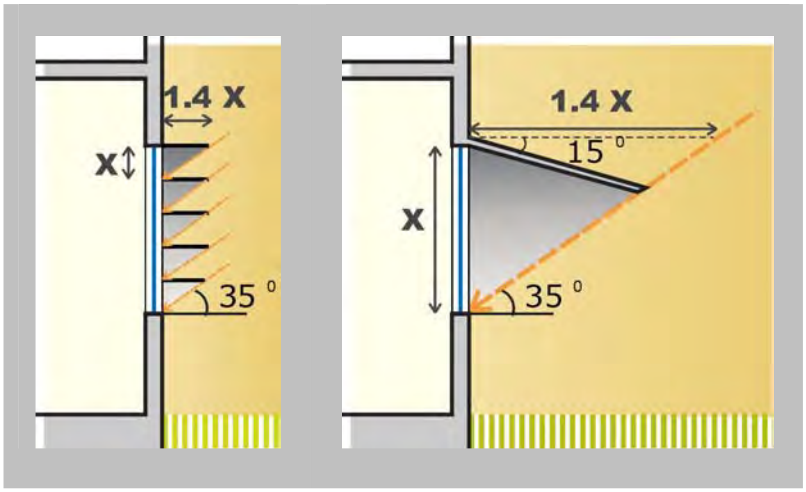


Figure 5-23. Plan view showing alternative design for vertical fins. Note that the cut-off angle remains unchanged.

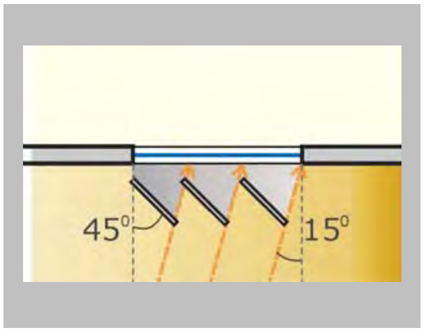


Figure 5-20 above shows that there is a certain amount of overlap between the period shaded by the horizontal overhang and that shaded by the vertical fins. Thus, there is some redundancy in this solution. As shown in Figure 5-24, additional shading is required only when the sun is between an angle of 15 degrees and 55 degrees. Therefore, the vertical fin can be smaller, angled and moved away from the wall, as shown in Figure 5-24. This will ensure that the shading device is not "over-designed." Figure 5-24 shows that this solution can also make the window feel less boxed in relative to Figure 5-19 where the vertical fin has not been "optimized" to prevent overshading. This design applies only to individual windows.

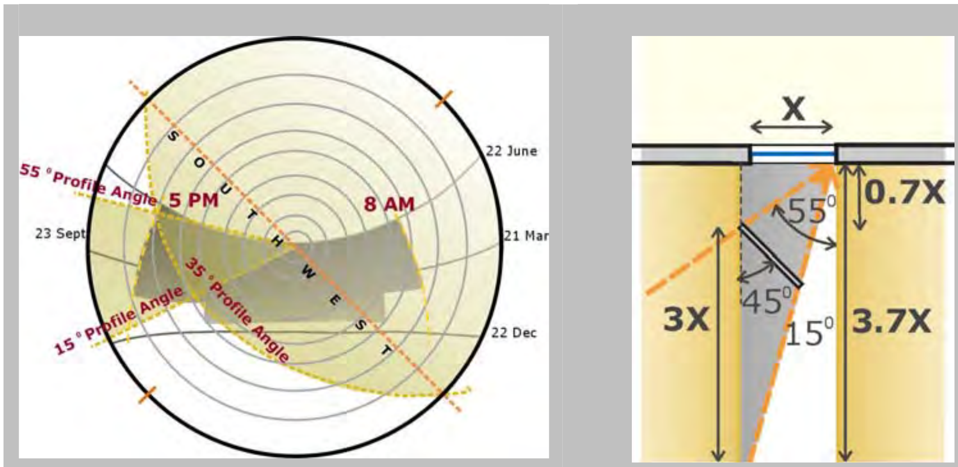


Figure 5-24. Left: Southwest window will be shaded by a combination of horizontal overhang and "optimized" vertical fins from 8 AM to 5 PM during all the times when shading is desired.

Right: Plan view of "optimized" shading fins.

In summary, a combination of overhangs and vertical fins will provide adequate shading for southwest windows in Hawaii.

- An overhang at a cut-off angle of 35 degrees can provide shading from 8 AM to 4 PM through most of summer, except during early and late summer.
- A vertical fin in addition to the overhang will provide complete shading. The vertical fin should have a cut-off angle of 15 degrees.

North Windows (Figure 5-25)

- Side fins can provide shading most of the time, except for the middle of the day in the summer. To provide shading during normal business hours, the depth of the fin should be at least 0.25 times the width of the window it is shading, or have a cut-off angle of 75 degrees.
- A small overhang (with a cut-off angle of 85 degrees or with depth equivalent to 10% of the window height) in addition to side fins with a cut-off angle of 75 degrees will provide complete shading during normal business hours.
- If the window does not face true north, then larger shading devices are necessary.
- North windows are very easy to shade, so it's possible to have relatively large expanses of north-facing glass without significantly increasing solar heat gain.

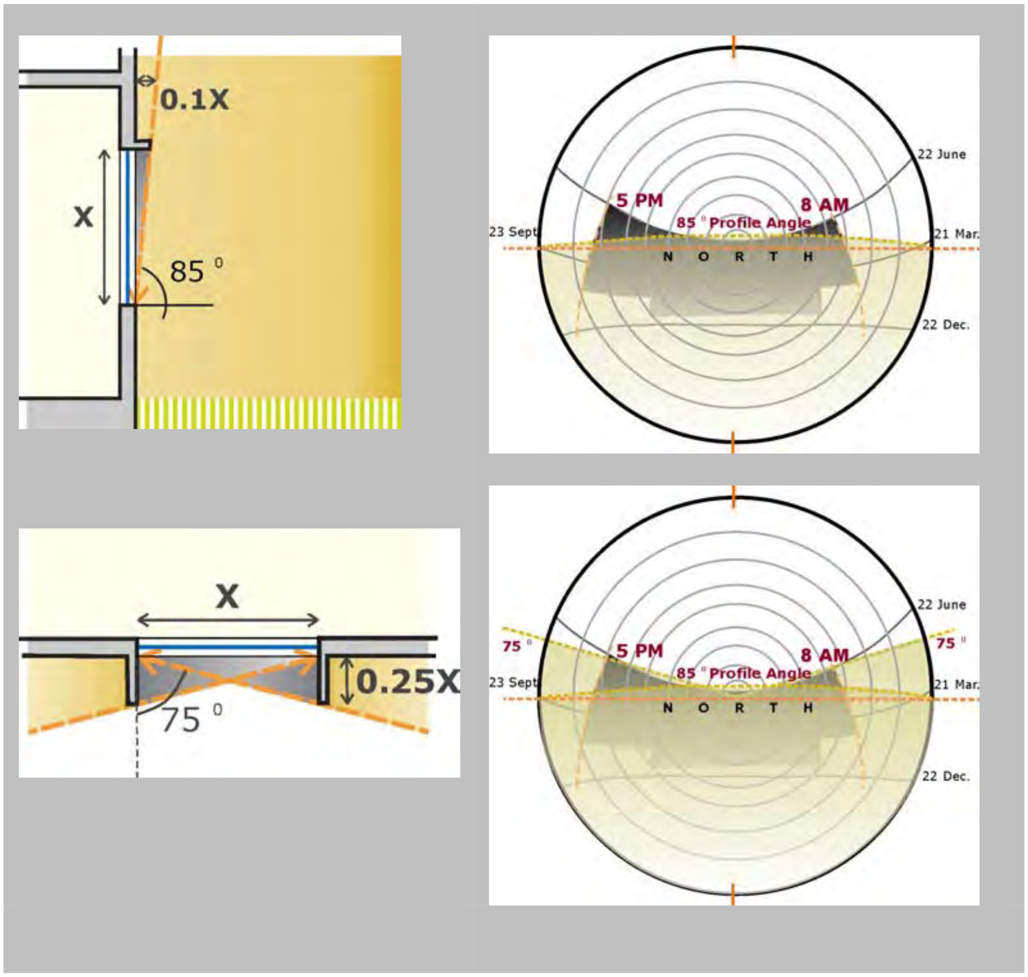


Figure 5-25. ***Top:*** *Overhang with 85-degree cut-off angle will shade north window from 8 AM to 5 PM at all desired times except during early morning and late afternoon in the peak summer months.*

Bottom: *A combination of overhangs (85-degree cut-off) and side fins (75-degree cut-off) will provide complete shading from 8 AM to 5 PM during all months.*

Northeast Windows (Figure 5-26)

- Either side fins or overhangs can provide nearly complete shading from 8 AM to 5 PM on northeast-facing windows.
- If overhangs are used, the overhang should have a cut-off angle of 35 degrees. The overhang depth recommended to completely shade the window in winter should be at least 1.4 times the window height.
- Alternatively, overhangs can be sloped away from the wall or a series of short louvers can be used, as shown in Figure 5-22.
- If fins are desired, the fin should have a cut-off angle of 30 degrees. A more practical approach would be to tilt the fins away from the normal to the window (see Figure 5-23).

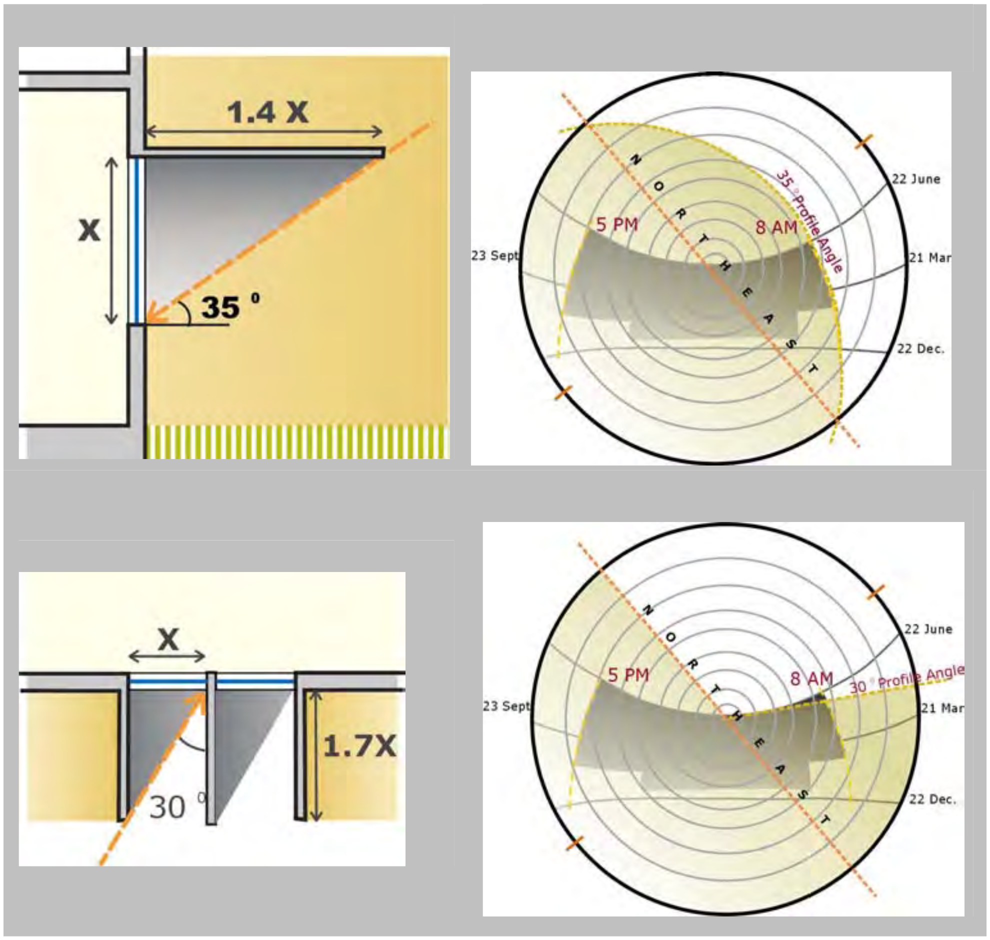


Figure 5-26. ***Top:*** *An overhang with a 35-degree cut-off angle will shade a northeast window from 8 AM to 5 PM during all months.*

Bottom: *Side fins with a 30-degree cut-off angle will shade a northeast window from 8 AM to 5 PM except for a couple of early morning hours for a few days in mid-summer.*

East Windows (Figure 5-27)

- Overhangs are the best option for east-facing windows, but the overhang must be very deep to block the sun from 8 AM to 5 PM in winter. The overhang should have a cut-off angle of 30 degrees. The overhang depth recommended to completely shade the window in winter should be at least 1.7 times the window height.
- Side fins will not be very effective.
- Consider interior shades in addition to an overhang if the overhang cannot be as deep as the ideal recommended size. Alternatively, overhangs can be sloped away from the wall or a series of short louvers can be use, as shown in Figure 5-22.

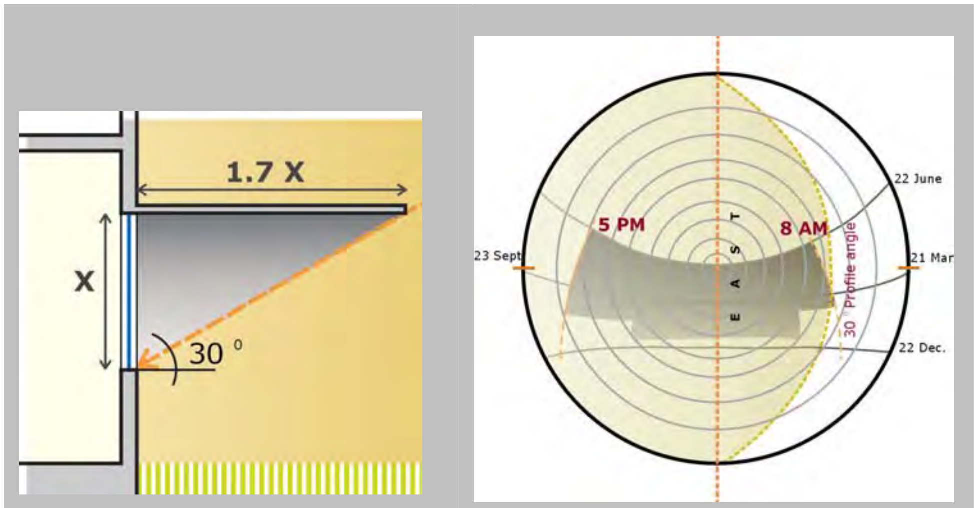


Figure 5-27. Overhang with 30-degree cut-off angle will shade an east window from 8 AM to 5 PM.

Southeast Windows (Figure 5-28)

- An overhang will provide nearly complete shading, but it must be fairly deep (1.7 times the window height).
- If such a large shading device isn't feasible, consider also using interior shades or rotate the window orientation to face true south.
- Alternatively, overhangs can be sloped away from the wall, or a series of short louvers can be used, as shown in Figure 5-22.

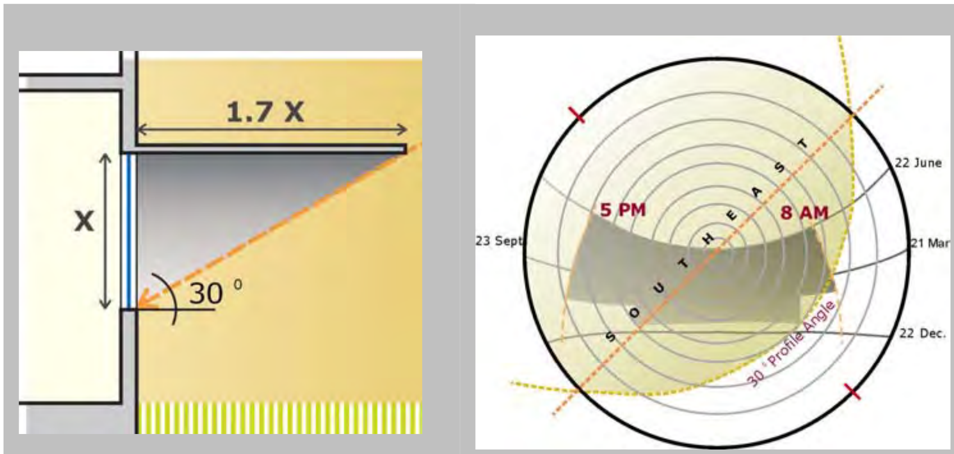
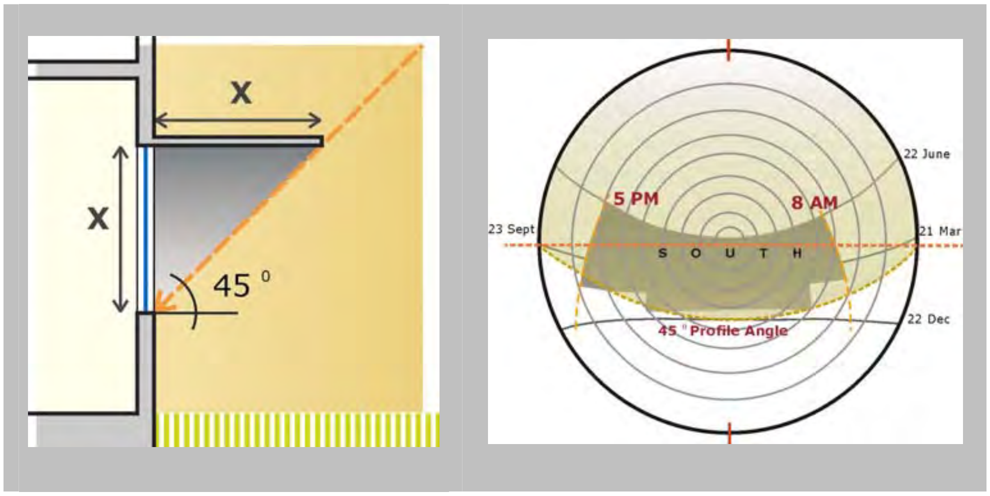


Figure 5-28. Overhang with 30-degree cut-off angle will shade southeast window from 8AM to 5 PM from March to September. It will not provide shade for a couple of hours in the morning during winter.

South Windows (Figure 5-29)

- Overhangs are the best shading option for south-facing windows, and they don't need to be excessively large. An overhang with a depth equal to the window height (or cut-off angle of 45 degrees) is sufficient to provide complete shading for the periods shown in the shading mask diagram.
- Side fins are not very useful on south-facing windows because they will provide shading only in the early morning and late afternoon.

Figure 5-29. Overhang with 45-degree cut-off angle will shade south window from 8AM to 5 PM during all desired times except for a few hours in the morning and late afternoon in winter.



West Windows (Figure 5-30)

- West windows are the most difficult to shade. The overhangs need to be very deep (4 times the window height) to be effective. This may not be desirable for both aesthetic and practical reasons.
- Where views are not a priority, it's best to avoid west-facing windows.
- If west windows are unavoidable, then choose solar-control glazing and/or interior shades in addition to smaller sloped overhangs (or multiple louvers) as shown in Figure 5-22.

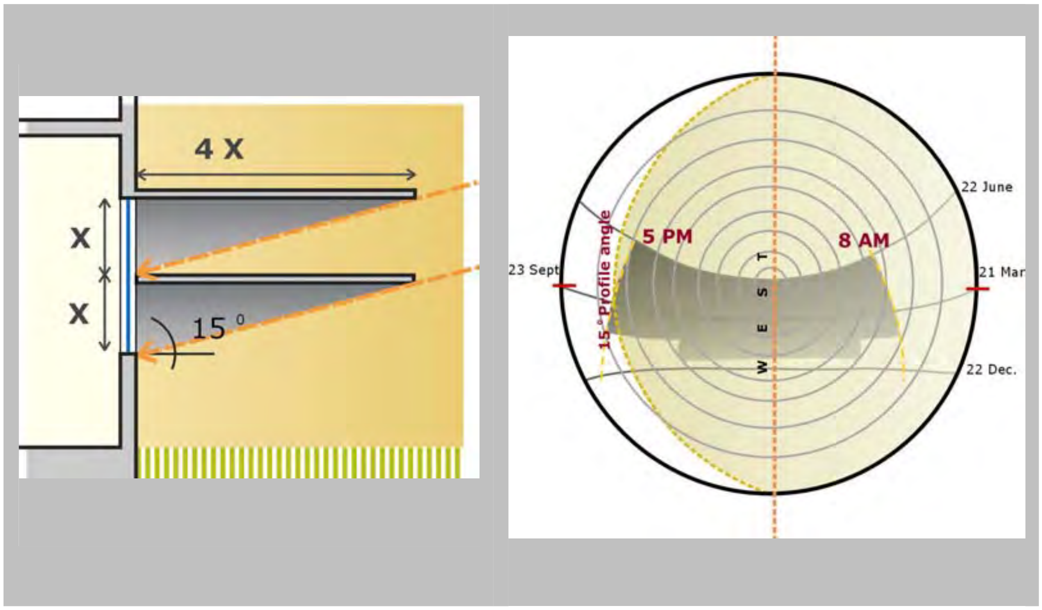


Figure 5-30. Large overhangs with a 15-degree cut-off angle will shade west windows from 8 AM to 5 PM, except in late afternoon from November to February.

Northwest Windows (Figure 5-31)

- Either side fins or overhangs can provide nearly complete shading from 8 AM to 5 PM.
- If overhangs are used, the overhang should have a cut-off angle of 25 degrees. To completely shade the window in winter, the overhang depth should be at least 2.2 times the window height. Alternatively, overhangs can be sloped away from the wall, or a series of short louvers can be used (see Figure 5-22).
- Northwest windows require deeper overhangs than northeast windows because afternoon shading is important until at least 5 PM.
- If fins are desired, the fins should have a cut-off angle of 25 degrees. A vertical fin would need to be 2.2 times as deep as the width of the window it is shading. A more practical approach would be to tilt the fins away from the normal to the window (see Figure 5-23).

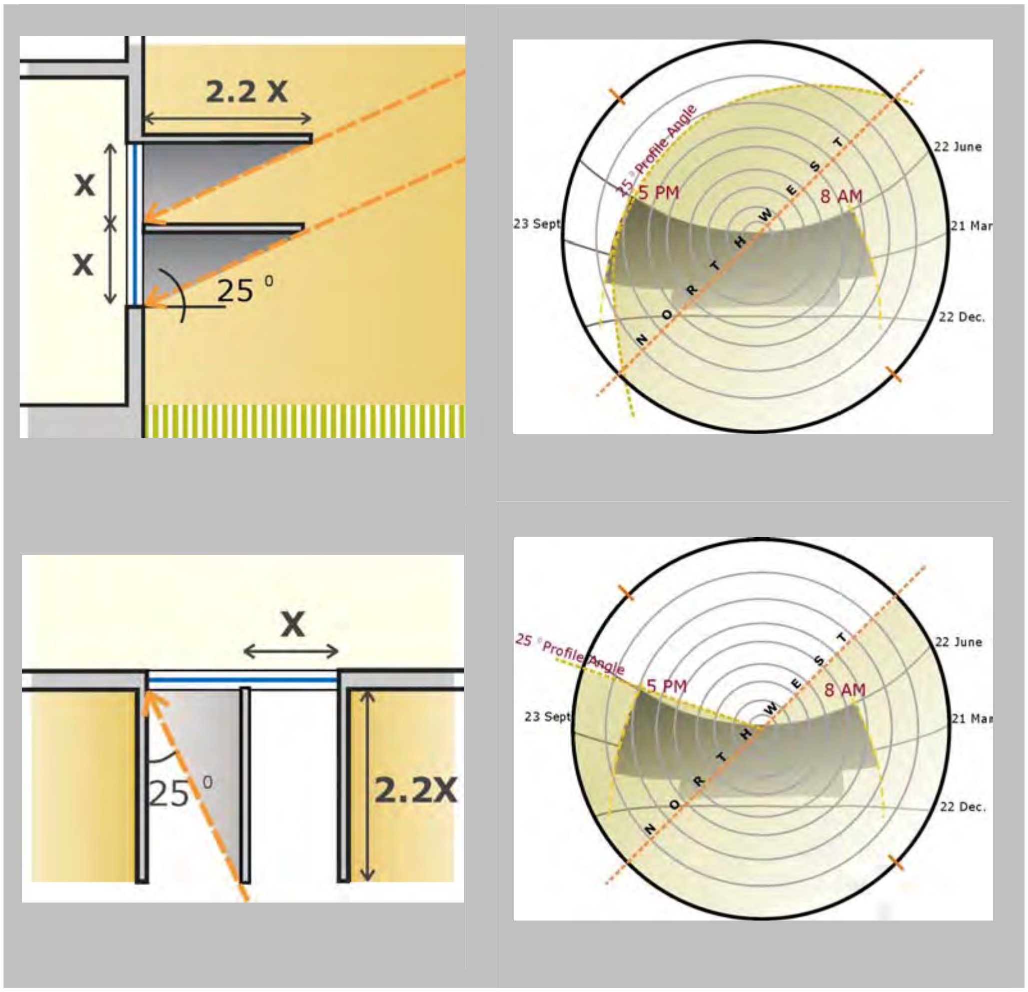


Figure 5-31. ***Top:*** *An overhang with a 25-degree cut-off angle will shade a northwest window from 8 AM to5 PM, except in late afternoon from November to February.*

Bottom: *Side fins with a 25-degree cut-off angle will shade a northeast window from 8 AM to 5 PM.*

Design and Analysis Tools

See the Design and Analysis Tools section in the General Principles of Window Design Guideline earlier in this chapter.

Operations and Maintenance

Some issues to consider with exterior shading devices are window cleaning access and the potential mess created by roosting birds.

Commissioning

Fixed window shading systems require little commissioning. However, design review is important to ensure that shading devices are correctly sized and oriented because mistakes are expensive to correct during or after construction. Operable shading systems must be tested to ensure that they work as intended.

Utility Programs

To take advantage of any existing opportunities for energy-efficient windows incentives, contact your utility company representative as early as possible in the design process.

Case Study

The Kaiser Permanente Honolulu Clinic uses both side fins and overhangs to block direct sunlight. Windows on the east and west sides are angled toward the south to make shading more effective (see Figure 5-32 and Figure 5-33).

Figure 5-32. Kaiser Permanente Honolulu Clinic. Photo: Erik Kolderup, Eley Associates.

Figure 5-33. Kaiser Permanente Honolulu Clinic. Photos: Erik Kolderup, Eley Associates.

Windows Performance Data

The graphs in this section were developed to supplement the information provided in the Energy-efficient Windows chapter. They can be used to help evaluate the most effective combinations of window size, orientation, shading and glass type.

For each orientation, the graphs show electricity consumption, peak cooling load impacts and lifecycle costs for windows with and without exterior shading. The same eight representative glass types are compared in each graph.

These graphs were developed with data based on a typical office building in Hawaii with manual or automatic daylighting controls in the perimeter spaces, operating five days a week for normal business hours (8 AM to 5 PM).

Figure 5-34. ***North window, no overhang.*** *Impact of WWR on electricity consumption, peak cooling load, and lifecycle cost, for windows with and without interior shades.*

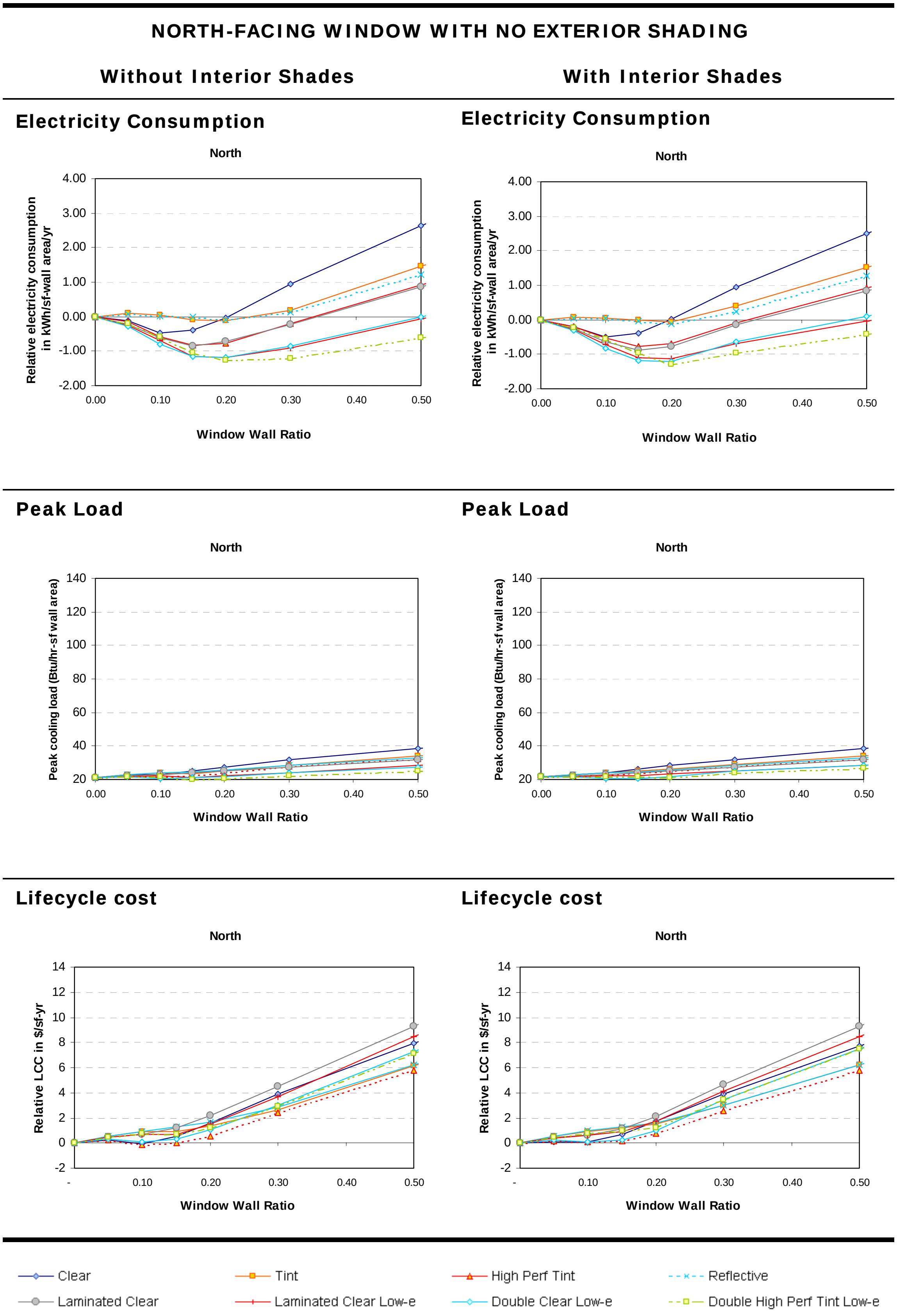


Figure 5-35. ***North window. Overhang PF = 0.25.*** *Impact of WWR on electricity consumption, peak load demand, and lifecycle cost.*

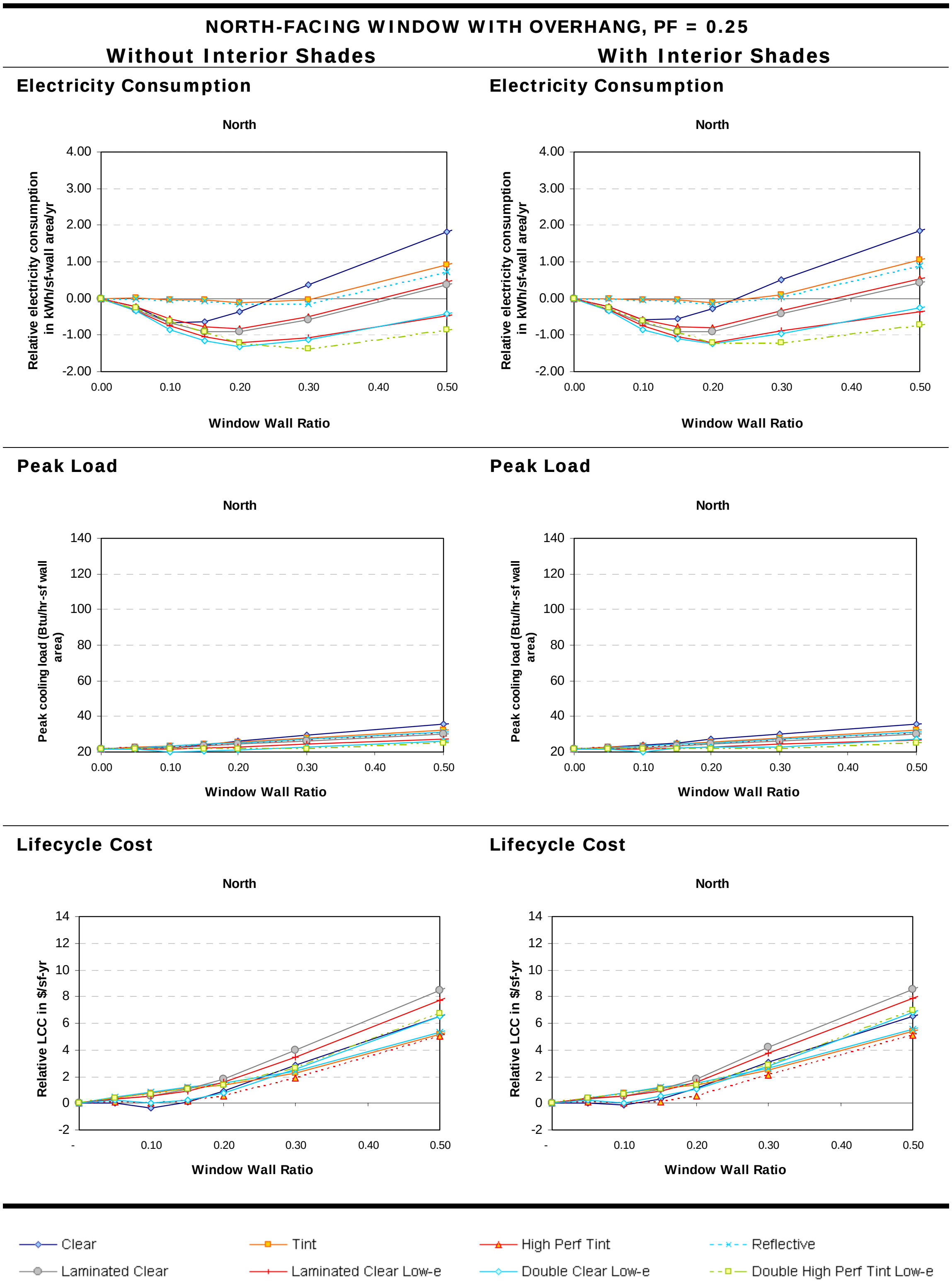
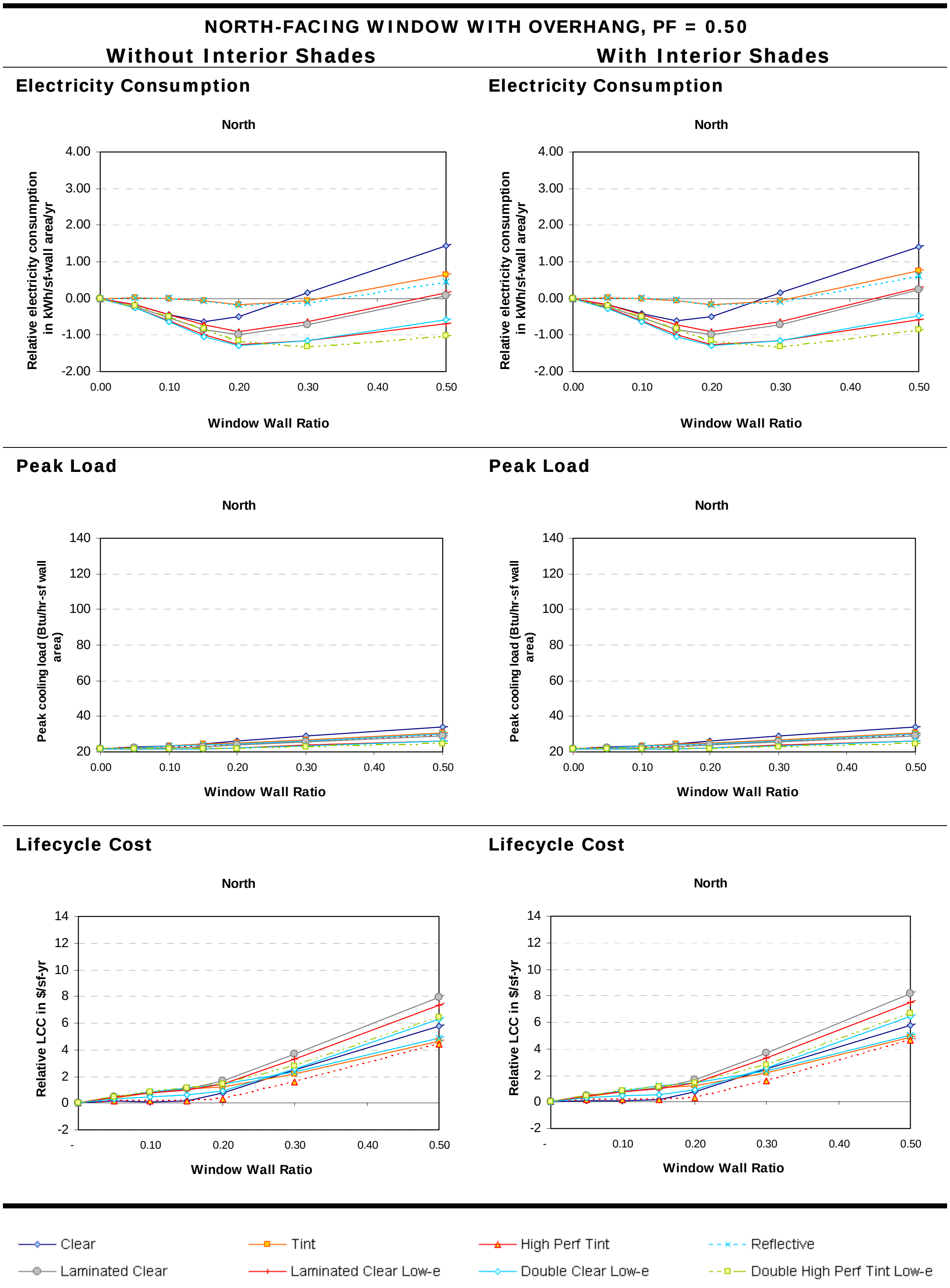


Figure 5-36. ***North window. Overhang PF = 0.50.*** *Impact of WWR on electricity consumption, peak load demand, and lifecycle cost.*



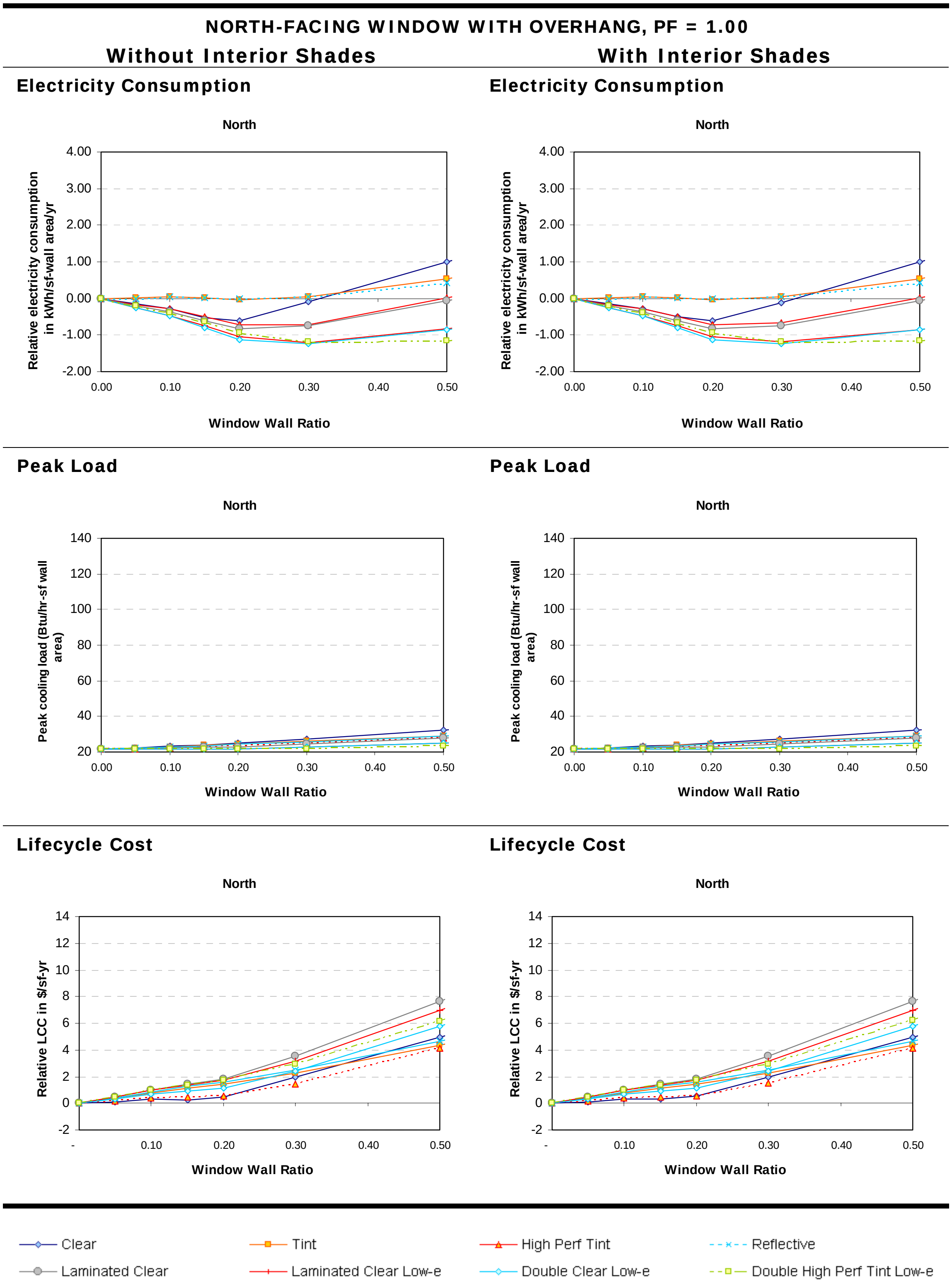
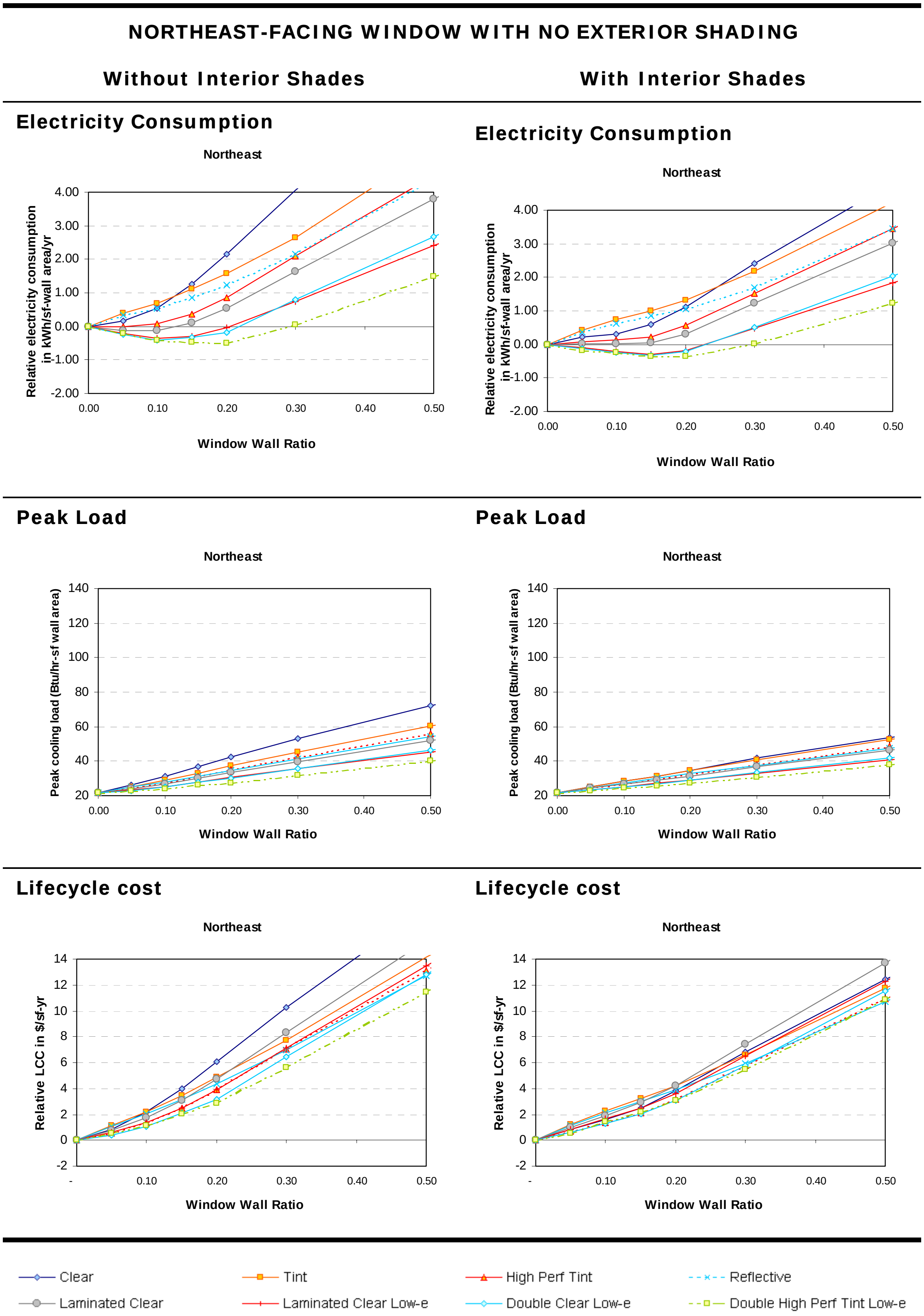


Figure 5-37. ***North window. Overhang PF = 1.00.*** *Impact of WWR on electricity consumption, peak load demand, and lifecycle cost.*

Figure 5-38. ***Northeast window, no overhang.*** *Impact of WWR on electricity consumption, peak cooling load, and lifecycle cost, for windows with and without interior shades.*



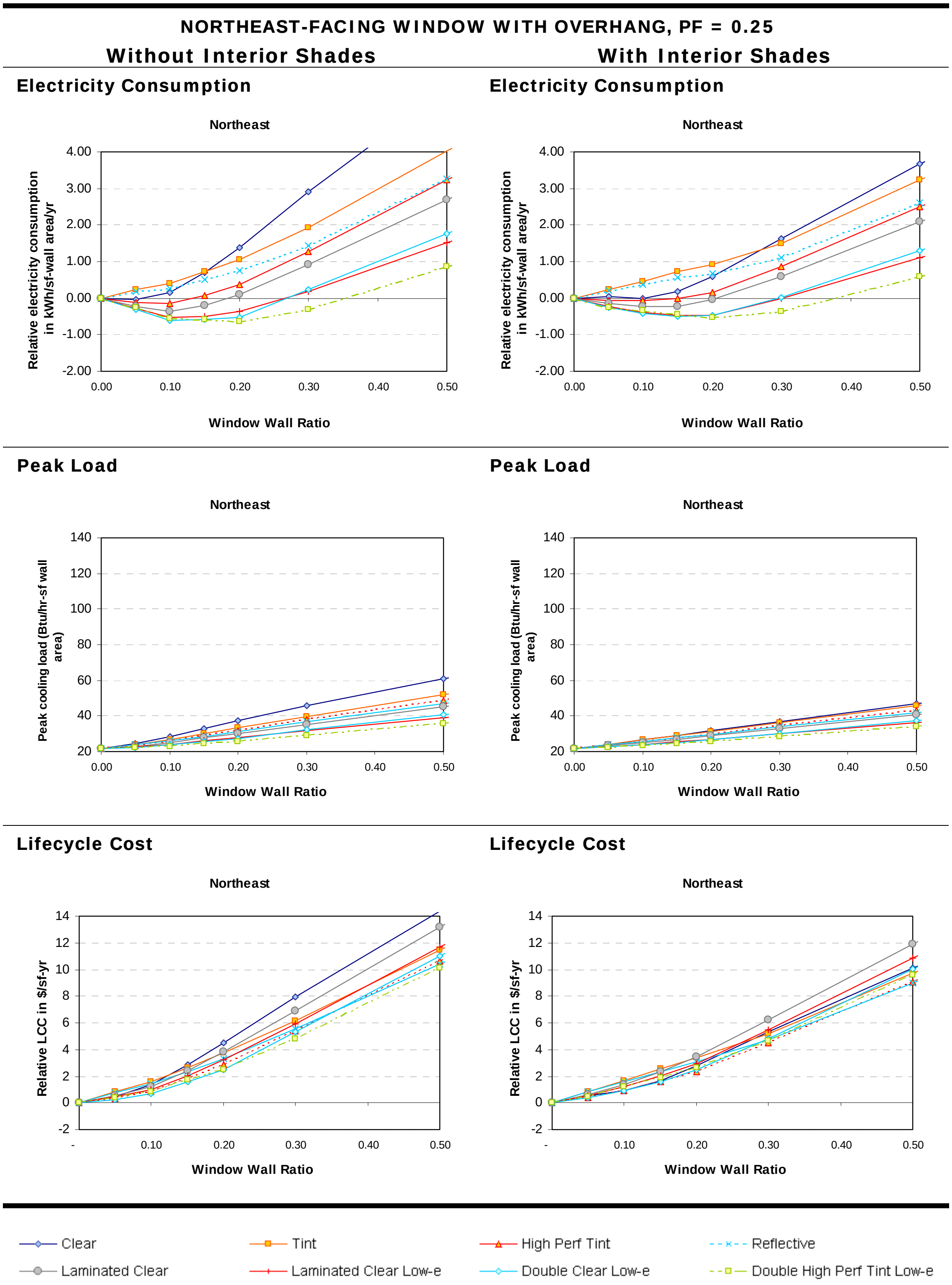


Figure 5-39. ***Northeast window. Overhang PF = 0.25.*** *Impact of WWR on electricity consumption, peak load demand, and lifecycle cost.*

Figure 5-40. ***Northeast window. Overhang PF = 0.50.*** *Impact of WWR on electricity consumption, peak load demand, and lifecycle cost.*

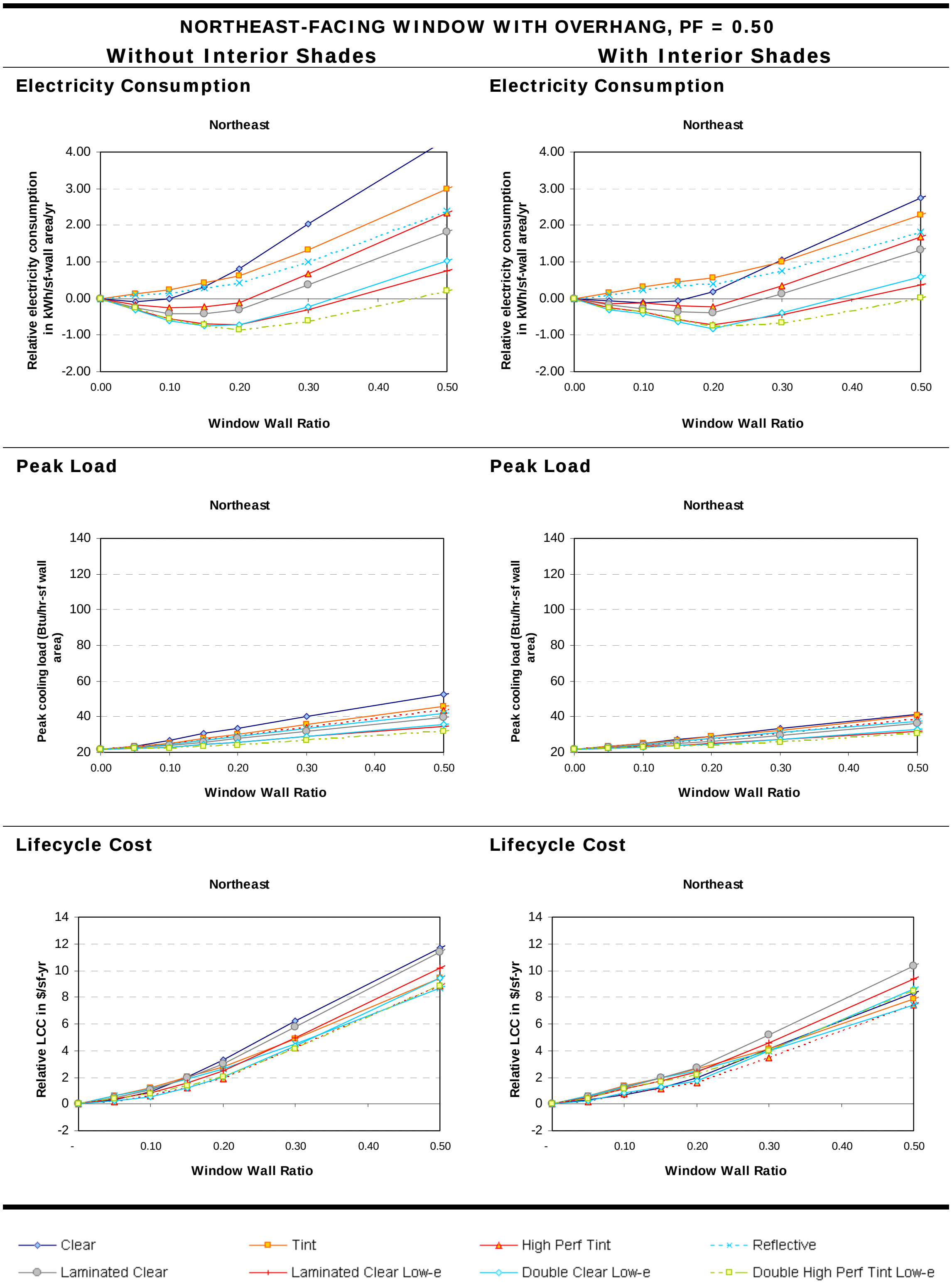


Figure 5-41. ***Northeast window. Overhang PF = 1.00.*** *Impact of WWR on electricity consumption, peak load demand, and lifecycle cost.*

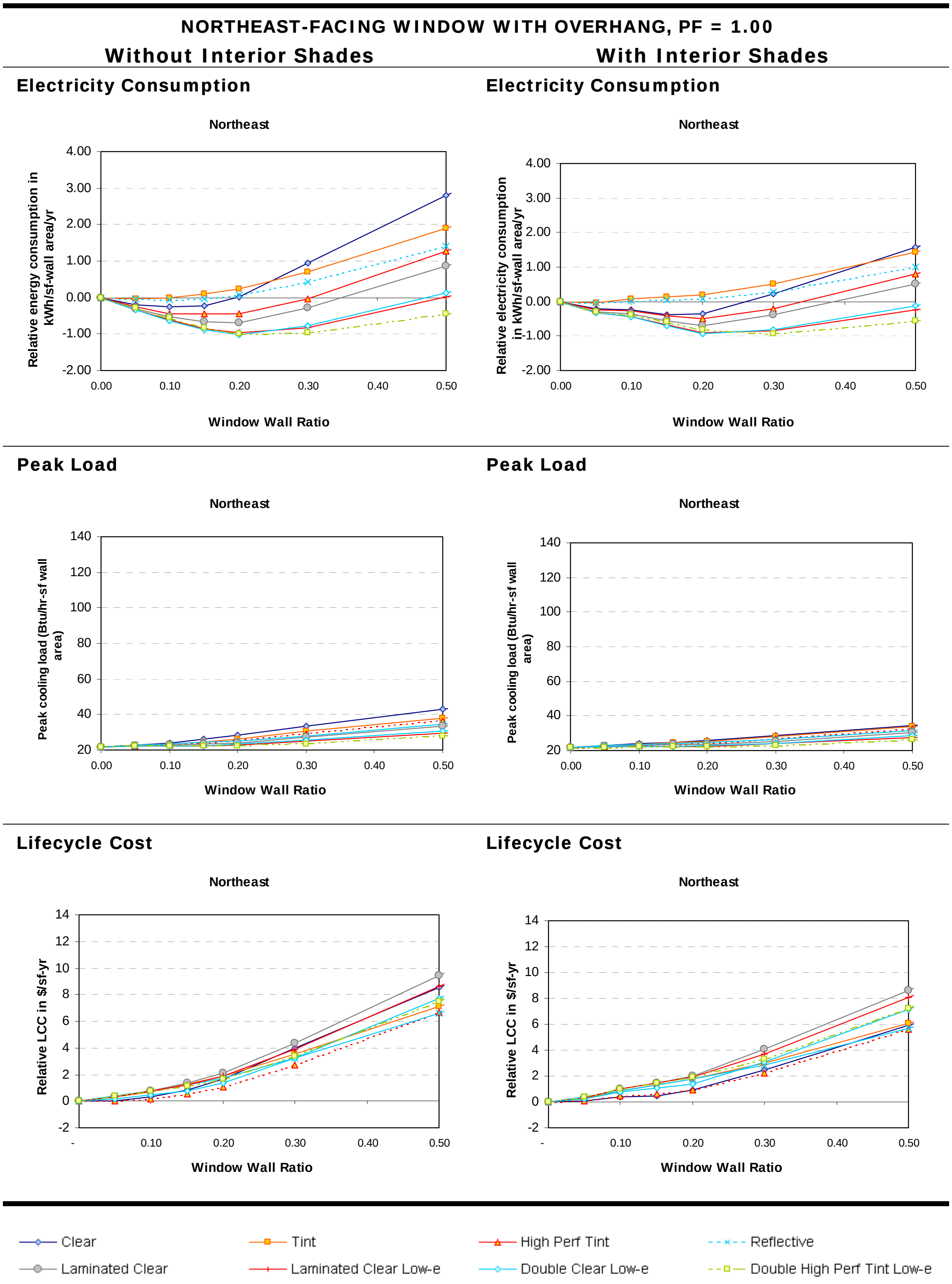


Figure 5-42. ***East window, no overhang.*** *Impact of WWR on electricity consumption, peak cooling load, and lifecycle cost, for windows with and without interior shades.*

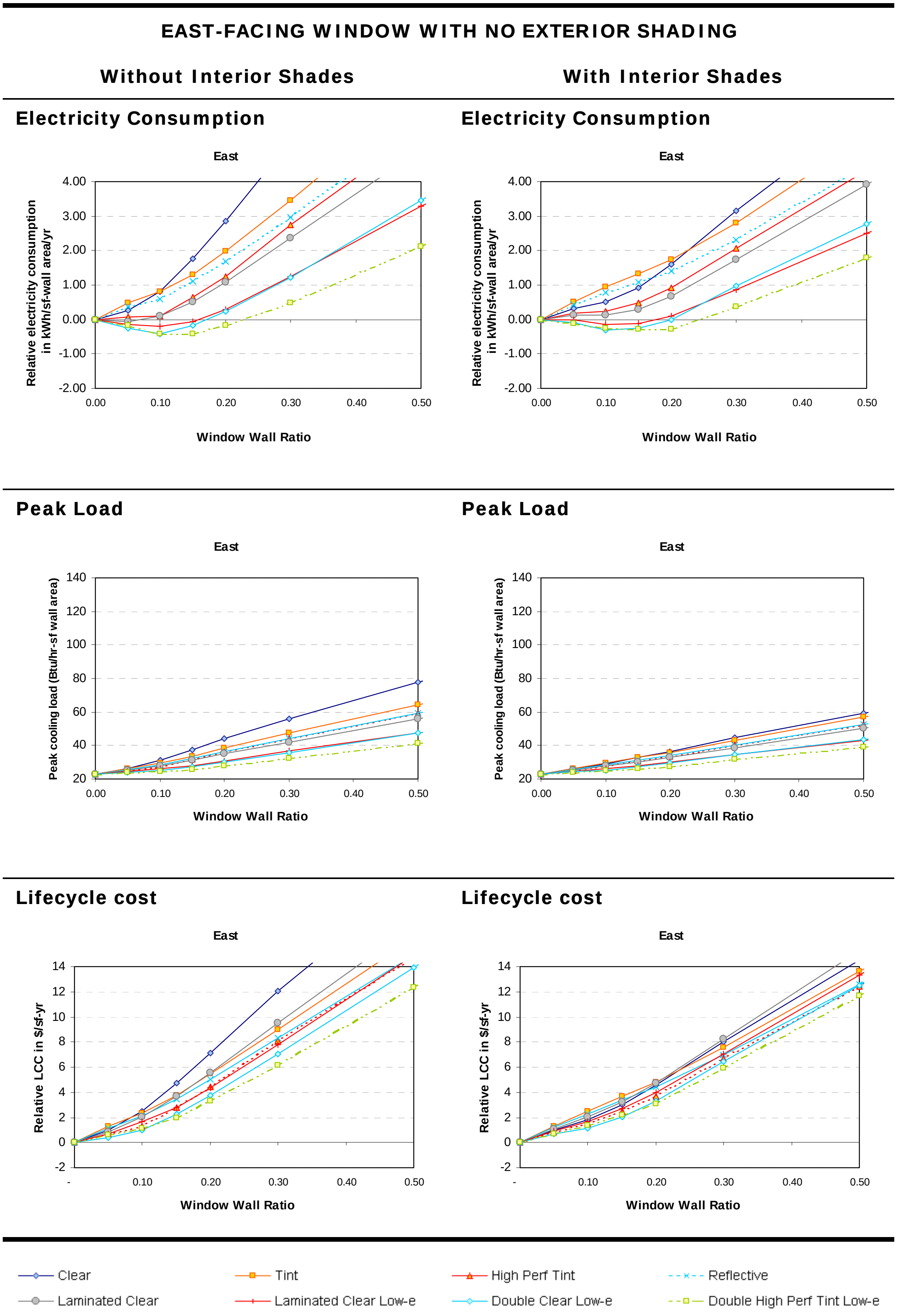


Figure 5-43. ***East window. Overhang PF = 0.25.*** *Impact of WWR on electricity consumption, peak load demand, and lifecycle cost.*

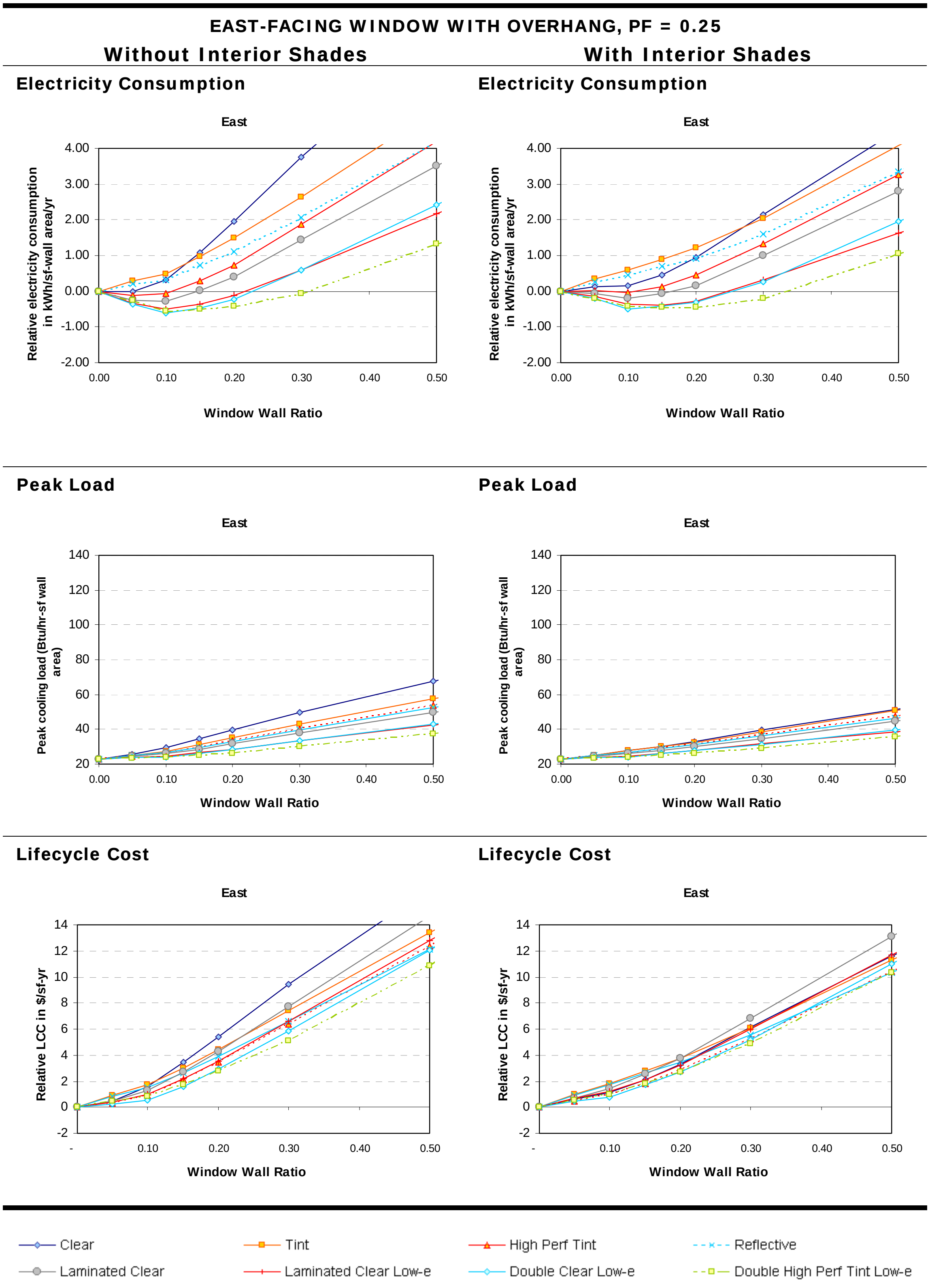


Figure 5-44. ***East window. Overhang PF = 0.50.*** *Impact of WWR on electricity consumption, peak load demand, and lifecycle cost.*

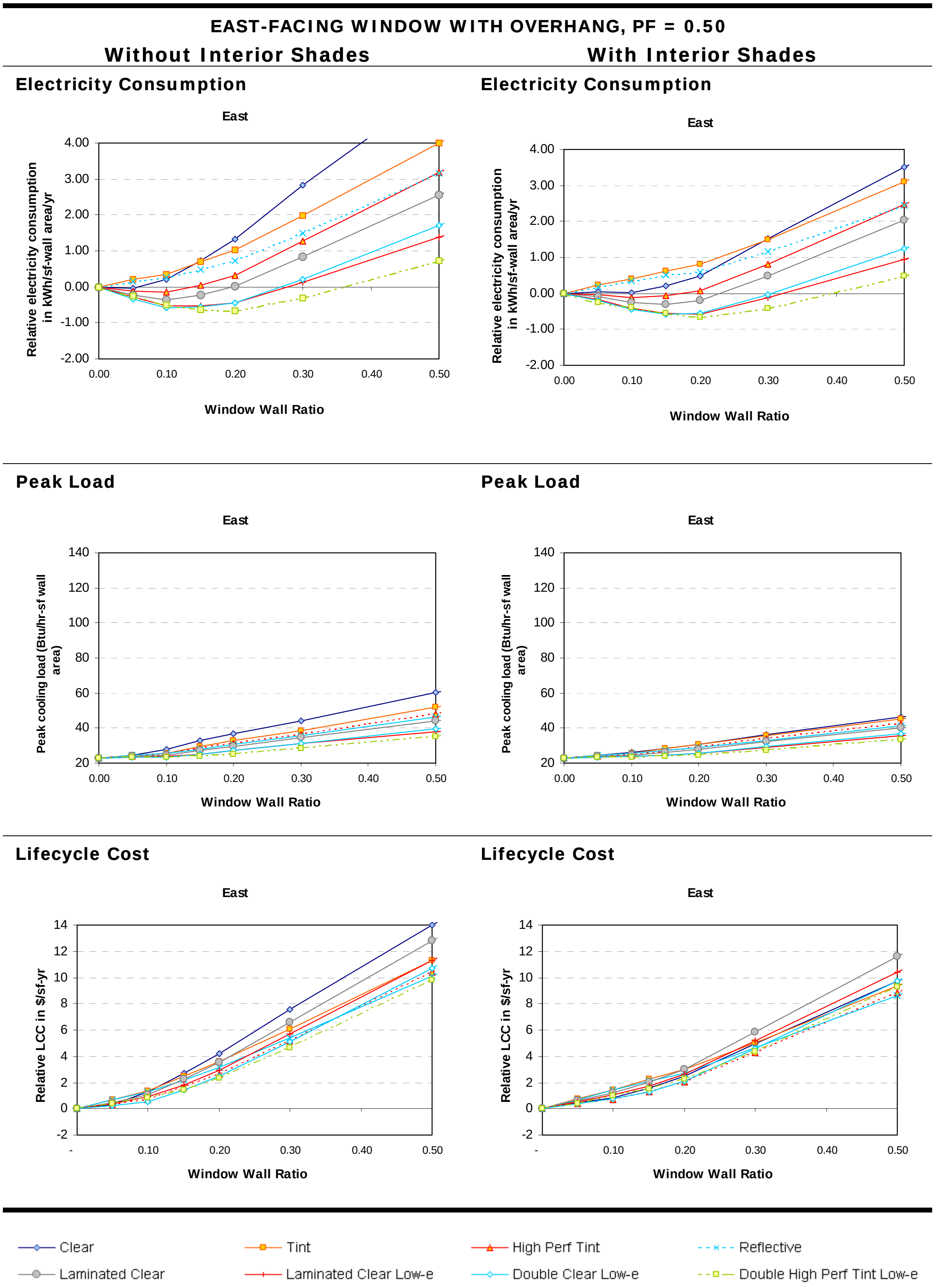


Figure 5-45. ***East window. Overhang PF = 1.00.*** *Impact of WWR on electricity consumption, peak load demand, and lifecycle cost.*

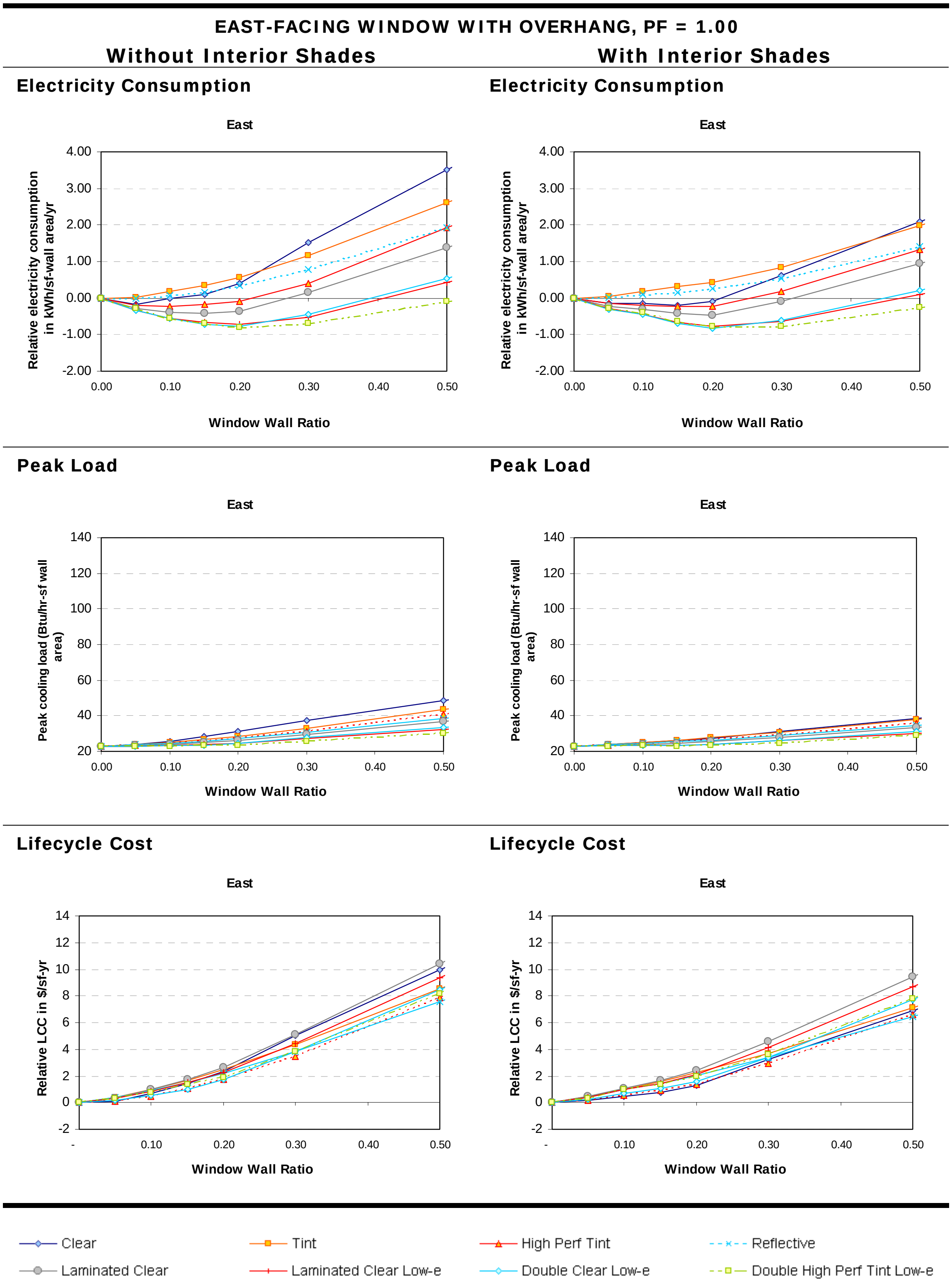


Figure 5-46. ***Southeast window, no overhang.*** *Impact of WWR on electricity consumption, peak cooling load, and lifecycle cost, for windows with and without interior shades.*

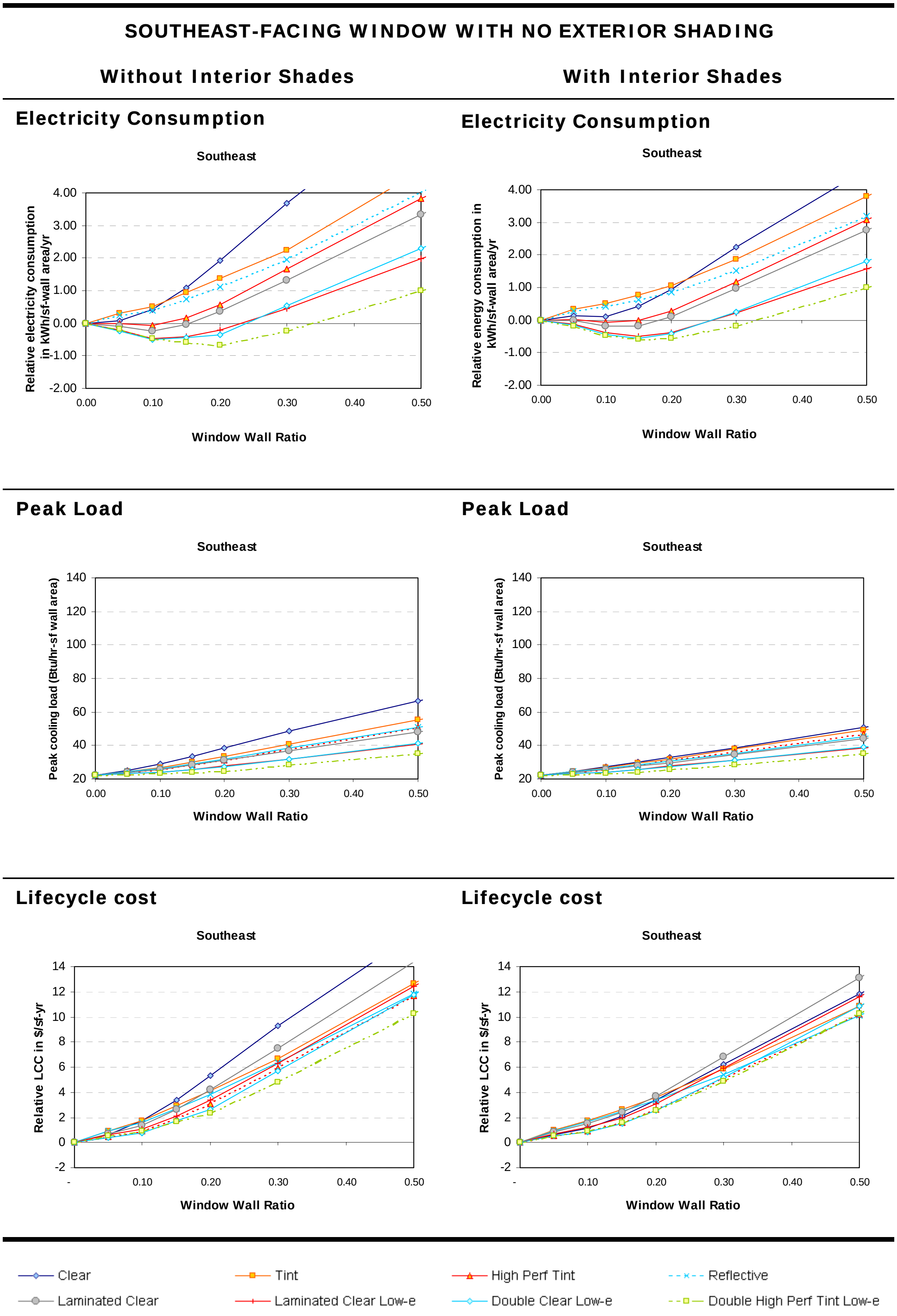
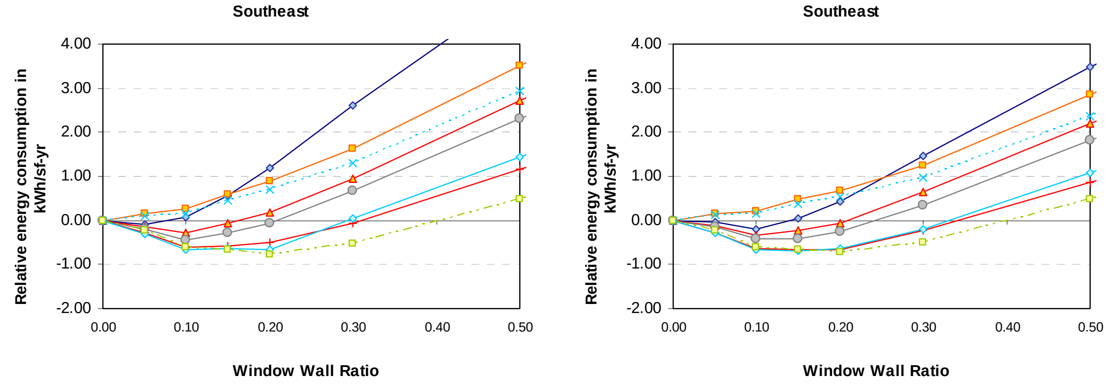


Figure 5-47. ***Southeast window. Overhang PF = 0.25.*** *Impact of WWR on electricity consumption, peak load demand, and lifecycle cost.*

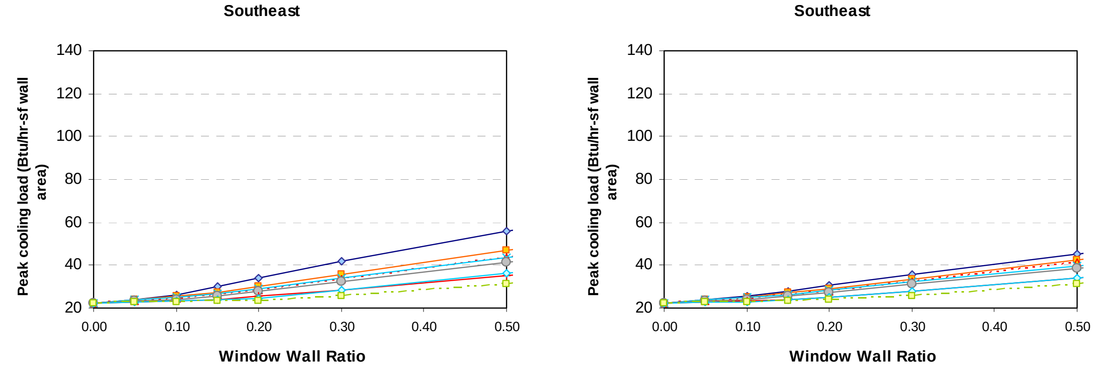
SOUTHEAST-FACING WINDOW WITH OVERHANG, PF = 0.25

Without Interior Shades | **With Interior Shades**

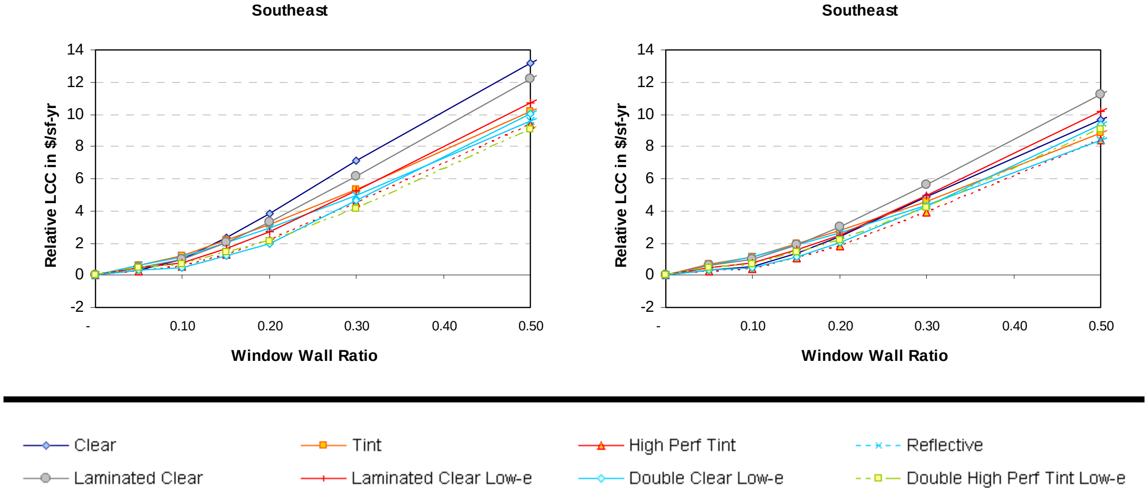
Electricity Consumption | **Electricity Consumption**



Peak Load | **Peak Load**



Lifecycle Cost | **Lifecycle Cost**



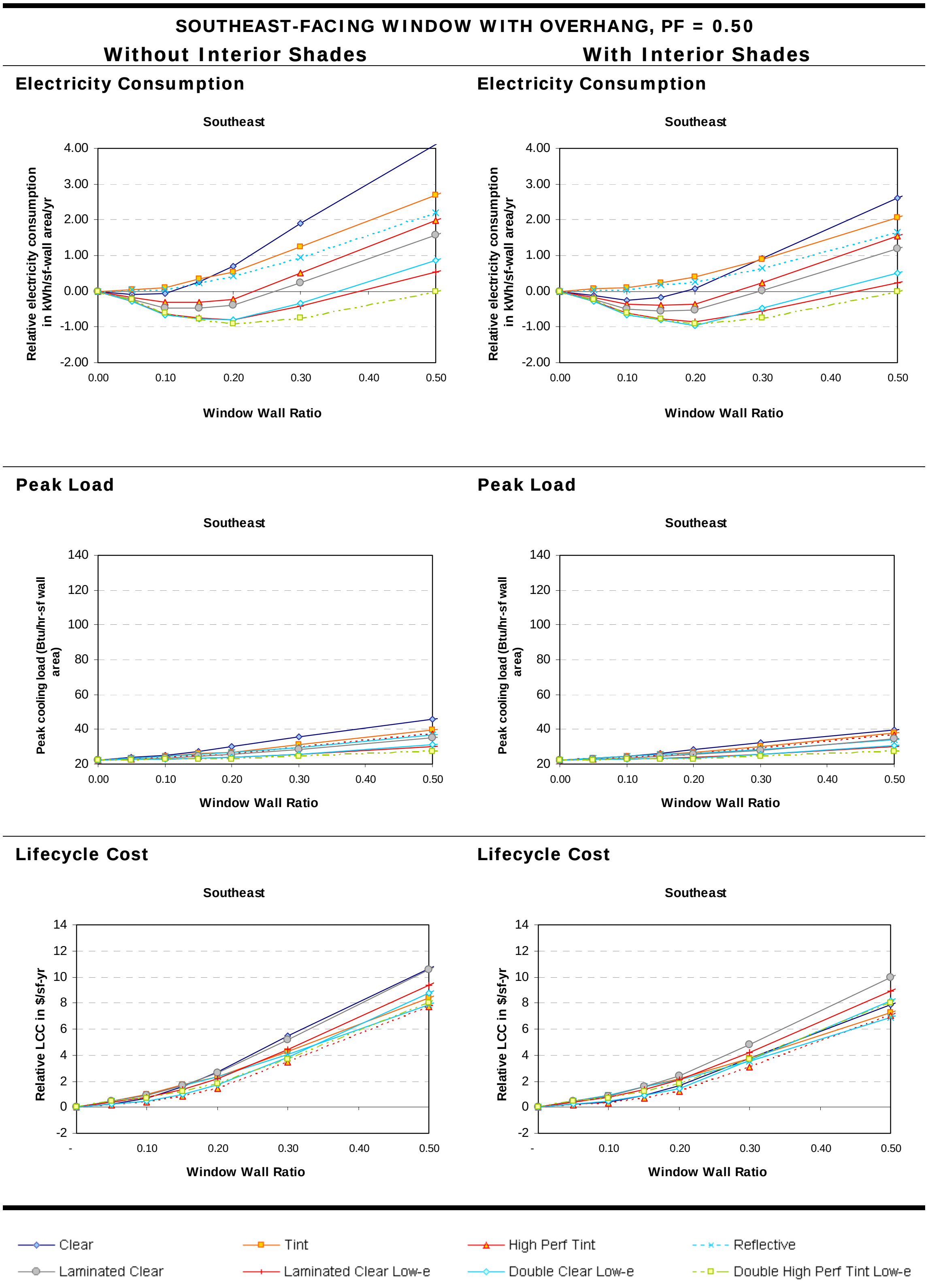


Figure 5-48. ***Southeast window. Overhang PF = 0.50.*** *Impact of WWR on electricity consumption, peak load demand, and lifecycle cost.*

Figure 5-49. ***Southeast window. Overhang PF = 1.00.*** *Impact of WWR on electricity consumption, peak load demand, and lifecycle cost.*

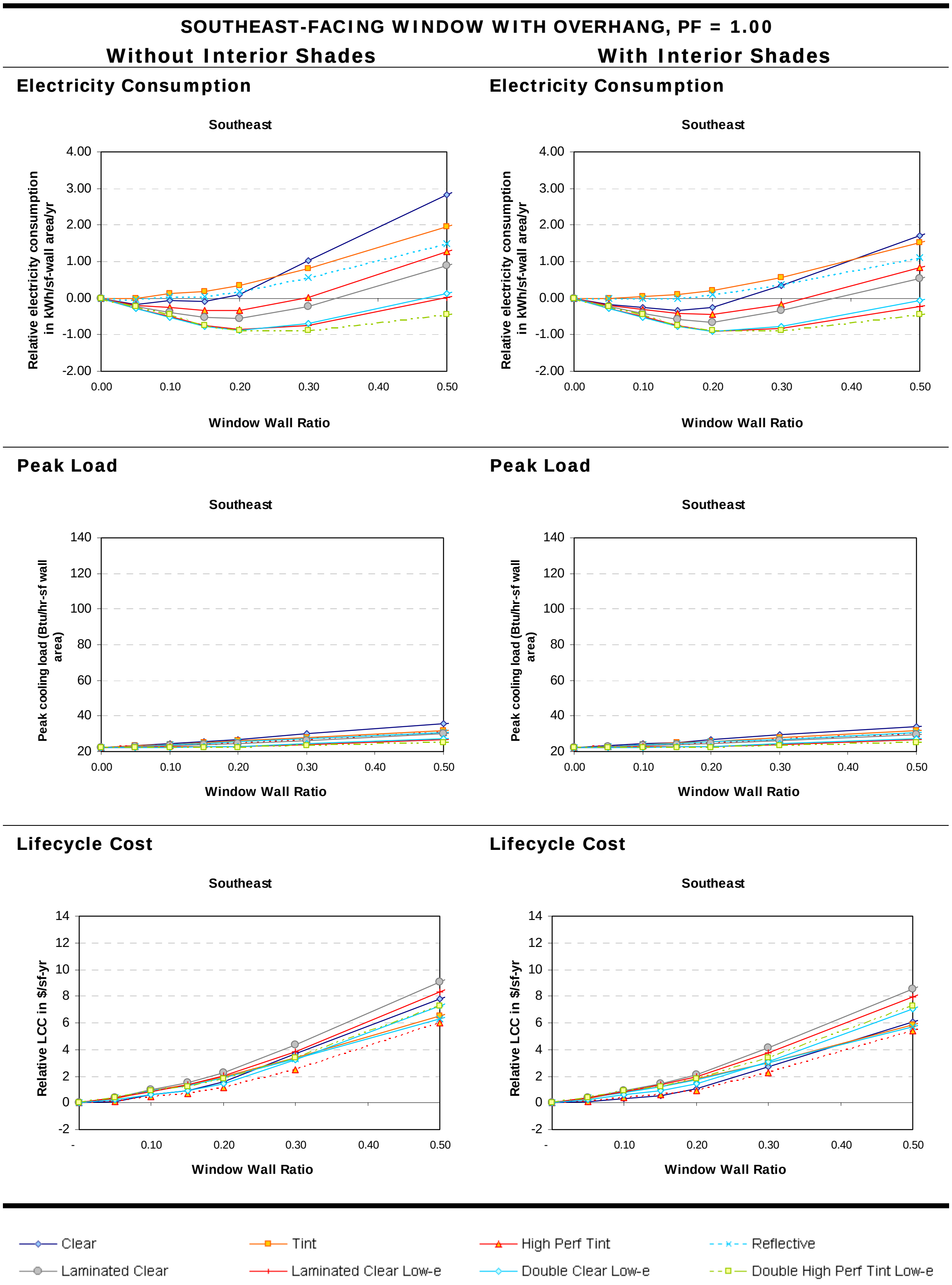


Figure 5-50. ***South window, no overhang.*** *Impact of WWR on electricity consumption, peak cooling load, and lifecycle cost, for windows with and without interior shades.*

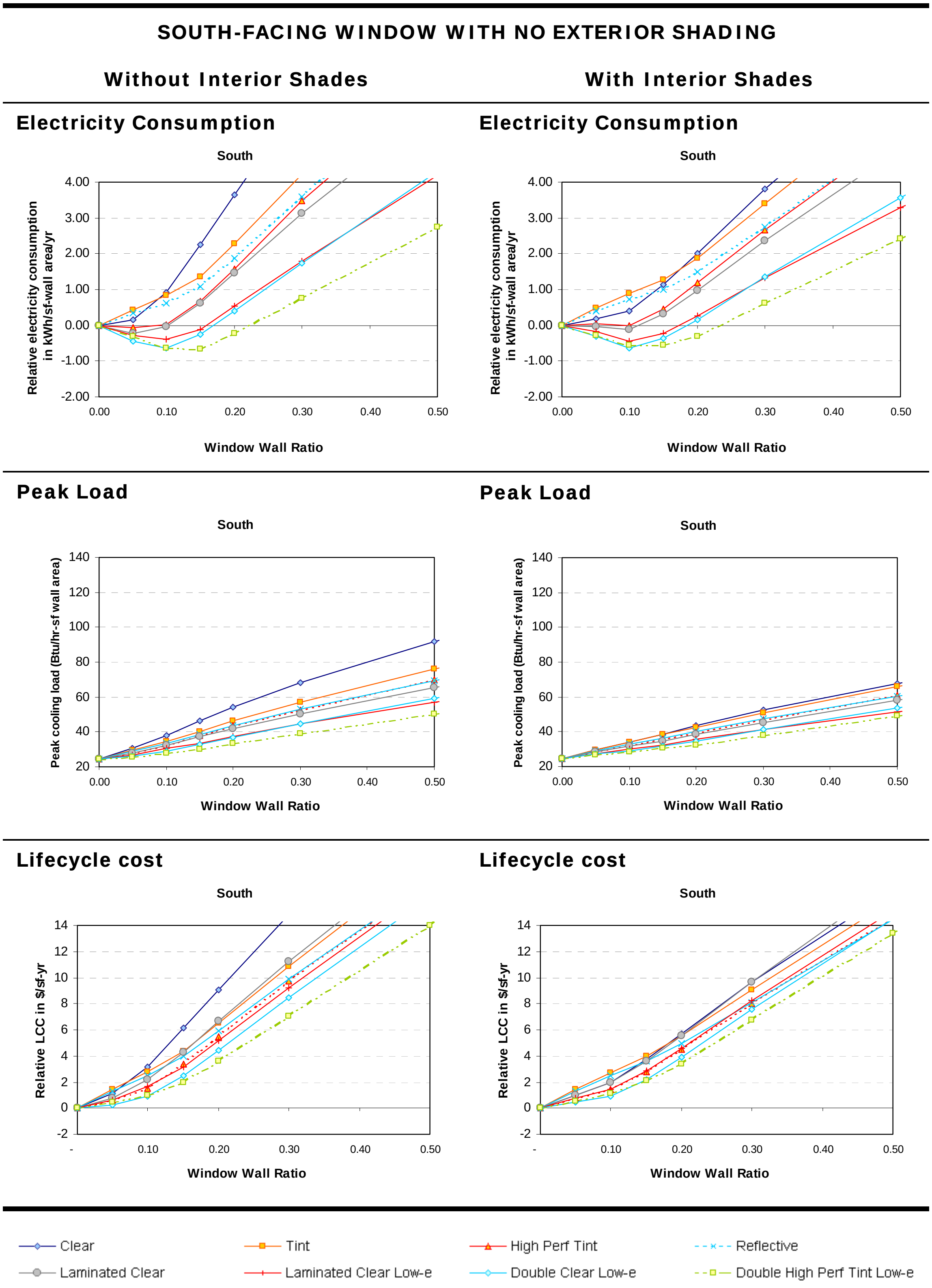


Figure 5-51. ***South window. Overhang PF = 0.25.****Impact of WWR on electricity consumption, peak load demand, and lifecycle cost.*

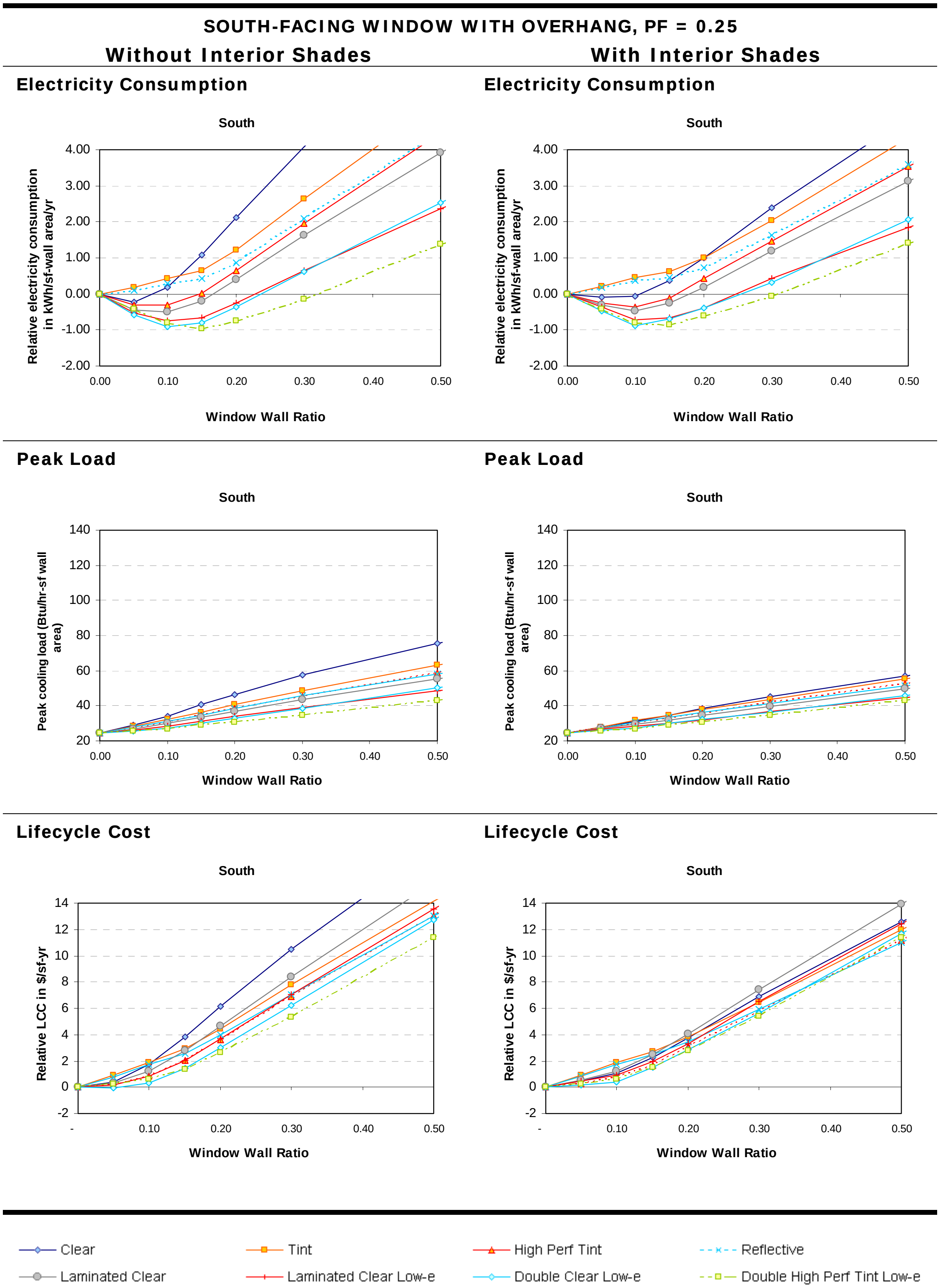


*Figure 5-52. **South window. Overhang PF = 0.50.**Impact of WWR on electricity consumption, peak load demand, and lifecycle cost.*

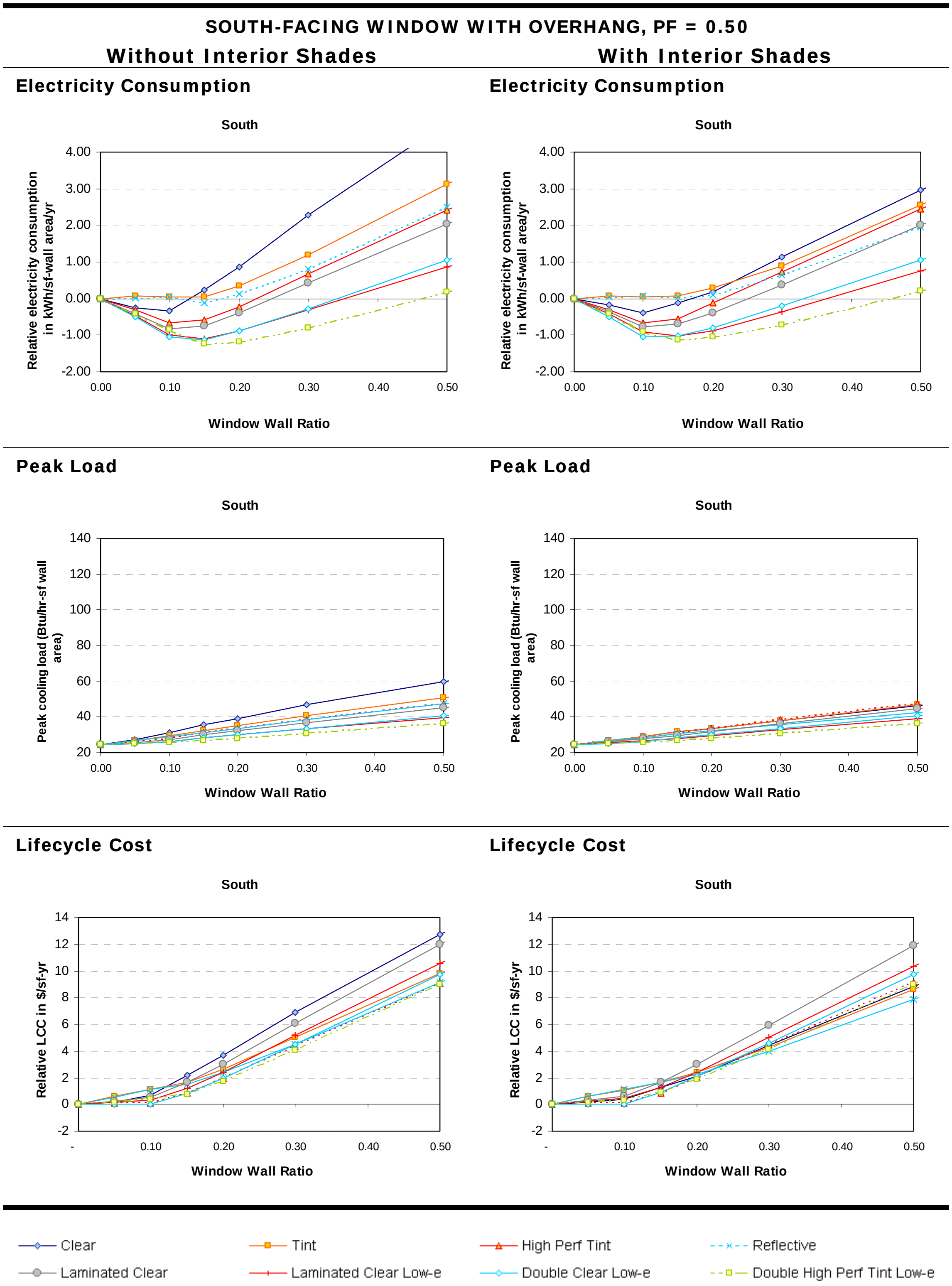


Figure 5-53. ***South window. Overhang PF = 1.00.Impact*** *of WWR on electricity consumption, peak load demand, and lifecycle cost.*

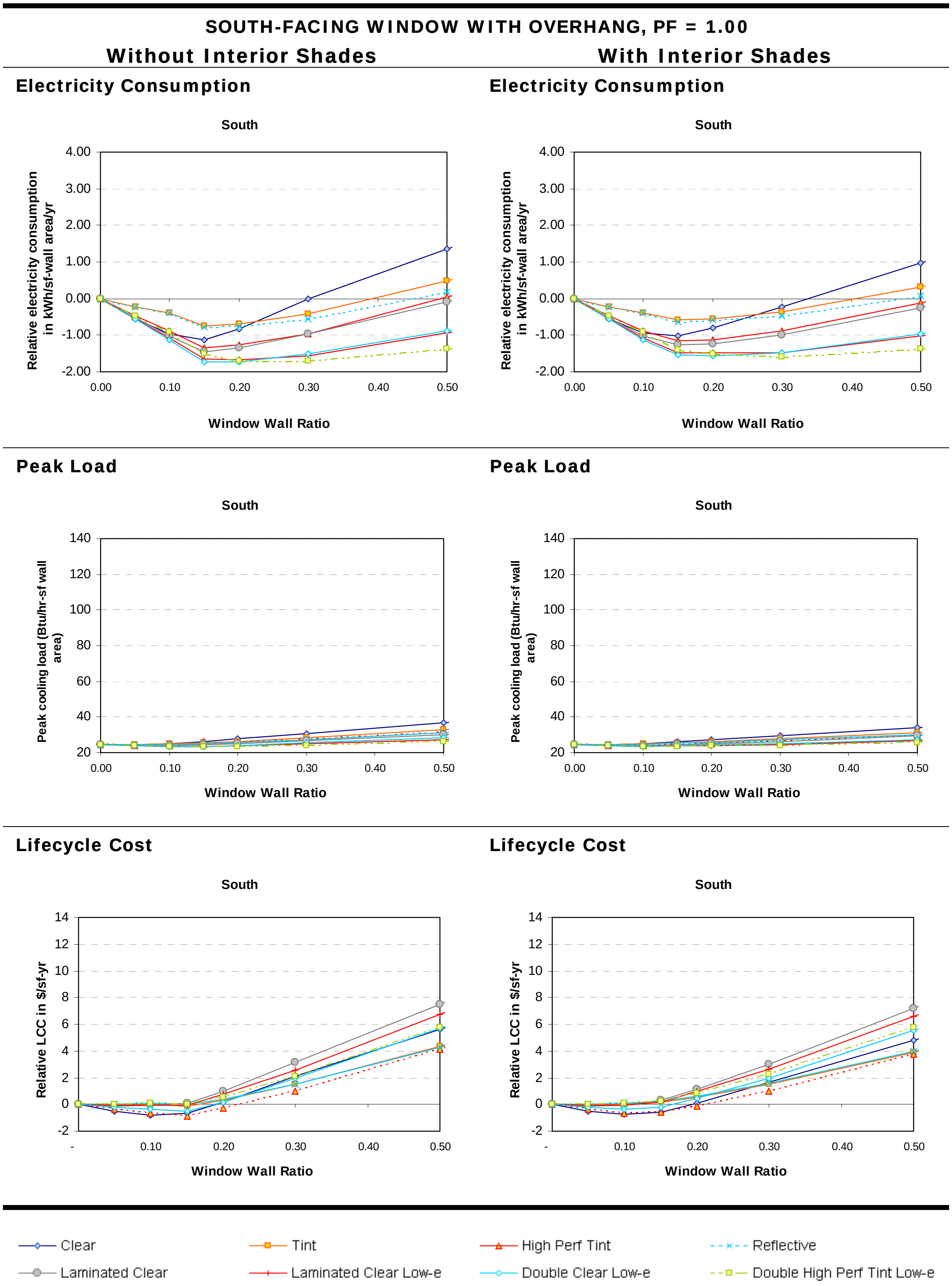
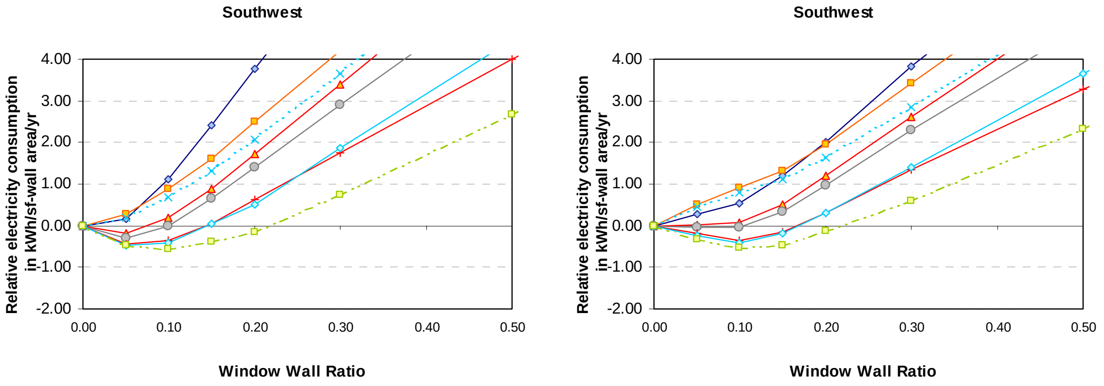


Figure 5-54.
Southwest window, no overhang.
Impact of WWR on electricity consumption, peak cooling load, and lifecycle cost, for windows with and without interior shades.

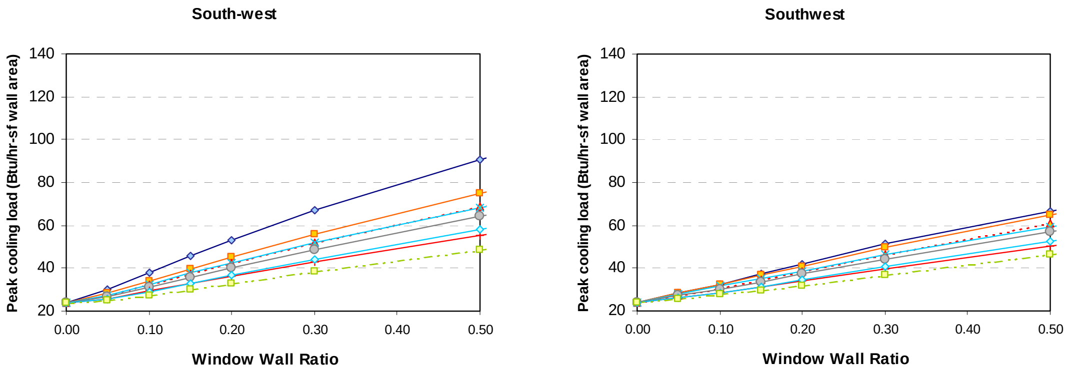
SOUTHWEST-FACING WINDOW WITH NO EXTERIOR SHADING

Without Interior Shades | **With Interior Shades**

Electricity Consumption



Peak Load



Lifecycle cost

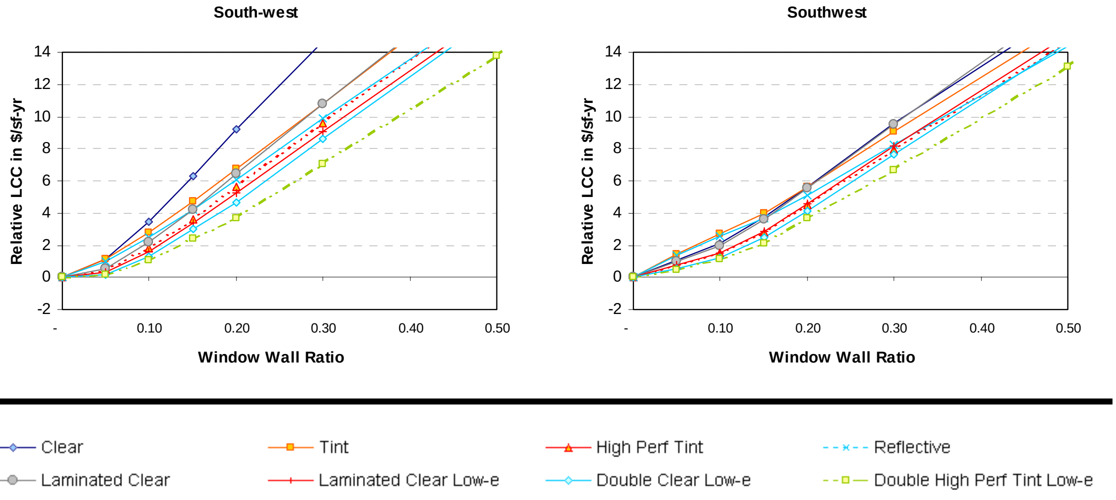


Figure 5-55. ***Southwest window. Overhang PF = 0.25.*** *Impact of WWR on electricity consumption, peak load demand, and lifecycle cost.*

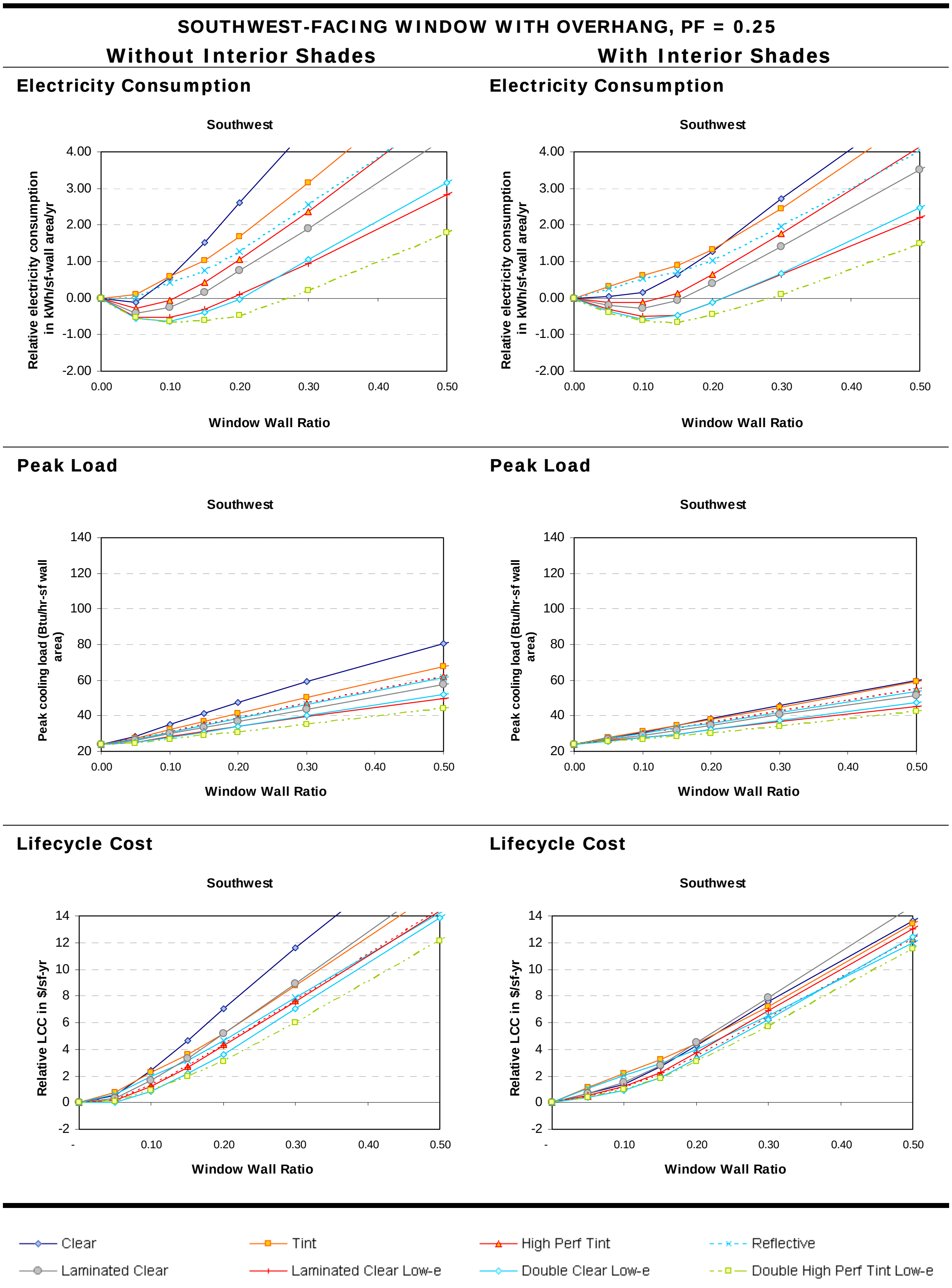


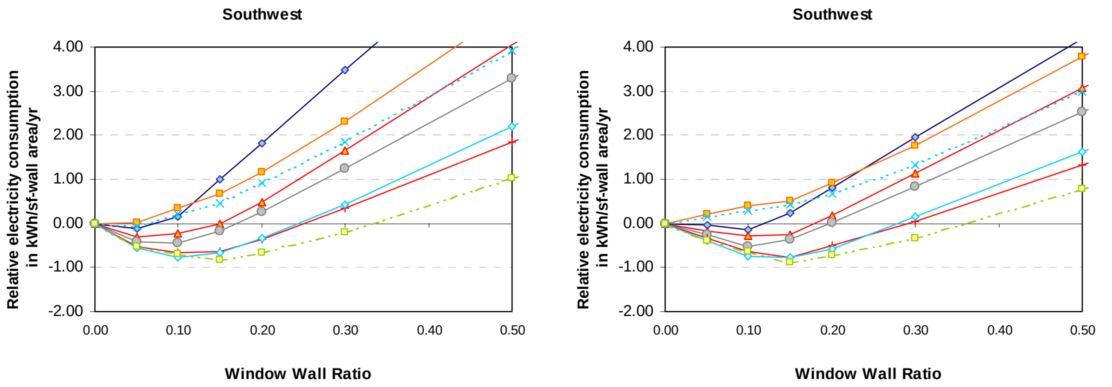
Figure 5-56. ***Southwest window. Overhang PF = 0.50.*** *Impact of WWR on electricity consumption, peak load demand, and lifecycle cost.*

SOUTHWEST-FACING WINDOW WITH OVERHANG, PF = 0.50

Without Interior Shades **With Interior Shades**

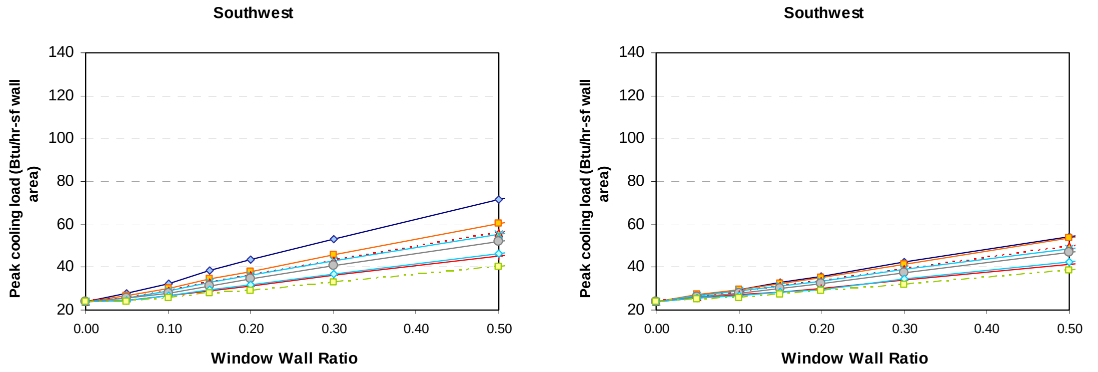
Electricity Consumption

Electricity Consumption



Peak Load

Peak Load



Lifecycle Cost

Lifecycle Cost

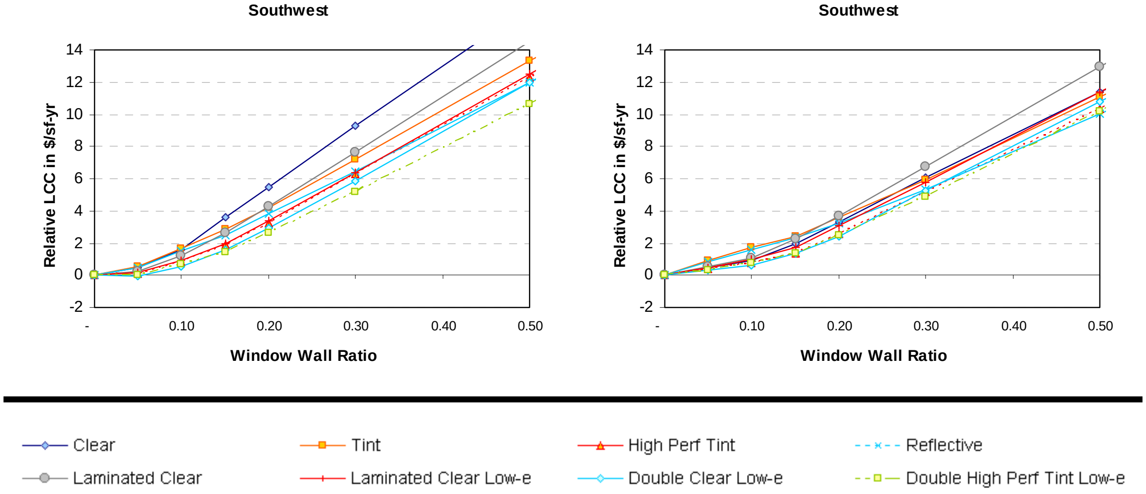


Figure 5-57. ***Southwest window. Overhang PF = 1.00.*** *Impact of WWR on electricity consumption, peak load demand, and lifecycle cost.*

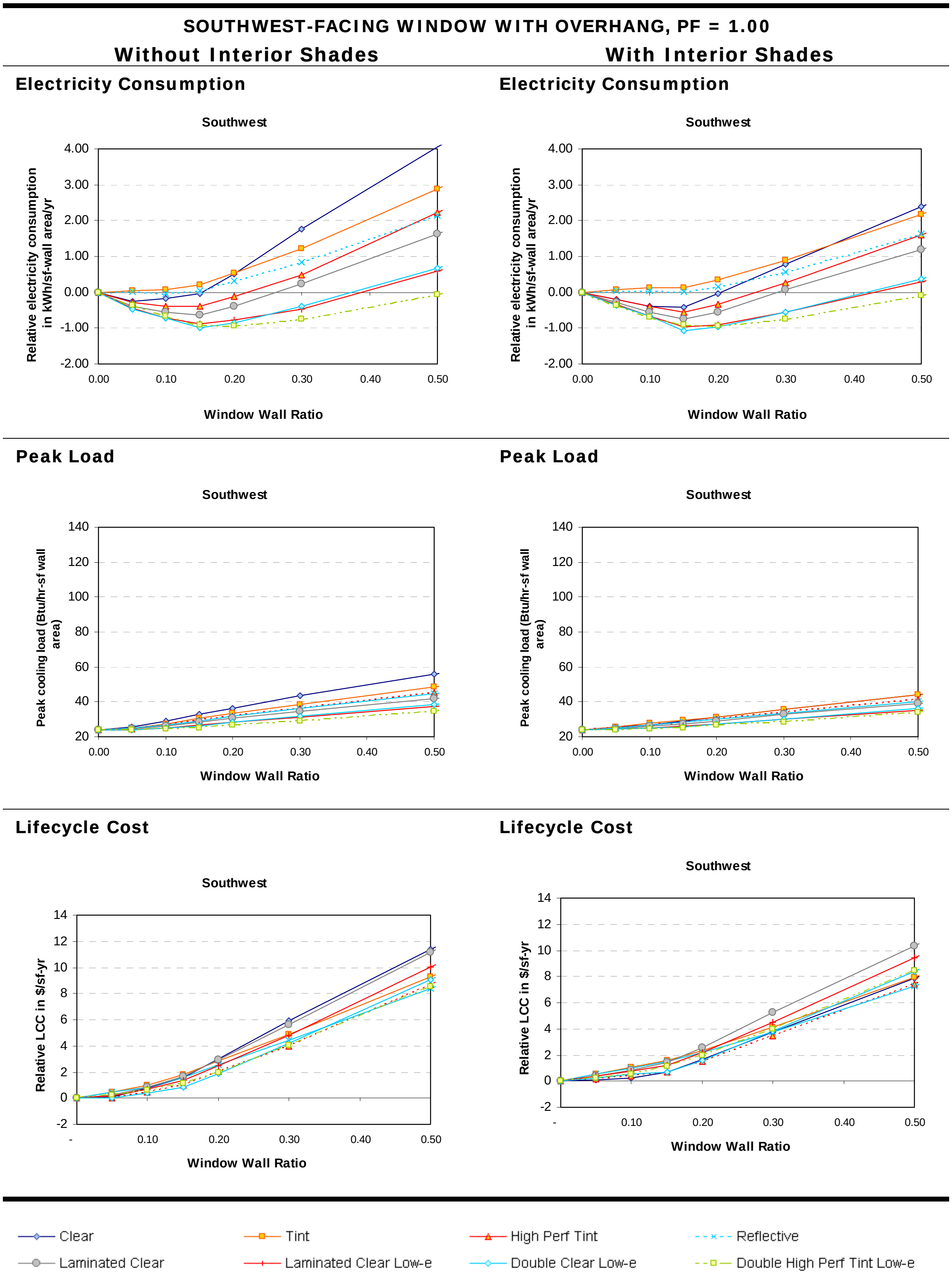


Figure 5-58. ***West window, no overhang.*** *Impact of WWR on electricity consumption, peak cooling load, and lifecycle cost, for windows with and without interior shades.*

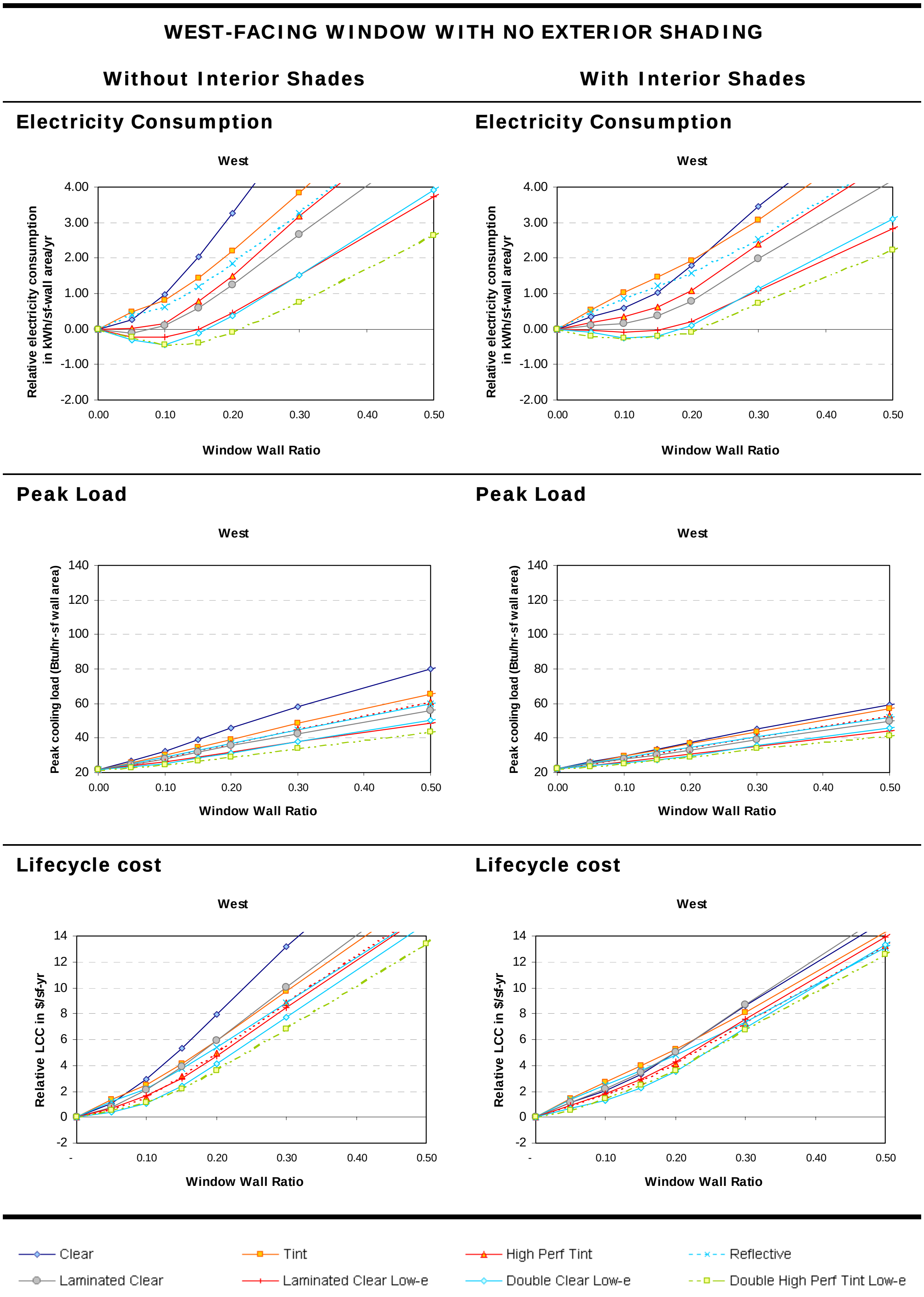


Figure 5-59. ***West window. Overhang PF = 0.25.*** *Impact of WWR on electricity consumption, peak load demand, and lifecycle cost.*

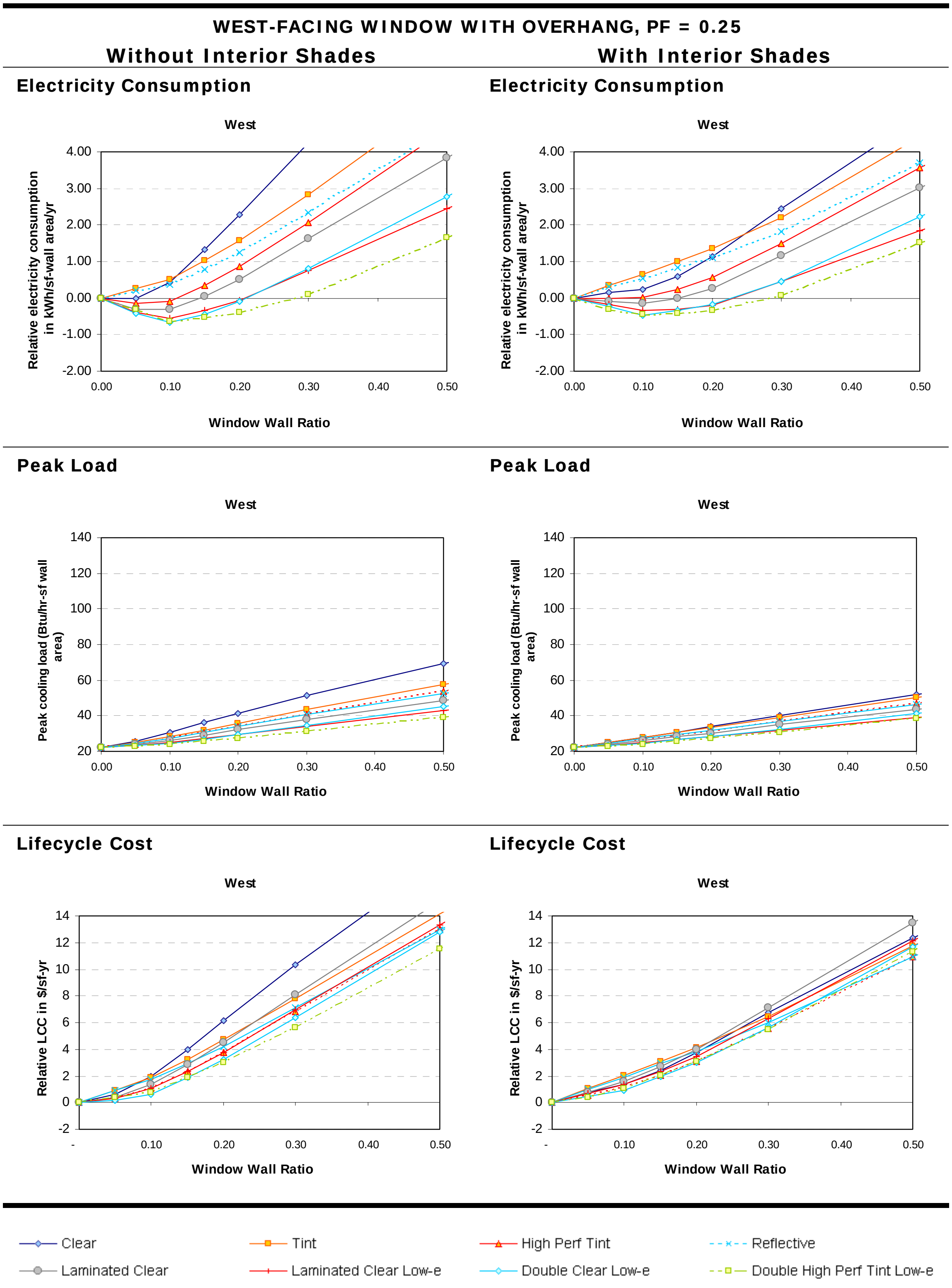


Figure 5-60. ***West window. Overhang PF = 0.50.*** *Impact of WWR on electricity consumption, peak load demand, and lifecycle cost.*

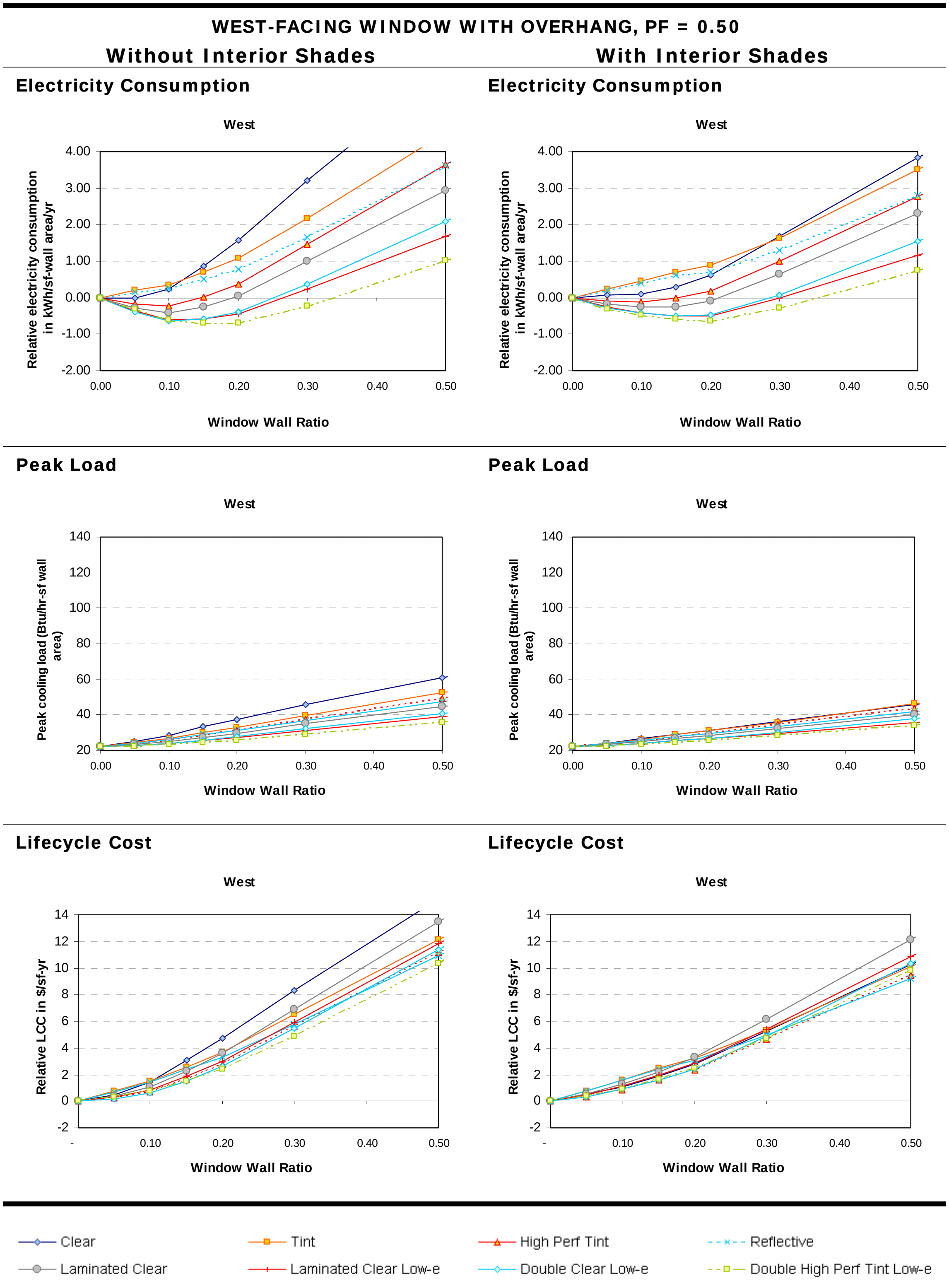


Figure 5-61. ***West window. Overhang PF = 1.00.*** *Impact of WWR on electricity consumption, peak load demand, and lifecycle cost.*

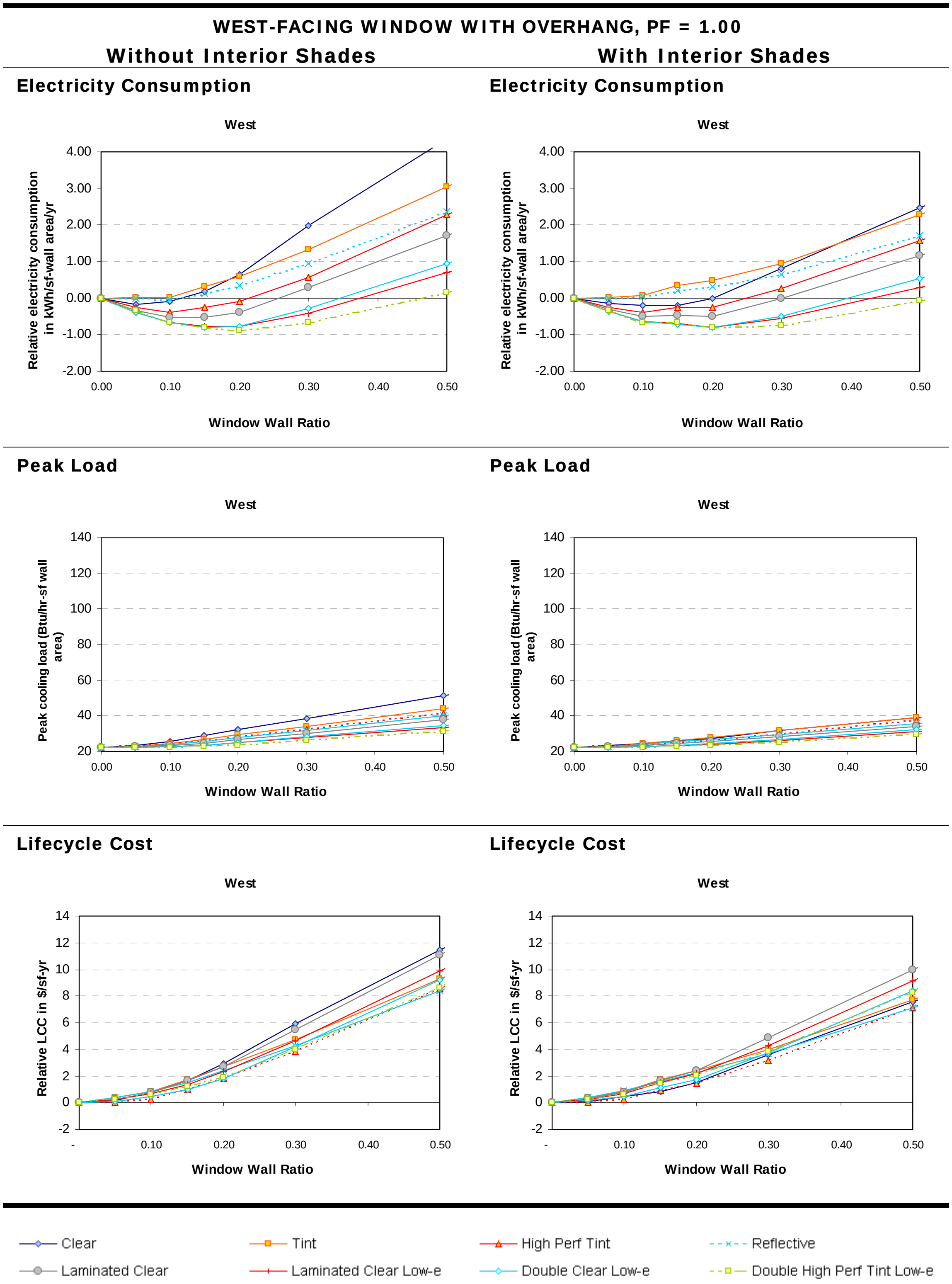
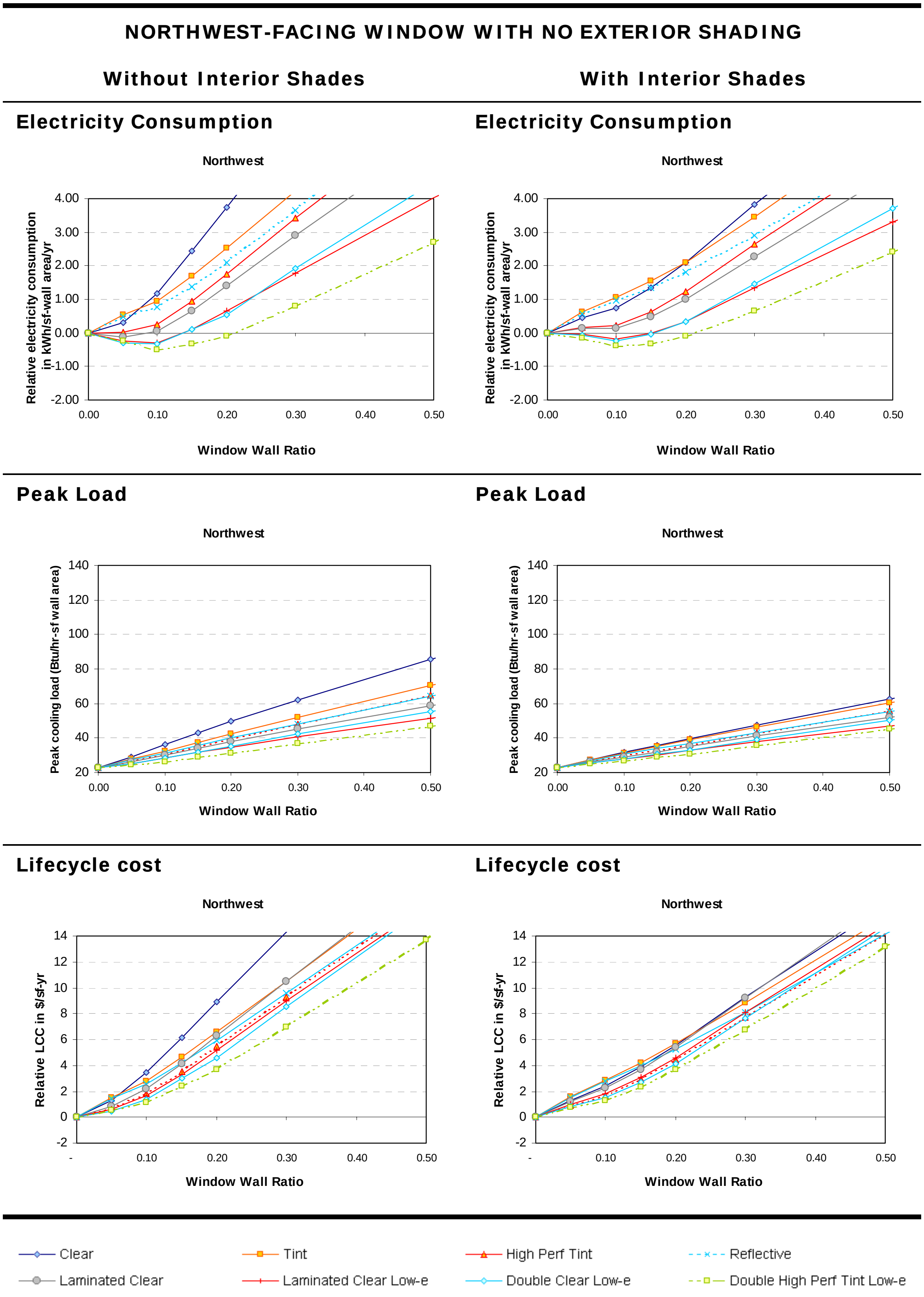


Figure 5-62. ***Northwest window, no overhang.*** *Impact of WWR on electricity consumption, peak cooling load, and lifecycle cost, for windows with and without interior shades.*



NORTHWEST-FACING WINDOW WITH NO EXTERIOR SHADING

Without Interior Shades | **With Interior Shades**

Electricity Consumption

Peak Load

Lifecycle cost

Figure 5-63. ***Northwest window. Overhang PF = 0.25.*** *Impact of WWR on electricity consumption, peak load demand, and lifecycle cost.*

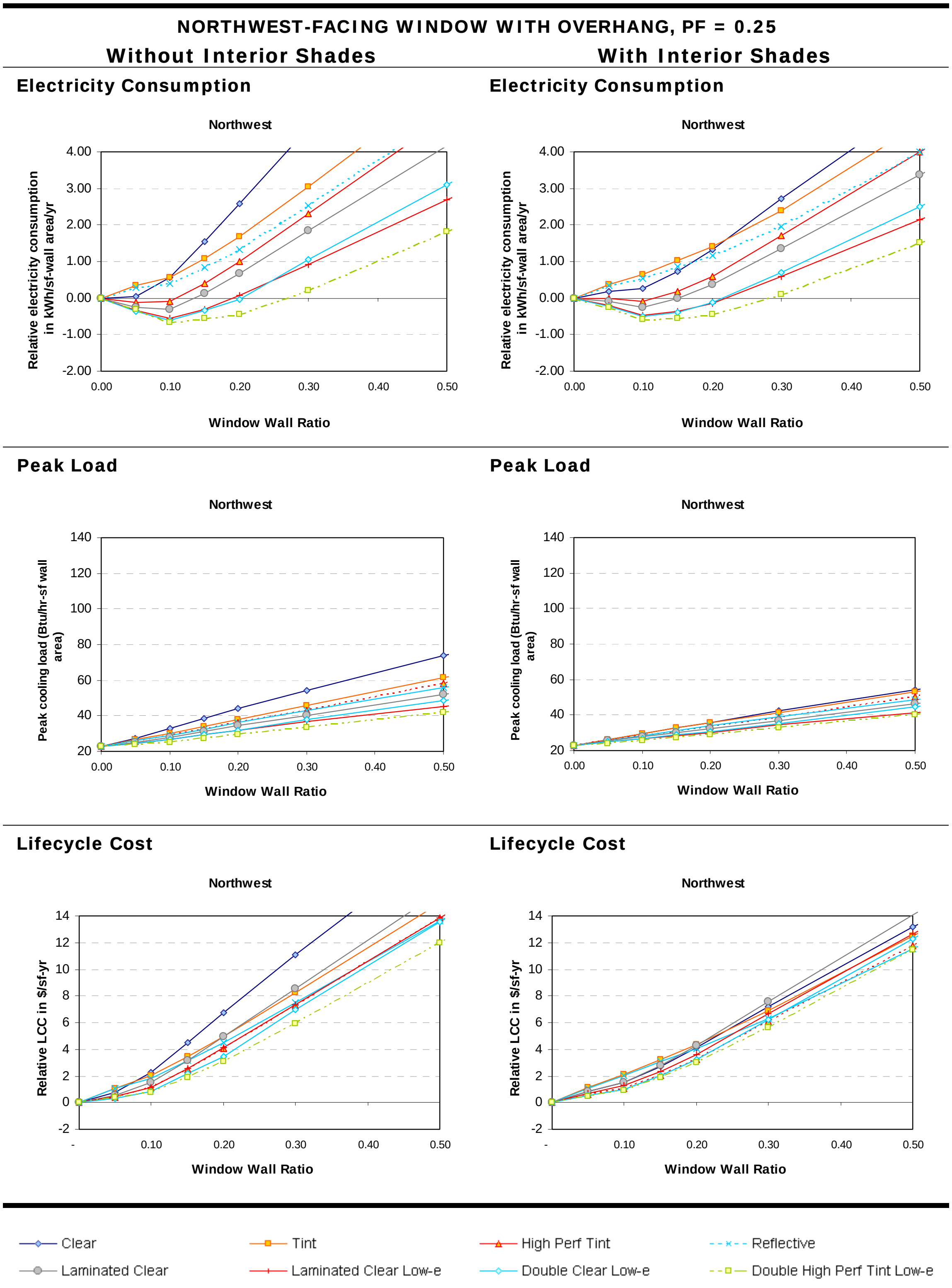
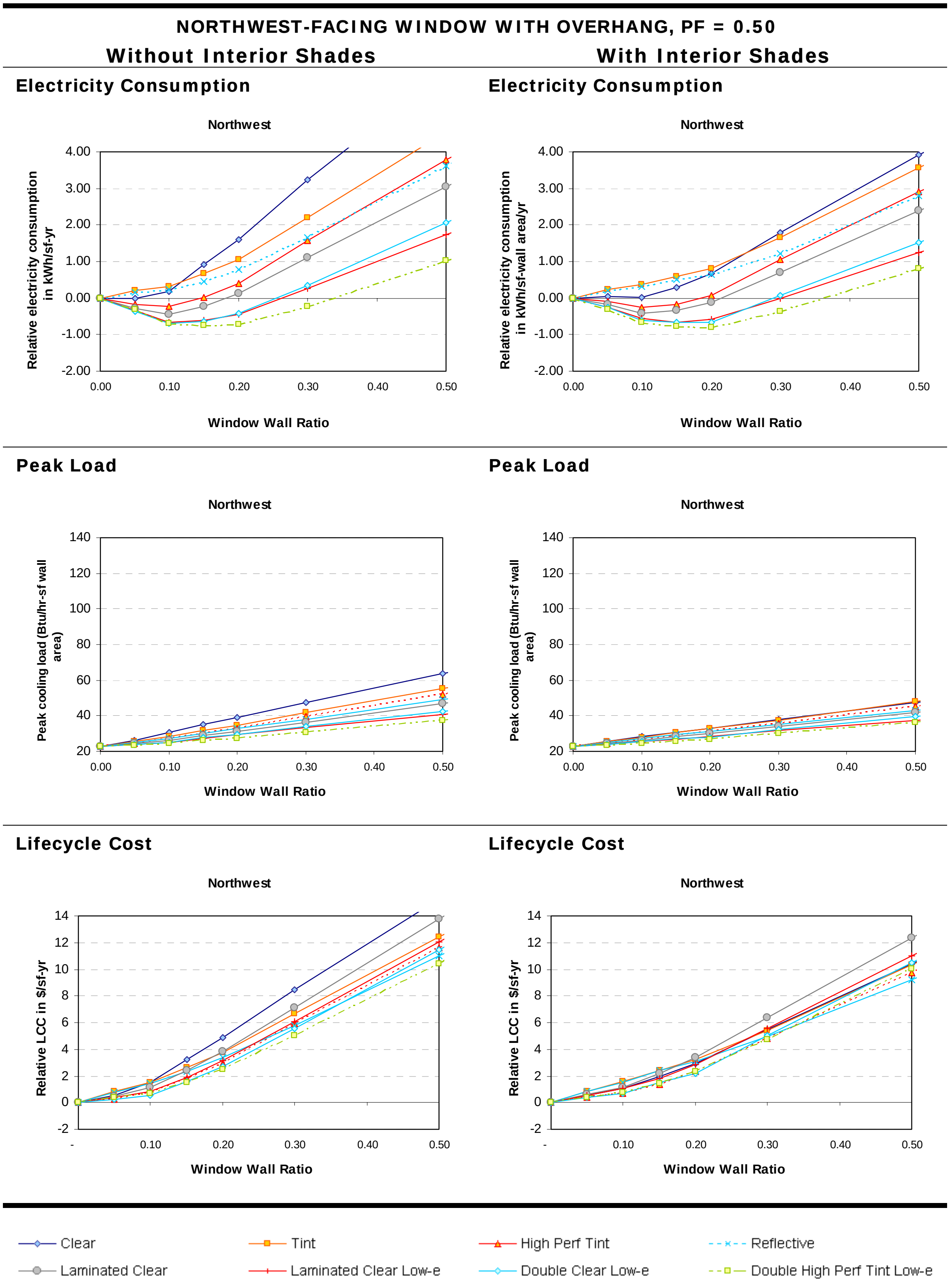


Figure 5-64. ***Northwest window. Overhang PF = 0.50.*** *Impact of WWR on electricity consumption, peak load demand, and lifecycle cost.*



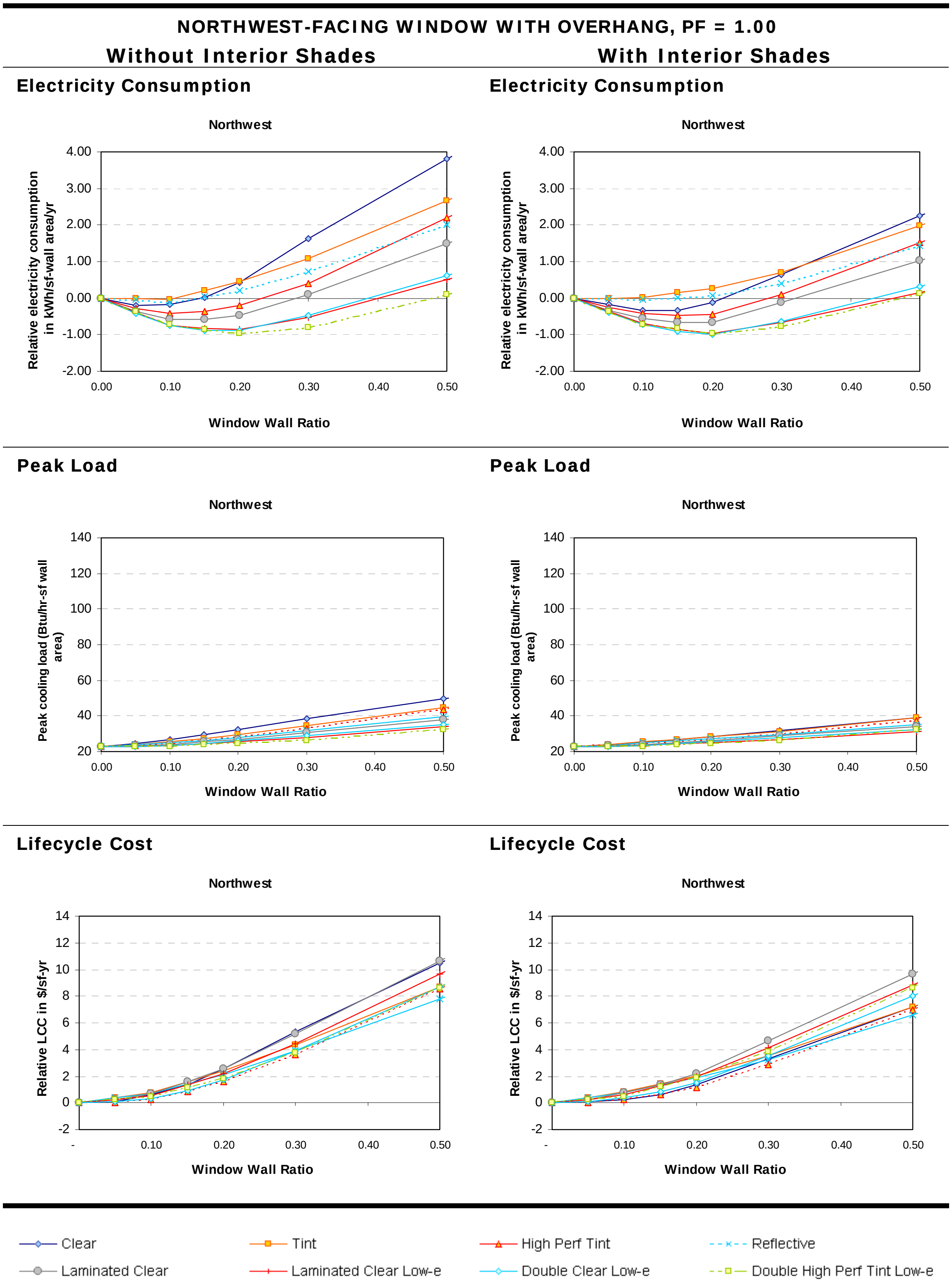


Figure 5-65. ***Northwest window. Overhang PF = 1.00.*** *Impact of WWR on electricity consumption, peak load demand, and lifecycle cost.*

6. COOL ROOF SYSTEMS

Overview

The purpose of this chapter is to provide designers with recommendations for cool roof systems that provide cost effective energy savings and meet or exceed the Hawaii Energy Code requirements. [1]

Description

"Cool roof systems" reduce solar heat gain using a combination of strategies, including "cool roof" surfaces, insulation, and radiant barriers.

The term "cool roof" is typically used to describe surfaces with high solar reflectance and high emissivity. A high solar reflectance means that more solar radiation is reflected and less is absorbed by the roof surface, keeping the surface temperature lower and reducing heat gain. Such surfaces are usually light in color. A high emittance helps the roof in rapidly losing heat by allowing radiation to the sky, when the surrounding environment is cooler.

Cool roof systems as described in this chapter cover more than just the surface. Several factors affect a roof's energy performance.

- Membrane characteristics
- Insulation type and thickness
- Use of a radiant barrier
- Presence of air gaps and ventilation

Fortunately for the designer, various combinations of these strategies can provide equal performance. The sections titled Low-slope Roofs and Sloped Roofs provide details on a range of recommended designs.

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[1] Note that even though the guideline focuses on thermal performance, moisture resistance is the primary roof function and must be the designer's first consideration.

Applicability

The recommendations in this chapter apply to both sloped and low-sloped roofs. These categories have been further classified into two sub-categories:

- Roofs with insulation entirely above deck, including concrete decks, wood decks and metal decks that have rigid insulation placed above the deck and the insulation is not interrupted by framing members.
- Roofs with insulation entirely below deck, including roofs where the insulation is installed entirely under the roof deck or inside the roof cavity, and may be interrupted by framing members.

Appropriate types of cool roof systems have been recommended for both these sub-categories categories.

Most of the recommendations in the following chapters are aimed towards new construction projects, but some of them can be applied to retrofit projects as well. These include:

- Replacing the old roofing membrane with a light-colored single ply membrane
- Using a liquid applied white elastomeric coating on flat built-up roofs.
- Adding foam board insulation on top of existing roof deck to increase thermal performance.
- Installing a radiant barrier within an existing attic space.

Insulation

Insulation reduces heat transfer between two surfaces by reducing thermal conduction. Insulation is a material with a high R-factor (thermal resistance) that can be installed in the envelope of a building to improve thermal performance. There are several types of insulation available. The most common ones are described below.

Glass Fiber Insulation

Glass fiber insulation is available as batts (blankets) that can be attached to the underside of a roof or laid on top of a ceiling and as loose-fill insulation, which can be blown inside an attic or plenum space.

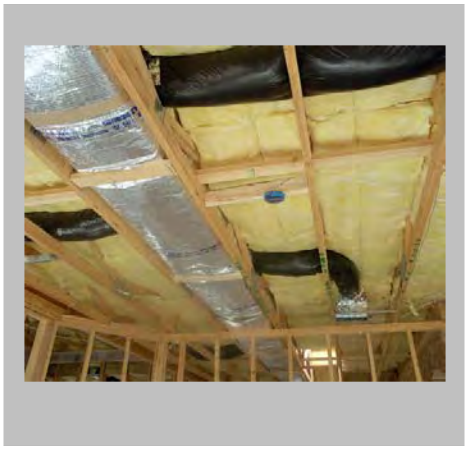

Figure 6-1: Batt insulation installed under the roof deck (Photo: Gretz, Warren, 2001. http://www.nrel.gov/data/pix/Jpegs/10221.jpg)

Glass fiber insulation is produced from sand and limestone or recycled glass and typically has a formaldehyde-based binder added to it. Some manufacturers make glass fiber insulation that is free of binders or that use acrylic binders. Glass fiber batts must be isolated from the occupied space by either installing an impervious barrier between the insulation and the inhabited space or by using a batt with Kraft paper, foil or flame-resistant foil facing.

Table 6-1 shows typical thickness and R-factor for the most commonly available rolls of batt insulation.

See http://www.naima.org for more information.

Table 6-1: Types of commonly available fiberglass insulation batts

R-factor ($hr.ft^2.°F/Btu$)	**Thickness (in.)**
R-13	3 ½”, 3 $^5/_8$”
R-19	6 ½”
R-30	10 ¼”
R-38	12”

Cellulose Insulation

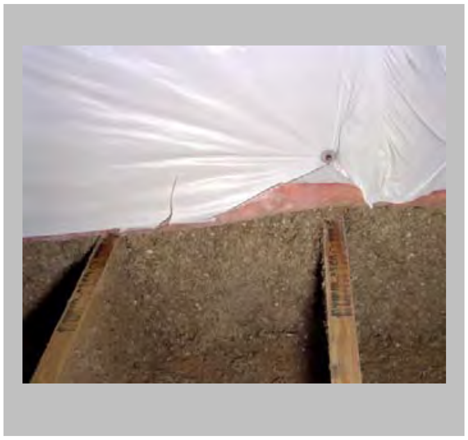

Figure 6-2: Cellulose insulation installed in attic space. (Photo: Gretz, Warren, 2001. http://www.nrel.gov/data/pix/Jpegs/08769.jpg)

Cellulose insulation is typically made from recycled newsprint, and can usually be produced locally. Since it takes relatively little energy to produce, it is usually the insulation product with the lowest embodied energy and lowest environmental impact. Cellulose is produced by either chopping newsprint into small pieces (hammer mill), shredding (disk refining) or disaggregating into fibers (fiberization). The simplest use is blowing or pouring loose-fill cellulose into the attic space to provide about R-3.7 per inch. To reduce flammability and deter pests, cellulose insulation is typically treated with boric acid, sodium borate (borax), or ammonium sulfate.

Wet-spray cellulose has water or binders added during installation to make it stick and can be used on vertical surfaces. Conventional wet-spray cellulose using a hammer mill product usually requires about 4 gallons of water per 30 lb. bag. A relatively new formulation of cellulose insulation, referred to as *stabilized* cellulose, has a binder added to prevent settling as is common in the case of conventional loose-fill cellulose used in attics. See http://www.cellulose.org for more information

Foam Board Insulation

Even though many foam insulation products are more expensive than other insulating materials, they are commonly used in buildings where there are space limitations or where very high R-factors are desirable. Foam boards are the usual choice when insulation is installed on top of the roof deck because they can tolerate some foot traffic and resist compression.

Three different types of foam board are typically used for building applications: molded expanded polystyrene (MEPS), extruded expanded polystyrene (XEPS), and polyisocyanurate.

Molded Expanded Polystyrene (MEPS) is commonly known as "beadboard". Beadboard is made from loose, unexpanded polystyrene beads containing liquid pentane and a blowing agent, which are heated to expand the beads and increase its thermal resistance. Adding a vapor diffusion retarder is essential in building applications since spaces between the foam beads can absorb water. R-factors vary from 3.8 to 4.4 per inch of thickness.

Extruded Expanded Polystyrene (XEPS) is a closed-cell foam insulation similar to MEPS. Polystyrene pellets are mixed with chemicals to form a liquid, and a blowing agent is injected into the mixture, to form gas bubbles. The liquid mixture is solidified through a cooling process and the gas bubbles are trapped to give it an insulating property. XEPS is more expensive than MEPS, and like MEPS the R-factor depends upon the density of the material and is typically equal to R-5 per inch. It has a higher compressive strength than MEPS, making it better suited for use on roofs or for wall panels. Extruded polystyrene also has excellent resistance to moisture absorption. The rigid foam board recommendations in the following chapters assume thermal resistance values for XEPS insulation.

Polyisocyanurate is a closed-cell foam that contains a low conductivity gas (such as HCFC or CFC) and has a high initial thermal resistance of about R-9 per inch, which decreases to between R-7 and R-8 per inch over time, as some of the infill gas escapes. These boards can be laminated with foil and/or plastic facings to prevent the gas from escaping. If a reflective foil is installed correctly, it can also act as a radiant barrier that can significantly increase the thermal performance of the insulating assembly.

See http://www.eren.doe.gov/consumerinfo/refbriefs/ed3.html for more information on foam insulation.

Radiant Barriers

Radiant barriers are reflective materials that reduce the amount of heat radiated across an air space. In Hawaii, they can be installed in an attic or within a roof construction to reduce the amount of solar heat that enters a building. Conventional insulations are usually rated by their R-factor. Since the performance of radiant barriers depends on many variables, simple R-factor ratings have not been developed for them. All radiant barriers have at least one reflective surface. Some radiant barriers have a reflective surface on both sides. At least one reflective side must face an air space to be effective.

Figure 6-3: Radiant barrier. (Photo: http://www.radiantbarrier.com/)

Radiant barrier products are available in several forms, including flexible sheets (as in Figure 6-3), laminated to wood roof deck products, or as a liquid applied coating. The sheet products have the potential for the best performance, because they can be installed with air gaps on both sides and may have low emissivity on both faces. And some products consist of foil laminated to bubble-wrap material, providing a small boost in insulation performance. The radiant barriers laminated to roof deck materials such as oriented strand board or plywood also work well and typically cost less to install. The liquid applied radiant barriers offer some benefit but do not perform as well as the other alternatives.

The performance of a radiant barrier is determined by its emissivity, which is a number between 0 and 1, with lower numbers indicating better potential for performance. To receive compliance credit for using a radiant barrier, the installation must have an emissivity no greater than 0.10, and should follow one of the installation procedures outlined in the Hawaii Energy Code. For comparison, most other materials have much higher emissivity values, between 0.8 and 0.9. Liquid applied radiant barriers have an emissivity of around 0.5.

Roof Membranes

Roofing membranes are surfaces that are applied or attached to a structural roof deck to provide water resistance. These include a wide range of products such as shingles, tiles, metal sheets, mineral cap sheets, and single-ply membranes.

For low-slope roofs the membrane typically consists of single or multiple rolls of (usually) petroleum derived impervious material that can be laid flat over a roofing substrate, and held in place by mechanical fasteners, adhesives or ballast laid on top of it. Typical single-ply roofing membranes include EPDM (ethylene-propylene-diene-terpolymer membrane), PVC (polyvinyl chloride), CPE (chlorinated polyethylene), TPO (thermoplastic polyolefin). These membranes are available both in dark and light colors.

Figure 6-4: Mineral Cap Sheet Roof Membrane. Typically has poor cool roof performance due to low reflectance.(Photo: Erik Kolderup, 2002)

Figure 6-5: Single Ply Roof Membrane. White products offer good cool roof performance. (Photo: Craig Miller Productions, 2000. http://www.nrel.gov/data/pix/Jpegs/03510.jpg)

Roofing membranes are typically available in shades of black, gray or white. The reflectance and emittance of roofing membranes have a significant impact on the air-conditioning load of a building. Products with a high reflectance and emittance are recommended. Light-colored membranes may cost more, but the additional cost is usually balanced out by reduction in thickness of insulation required to comply with code.

Typically most roofing materials have a high emittance with the exception of unpainted metal roofs, which have a low emittance. It’s important to note that:

- All colors of asphalt shingle have poor reflectance (0.03–0.26). White asphalt shingles are slightly better (0.31).
- White elastomeric coatings have a high reflectance (0.65–0.78) and high emittance.

- White single-ply membranes have a high reflectance (0.69–0.81) and high emittance.

Other coated white roofing systems (such as white metal roof and painted concrete) have high reflectance (0.67– 0.85).

See http://www.coolroofs.org/ratedproductsdirectory.html for a directory of rated cool roof products.

The Cool Roof Rating Council (CRRC) is a non-profit organization founded in 1998 to develop accurate and credible methods for evaluating and labeling the solar reflectance and thermal emittance of roofing products and to make the information available to interested parties. The EPA EnergyStar ® Roof Products Program (http://www.energystar.gov) is a voluntary initiative with roofing manufacturers that encourages them to promote products that meet agreed upon energy efficiency criteria.

Definitions

Absorptivity (α): Absorptivity is the fraction of solar radiation absorbed by a surface. Absorptivity is a term in the roof heat gain factor (RHGF) calculation

Reflectance: Percentage of radiant energy reflected by a material. This is equal to ($1-\alpha$) for opaque materials such as roof membranes.

Emissivity: The ratio of the radiant heat flux emitted by a specimen to that emitted by a black body at the same temperature and the same conditions. Galvanized metal and other metallic finishes have a low emittance, which means that when they warm up, they can not easily release their heat by radiating it back to the sky. For roof surfaces a high emissivity is desired while for radiant barriers a low emissivity is necessary.

R-factor or R-value (thermal resistance): The R-factor or R-factor of a material is its ability to resist conductive heat transfer between two surfaces and is measured in units of hr. sq. ft. °F/Btu at a specified temperature. The R-factor does not include the thermal resistance of air films.

U-factor or U-value (coefficient of heat transmission): U-factor or U-value is a measure of the ability of a building envelope to transfer heat in units of Btu/hr. sq. ft. °F (and is usually measured at temperature of 75 °F). It describes the insulating properties of building envelope components such as walls and roofs. U-factor is the inverse of the sum of R-factor (ΣR), which is thermal resistance. ΣR includes resistances of surfaces, structural components, and insulation. A lower U-factor means lower heat flow through the envelope.

Hawaii Energy Code Requirements

Section 8.4 of the code contains the prescriptive criteria for the building envelope of commercial buildings.[2] The prescriptive option provides the easiest way to comply with the envelope requirements of the Code, but offers limited trade-off possibilities.

The requirement for opaque roof surfaces is a maximum *roof heat gain factor* (RHGF) of 0.05. The RHGF is a product of three elements of roof design that effect solar heat gain: insulation (U-factor), color (absorptivity) and the presence of a radiant barrier (radiant barrier credit).

The RHGF of the opaque roof may be calculated with the following equation:

$$RHGF = U \times \alpha \times RB$$

where,

U = U-factor of the roof construction.
α = absorptivity of the roof surface.
RB = radiant barrier credit. RB equals 0.33 if a radiant barrier is installed or 1.0 if there is no radiant barrier. See Radiant Barriers for installation requirements.

If there is more than one type of roof construction, then determine the RHGF for each portion and take an area-weighted average.

Note that the average RHGF for the whole roof must be less than 0.05. Portions of the roof may fall short of the requirement if other parts have more insulation than is necessary.

Benefits

There are a number of benefits provided by cool roof systems, including:

- Smaller AC equipment; in some cases eliminating the need for AC.
- Lower cooling costs.

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[2] Low-rise residential roofs are covered by a separate code, adopted in Honolulu in 2001.

- Better comfort due to a cooler ceiling.

There are additional benefits to a cool roof *surface*.

- Longer roof life due to lessened thermal expansion and contraction because the roof stays cooler.
- Reduced energy consumption by the HVAC system when the air-conditioning ducts are located in the attic space.
- Reduced urban heat island effect. On a larger scale, if the albedo[3] of an entire region can be significantly increased by installing cool roofs, light colored paved surfaces etc. the urban heat island effect can be reduced. Increasing the average albedo of roof areas and other exposed surfaces would result in lower temperature rise in the urban microclimate, reducing overall peak energy demand. This also implies a reduction in urban air pollution produced during generating power to meet peak loads.

Costs

The following tables list approximate costs for some of the roofing and insulation products discussed in this chapter

Table 6-2: Cost of commonly available insulation

Type of insulation	**Material Cost ($/ft²)**	**Material Cost ($/"R-value")**
Batt or blown insulation (5.5 inches, R-19)	$0.40	$0.02
Extruded Expanded Polystyrene (3 inches, R-15)	$1.35	$0.09
Polyisocyanurate (2 inches, R-14)	$0.95	$0.07

Table 6-3: Cost of different types of radiant barrier

Type of Radiant Barrier	**Material Cost ($/ft²)**
Flexible Sheet	$0.15 to $0.20
Insulated Radiant Barrier	$0.40 to $0.60
Laminated Deck	$0.10 to $0.20 (added to wood panel cost)

Cost Effectiveness

The roof constructions recommended in the following sections are intended to be cost effective. That means that the energy savings over time more than pays for the insulation, radiant barrier and/or white membrane. And improved roof performance might allow installation of smaller and less expensive AC equipment.

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[3] A combination of reflectance and emmisivity

Lighter roof surfaces can cost more, but that is not always the case. Radiant barriers can be relatively inexpensive, especially the type that is laminated to roof deck material at the factory. The most cost effective option will vary from one project to the next depending on design details, but the recommendations in this chapter should be a good starting point.

Operations and Maintenance

To assure continued performance of cool roof surfaces (white roofs), they should be cleaned periodically with a high-pressure water spray or with soap and water. (Verify that doing this does not void the product warranty.) Cleaning is especially important in dusty areas. Liquid-applied roof coatings may need to be reapplied every five years or so.

Shiny surfaces of radiant barriers should be free of dust, paint or any other coating that would reduce the reflectivity of the radiant barrier. Avoid poking holes/perforations in the radiant barrier as too many holes will affect the performance of the radiant barrier. Seal visible holes with foil tape.

If any part of the insulation is moved around or removed due to repairs in the roof or ceiling, ensure that the insulation is replaced or moved back in place to ensure continued thermal benefits.

Commissioning

While no field testing is appropriate, there are a few important steps.

- Review contractor submittals to ensure that any product substitutions provide equal or better performance compared to the specified products. Pay attention to roof membrane reflectance, insulation R-factor and radiant barrier emissivity.
- Inspect construction to ensure that the proper insulation type and thickness is installed, that any radiant barriers are installed facing the proper direction and with adequate air gaps, and that the correct roof membrane is installed and properly cleaned.

References

Impact of cool roofs and cool roofs materials database. Heat Island Group, Lawrence Berkeley National Laboratory. http://eetd.lbl.gov/HeatIsland/CoolRoofs/)

Cool Roof Rating Council. http://www.coolroofs.org

Cool roofs resources and information. Energy Star Roof Products Program.
http://www.nationalcoatings.com/coolroof/estar/)

Energy Star Roof Products. http://yosemite1.epa.gov/estar/consumers.nsf/content/roofbus.htm

Roof heat gain factor. Hawaii Model Energy Code. http://www.state.hi.us/dbedt/ert/model_ec.html

ASHRAE. 2001. ANSI/ASHRAE/IESNA Standard 90.1-2001. Atlanta, GA. Includes tables of U-factors for a wide range of typical roof constructions.

ASHRAE. 2001. 2001 Fundamentals. Atlanta, GA. Provides guidelines and material performance data for U-factor calculations.

Low-slope Roofs

Recommendation

Use a roof surface that is light in color (high reflectance), yet has a non-metallic finish (high emissivity). The basic recommendation is to install a single ply membrane (with an initial reflectance greater than 0.7 and an emittance greater than 0.8) with 1.5 to 2 inches of foam board insulation. See also Figure 6-6 through Figure 6-14 for alternative recommendations for low-slope roofs.

Description

Low slope roofs are roofs that have a slope of less than 1 in 6.

Applicability

The recommendations in this chapter apply to concrete, metal and wood decks.

Integrated Design Implications

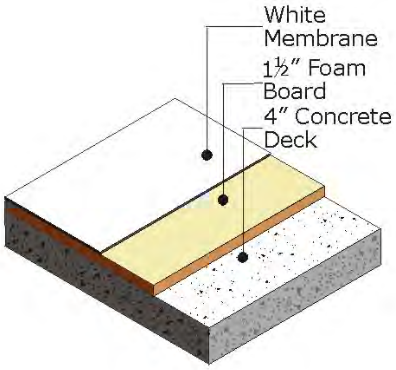
Like all roofing systems, skylights and other roof penetrations, as well as the roof-top equipment mounts, should be considered in the design of the roof. Equipment access should be provided in a manner that does not create undue wear or damage to the roof membrane. Slopes for moisture drainage should be carefully designed to prevent “ponding” of water, which would promote growth of mildew and reduce the effectiveness of the “cool roof”. In order to take advantage of cooling equipment downsizing, cool roofs should be considered in the schematic design phase.

Design Details

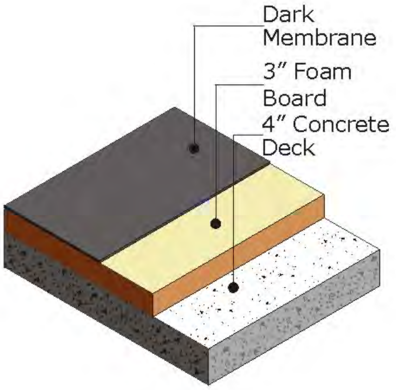
The following figures show a variety of options for achieving similar performance and complying with the energy code. These examples include one of two surface types, one dark and one white. The dark option represents either a dark gray EPDM roof or typical mineral cap sheet (α=0.80). The light roof membrane cases assume aged value of white T-EPDM

(α=0.50)[4]. Use faced batts in all cases where there is no hard ceiling.

Figure 6-6: Low-slope concrete deck roof assembly



LAYER	**R-FACTOR**
Outside Air[a]	0.17
Membrane[b]	0
1½" Foam[c]	7.5
4" Concrete[d]	2.4
Inside Air[e]	0.92
Total R-Factor	**10.99**
U-Factor	**0.091**
RHGF	**0.045**



LAYER	**R-FACTOR**
Outside Air[a]	0.17
Membrane[b]	0
3" Foam[c]	15.0
4" Concrete[d]	2.4
Inside Air[e]	0.92
Total R-Factor	**18.49**
U-Factor	**0.050**
RHGF	**0.043**

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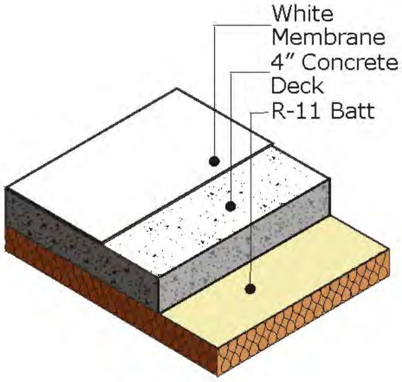
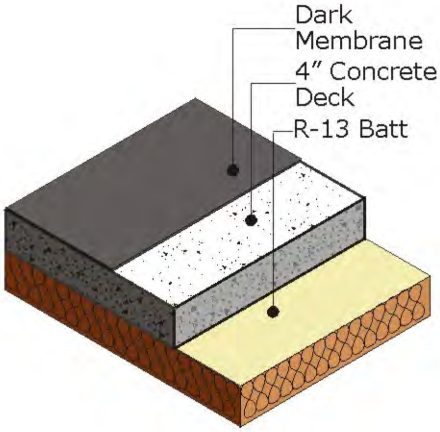
[4] This is the worst-case assumption for degradation. In reality, with regular maintenance, aged value for solar reflectance would be somewhat better than 0.50.

Figure 6-7: (cont'd.) Low-slope concrete deck roof assembly

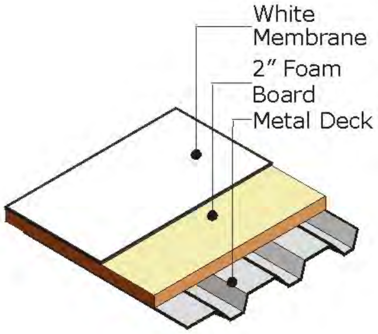


LAYER	R-FACTOR
Outside Air[a]	0.17
Membrane[b]	0
4" Concrete[d]	2.4
R-11 Batt	11
Inside Air[e]	0.92
Total R-Factor	**14.49**
U-Factor	**0.069**
RHGF[f]	**0.035**

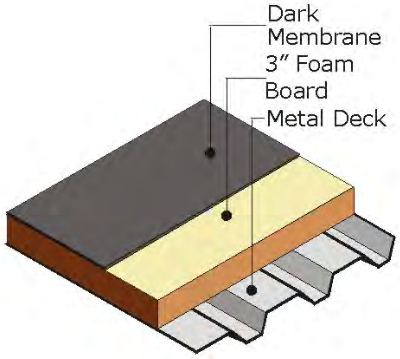


LAYER	R-FACTOR
Outside Air[a]	0.17
Membrane[b]	0
4" Concrete[d]	2.4
R-13 Batt	13
Inside Air[e]	0.92
Total R-Factor	**16.49**
U-Factor	**0.061**
RHGF	**0.049**

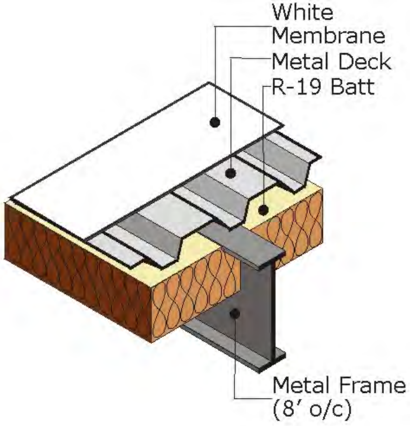
Figure 6-8: Low-slope metal deck roof assembly



LAYER	R-FACTOR
Outside Air[a]	0.17
Membrane[b]	0
2" Foam[c]	10.0
Metal Deck[g]	0
Inside Air[e]	0.92
Total R-Factor	**11.09**
U-Factor	**0.090**
RHGF	**0.045**

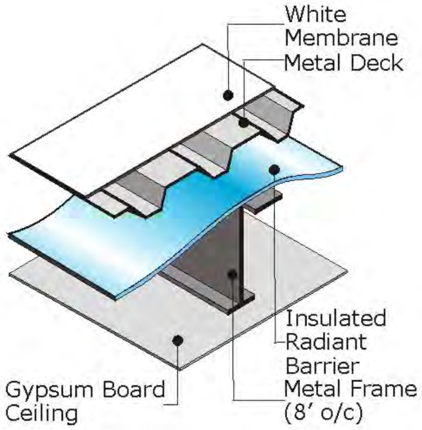


LAYER	R-FACTOR
Outside Air[a]	0.17
Membrane[b]	0
3" Foam[c]	15.0
Metal Deck[g]	0
Inside Air[e]	0.92
Total R-Factor	**16.09**
U-Factor	**0.062**
RHGF	**0.050**

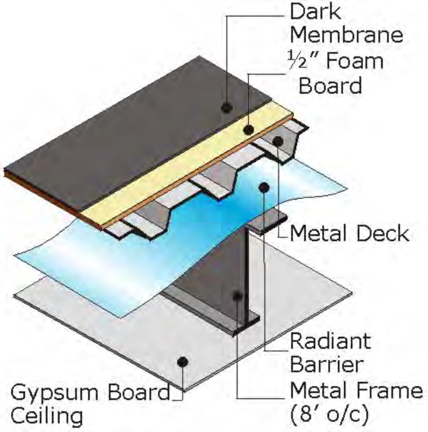


LAYER	R-FACTOR	
	Zone A[h]	Zone B[h]
Outside Air[a]	0.17	0.17
Membrane[b]	0	0
Metal Deck[g]	0	0
R-19 Batt	1.7	19
Inside Air[e]	0.92	0.92
Total R-Factor	**2.79**	**20.09**
U-Factor[h]		**0.088**
RHGF[i]		**0.044**

Figure 6-9: (cont'd.) Low-slope metal deck roof assembly

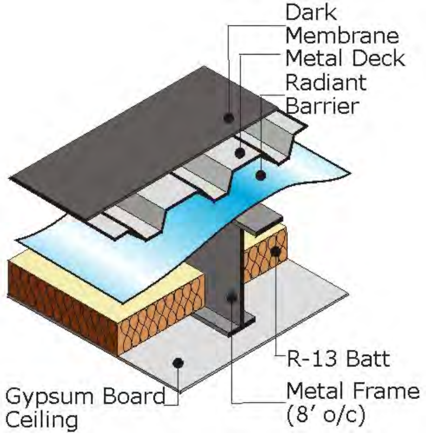


LAYER	**R-FACTOR**	
	Zone A[h]	Zone B[h]
Outside Air[a]	0.17	0.17
Membrane[b]	0	0
Metal Deck[g]	0	0
Air Gap[j]	N/A	0.85
RB[k]	0.90	0.90
Air Gap[l]	0.66	1.00
Ceiling[m]	0.45	0.45
Inside Air[e]	0.92	0.92
Total R-Factor	**3.1**	**4.29**
U-Factor[h]		**0.244**
RHGF		**0.040**



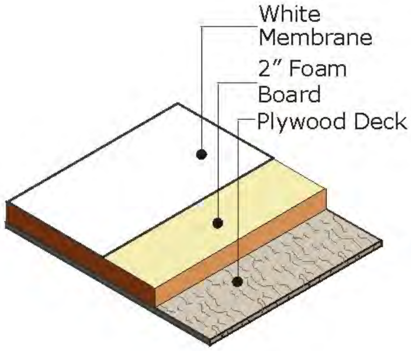
LAYER	**R-FACTOR**	
	Zone A[h]	Zone B[h]
Outside Air[a]	0.17	0.17
Membrane[b]	0	0
Metal Deck[g]	0	0
½" Foam[c]	2.5	2.5
Air Gap[j]	N/A	0.85
RB[n]	0	0
Air Gap[l]	0.66	1.00
Ceiling[m]	0.45	0.45
Inside Air[e]	0.92	0.92
Total R-Factor	**4.78**	**5.89**
U-Factor[h]		**0.175**
RHGF		**0.046**

Figure 6-10: (cont'd.) Low-slope metal deck roof assembly

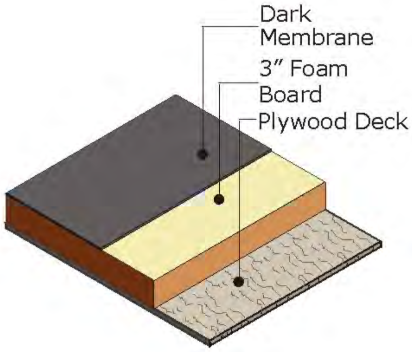


LAYER	**R-FACTOR**	
	Zone A[h]	Zone B[h]
Outside Air[a]	0.17	0.17
Membrane[b]	0	0
Air Gap [j]	N/A	0.85
RB[n]	0	0
Air Gap [l]	0.55	1.00
R-13 Batt	0.57	13.0
Ceiling[m]	0.45	0.45
Inside Air[e]	0.92	0.92
Total R-Factor	**2.66**	**16.39**
U-Factor[h]		**0.100**
RHGF		**0.027**

Figure 6-11: Low-slope plywood deck roof assembly

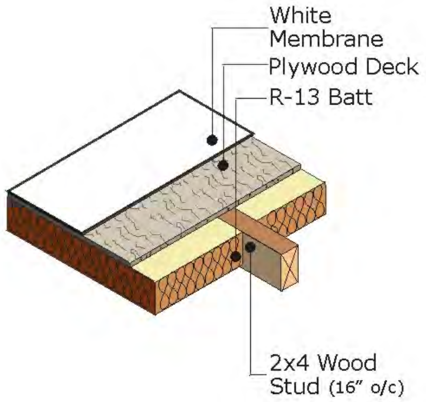


LAYER	**R-FACTOR**
Outside Air[a]	0.17
Membrane[b]	0
2" Foam[c]	10
Plywood[o]	0.62
Inside Air[e]	0.92
Total R-Factor	**11.71**
U-Factor	**0.085**
RHGF	**0.043**

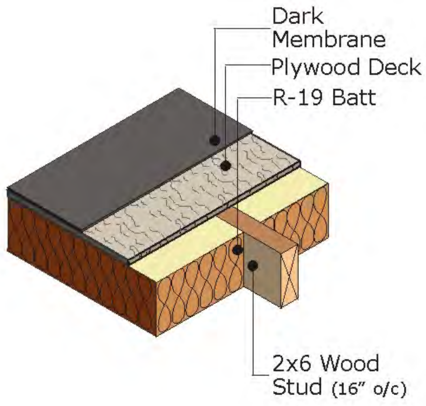


LAYER	**R-FACTOR**
Outside Air[a]	0.17
Membrane[b]	0
3" Foam[c]	15
Plywood[o]	0.62
Inside Air[e]	0.92
Total R-Factor	**16.71**
U-Factor	**0.060**
RHGF	**0.049**

Figure 6-12: (cont'd.) Low-slope plywood deck roof assembly

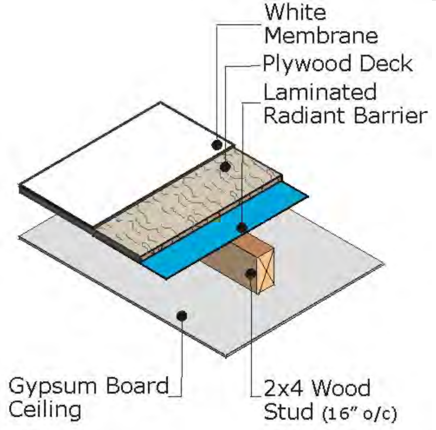


LAYER	**R-FACTOR**	
	Zone A[p]	Zone B[p]
Outside Air[a]	0.17	0.17
Membrane[b]	0	0
Plywood[o]	0.62	0.62
R-13 Batt	N/A	13
2x4 Stud[q]	4.38	N/A
Inside Air[e]	0.92	0.92
Total R-Factor	**6.09**	**14.71**
U-Factor[p]		**0.080**
RHGF		**0.040**

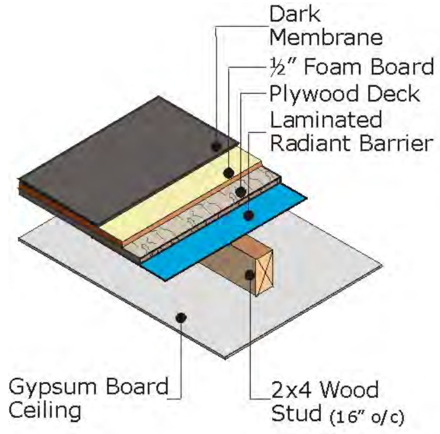


LAYER	**R-FACTOR**	
	Zone A[p]	Zone B[p]
Outside Air[a]	0.17	0.17
Membrane[b]	0	0
Plywood[o]	0.62	0.62
R-19 Batt	N/A	19
2x6 Stud[q]	6.57	N/A
Inside Air[e]	0.92	0.92
Total R-Factor	**8.28**	**20.71**
U-Factor[p]		**0.057**
RHGF		**0.046**

Figure 6-13: (cont'd.) Low-slope plywood deck roof assembly

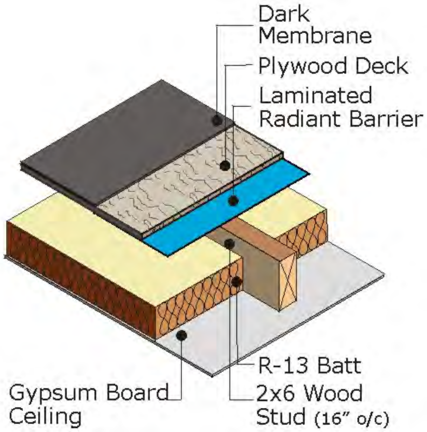


LAYER	R-FACTOR	
	Zone A[p]	Zone B[p]
Outside Air[a]	0.17	0.17
Membrane[b]	0	0
Plywood[o]	0.62	0.62
RB[r]	0	0
Air Space[l]	N/A	1.00
2x4 Stud[h]	4.38	N/A
Ceiling[m]	0.45	0.45
Inside Air[e]	0.92	0.92
Total R-Factor	**6.54**	**3.16**
U-Factor[e]		**0.296**
RHGF		**0.049**

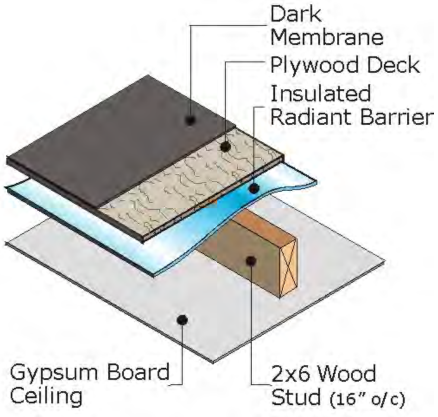


LAYER	R-FACTOR	
	Zone A[p]	Zone B[p]
Outside Air[a]	0.17	0.17
Membrane[b]	0	0
½" Foam[c]	2.5	2.5
Plywood[o]	0.62	0.62
RB[r]	0	0
Air Space[l]	N/A	1.00
2x4 Stud[q]	4.38	N/A
Ceiling[m]	0.45	0.45
Inside Air[e]	0.92	0.92
Total R-Factor	**8.28**	**20.71**
U-Factor[p]		**0.168**

Figure 6-14: (cont'd.) Low-slope plywood deck roof assembly



LAYER	R-FACTOR	
	Zone A[p]	Zone B[p]
Outside Air[a]	0.17	0.17
Membrane[b]	0	0
Plywood[o]	0.62	0.62
RB[r]	0	0
Air Space[l]	N/A	1.00
R-13 Batt		13.00
2x6 Stud[q]	6.57	N/A
Ceiling[m]	0.45	0.45
Inside Air[e]	0.92	0.92
Total R-Factor	**8.73**	**16.12**
U-Factor[p]		**0.069**
RHGF		**0.018**



LAYER	R-FACTOR	
	Zone A[p]	Zone B[p]
Outside Air[a]	0.17	0.17
Membrane[b]	0	0
Plywood[o]	0.62	0.62
Air Space[j]	N/A	0.85
RB[k]	0.90	0.90
Air Space [l]	N/A	1.00
2x6 Stud[q]	6.57	N/A
Ceiling[m]	0.45	0.45
Inside Air[e]	0.92	0.92
Total R-factor	**9.63**	**4.91**
U-Factor[p]		**0.191**
RHGF[s]		**0.050**

Sloped Roofs

Recommendation

Specify a roof surface that is light in color (high reflectance), yet has a non-metallic finish (high emissivity) such as a white standing seam metal roof and minimum R-13 batt insulation to reduce solar heat gain. Or combine a white roof with a radiant barrier to reduce or eliminate the need for insulation.

Description

Sloped roofs are those that have a slope of more than 2 in 12.

Applicability

The recommendations included in this section apply to both metal and wood-framed sloping roofs.

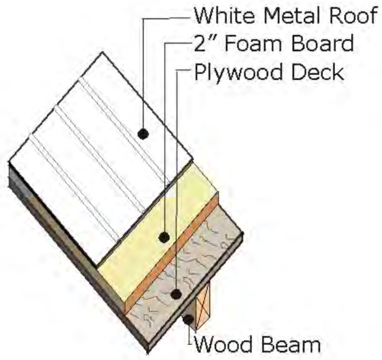
Integrated Design Implications

Like all roofing systems, skylights and other roof penetrations, as well as the roof top equipment mounts, should be considered in the design of the roof. Equipment access should be provided in a manner that does not create undue wear or damage to the roof membrane. In order to take advantage of equipment downsizing, cool roofs should be considered in the schematic design phase.

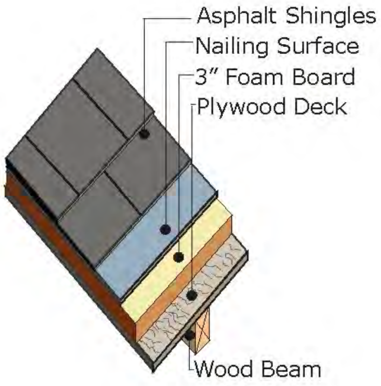
Design details

The following figures show combinations of roof surfaces, radiant barriers, and insulation that comply with the energy code and provide roughly equal performance. The base case assumes brown asphalt shingles ($\alpha=0.80$). The light roofing membrane cases assume a standing seam metal roof with white coating ($\alpha=0.50$)[5].

Figure 6-15: Sloped roof construction with insulation over deck



LAYER	R-FACTOR
Outside Air[a]	0.17
Metal Roof[g]	0.0
2" Foam[c]	10.0
Plywood[o]	0.62
Inside Air[e]	0.76
Total R-factor	**11.55**
U-FACTOR	**0.087**
RHGF	**0.043**



LAYER	R-FACTOR
Outside Air[a]	0.17
Shingles[t]	0.44
Nailing Surface[o]	0.62
3" Foam[c]	15.0
Plywood[o]	0.62
Inside Air[e]	0.76
Total R-factor	**17.61**
U-FACTOR	**0.057**
RHGF	**0.045**

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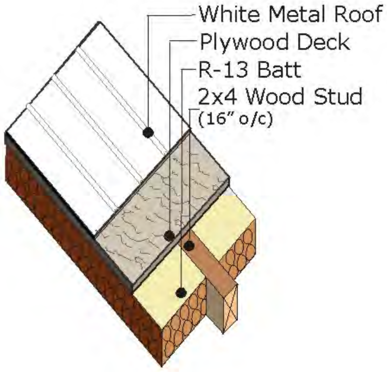
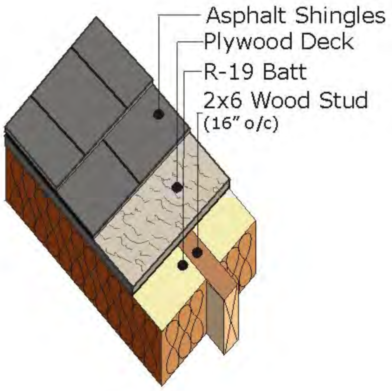
[5] This is the worst-case assumption for degradation. In reality, with regular maintenance, aged value for solar reflectance would be somewhat better than 0.50.

Figure 6-16: Sloped roof constructions with insulation under deck

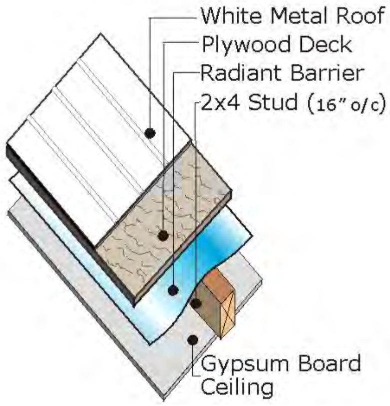


LAYER	**R-FACTOR**	
	Zone A[p]	Zone B[p]
Outside Air[a]	0.17	0.17
Metal Roof[g]	0	0
Plywood[o]	0.62	0.62
R-13 Batt	N/A	13
2x4 Stud[q]	4.38	N/A
Inside Air[e]	0.76	0.76
Total R-factor	**8.93**	**14.55**
U-Factorp		**0.081**
RHGF		**0.041**

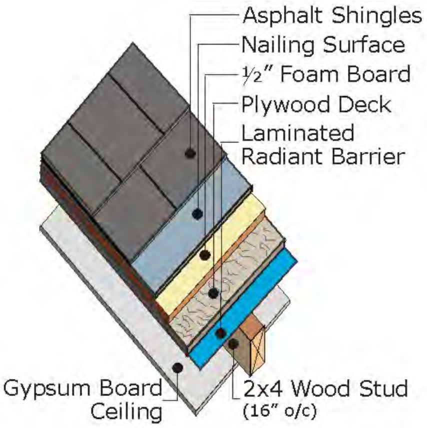


LAYER	**R-FACTOR**	
	Zone A[p]	Zone B[p]
Outside Air[a]	0.17	0.17
Shingles[t]	0.44	0.44
Plywood[o]	0.62	0.62
R-19 Batt	N/A	19
2x6 Stud[q]	6.57	N/A
Inside Air[e]	0.76	0.76
Total R-factor	**8.56**	**20.99**
U-Factor[p]		**0.056**
RHGF		**0.045**

Figure 6-17: Sloped roof construction with radiant barrier

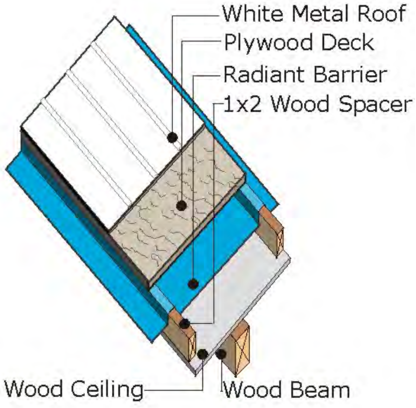


LAYER	R-FACTOR	
	Zone A[p]	Zone B[p]
Outside Air[a]	0.17	0.17
Metal Roof[g]	0	0
Plywood[o]	0.62	0.62
Air Gap[j]	N/A	0.84
RB[n]	0	0
Air Gap[l]		0.90
2x4 Stud[q]	4.38	N/A
Ceiling[m]	0.45	0.45
Inside Aire	0.76	0.76
Total R-factor	**6.38**	**3.74**
U-Factor[g]		**0.254**
RHGF		**0.042**

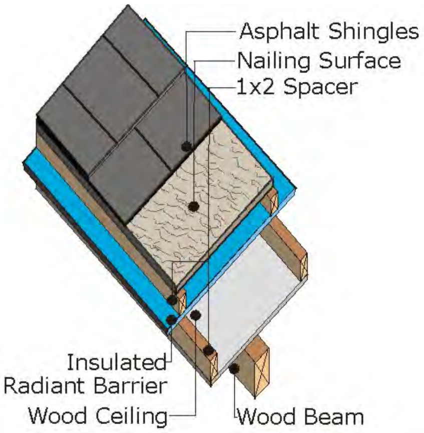


LAYER	R-FACTOR	
	Zone A[p]	Zone B[p]
Outside Air[a]	0.17	0.17
Shingles[t]	0.44	0.44
Nailing Surface[o]	0.62	0.62
½" Foam[c]	2.5	2.5
Plywood[o]	0.62	0.62
RB[r]	0	0
Air Gap[l]	N/A	0.90
2x4 Stud[q]	4.38	N/A
Ceiling[m]	0.45	0.45
Inside Air[e]	0.76	0.76
Total R-factor	**9.94**	**6.46**
U-Factor[p]		**0.148**

Figure 6-18: Sloped roof constructions with radiant barrier and open beam ceiling



LAYER	**R-FACTOR**	
	Zone Ap	Zone B[p]
Outside Air[a]	0.17	0.17
Metal Roof[g]	0	0
Plywood[o]	0.62	0.62
Air Gap[j]	N/A	0.84
RB[n]	0	0
Air Gap[j]	N/A	0.84
Spacer[q]	2.19	N/A
Ceiling[o]	0.62	0.62
Inside Air[e]	0.76	0.76
Total R-factor	**4.36**	**3.85**
U-Factor[p]		**0.257**
RHGF		**0.042**



LAYER	**R-FACTOR**	
	Zone A[p]	Zone B[p]
Outside Air[a]	0.17	0.17
Shingles[t]	0.44	0.44
Nailing Surface[o]	0.62	0.62
Air Gap [u]	N/A	0.90
Spacer[q]	2.19	N/A
RB[k]	0.90	0.90
Air Gap[u]	N/A	0.90
Spacer[q]	2.19	N/A
Ceiling[o]	0.62	0.62
Inside Air[e]	0.76	0.76
Total R-factor	**7.89**	**5.31**
U-Factor[p]		**0.183**

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[a] Table 1, Chapter 25, 2001 ASHRAE Fundamentals Handbook.

[b] Assumed negligible thermal resistance for single-ply membrane.

[c] Assumed R=5.0 per inch for rigid polystyrene foam board. Table 4, Chapter 25, 2001 ASHRAE Fundamentals Handbook.

[d] Assumed R=0.60 per inch for gypsum concrete. Table 4, Chapter 25, 2001 ASHRAE Fundamentals Handbook.

[e] Table 1, Chapter 25, 2001 ASHRAE Fundamentals Handbook.

[f] A darker roof surface, such as light gray ($\alpha = 0.70$ or less) would be adequate to keep the RHGF below 0.050, as required by the Hawaii Energy

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Code. A more cost-effective solution is using 1½” of rigid foam board on top of the deck as shown in Figure 6-6.

[g] Assumed negligible resistance for metal deck.

[h] The zone method of calculation has been used to account for the thermal bridging effect of the framing member. See Example 3-L, p.3-40, Hawaii Energy Code Application Manual. Zone A refers to the width of the zone containing the metal frame, and affected by it. Zone B refers to the remaining section of the assembly unaffected by the framing member. Assumed a steel I-Beam with 6” wide flanges and ¼” thick webbing. R-factor for steel from Table 3, Chapter 38, 2001 ASHRAE Fundamentals Handbook.

[i] Note that with current assumptions for frame dimensions and spacing, insulation equivalent to R-38 and a dark roof, this roof assembly will not have an RHGF of less than 0.05, as required by the Hawaii Energy Code. For a metal framed metal deck with a dark roof, the more practical option is to have 3” of rigid foam board on top of the metal deck as shown above.

[j] Assumed ¾” air gap. Table 3, Chapter 25, 2001 ASHRAE Fundamentals Handbook

[k] Astrofoil website (http://www.insul.net/rv_airspace_effects1.htm).

[l] Assumed air gap of approximately 3 ½”. Table 3, Chapter 25, 2001 ASHRAE Fundamentals Handbook.

[m] Assumed ½” gypsum board. Table 4, Chapter 25, 2001 ASHRAE Fundamentals Handbook.

[n] Assumed negligible thermal resistance for radiant barrier sheet.

[o] Assumed ½” Plywood Deck. Table 4, Chapter 25, 2001 ASHRAE Fundamentals Handbook.

[p] The parallel path calculation method has been used to account for the framing member. See Example 1, Chapter 25, 2001 ASHRAE Fundamentals Handbook. Zone A refers to the width of the zone containing the frame. Zone B refers to the remaining section of the assembly without the frame.

[q] Table 4, Chapter 25. 2001 ASHRAE Fundamentals Handbook.

[r] Assumed negligible thermal resistance for laminated radiant barrier.

[s] This assembly with a dark roof and suspended insulated radiant barrier complies only if 2x6 at 16” o/c is used.

[t] Table 4, Chapter 25. 2001 ASHRAE Fundamentals Handbook.

[u] Assumed air gap of approximately 1.5”. Table 3, Chapter 25, 2001 ASHRAE Fundamentals Handbook.

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[v] This assembly complies only if two rows of 1x2 spacers are used as shown in the corresponding figure.

7. DEHUMIDIFICATION GUIDELINES

Overview

Introduction

In commercial buildings, temperature control often receives far more attention than humidity control. But moisture-related problems do occur in commercial buildings, especially in climates such as Hawaii’s, and these problems can be costly. A significant portion of the construction claims against architects, engineers and contractors are related to moisture and humidity problems. Mold and mildew cost the hotel industry over $68 million every year in lost income and replacement furnishings, according to the American Hotel and Motel Association. Microbial growth accounts for more than one-third of indoor air quality (IAQ) problems.

HVAC systems are typically designed to ensure that they meet indoor comfort conditions at peak cooling loads. These systems, however, may not be able to provide adequate dehumidification during low load periods. These guidelines introduce system alternatives designed to improve part-load dehumidification performance as well as energy efficiency.

Finding the proper balance between energy efficiency and acceptable indoor air quality has become a critical problem for designers, building owners and operators, and maintenance personnel. For indoor thermal comfort, relative humidity levels up to 70% in summer may be acceptable. But for indoor air quality, the optimal humidity is between 40% and 60%. Poor indoor air quality may lead to an increased incidence of health-related symptoms, which in turn may lead to a rise in absenteeism and a loss of productivity. Increased ventilation can improve the indoor environment but may add to the first cost and operating cost of air conditioning systems, particularly in Hawaii.

Excess moisture and humidity problems in buildings are mostly caused by the intrusion of rain and groundwater and the infiltration of humid outside air through the building envelope, coupled with inadequate dehumidification capability and the inadequate operation of HVAC systems to remove the moisture and humidity. These problems can be resolved by correct air pressurization in buildings, adequate dehumidification capability and proper operation of HVAC systems.

Good control of humidity will reduce operation and maintenance costs of buildings, provide a healthy working environment and improve worker productivity. Most importantly, an energy-efficient cooling and dehumidification system does not necessarily have a higher initial cost than a conventional system, and it will save a significant amount in lifecycle costs.

There are basically two types of dehumidification: cooling-based systems and desiccant systems. Cooling-based systems extract moisture in a liquid state by using coils to cool the air to a saturation state, with the air temperature lower than the space air's dew-point temperature. In contrast, desiccant systems directly extract moisture from the air in a vapor state; this occurs without a cooling effect and produces air with a higher temperature (due to heat of adsorption) and lower humidity content.

Applicability

Buildings in hot/warm and humid climates, with high space latent loads, high outside air ventilation rate, low interior space humidity requirement or stringent humidity control, will need dehumidification. These types of buildings include supermarkets, hospitals, labs, clean rooms and theaters.

Codes and Standards

Section 9.3(e) of the Hawaii Model Energy Code states: "Where a humidistat is used for comfort dehumidification, it shall be capable of being set to prevent the use of fossil fuel or electricity to reduce relative humidities below 60%."

The following standards address dehumidification in buildings:

- ASHRAE Standard 62–1999, Ventilation for Acceptable Indoor Air Quality
- ANSI/ASHRAE Standard 55–1992, Thermal Environmental Conditions for Human Occupancy

Weather Data

Hawaii has a subtropical climate, with very consistent weather and only moderate changes in temperature throughout the year. There are only two seasons in Hawaii: summer extends from May to October and winter runs from November to April. The average daytime summer temperature at sea level is 85°F while the average daytime winter temperature is 78°F. Nighttime temperatures are approximately 10°F lower. The wettest months are from November to March. The following figures provide average weather data for Honolulu.

Figure 7-1. Honolulu average temperature and precipitation data, 1961–1990. Source: Western Regional Climate Center, www.wrcc.dri.edu.

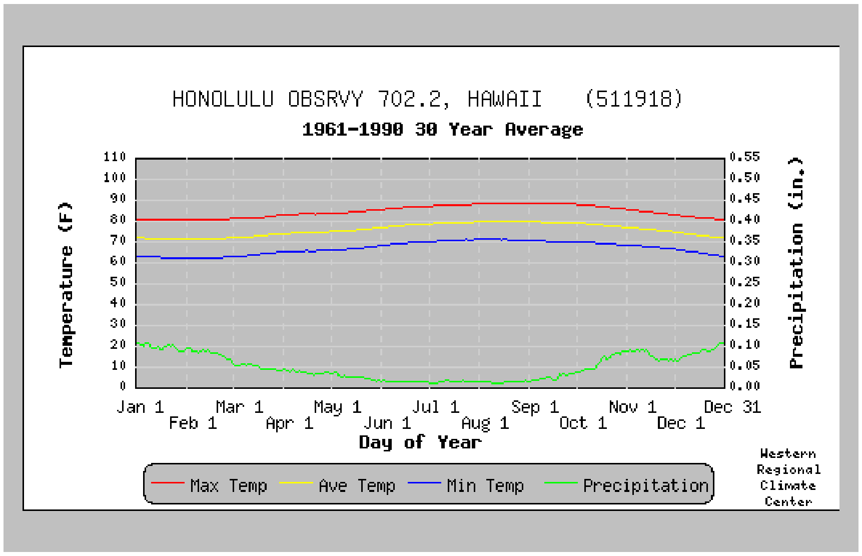
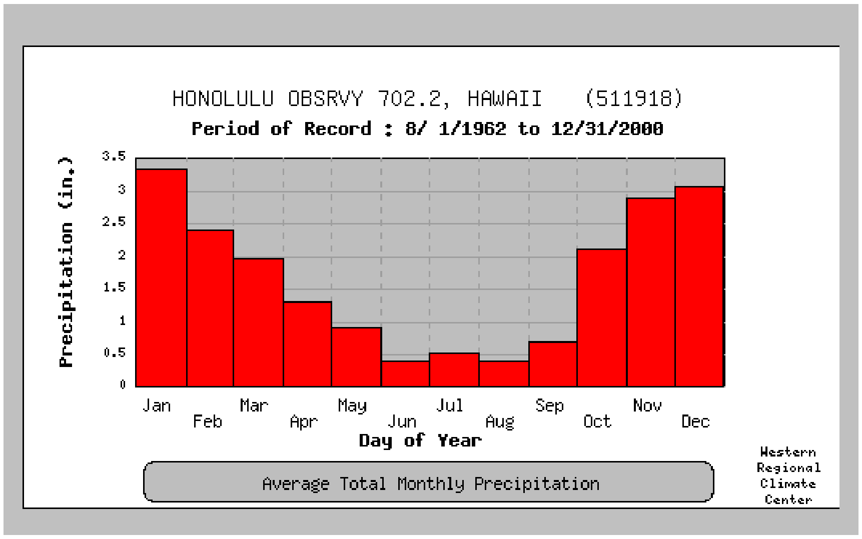


Figure 7-2. Honolulu average monthly precipitation data, 1962–2000. Source: Western Regional Climate Center, www.wrcc.dri.edu.



About 93% of the time, the outside air dew-point temperature is higher than that of the indoor air setpoint of 73°F DB and 60% RH. Therefore, ventilation air requires dehumidification almost all year. Less than 10% of the time the outside air enthalpy is less than that of the indoor air, and less than 24% of time the outside air dry-bulb temperature is less than that of indoor air temperature setpoint. Therefore, **from an energy efficiency perspective, economizer and nighttime ventilation are not applicable in Hawaii.**

The ventilation air load for typical office occupied from 8 A.M. to 6 P.M., Monday through Friday, is 1.74 ton-hr/cfm for sensible load and 2.85 ton-hr/cfm for latent load, which means latent load dominates the ventilation load.

Load Calculation

The first and most important task in designing a dehumidification system is to calculate the moisture load. There are two key issues in moisture-load calculation:

1. Select design conditions for outdoor air and indoor air. For dehumidification, the design day is not hot, but rather warm and raining. Peak latent load should be calculated at ASHRAE 0.4% design dew-point temperature condition rather than ASHRAE 0.4% design dry-bulb temperature condition. **For Honolulu, the former will result in about a 31% higher moisture load.** The 0.4% design conditions mean the moisture outdoors is not likely to exceed the selected value for more than 35 hours in a typical year, which is quite enough for most engineering applications.

   Depending on the application, the indoor air temperature setpoint can range from 70°F to 78°F for cooling; relative humidity can range from 30% to 60%.

2. Calculate moisture loads from people, ventilation, infiltration through the building envelope (doors, walls and windows), and moisture released by food, products, equipment, etc. Occupant loads have a wide range, from 0.1 lb/hr at seated/rest state to 1.04 lb/hr at an athletics level of activity. Ventilation is the largest moisture source in commercial buildings. Ventilation should provide: 1) enough fresh air for occupants, typically 20 cfm/person for offices; 2) enough makeup air if there is exhaust air; and 3) enough air to pressurize the building.

   A slight positive space pressure is very useful to reduce infiltration; as a rule-of-thumb, assume 10% additional ventilation air for pressurization. Infiltration exists in all buildings, even those with positive pressure. Typical values to use are 0.1, 0.3 and 0.6 cfm/ft² for tight, average and loose wall constructions respectively. Rain-soaked masonry or concrete walls add moisture to infiltration air. Moisture transfer through the building envelope and leakage of the return air duct should also be taken into account.

Table 7-1. ASHRAE design conditions for Hawaii.

Location	ASHRAE Design Conditions	Dry-bulb temp. °F	Wet-bulb temp. °F	Dewpoint temp. °F	Rel. hum. %	Enthalpy Btu/lb	Humidity Ratio gr/lb
Honolulu	0.4% dry-bulb temp.	89	73	66.2	47.0	36.6	97
	0.4% dew-point temp.	80	75.6	74	82.0	39.2	127
Hilo	0.4% dry-bulb temp.	85	74	69.6	60.1	37.6	109
	0.4% dew-point temp.	79	76.1	75	87.6	39.6	132
Kahului	0.4% dry-bulb temp.	89	74	67.9	49.8	37.6	103
	0.4% dew-point temp.	80	75.6	74	82.0	39.2	128
Kaneohe, MCAS	0.4% dry-bulb temp.	86	75	70.7	60.5	38.5	114
	0.4% dew-point temp.	81	77.3	76	84.8	40.8	136
Ewa, Barbers Point NAS	0.4% dry-bulb temp.	92	73	64.7	40.7	36.6	92
	0.4% dew-point temp.	83	76.4	74	74.4	39.9	128
Lihue	0.4% dry-bulb temp.	85	75	71.2	63.4	38.6	116
	0.4% dew-point temp.	80	76.3	75	84.8	40.0	133
Molokai	0.4% dry-bulb temp.	88	73	66.8	49.5	36.9	100
	0.4% dew-point temp.	80	75.6	74	82.0	39.5	130

System Alternatives

A variety of dehumidification systems have been developed to improve the energy efficiency of conventional reheat systems. Their target is zero reheat and zero overcooling in the dehumidification process by energy recovery, recycling, reuse and load reduction. These systems, which are discussed later in this chapter, include:

- Conventional reheat systems
- Run-around coil systems
- Heat pipe systems
- Dual-path systems
- Desiccant systems

Refrigerant subcooling systems are discussed in the single-zone direct-expansion (DX) Systems section of the HVAC Guidelines.

Integrated Design Implications

When dehumidification is integrated into a cooling system, pay special attention to these issues:

- Select and size HVAC equipment (coils, fan, pump, damper, etc.) for sensible and latent cooling at peak load conditions. These usually don’t occur simultaneously.
- Design for energy efficiency at part-load conditions because peak load usually occurs for only about 2% of the operating time

System Performance

Annual energy consumption for three system types is estimated using Honolulu bin weather data for the three common systems used in commercial buildings. See the individual system sections below for detailed performance data. Table 7-2 summarizes the system performance results.

Table 7-2. Estimated annual energy performance of dehumidification systems.

	KWh			Savings		
System Specifications	**Conventional System (base case)**	**Run-around System**	**Dual-path System**	**Conven-tional System (base case)**	**Run-around System**	**Dual-path System**
CAV, 1000 cfm, 10% OA	11,993	5998	5923	0	50%	50%
CAV, 1000 cfm, 20% OA	12,315	6236	5887	0	49%	52%

Notes: The following data and assumptions were used in the calculations.

- System location: Honolulu
- System type: Constant air volume (CAV)
- Space setpoint: 73°F DB, 60% RH
- Airflow: supply air 1000 cfm, outside air 100 cfm, return air 900 cfm
- Space loads: total 1.92 ton, sensible load ratio 81%
- Space load variation: sensible load changes, latent load constant
- Operating hours: Monday to Friday, 8 AM to 6 PM, total 2860 hrs/yr
- Electric reheat is used whenever needed
- Fan heat increases air temperature by 1.5°F, no return air temperature rise due to duct heat loss
- Efficiency: cooling system total 0.8 kW/ton, chiller 0.6 kW/ton
- Four typical load conditions are calculated: 100%, 75%, 50% and 25%
- TMY2 weather data for Honolulu
- Run-around loop effectiveness 50%

Some important observations from the calculations and results:

- Conventional electric reheat systems double the annual energy use compared with run-around systems or dual-path systems.
- Conventional systems need more reheat in lower load conditions when the supply air volume remains constant (CAV systems).
- Run-around coil systems and dual-path systems are energy efficient in dehumidification applications. They reduce coil loads and avoid reheat for most load conditions.

- Run-around systems and dual-path systems may need reheat at very low load conditions when space latent load dominates the total cooling load and the ventilation rate remains constant. A special case occurs in supermarkets where refrigerated display cases cool the store during unoccupied hours or when the store is cool due to cool weather. In this case, dual-path systems are equipped with reversing valves that allow the return air circuit to provide heating (see the Foodland Lahaina case study in the Dual-path Systems Guideline).

Design Details

To achieve an energy-efficient dehumidification system design, consider the following factors:

- From an energy efficiency perspective, economizer and nighttime ventilation are not applicable in Hawaii.
- Size and select cooling coils with enough cooling capacity to handle the peak sensible cooling load and peak latent cooling load that occur at different load conditions. Use low-approach cooling coils and low temperature water.
- Design systems considering various load conditions rather than only the peak load condition. For conventional cooling with reheat systems, size reheat equipment to handle a higher reheat requirement in lower load conditions, especially for constant-volume systems.
- Integrate heat recovery equipment into conventional cooling systems to reduce cooling loads and reheat energy. Run-around loop systems are much more energy efficient than conventional cooling systems, especially when operating in part-load conditions.
- Dual-path systems offer competitive energy efficiency with run-around loop systems, and provide better control of the outside air ventilation rate. Dual-path systems decouple sensible cooling and latent cooling for easy control of the supply air temperature and humidity. Equipment is available to provide both cooling and reheat (for example, ClimateMaster).
- Desiccant systems are more competitive when a low supply air dew-point temperature is required, latent load fraction is high, low- or no-cost reactivation heat from steam, hot water or waste heat is available, and electricity costs are high when compared to gas costs.
- Lay out equipment correctly. Place filters upstream of coils. Place fans downstream of coils (draw-through mode) to provide a small amount of reheat.

- Select low face velocity coils to reduce air pressure drop and improve dehumidification performance.
- When using heat pipes, make sure that the additional delta-P is accounted for.

Operation and Maintenance

To maintain efficient operation of cooling and dehumidification systems:

1. Coils must drain condensate and be cleaned regularly.
2. Filters must be cleaned or replaced regularly.
3. Chilled water temperature reset should not sacrifice the dehumidification requirement of cooling coils. A system analysis (air and water) can tell you what the optimum chilled water temperature is.

Utility Programs

The utilities that serve Oahu, Maui, Molokai, Lanai and the Big Island (HECO, MECO and HELCO) have a rebate program called the Commercial and Industrial Customized Rebate (CICR) program. Under this program innovative technologies that save energy and demand qualify for a rebate based on $125 per kW of peak demand reduction and $0.05 per kWh for a year of energy savings. Rebates are based on engineering estimates of energy and demand savings. In the case of unproven technologies, the rebate may be paid over a period of five years based on metered savings.

Resources

American Gas Cooling Center (AGCC), www.agcc.org

ASHRAE Handbooks, www.ashrae.org

ASHRAE, *Humidity Control Design Guide for Commercial and Institutional Buildings*

Electrical Power Research Institute (EPRI), www.epri.com

ESource, *Technology Atlas Series — Space Cooling,* www.esource.com

Federal Energy Management Program (FEMP), www.eren.doe.gov/femp

Gas Technology Institute (GTI), www.gri.org

Hawaiian Electric Co., Hawaii Electric Light Co., Maui Electric Co., www.heco.com

HPAC (Heating/Piping/Air-conditioning) Engineering journal, www.hpac.com

Munters Corporation, *The Dehumidification Handbook,* www.dehumidification.com

National Renewable Energy Laboratory (NREL), http://www.nrel.gov

Penn State University, *The Dedicated Outside Air System,* www.doas.psu.edu

J. David Odom and George DuBose, *Preventing Indoor Air Quality Problems in Hot, Humid Climates: Problem Avoidance Guidelines,* Revised 1996, CH2M Hill.

Conventional Cooling Systems with Reheat

Recommendation

Install conventional systems in applications with low latent loads, with no requirements for indoor air quality or humidity control, and where low first cost is a high priority. Consider the use of cooling-coil face and bypass dampers or cold air distribution to reduce the need for reheat.

Description

Conventional cooling systems dehumidify the mixed air by passing it across a cooling coil that is cold enough to condense water vapor, and then reheating it to the required supply air temperature. The cooling coil can be powered by chilled water from central chiller plant or it can be a direct expansion refrigerant coil. Reheat may be trivial or not needed at peak load conditions, which is usually based on the design dry-bulb temperature that gives maximum sensible cooling loads instead of maximum latent loads. Reheat is often needed at typical low-load conditions with higher latent load fraction. Conventional systems often double the total energy use because of overcooling and reheating of the supply air.

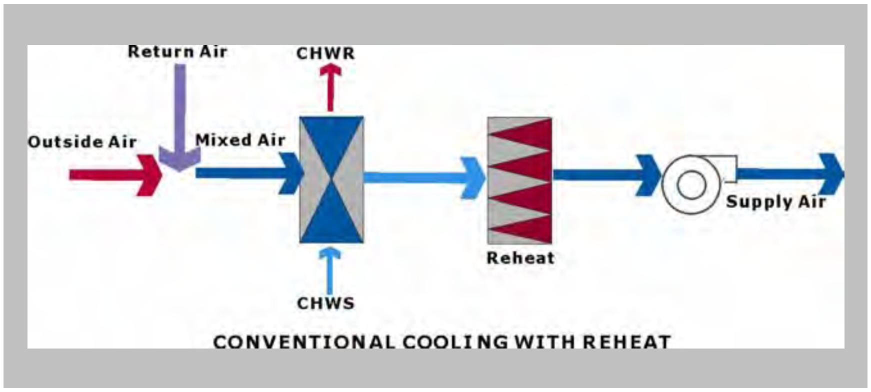


Figure 7-3. Conventional cooling with reheat. CHWR = chilled water return. CHWS = chilled water supply.

Applicability

Conventional reheat systems are most applicable in buildings with:

- No requirements for humidity control of supply air
- Dry climates where sensible cooling dominates
- Low outside air ventilation rate and low space latent load
- Space relative humidity settings of 55% and higher
- Low- or no-cost waste heat, steam or hot water available for reheat use

Codes and Standards

The Hawaii Model Energy code sets limits on simultaneous heating and cooling. Section 9.4(b) limits the use of reheat to several specific cases. It's allowed in:

- Variable-air-volume systems,
- Zones with special pressurization requirements,
- Systems with at least 75% of reheat energy from recovered or solar energy,
- Zones with specific humidity requirements for process needs, or
- Small zones where peak airflow is 300 cfm or less.

Benefits

Benefits of conventional cooling with reheat include:

- Simple system configuration
- Good humidity control by adjusting the off coil air temperature
- Low initial cost

Design Details

The need for reheat can be reduced using a bypass damper in parallel with the cooling coil. This allows a portion of the air to be cooled to a low temperature and dehumidified, and then remixed with the bypass air. The total moisture removal is greater than if all the air passes through the cooling coil but is not cooled to as low a temperature.

Another means to reduce reheat requirements is through cold air distribution in which supply air is delivered at 50ºF or lower, instead of the typical 55ºF. More moisture is extracted as the air is cooled to the lower temperature, and the air distribution system is designed to handle the lower temperature air. This approach requires careful selection of diffusers to maintain comfort and is also more susceptible to condensation on ductwork. Another benefit is that lower airflow and therefore less fan energy is needed. The downside is that lower chilled water temperatures are necessary and chiller energy consumption may increase. Cold air distribution is a good match for ice thermal storage systems, which can deliver colder than normal chilled water.

If a true cold air distribution system is not used, then dehumidification will be improved by choosing a cooling coil to provide a low approach temperature (the difference between chilled water temperature and supply air temperature). Coils can be selected to provide 52ºF supply air, while still operating at standard chilled water temperatures.

Design and Analysis Tools

DOE-2.1E program for building energy simulations from Lawrence Berkeley National Laboratory (LBNL), available at http://gundog.lbl.gov.

Costs

Conventional air handling systems with reheat cost approximately $4.00 to $5.00/cfm.

Cost Effectiveness

Conventional reheat systems may have a lower initial cost but their operating costs are much higher because energy is wasted in overcooling and reheating the supply air.

System Performance

The following table presents the system performance at four typical load conditions.

Table 7-3. Energy performance of a conventional system, CAV, 10% OA.

					Outside Air			Supply Air			
Load %	Cooling Ton	Reheat kW	Total kW	Hours	cfm	DB	WB	cfm	DB	WB	KWh
100%	2.60	0.00	2.63	225	100	87	75	1000	56	55	592
75%	2.09	1.09	3.31	1396	100	82	70	1000	61	58	4621
50%	1.98	2.88	5.02	897	100	77	66	1000	66.5	59.4	4503
25%	1.92	4.57	6.66	342	100	72	64	1000	71.7	61.9	2278
Total											11,993

Table 7-4. Energy performance of a conventional system, CAV, 20% OA.

					Outside Air			Supply Air			
Load %	Cooling Ton	Reheat kW	Total kW	Hours	cfm	DB	WB	cfm	DB	WB	KWh
100%	2.95	0.00	2.91	225	100	87	75	1000	56	55	655
75%	2.28	1.09	3.47	1396	100	82	70	1000	61	58	4844
50%	2.03	2.88	5.06	897	100	77	66	1000	66.5	59.4	4539
25%	1.92	4.57	6.66	342	100	72	64	1000	71.7	61.9	2278
Total											12,315

Products

Carrier, www.carrier.com

Dectron, www.dectron.com

Desert Aire, www.desert-aire.com

Dri-Eaz Products, www.dri-eaz.com

DryAire Systems, www.dryaire.com

Dumont Refrigeration, www.dumontgroup.com

EBAC Dehumidifiers, www.ebac.co.uk

McQuay Corporation, www.mcquay.com

Nautica Dehumidifiers, www.nauticadehumid.com

Trane Company, www.trane.com

York, www.york.com

Run-around Coil Systems

Recommendation

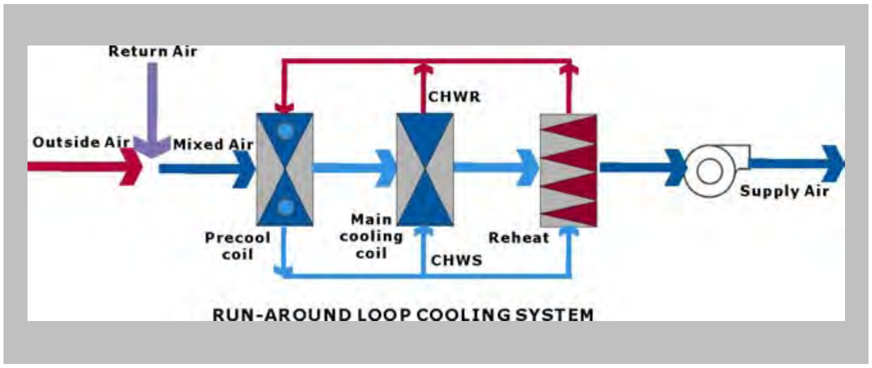
Install run-around coils in applications with large dehumidification requirements where the air must be reheated after passing the cooling coil.

Description

A run-around coil system is a simple piping loop with an upstream precooling coil and a downstream reheating coil that sandwiches the main cooling coil. The circulating fluid is pumped to transfer heat from the warm mixed air to the off coil cold supply air. The run-around system reduces the cooling load on the main cooling coil; reheat is provided by the heat picked up by the circulating fluid in precooling coil instead of by an external source of expensive energy.

In new building designs and retrofits, a run-around system can reduce peak heating and cooling loads as well as total heating and cooling energy. The run-around system can have a significant impact on the heating and cooling capacity in new HVAC designs.

Figure 7-4. Run-around loop cooling system.



The heat recovery effectiveness of the run-around loop is defined as the ratio of the actual heat transfer to the maximum possible heat transfer between the air streams. This is equivalent to the ratio of the difference between the mixed air temperature and the air temperature off the precool coil to the difference between the mixed air temperature and the air temperature off the main cooling coil. The effectiveness ranges from 50% for a normal loop to 65% for a high performance loop. Because of the relatively small temperature differences between the energy exchange coils, low approach cooling coils should be used. Designers must account for the additional pressure drop from the added coil.

Applicability

Run-around coil systems are most applicable in situations requiring substantial dehumidification.

Codes and Standards

ANSI/ASHRAE Standard 84–1991, Method of Testing Air-to-Air Heat Exchangers

Benefits

Benefits of run-around coil systems include:

- Lower cooling load contributes to a smaller cooling system and less pumping energy use, but fan energy increases due to extra air pressure drop through the run-around coils.
- Reheat energy is saved
- Lower total energy use

Integrated Design Implications

The increased dehumidification capacity provided by run-around coils allows for a smaller cooling system. However, the addition of coils will increase the pressure drop, and fan power must be adjusted accordingly.

Design Details

The run-around loop can either be applied to existing systems or can be installed at the factory. The run-around loop requires a fractional horsepower pump, a 120V–60HZ single-phase electrical circuit, and a three-way valve or a variable-speed drive (VSD) for the pump. For bigger systems, an expansion tank with air vent may be needed.

Design and Analysis Tools

Run-around coils can be selected by manufacturers or by design engineers using coil selection programs from manufacturers.

Costs

The initial cost of a run-around system is about double that of a conventional system, but if the downsizing of the chiller and cooling tower is counted, the total initial cost will be very close. The total installation cost is approximately $4.50 to $5.00/cfm.

Cost Effectiveness

The cost effectiveness of a run-around system depends on the system it is replacing. When used instead of a dehumidifying system requiring reheat, the simple payback is about two to three years. However, when the system replaces a system without reheat (no humidity control), there are additional benefits including increased comfort and enhanced indoor air quality, which are difficult to quantify.

Operations and Maintenance

Run-around systems require extra maintenance for the two coils and the loop. Air trapped in the coils, pump and piping must be vented upon initial startup to ensure effective fluid flow and heat transfer. The precooling and reheating function can be controlled by adjusting the pump speed with VSD, cycling the pump on-off, or using valve control and bypass.

Commissioning

Commissioning of a run-around system must be done for typical various load conditions to determine whether additional reheat is needed at very low load conditions.

System Performance

The following tables present the system performance at four typical load conditions.

Table 7-5. Energy performance of a run-around system, CAV, 10% OA.

					Outside Air			Supply Air			
Load %	Cooling Ton	Reheat kW	Total kW	Hours	cfm	DB	WB	cfm	DB	WB	KWh
100%	2.60	0.00	2.72	225	100	87	75	1000	56	55	612
75%	1.78	0.00	2.07	1396	100	82	70	1000	61	58	2890
50%	1.16	0.00	1.57	897	100	77	66	1000	66.5	59.4	1408
25%	1.10	1.65	3.18	342	100	72	64	1000	71.7	61.9	1088
Total											5998

Table 7-6. Energy performance of a run-around system, CAV, 20% OA.

					Outside Air			Supply Air			
Load %	Cooling Ton	Reheat kW	Total kW	Hours	cfm	DB	WB	cfm	DB	WB	KWh
100%	2.95	0.00	3.00	225	100	87	75	1000	56	55	675
75%	1.93	0.00	2.19	1396	100	82	70	1000	61	58	3057
50%	1.18	0.00	1.59	897	100	77	66	1000	66.5	59.4	1426
25%	1.07	1.65	3.15	342	100	72	64	1000	71.7	61.9	1077
Total											6236

Products

Run-around coils with ARI certification are available from at least 10 manufacturers.

Heat Pipe Systems

Recommendation

Install heat pipes in applications with large dehumidification requirements where the air must be reheated after passing the cooling coil.

Description

Heat pipes increase the effectiveness of air conditioning systems by helping to decrease the total cooling load of the air. The typical design consists of a refrigerant loop with two connected heat exchangers placed upstream and downstream from the cooling coil. As the air passes through the first heat exchanger it vaporizes the refrigerant and is precooled. This allows the coil to more effectively cool the air to a point below the dew-point temperature and to extract more moisture. The air then passes through the second heat exchanger and is reheated, which liquefies the refrigerant, causing it to flow back to the first heat exchanger. The heat pipe system is hermetically sealed, uses a wicking action, and requires no pump.

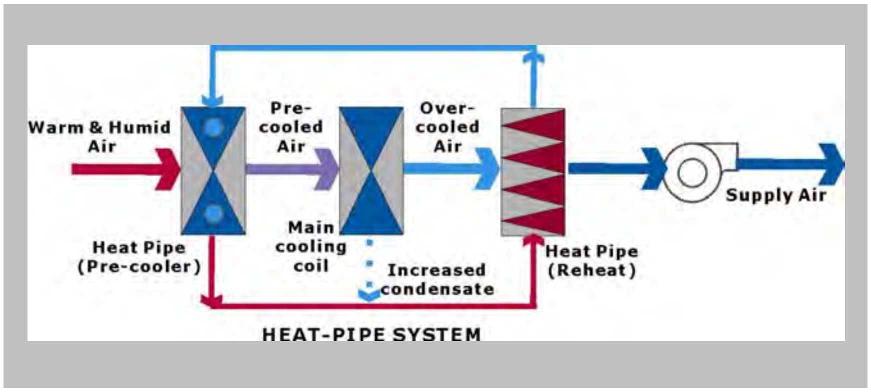


Figure 7-5. Heat pipe system.

Applicability

Most applicable in situations requiring substantial dehumidification.

Codes and Standards

None

Benefits

Benefits of heat pipe systems include:

- Removes 50% to 100% more moisture than systems without heat pipes.
- Saves energy compared to systems that provide similar amounts of dehumidification.
- Simple system with no moving parts or external connections makes it basically maintenance free.

Integrated Design Implications

The increased dehumidification capacity provided by heat pipes allows for a smaller cooling system. However, the addition of heat pipes will increase the pressure drop, and fan power must be adjusted accordingly.

Design Details

Heat pipes can either be applied to existing HVAC systems or can be installed at the factory. The heat pipe loop is usually controlled by cycling on-off or modulating the refrigerant flow with a control valve.

Design and Analysis Tools

Heat Pipe Technologies product selection software, www.heatpipe.com.

Costs

The installation cost of a heat pipe loop for a cooling system is approximately $2.50/cfm.

Cost Effectiveness

The cost effectiveness of heat pipes depends on the system it is replacing. When used instead of a dehumidifying system requiring reheat, the simple payback is two to three years. However, when the system replaces a system without reheat (that is, no humidity control), there are additional benefits including increased comfort and enhanced indoor air quality, which are difficult to quantify.

Operations and Maintenance

Some heat pipe applications require the same routine maintenance as any air conditioning unit. Valveless units require no maintenance aside from cleaning. Valved units have normal balancing requirements.

Commissioning

The precooling and reheating heat pipes should be installed closely to sandwich the main cooling coil.

Case Study

A Dinh-style heat pipe dehumidification system was installed in the air handling system (19,000 cfm) in Building 49 at the EPA’s Gulf Breeze laboratory in Pensacola, Florida, in 1996. The heat pipe was effective in reducing inside humidity levels by about 10%, from an average of 75% before installation to an average of 65% after installation, without affecting the inside temperatures. An additional 20 tons of mechanical cooling would have been necessary to provide this additional dehumidification during peak conditions.

The heat pipe cost $42,000 to install; the additional mechanical cooling equipment necessary to provide the same level of dehumidification would have cost $30,000. Therefore the additional cost of installing a heat pipe instead of mechanical cooling to provide the 10% lower indoor humidity was $12,000.

Using a weather bin method analysis, the heat pipe in this location provides a maximum 20 tons of precooling and 240 kBTU/h of reheat with no energy input, saving an estimated 56 kW in peak summer demand, 153,775 kWh in annual energy consumption (about 10% of the total), and $7,700 in annual energy costs. The simple payback of using a heat pipe to provide the enhanced dehumidification for this installation is therefore 15 months. The payback will vary for other installations based on weather data, mechanical system efficiencies, and utility rates.
A comparison of the EPA Building 49 utility bills for the 12 months before installation and the 12 months following installation, normalized for weather variations, showed an actual energy reduction of 230,750 kWh (14%) and a cost reduction of $9,980.

Products

Heat Pipe Technologies, www.heatpipe.com

Resources

Island Energy Systems (sales representative)
Contact: Joseph Petrie
PO Box 316, 111
Kaapahu Road, Paauilo, HI 96776
Phone: 808-776-1333
Fax: 808-776-164

Heat Pipe Technologies, www.heatpipe.com

Dual-path Systems

Recommendation

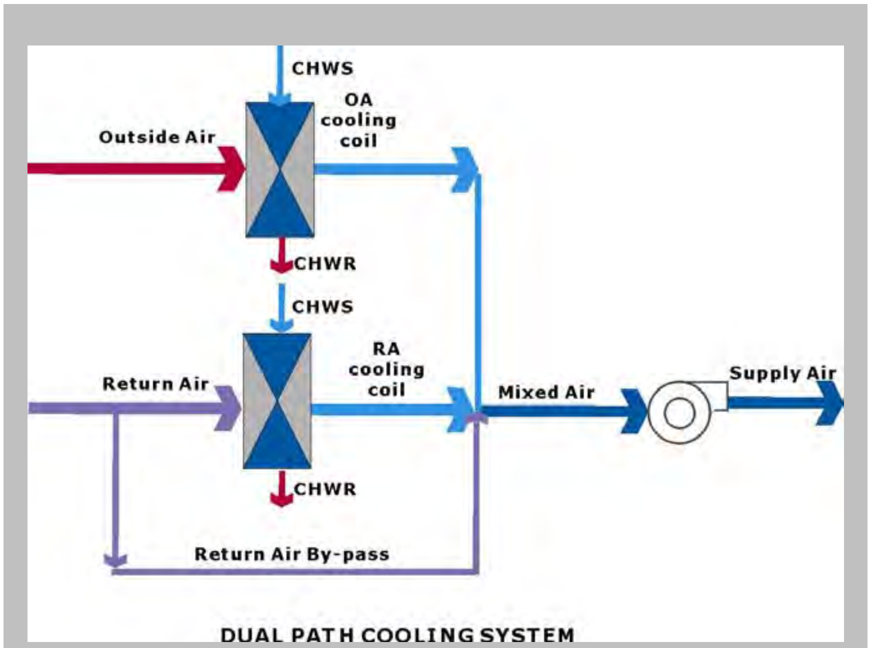
Install dual-path systems in applications with return air and large dehumidification load due to high outside air ventilation rate.

Description

A dual-path system uses two coils (either chilled water or DX) to separately cool the incoming outside air and return air. The hot and humid outdoor air is cooled by a primary coil to 42°F to 45°F for dehumidification. The secondary coil furnishes the sensible cooling of part of the relatively cool and dry return air. A portion of the return air may bypass the secondary coil and mix with the cooled return air stream. These two air streams are then mixed into supply air with appropriate temperature and humidity.

In systems where the fraction of outside air is low and the space latent load is high, the outside air alone may not be enough to handle the total latent load of the supply air, which requires some moisture to be extracted from the return air stream. This means a portion of the return air needs to be overcooled to extract moisture, and additional reheat may be necessary to increase the air temperature for comfort supply. One zero-reheat solution is to direct a portion of the return air to mix with the outside air before dehumidification.

Figure 6. Dual-path cooling system.



In chilled water dual-path systems, the outdoor air (OA) coil can use cold chilled water at 40°F to 42°F for latent cooling, while the return air (RA) coil can use warmer chilled water at 50°F to 60°F for sensible cooling, thus improving chiller efficiency. Dual-path systems decouple the sensible cooling and latent cooling of the supply air, thereby improving control of temperature and humidity.

Applicability

Dual-path systems are best in HVAC applications where the moisture load arises primarily from the outdoor air. These applications include commercial buildings in humid climates, schools, clean rooms, theaters, supermarkets, hotels and motels. For larger systems, separate air-handling units for outside air and return air can be used.

Codes and Standards

None

Benefits

Benefits of dual-path systems include:

- Reduces the installed cooling tons over a conventional single-path system
- Provides low operating cost with efficient cooling and no reheat
- Provides direct control of ventilation air quantity for improved indoor air quality
- Provides good humidity control at all times, including part load, as moisture is removed at its source, regardless of building load

Integrated Design Implications

Dual-path systems avoid overcooling and reheating the supply air, thus reducing the size of cooling and heating systems. The sensible cooling of the return air can use chilled water with higher temperature to improve chiller efficiency. The additional costs of coil, duct and pipe work, and damper or VSD control must be adjusted accordingly.

Design Details

Dual-path systems can be installed separately or integrated with additional HVAC/R equipment. They are currently available in factory package units for indoor and outdoor installation. The OA cooling coil should be sized for peak latent load, while the RA cooling coil should be sized for peak sensible load. The OA path controls the humidity of the supply air by modulating the chilled water flow, while the RA path controls the supply air temperature by adjusting the bypass damper position.

Design and Analysis Tools

Selection of dual-path systems can be made by manufacturers or by design engineers using selection programs from manufacturers.

Costs

The installation price of a dual-path system varies between $5–$6/cfm.

Cost Effectiveness

Dual-path systems are energy efficient while assuring an acceptable humidity level at all ventilation air volumes. Its use can also reduce demand and energy charges sufficiently to offset the higher first cost.

Operations and Maintenance

Maintenance of an additional coil and equipment in the return air stream is required. The outside air path runs as cool as possible almost all the time while the return air path is controlled to obtain the required temperature and humidity of the supply air.

Commissioning

Measurement of airflows and temperatures of both air streams must be done to confirm that the system is operating as designed.

Case Study

Dual-path heat pump systems were installed in the 200,000-ft^2 Wal-Mart Supercenter in 1995 in Moore, Oklahoma. In 1996 the system met the stringent target of 45% RH for 99.2% of all operating hours. The system also saves on peak electricity use and costs compared to the best conventional systems using air-source vapor compression air conditioning, gas-driven dehumidification, and air-cooled refrigeration racks. In all, monitoring showed total energy savings of more than $70,000 per year. This project won the 1998 ASHRAE Technology Award.

Based on the success of the Wal-Mart installation, a dual-path system was installed at the Foodland Supermarket in Lahaina, Maui, in 1999. This supermarket achieved its design goal of 45% RH and 75ºF store conditions after VaCom Technologies installed a new digital control system. This store has achieved one of the lowest operating costs of the 30 or so Foodland sites in Hawaii. This project received Maui Electric's 1999 Energy Project of the Year award.

The Pearl Harbor Naval Shipyard employs a dual-path strategy to provide 150 tons of cooling. A dedicated outside air unit provides most of the latent cooling, while two large return air units control sensible cooling.

System Performance

The following tables present the dual-path system performance with 10% OA and 20% OA at four typical load conditions.

Table 7-7. Energy performance of a dual-path system, CAV, 10% OA.

					Outside Air			Supply Air			
Load %	Cooling Ton	Reheat kW	Total kW	Hours	cfm	DB	WB	cfm	DB	WB	KWh
100%	2.60	0.00	2.69	225	100	87	75	1000	56	55	605
75%	1.79	0.00	2.04	1396	100	82	70	1000	61	58	2848
50%	1.61	0.00	1.90	897	100	77	66	1000	66.5	59.4	1704
25%	0.90	0.91	2.24	342	100	72	64	1000	71.7	61.9	766
Total											5923

Table 7-8. Energy performance of a dual-path system, CAV, 20% OA.

					Outside Air			Supply Air			
Load %	Cooling Ton	Reheat kW	Total kW	Hours	cfm	DB	WB	cfm	DB	WB	KWh
100%	2.95	0.00	2.97	225	100	87	75	1000	56	55	668
75%	1.98	0.00	2.19	1396	100	82	70	1000	61	58	3057
50%	1.23	0.00	1.59	897	100	77	66	1000	66.5	59.4	1426
25%	0.87	0.84	2.15	342	100	72	64	1000	71.7	61.9	735
Total											5887

Products

ClimaDry System, ClimateMaster, www.climatemaster.com

Trane Company, www.trane.com

VaCom Technologies, www.vacomtech.com

Resources

Dadanco Company, www.dadanco.com

Electrical Power Research Institute (EPRI), www.epri.com

Hawaiian Electric Company, Inc.
Contact: Paul Fetherland, Director, CTA Division

VaCom Technologies, www.vacomtech.com
Contact: Doug Scott, President

Desiccant Systems

Recommendation

Install desiccant systems in applications requiring large dehumidification and low space humidity levels that would be difficult to achieve with cooling-type dehumidification.

Description

Desiccant materials can absorb between 20% and 40% of their dry weight in water vapor from humid air. Both solid and liquid desiccants are used in cooling systems, but solid desiccants are much more common in commercial buildings. Liquid desiccants employ solutions such as glycol or salts such as lithium chloride ($LiCl_2$).

In solid desiccant systems, desiccant is formed in place in a honeycomb matrix wheel mounted between the process air stream and the reactivation air stream; air seals separate the air streams from each other. The desiccant wheel rotates slowly (6 to 20 rph) between the two air streams. The process airflows through the wheel, gives up its moisture to the desiccant and increases dry-bulb temperature (up to 120°F), and finally is cooled by coils for comfort supply. After drying the process air, the desiccant wheel is saturated with moisture and rotates slowly into the reactivation air. The hot reactivation air (with temperature up to 250°F typically required) heats the honeycomb, absorbs moisture released by the hot desiccant, and is released as exhaust air from the building. Desiccants are also available that can be regenerated at temperatures as low as 120ºF, allowing a greater range of options for heat sources such as heat pumps or solar sources.

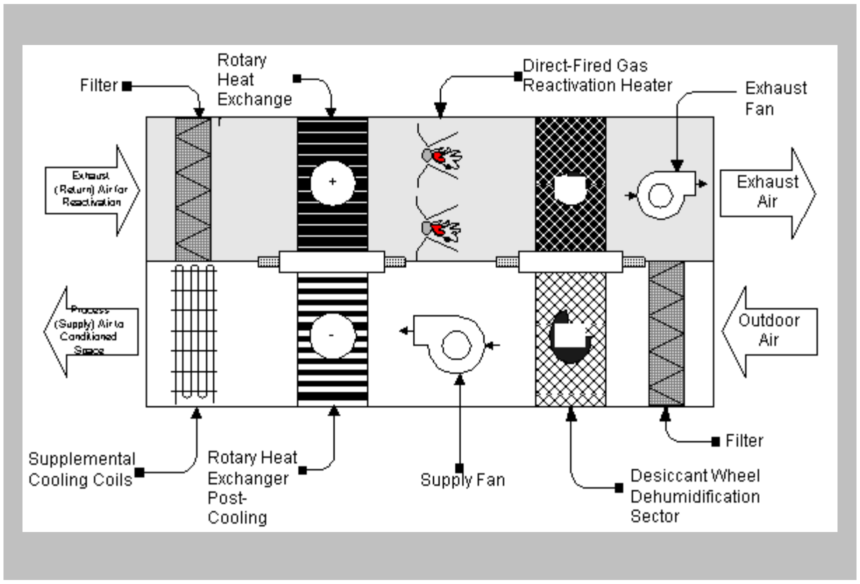


Figure 7.
Desiccant system.

Desiccant systems often incorporate heat recovery equipment. If exhaust air is available, it can be used to cool the warm air (leaving the desiccant section) before it passes through the cooling coil. When there is no exhaust air, outside air can be used to cool this warm air, and the heated outside air can be used to reactivate the desiccant.

In commercial air conditioning systems, desiccants last between 10,000 hours and 100,000 hours before they need replacement. According to the manufacturers, a well-maintained desiccant wheel will last for approximately 100,000 hours of operation (10 to 15 years).

Desiccant systems improve an air conditioning system by removing moisture from ventilation air. Since the cooling system no longer has to remove moisture, it operates more efficiently in sensible cooling mode. Desiccant systems usually use heat from natural gas as their primary energy source, and use very little electricity. On the mainland, these systems can save money when the cost of power is high during the peak demand periods of summer. In Hawaii, however, there is little seasonality. But desiccant systems offer a wide range of other benefits that are specific to the types of buildings in which they are installed. Those benefits are usually associated with keeping humidity lower than would be practical with conventional cooling-based systems.

There are several circumstances that may favor desiccant systems rather than cooling-based dehumidification systems. These include:

- Economic benefit from low humidity
- High moisture loads with low sensible load
- Need for more fresh air
- Exhaust air available for desiccant post cooling
- Low thermal energy cost with high electrical demand charges
- Economic benefit to dry duct work
- Low-cost heat available for desiccant regeneration

Applicability

Desiccant systems are applicable to existing or new HVAC systems for clean rooms, supermarkets, refrigerated warehouses, ice rinks, schools, restaurants, theaters, hotels, hospital/healthcare facilities, and situations where one or more of the following situations apply:

- Low indoor humidity (dew point below 50°F)
- High latent load fraction (greater than 25%)
- High outside air fraction (greater than 20%)
- High electrical cost and low gas costs
- Available heat source from waste heat, steam, hot water or gas for regeneration of desiccant

Codes and Standards

ARI Standard 940-1998, Desiccant Dehumidification Components

Benefits

- Decouples latent cooling from sensible cooling for precise control of humidity independent of temperature.
- Lower operating cost. Cooling system runs more efficiently to produce chilled water with higher temperature for sensible cooling.
- No wet coils or draining/cleaning requirement. Dry duct systems help avoid microbial and fungal growth associated with sick building syndrome.
- Dehumidification process can use low-grade heat from natural gas, steam, hot water and solar energy.
- Provide supply air with dew-point temperature below the practical limits of cooling technology.

Integrated Design Implications

The choice of a desiccant system affects the selection and sizing of the cooling coil, because the cooling coil only needs to handle the sensible load of the supply air, which allows for higher chilled water temperature and efficient operation. The sensible cooling load will be higher because of the hot dry air leaving from the desiccant wheel (due to heat of adsorption). However, the addition of a desiccant wheel will increase the pressure drop, fan power and maintenance, and an additional motor is required to rotate the wheel. This extra energy usage must be counted accordingly.

Design Details

Desiccant systems should use low-cost surplus heat, waste heat or solar heat for desiccant reactivation. Dampers or VSD for fans should be installed to control airflow through the wheel. Side access for wheel and filter replacement and maintenance should be provided. Energy recovery and direct/indirect evaporative cooling are frequently incorporated in desiccant systems to reduce the cooling and heating energy.

Design and Analysis Tools

DesiCalc program from InterEnergy, www.interenergysoftware.com

Costs

Costs of desiccant systems are typically given in terms of $/cfm. For large commercial systems, the cost is approximately $5/cfm, while smaller units (less than 1000 cfm) may cost up to $8/cfm.

Cost Effectiveness

The higher initial cost of desiccant systems may be offset by lower operating costs and improved productivity because of increased comfort and enhanced indoor air quality. In large buildings where non-electric heat is available for reactivation of desiccants, desiccant systems can reduce HVAC electricity use by 30% to 60% and peak electricity demand by 65% to 70%.

Operations and Maintenance

The maintenance requirements of desiccant systems can be modest compared to conventional cooling-based dehumidification systems. Filters located in the inlet of process air and reactivation air need to be cleaned or replaced every two months. About 90% of reported problems related to desiccant systems can be traced to clogged filters. The wheel can be vacuumed to remove dust from the wheel face. The drive belt around the heat wheel needs to be tight enough to turn the wheel without putting excessive load on the drive motor shaft bearings. No regular maintenance is required for the desiccant materials.

Commissioning

Measurement of airflow, temperature and moisture must be done for both the dehumidified air and the reactivation air during commissioning to confirm that a desiccant system is operating as designed.

Case Study

The Sanders Research and Education building at the Medical College of Georgia in Augusta contains 250,000 ft^2 of classroom and laboratory space. The original conventional cooling system was equipped with 1200 tons of chiller capacity for cooling and dehumidification in summer and gas-fired steam boilers to provide heating in winter and reheat for humidity control. While the space temperature can be maintained between 70°F to 75°F, the relative humidity swings as high as 70% and as low as 40% as the weather changes. A desiccant system was installed to improve control humidity between 45% and 55%. The system saves 45% of the annual operation cost, about $200,000, compared with a conventional system.

Products

Air Technology Systems, www.air-tech.com

Bry-Air, www.bryair.com

DehuTech AB, www.dehutech.com

Dri-Eaz Products, www.dri-eaz.com

DryKor, www.drykor.com

Engelhard/ICC, www.engelhardicc.com

Fresh Air Solutions, www.freshairsolutions.com

Humidity Control Systems Ltd, www.humiditycontrol.co.uk

Kathabar Systems Division, Sommerset Technologies, www.kathabar.com

Munters Corp., www.muntersamerica.com

NovelAire Technologies, www.novelaire.com

Octagon Air System, www.octagonair.com

Seasons-4, www.seasons4.net

SEMCO, www.semcoinc.com

Resources

American Gas Cooling Center (AGCC), Applications Engineering Manual for Desiccant Systems, www.agcc.org

ASHRAE Handbooks, www.ashrae.org

ESource, *Technology Atlas Series – Space Cooling,* www.esource.com

Federal Energy Management Program (FEMP), www.eren.doe.gov/femp

Gas Research Institute (GRI), www.gri.org

National Renewable Energy Laboratory (NREL), http://www.nrel.gov

Related Standards:

- ANSI/ASHRAE Standard 84–1991, Method of Testing Air-to-Air Heat Exchangers
- ARI Standard 1060–2000, Rating Air-to-Air Energy Recovery Ventilation Equipment
- ARI Standard 940–1998, Desiccant Dehumidification Components

8. HVAC AND WATER HEATING

Sizing AC Systems

Overview

Air conditioning systems are intended to provide adequate cooling comfort, dehumidification, and ventilation to occupied spaces at a reasonable cost. AC sizing, together with zoning and system layout, is an important aspect of AC design. AC sizing is a complex issue that needs to be approached systematically. Appropriate size depends on many factors, including climate, building configuration, space usage, system zoning and layout.

AC sizing includes sizing of primary systems and secondary systems. Depending on the system type and configuration, primary systems may include chillers, cooling towers and pumps for central systems, or direct-expansion (DX) equipment for packaged systems. Secondary systems may include fans, coils, filters, silencers, dampers, valves, air duct, diffusers and pumps.

Appropriate sizing of AC components is critical to the design of energy-efficient AC systems. Correctly sized systems cost less to install, operate and maintain. Undersized systems will not meet a space's temperature, humidity or indoor air quality requirements. Oversized systems cost more to install, need more space, operate less efficiently in part-load conditions, often provide poorer dehumidification performance, and shorten equipment life because of frequent on/off cycles.

Early in the design phase, when zone layout is unknown, rough AC sizing can be based on rules of thumb. In the detailed design phase, accurate calculations of cooling loads at zone, system and plant levels should be done once zoning and system layout are determined. Correct sizing is based on accurate load calculation and reasonable design margin considerations, which require professional knowledge and experience in the air-conditioning field.

Like there are code compliance requirements for the building envelope, AC component ratings, and whole building energy performance, there are also code requirements for AC sizing. Both the Hawaii energy codes and ASHRAE Standard 90.1 include load calculation and sizing guidelines. However, surveys and experience have revealed that most AC systems are oversized. In most cases oversizing is not a good design practice. It is much more effective to pursue a lean design that correctly sizes individual components and makes them work together for maximum energy performance — not only at design conditions but also at off-design conditions.

Oversizing

There are many factors that lead to oversizing of air conditioning systems and components. This section addresses those factors, describes the impacts of oversizing, and provides some solutions to minimizing the negative impact of oversizing. There are a number of factors that lead to selection of systems that are larger than necessary.

- Unrealistically high internal heat gain assumptions. Actual lighting power and plug loads are often lower than assumed in load calculations.
- Unnecessarily restrictive design parameters such as high occupant densities, outside air of 20 cfm/person, indoor thermostat of 72°F for cooling
- Limited options for component size (selecting “next size up”)
- Use of excessive safety margins in load calculations
- Increasing use of software design packages without competent knowledge of the calculations and margins they use
- Security against system breakdown and maintenance
- Allowance for actual capacity to be lower than nominal capacity due to anticipated lack of commissioning or to improper operation
- Designer’s liability concerns
- Allowance for future changes in building operation that might increase cooling loads.

There are several potential negative impacts of oversizing. Oversizing usually is a significant contributor to high energy use. A variety of problems identified during commissioning and diagnostic processes also reveal that oversizing causes more operation problems. Bigger is neither better nor safer; on the contrary, oversized components cost more to purchase, take up more space, and tend to cause more operation and maintenance problems.

Oversizing should be avoided for most applications in most situations. However, in some situations, oversizing some components may improve system performance. For example, a cooling tower oversized to a certain degree will improve chiller efficiency; oversized air ducts and pipes will decrease pressure drop, thereby allowing fans, pumps and motors to be downsized. Chillers, fans, pumps, motors, valves and dampers should rarely be oversized.

Negative impacts of oversizing can be reduced by incorporating capacity controls and unloading strategies. For example, select multiple chillers of different sizes instead of one large chiller; select a multi-compressor chiller instead of a single compressor chiller; select a multi-stage compressor instead of a single-stage compressor; or select variable-speed motors instead of constant-speed motors. Try to avoid oversizing chillers, fans, pumps, and motors if there are no capacity control or unloading strategies.

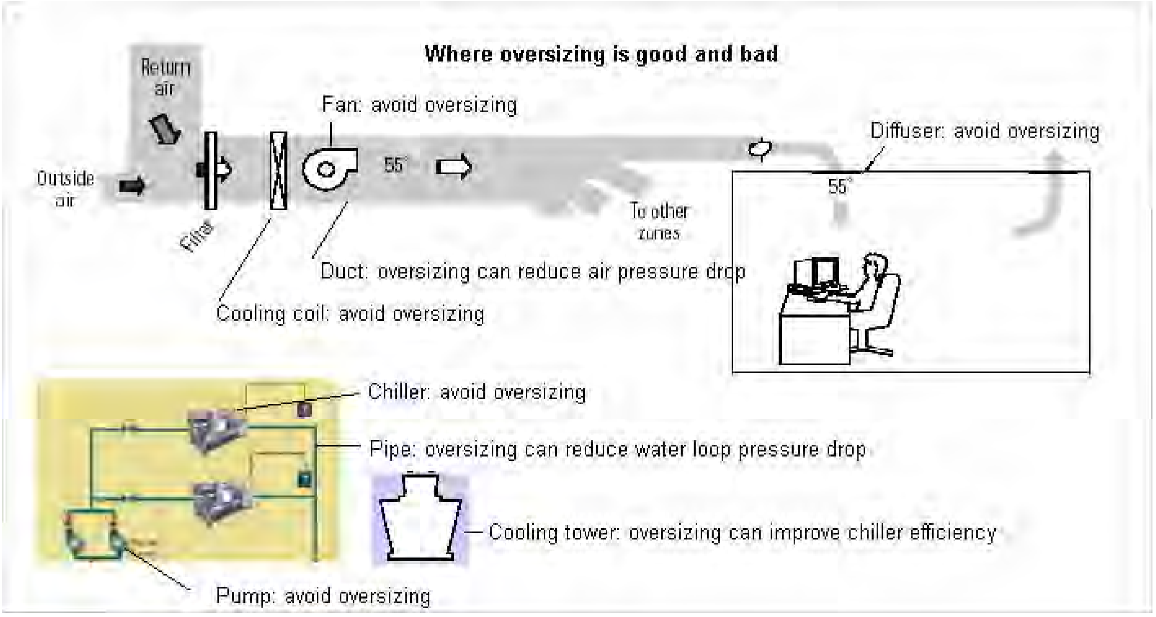


Figure 1 – Effect of Oversizing on AC Components

There are a variety of uncertainties involved in load calculation, building occupancy and use. Optimal sizing should be a tradeoff among cost, performance and safety. Legal design risks related to AC sizing need to be addressed in the design intent and clearly conveyed to building owners and tenants. For example, oversized cooling systems can lead to poor humidity control and result in higher liabilities. Also, design engineers should be encouraged to avoid oversizing where it has negative impacts. Education and communication in the AC design community are crucial for resolving the problem of oversizing.

Load Calculations

Good AC sizing requires detailed and accurate cooling load calculations. Computer programs are usually employed in load calculation and sizing because these procedures are usually too difficult and tedious for hand calculation. The cooling load calculation is usually done for a summer design day. The calculated results provide no more than the peak load and a 24-hour profile. While design cooling load is adequate to determine the total cooling capacity of AC equipment, *optimal selection* of AC equipment may need an annual cooling load profile, which can help decide the number and size of chillers that should be selected to achieve the most energy-efficient operation.

The variables affecting load calculations are numerous and involve a variety of uncertainties; a load estimate is no better than the assumptions that went into it, including physical makeup of the various envelope surfaces, conditions of occupancy and use, and outside weather conditions. Even with the availability of computer programs for load calculations, the practitioner's experience is extremely important. The load estimating process requires proper engineering judgment, including a thorough understanding of heat balance fundamentals.

Cooling load calculation involves three steps:

1. Determine the zone cooling load. This consists of external loads through the building envelope and internal loads from people, lights, appliances, infiltration loads, moisture loads, and other heat sources.

2. Calculate the system cooling load. This step adapts the selected air distribution system to the zone load and involves the introduction of the required outdoor air volume into the air conditioning system for ventilation.

3. Calculate the plant load which has to meet the maximum coincident system cooling load and compensate for pipe losses.

Zone Loads

Zone loads address the cooling energy required to maintain the design indoor conditions. To calculate a space cooling load, the design indoor and outdoor conditions, detailed building design information, and individual load components need to be collected and evaluated.

Design conditions. Design outdoor conditions are tabulated in the ASHRAE *Fundamentals Handbook* (2001). In Hawaii, for applications that don't require humidity control, use the ASHRAE 0.4% design dry-bulb with mean coincident wet-bulb temperatures. However, for dehumidification applications, which might be considered the majority of Hawaii applications, the peak load for a space that requires both large quantities of outside air and close control of moisture may occur at peak wet-bulb or peak dew-point conditions when the corresponding dry-bulb temperature is significantly lower than normal design conditions. For sizing cooling towers and evaporative cooling systems, use the design wet-bulb temperature. For sizing desiccant cooling systems, use the design dew-point conditions.

Design indoor conditions should comply with the latest version of ASHRAE *Standard 55.*

Conditions for human occupancy. For thermal comfort and indoor air quality, the design indoor relative humidity should be between 40% to 60%, and the temperature should be between 72°F to 78°F. It is important to note that when the relative humidity is at the lower end of the range that people will usually feel comfortable at higher temperatures.

Internal loads. Internal loads include sensible loads from lights, equipment and occupants, and latent loads mostly from occupants. Use up-to-date values for lighting and equipment power, since lighting and equipment efficiency have improved significantly in recent years. Double check any values posted a decade ago or even several years ago before using them.

For densely occupied buildings, adjust occupant loads by occupant activity level; latent loads should be correctly estimated. Diversity factors should be used while calculating internal loads because it is very unlikely that all lights are on, all equipment is on or all occupants are present at the same time. Reasonable values of lighting and equipment can be found in the Hawaii energy codes and in ASHRAE *Standard 90.1: Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings.*

Envelope loads. Calculate heat transmission through walls, windows, roofs, floors and slabs together with solar gains through fenestration. In the load calculations, account for external shading effects of walls, roofs and windows from trees and adjacent buildings. At this point, also consider any envelope improvements that might reduce loads. See the Whole Building Design chapter for discussion of load reduction strategies.

Infiltration load. Estimate infiltration load according to the tightness of the building structure and the pressurization requirement of the spaces. Infiltration may contribute to a significant amount of moisture load in Hawaii's commercial buildings. Infiltration exists even in spaces with positive pressure, such as in supermarkets where wind pressure easily overcomes the building pressurization.

Calculation methods and accuracy. Detailed and accurate cooling load calculation procedures are published in the ASHRAE *Fundamentals Handbook* and are updated every four years. The 2001 edition describes a heat balance method, and its simplified and derived variant, the radiant time series method. The transfer function method is still being used in many commercial load calculation programs. Earlier methods like total equivalent temperature differential method with time averaging, and cooling load temperature differential method with solar cooling load factors were developed mainly for manual calculations in the days when computer use was limited. Avoid these load calculation methods today. The heat balance method is recommended for accurate peak load calculation.

A realistic cooling load calculation provides values for acceptable system performance. Variation in the heat transmission coefficients of typical building materials and composite assemblies, the differing motivations and skills of those who construct the building, and the manner in which the building is actually operated are some of the variables that make a precise calculation impossible. Even if the designer uses reasonable procedures to account for these factors, the calculation can never be more than a good estimate of the actual cooling load.

System Loads

The proper design and sizing of central AC systems require more than calculating the cooling load in the space to be conditioned. A zoned system needs to provide no greater total cooling load capacity than the largest hourly summary of simultaneous zone loads throughout a design day; however, it must handle the peak cooling load for each zone at its individual peak hour.

When estimating the load of a system serving a group of spaces, the assembled zones must be analyzed to consider: 1) diversity of zone loads due to different zone orientation and occupancy; 2) ventilation loads; and 3) miscellaneous heat gain from fan heat, duct heat, duct leakage and other unique circumstances. Correct zoning will prevent system loads from varying widely.

Adequate system design and component sizing require that system performance be analyzed as a series of psychrometric processes. The conventional assumption of a fixed relative humidity for the cooling coil leaving-air condition can give the wrong value for the system cooling load. To meet the same amount of zone loads, systems with heat recovery devices may come up with lower cooling loads, especially for applications with a high volume of outside air that indicates a higher dehumidification load.

Plant Loads

For central air conditioning systems, the cooling plant needs to provide no greater total cooling load capacity than the largest hourly sum of simultaneous cooling coil loads throughout a design day; however, it must handle the peak cooling load for each system at its individual peak hour. Plant loads need to meet system loads and compensate for pipe losses. With buildings that involve more than a single AC system, simultaneous loads and any additional diversity must be considered. Design cooling load determines the total cooling capacity of plant. The annual cooling load profile is very useful for sizing and selecting multiple size chillers instead of one single chiller. Equal size chillers are not necessarily the optimum choice.

Other Issues

Underground surface heat transfer. For underground spaces, heat transfer through underground surfaces behaves quite differently from heat transfer through above-grade surfaces. Make sure the load calculation procedures address this.

Site elevation. Air flow calculations are normally based on volume. They are assumed to be at a standard condition of 60°F at saturation and 69°F dry air at standard atmospheric pressure. For site locations with much higher or lower elevations than sea level, the deviation of air density due to local atmospheric pressure can be significant. This should be adjusted by a correction factor or by using more accurate engineering equations based on air mass instead of volume.

Safety margins. Because design parameters, load calculation procedures and computer programs may already have some built-in safety margins, use the calculated loads as-is to size and select equipment rather than introducing additional safety margins. Controlling the use of safety margins is a key to avoiding oversizing. Safety margins used in load calculation and sizing should be carefully justified based on individual application requirements and professional experience.

Design Tools

There are a variety of computer programs for load calculation and sizing, but some use very simple methods that may result in a very overestimated or underestimated cooling load. Choose computer programs with procedures compatible with those defined in the 1997 or 2001 editions of the ASHRAE *Fundamentals Handbook*.

Load calculation programs can be complicated and require hundreds of inputs. The user, of course, has to spend time collecting and preparing these data. Programs that promise a "one-click" answer will probably not provide very accurate results. To get a more accurate load estimation, the user must:

- Collect detailed data including building geometry, construction details, fenestration details, internal heat gains, schedules, design outside and inside conditions, etc.
- Master the program including the procedures to set up the model; understand assumptions, simplifications, default values, and safety margins used by the program.
- Understand how to interpret the calculation results, and how to troubleshoot.

- Double check calculated results with rules of thumb or compare with results from other programs.

Currently, four programs are widely used in load calculations for commercial buildings: HAP from Carrier, Trace from Trane, CHVAC from Elitesoft and Right-CommLoad from Wrightsoft. Although DOE-2.1E is popular in building energy simulation, it is not commonly employed for load calculation or sizing. EnergyPlus estimates loads more accurately based on the heat balance method. The Hbfort program uses the ASHRAE heat balance method and was released with the book, *Cooling and Heating Load Calculation Principles.*

An ideal design tool would:

1. Calculate design cooling loads with heat balance method;
2. Calculate annual cooling load profile;
3. Do psychrometric analysis for system load calculation and sizing; and
4. Provide interface to CADD programs for air duct and pipe sizing.

Component Sizing

Use rules-of-thumb such as square-foot-per-ton, cfm-per-square-foot, cfm-per-ton, kW-per-cfm and gpm-per-kW *for only rough sizing*. Accurate sizing should be based on detailed design parameters like temperature, humidity, air flow, water flow and static pressure. Sizing individual component correctly is only one side of the coin; the other is to match the capacity of each component in a system so that they work together efficiently.

Zone Air Flow

Normally, zone air flow is calculated based on design sensible loads and design supply air flow, which may not meet humidity requirements. For dehumidification applications, the design air flow must meet both temperature and humidity requirements. Zone air flow should also maintain air velocity between 10 to 50 fpm in the vicinity of occupants to prevent a draft effect, and should address ventilation and space pressurization needs.

Zone supply air temperature is established to maintain certain comfort conditions. Supply temperature varies with system type. While normal supply air temperature is 55°F, displacement or underfloor ventilation systems may use higher temperatures of up to 65°F. Cold air distribution systems may use supply temperatures between 40°F to 50°F. In Hawaii, cold air systems have been used successfully at a number of sites.

If the zone air flow is oversized, then the supply air temperature must be reset upward in order to meet sensible load, which may decrease dehumidification. At low load conditions, the zone latent cooling load may dominate the total cooling load, which requires a small amount of cold air or a large amount of warm and dry air to maintain the design zone temperature and humidity level. When determining the zone design air flow and supply temperature, consider the zone cooling and dehumidification needs at *both* design and off-design conditions.

Cooling Coil

A cooling coil serving one or more conditioned spaces is sized to meet the highest sum of the instantaneous space loads for all the spaces served by the coil, plus any external loads such as fan heat gain, duct heat gain, duct air leakage, and outdoor air ventilation loads (sensible and latent).

At design condition, a cooling coil provides design air flow at design off-coil air temperature and humidity, which are determined to meet each zone’s temperature and humidity requirements. For dehumidification applications, the cooling coil should have adequate latent cooling capacity as well as sensible cooling capacity. The Dehumidification Guidelines provide more detail.

Cooling coil sizing and selection must take into account the design air-side and water-side entering and leaving temperatures, flow rates, and pressure drops. Cooling coil manufacturers usually provides computer programs for coil selection. To improve coil heat transfer performance and reduce air-side pressure drop, select coils with a low face velocity of 250 to 300 fpm instead of 500 to 600 fpm, and low approach temperatures of 5°F to 8°F instead of 10°F to 15°F.

Chiller

Chiller sizing is based on the system's total cooling capacity. The design chilled water flow and the supply and return water temperatures are important criteria for selecting chillers. Try to avoid oversizing chillers (see the Oversizing section above). An oversized chiller not only costs more to purchase, it also leads to substantial energy losses and more chiller wear and tear from excessive cycling. Based on the annual load profile, selecting two or more smaller chillers to meet varying load requirements may be cost effective. Multiple chillers also provide redundancy for routine maintenance and equipment failure. For many typical facilities, sizing one chiller at one-third and another chiller at two-thirds of the peak load enables the system to meet most cooling conditions at relatively high chiller part-load efficiencies. When one single chiller is used, try to select a chiller with effective unloading (VSD, multiple stage compressor, etc.). PG&E's *CoolTools Chilled Water Plant Design and Specification Guide* describes optimal chiller sizing procedures.[1]

Cooling Tower

Cooling tower sizing is based on the chiller condenser load and other heat gains from the pipe, pump and other components. The condenser load equals the evaporator load (cooling load) plus the chiller compressor heat. Once cooling capacity is determined, size the cooling tower using the ASHRAE design wet-bulb temperature conditions. Select cooling towers with multiple cells and with VSD fans. An oversized cooling tower will provide cooler condenser water temperature and thus improve chiller efficiency. PG&E's *CoolTools Chilled Water Plant Design and Specification Guide* describes optimal chiller sizing procedures.

Fan

Size the fan to meet the system design air flow and air loop pressure drop. When selecting the fan, also consider the noise level, type and efficiency. In general, avoid oversizing fans. If a fan has to deal with a wide range of air flows, a variable-speed drive should be installed for the fan motor. See the *Advanced VAV System Design Guide*[2] for more details on fan selection for large HVAC systems.

Pump

Size the pump to meet the design chilled water flow and pressure drop. When selecting the pump, also consider the noise level, type and efficiency. Avoid oversizing pumps. If a

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[1] Available at www.hvacexchange.com/cooltools.

[2] Available at www.newbuildings.org.

pump has to deal with a wide range of water flows, a variable-speed drive should be installed for the pump motor.

Duct

Duct sizing is based on air flow rate, pressure drop and noise level. As far as space and cost allows, oversizing air ducts will decrease air velocity and pressure drop and will allow the fan to be downsized. A round duct is better than a rectangular one due to lower pressure loss. The T-Method described in the 2001 edition of ASHRAE's *Fundamentals Handbook* is used to optimize duct sizes together with fans.

Diffuser

Diffusers are designed to inject high velocity air so as to entrain and mix it with room air. Base diffuser sizing on design air flow and noise level. Avoid oversizing diffusers because during low load conditions, air flow may be low and oversized diffusers may dump cold air.

Pipe

Base pipe sizing on fluid flow rate and pressure drop. As far as space and cost allow, oversized pipes will downsize pumps and save energy, as long as there are no partial flow and cavitation problems.

Noise, erosion, and installation and operating costs all limit the maximum and minimum velocities in piping systems. If piping sizes are too small, noise levels, erosion levels, and pumping costs can be unfavorable; if piping sizes are too large, installation costs are excessive. Therefore, pipe sizes are chosen to optimize initial cost while avoiding the undesirable effects of high velocities. PG&E's *CoolTools Chilled Water Plant Design and Specification Guide* describes procedures to optimize pipe sizing based on lifecycle cost.[3]

System Issues

Many factors affect system load and sizing, including the AC system type, fan energy, fan location, duct loss, vented lighting fixtures, and the type of return air system.

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[3] Available at www.hvacexchange.com/cooltools.

Start Up

During the start-up period, AC systems may need to run at full capacity to bring zone conditions to the comfort level. Conventional design practice is to add extra cooling capacity to the design loads. But during the start-up period, the building is not yet occupied, and for most applications, there is no need for outside air ventilation; therefore the AC system runs at 100% return air mode and most probably will meet the cooling requirement without extra capacity.

Intermittent Cooling

Systems running intermittently may need extra cooling capacity to cool down the building in a specified time period. Double check whether this has already been taken care of in the load calculation procedures before adding extra capacity.

Radiant Cooling

Most load calculations assume an all-air system. For radiant cooling systems (which are used frequently in Europe), the heat balance method still applies, but the user must verify that the computer program is capable of dealing with radiant systems and that it takes appropriate input data. Depending on the type and configuration of radiant systems, the design load may vary. The start-up effect must be investigated in more detailed for radiant systems. This usually involves the delay or temperature control of radiant cooling until the relative humidity in the space is below a specified threshold in order to prevent condensation.

Packaged Systems

The rated EER/SEER for packaged units is normally based on the sensible cooling load under design conditions. A higher EER/SEER unit may yield a lower latent cooling capacity. When sizing packaged systems, make sure there is adequate latent cooling capacity. Air flow for packaged systems usually maintains over 400 cfm/ton to prevent coil freezing, which may require a significant amount of reheat for dehumidification applications running in low load conditions. The dehumidification performance of packaged systems can be substantially improved by installing a heat recovery loop such as run-around coils or heat pipes to precool the supply air and post-heat the air leaving the DX coil. Another attractive option is to use heat pumps (i.e. reversing valves) on the return air circuits.

Resources

ACCA, *Manual N: Commercial Load Calculation*

ASHRAE, www.ashrae.org.

- *Fundamentals Handbook,* 2001 and 1997
- *Cooling and Heating Load Calculation Manual*
- *Cooling and Heating Load Calculation Principles*
- *Standard 55: Thermal Environmental Conditions for Human Occupancy*
- *Standard 62: Ventilation for Acceptable Indoor Air Quality*
- *Standard 90.1: Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings*

BSRIA, *Application Guide AG 1/2000: Enhancing the Performance of Oversized Plant*

DOE-2, and EnergyPlus, http://www.eren.doe.gov/buildings/energy_tools/energyplus

Elitesoft, www.elitesoft.com

Electric Power Research Institute, TR102545 Guide to Energy Efficient Office Equipment.

ESource, *Technology Atlas: Space Cooling.*

New Buildings Institute, *Advanced VAV System Design Guide*, www.newbuildings.org.

PG&E, *CoolTools Chilled Water Plant Design and Specification Guide,* www.hvacexchange.com.

Wrightsoft, www.wrightsoft.com

Efficient Air Distribution System

Recommendation

Design the air distribution system to minimize pressure drop and noise by increasing duct size, eliminating duct turns and specifying low-loss duct transitions and plenums. Use the lowest possible fan speed that maintains adequate air flow. Pay special attention to the longest or most restricted duct branch because the fan pressure required for adequate air flow is dictated by the duct run with the greatest pressure loss.

Description

Optimal air distribution system design is fairly complicated. An optimal design balances the need for comfort and low noise with overall HVAC system cost, energy cost, and long-term maintenance and replacement costs. Many factors affect performance: diffuser type, number of diffusers, diffuser size, duct size, duct material, plenum type and size, fitting types, length of ducts, number of turns, type of turns, location of duct system (for example, within unconditioned or conditioned space), and fan characteristics (pressure vs. air flow).

For small systems, a detailed analysis is not common. Typically designers and contractors rely on experience or rules of thumb in choosing system components. Even if design calculations are performed, however, decisions are not always the best in terms of energy efficiency and acoustic performance.

This section addresses small, constant-volume duct systems and covers design targets for air velocities and pressure loss that help ensure an efficient and quiet system. For information about designing larger variable air volume systems, see the Advanced VAV System Design Guide.[4]

Figure 2 – Ducted air system.

Applicability

All ducted air systems.

Applicable Codes and Standards

The energy code sets requirements for duct insulation, sealing and testing. In addition, individual HVAC systems with more than 25 hp of fans face efficiency limits of 0.8 W/cfm for constant-volume systems and 1.25 W/cfm for variable-volume systems.

Integrated Design Implications

Air distribution design options are closely tied to the architectural design. The choice of duct type is often limited by space availability.

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[4] Available at www.newbuildings.org.

Ducts may be located outside, in unconditioned space, or within the conditioned space. The most efficient option is usually within the conditioned space. More expensive sheet-metal ducts are usually required, but they need not be insulated. If ducts are located in an unconditioned attic, then the roof should be insulated, and/or equipped with a radiant barrier to reduce heat gain to the ducts. Outdoor ducts should not be used unless no other option is feasible.

Consideration of potential condensation is necessary regardless of whether ducts are in conditioned or unconditioned space. For ducts inside conditioned space, the cooling system should be properly sized and controlled to keep the space dry so that condensation does not occur on the cool outer surface of the ducts. For ducts outside conditioned space, careful attention to insulation, duct sealing and vapor barriers can limit condensation.

Coordinate the location of supply air outlets with the lighting design (for outlets located in the ceiling) or with the space plan and furniture (for wall or floor outlets).

Cost Effectiveness

Sometimes extra cost for low-loss fittings or larger ducts is necessary to achieve a high performance design. These costs can often be offset by carefully sizing the heating and cooling system to reduce overall system size. In addition, many air distribution improvements — such as proper installation of flex duct — cost little or no extra.

Design Tools

Numerous duct sizing computer programs are commercially available.

A common tool is a “ductilator," a manual device used to calculate pressure loss for different types of ducts.

SMACNA and ASHRAE publish tables listing pressure loss data for a variety of common duct fittings.

Design Details

These guidelines cover typical small single-zone systems. Additional criteria appropriate for multi-zone air distribution systems are not covered here.

Air Flow

System cooling air flow. Total system air flow should generally fall between 350 and 450 cfm/ton for systems with cooling. If air flow is greater, then condensation might blow off the cooling coil. If air flow is less than 350 cfm/ton, then the cooling capacity and efficiency drop somewhat. However, the capacity loss due to low air flow is worst in dry climates where latent cooling loads are low. Therefore it may be appropriate for systems in Hawaii to operate at the lower end of the airflow range because the air temperature leaving the cooling coil will be lower and more dehumidification occurs.

System heating air flow. For heating-only systems, a good target is 25 cfm per kBtu/h of heating capacity, providing about 105°F supply air. Heating air flow should not be lower than 15 cfm per kBtu/h because supply air temperature will exceed 135°F. If the air flow is low, then supply air will be too warm and air velocity too low, and poor mixing occurs in the room. Excessive air flow during heating creates more noise and can cause uncomfortable drafts. In Hawaii, heating scenarios will be limited.

Air flow adjustment. After system installation, air flow can be adjusted by either changing the fan speed or altering the duct system. To reduce air flow, lower the speed of the fan rather than install dampers. Try to use the lowest fan speed possible because fan energy consumption drops rapidly as fan speed decreases. If possible, specify a variable-speed fan or multiple-speed fan. To increase air flow, try to modify the duct system rather than increasing the fan speed. Possible measures include replacing the most restrictive ducts with larger sizes, improving duct transitions to reduce pressure loss, and eliminating duct turns or constrictions (especially in flex duct).

Air Velocity

Supply diffuser. The velocity of air leaving the supply air diffusers should generally not exceed 700 fpm to minimize noise. Most diffusers also have a minimum velocity needed for proper mixing and to avoid dumping cool air on occupants. Refer to manufacturers' guidelines for specific types of supply diffusers. When choosing diffusers based on NC (noise criteria) noise rating, remember that manufacturers' data are usually at ideal conditions (long, straight duct attached to diffuser) and actual noise level is likely to be higher.

Return grille. The return air grille or grilles must be larger than the total supply air diffuser area to avoid excessive noise. Air velocity should not exceed 300 fpm at the inlet.

Duct. Air velocity should not exceed 700 fpm in flex ducts and 900 fpm in sheet metal ducts. Higher flow creates excessive turbulence, noise, and pressure drop. There is usually a practical lower limit to duct air velocity, where the duct becomes too large and expensive.

Cooling coil. Minimize air velocity through the cooling coils to reduce pressure loss. A good target is 300 fpm. However, designers seldom have a choice of coil area in small packaged HVAC units, though it is possible to compare air flow and fan power data from different manufacturers to identify units with lower internal pressure loss.

Duct Type

Flex duct. Flexible ducts are widely used. They offer a number of advantages when properly installed but also have some disadvantages.

Flex ducts are most popular for their low cost and ease of installation. In addition, they attenuate noise much better than sheet metal ducts, offer lower air leakage, are usually pre-insulated, and provide some flexibility for future changes.

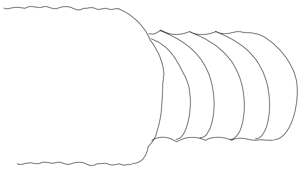
On the downside, pressure loss is greater in flex ducts, even when they are perfectly installed. They are also prone to kinking, sagging and compression, problems that further reduce air flow. And since they are flexible, flex ducts are usually installed with more turns than sheet metal ducts. Actual performance of flex ducts in the field is often poor because of these installation problems. As a final disadvantage, flexible ducts are typically warranted for only about 10 years and will need replacement more often than a sheet metal equivalent.

If flex duct is used, there are several important points to consider:

- The duct must be large enough for the desired air flow (see Table 1).
- The ducts must be properly suspended according to manufacturer guidelines without compression or sagging.
- All ducts must be stretched to full length (see note in Table 1).
- Keep flexible duct bends as gentle as possible; allow no tight turns.
- Fasten all flex ducts securely to rigid sheet metal boots and seal with mastic.

- Limit duct lengths to no longer than about 20 ft (otherwise pressure loss may be too high).

Table 1 – Minimum and maximum air flow for flex ducts.

	Flex Duct Diameter (inches)	**Minimum Air flow (cfm)**	**Maximum Air flow (cfm)**
	4	20	60
	5	40	100
	6	60	140
	7	90	190
	8	130	240
	9	175	310
	10	230	380
	12	380	550

Notes:

- Maximum air flow limits correspond to velocity of 700 fpm. Higher flows create turbulence and noise in flex ducts.
- Minimum air flow corresponds to a design friction rate of 0.06 in./100 ft.
- The air flow values in the table assume that the flex duct is stretched to its full length. Air flow resistance increases dramatically if flex duct is compressed in length. **Pressure loss doubles if the duct is compressed to 90% of its full length and triples if it is 80% compressed.**[5]

Sheet metal duct. The advantages to sheet metal ducts are lower pressure loss, longer life, greater durability and the potential for reuse or recycling at the end of the system’s life. They are the only option for long duct runs or medium to high pressure duct systems. In addition, sheet metal ducts may remain exposed in conditioned spaces.

Disadvantages to sheet metal ducts are higher cost, higher sound transmission (sometimes they require noise attenuation measures that offset some of the pressure loss advantage), insulation requirement, and potentially greater leakage (though leakage is not an issue if they are properly sealed).

Round or oval sheet metal ducts are preferred over rectangular when adequate space is available. Round ducts are likely to be quieter and cause less pressure loss for the same cross-sectional area. Rectangular ducts are susceptible to noisy drumming at high air flow. However, in Hawaii round or oval ducts are not commonly used due to lack of suitable

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[5] Flex duct compression impact from ASHRAE HOF 1997 p 32-8, Figure 8.

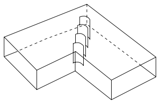
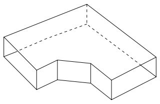
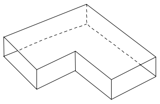
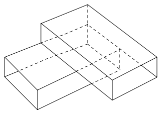
sheetmetal equipment and need to ship materials from the mainland U.S.

Reducing Pressure Loss

A number of measures may be taken to reduce pressure loss and improve air flow. Knowledge of the following simple principles may help the designer improve air flow:

- Air resists changing direction. The pressure drop of a turn can be reduced dramatically by smoothing the inside radius (the turn's outer radius does not matter as much). When possible, avoid sharp turns in ducts and never allow kinks in flexible ducts. Turning vanes are another option to reduce the pressure drop in a sharp turn.

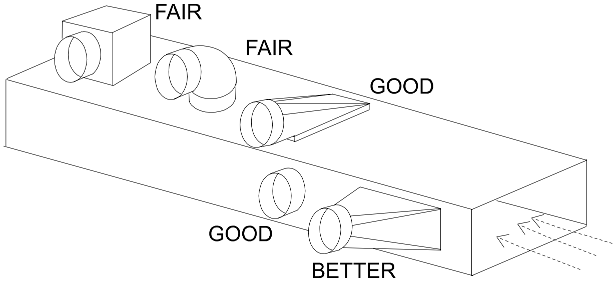
Figure 3 – Relative pressure loss for various types of duct turns.

				
	BEST	GOOD	FAIR	POOR
Relative Pressure Loss	1.0	X 1.3	X 4.7	X 13.0

Note: Total pressure loss calculated at 800 fpm air velocity.

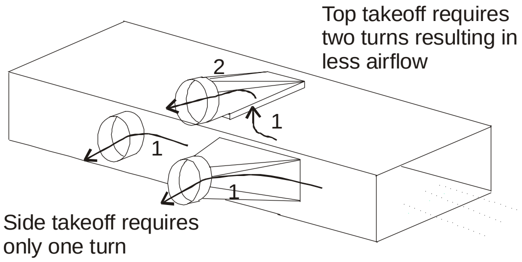
- Air flow into branch ducts will be improved by using angled transitions (or conical taps) rather than typical straight connections. The angled transition is especially useful for critical branches that aren't getting enough air.

Figure 4 – Angled transitions improve air flow into branch ducts.



- The fewer turns the better. For example, a side branch takeoff provides less flow resistance than a top branch takeoff because the top takeoff requires the air to turn twice.

Figure 5 – Side branch takeoff provides less flow resistance than top branch takeoff.



Reducing noise

Noise reaching the space via the duct system is either transmitted from the air conditioning unit or generated by air turbulence within the air distribution system.

Several measures can prevent sound transmission through the duct, such as sound-absorbing duct liner, flex duct, duct turns, sound attenuators, and active noise canceling. The first three measures are the most feasible for small single-zone systems because they are not prohibitively expensive and do not necessarily cause excessive pressure loss (small packaged systems usually don't have a lot of pressure to spare). Careful design is important to balance noise attenuation benefits vs. additional pressure loss.

Noise generation within the ducts or at grilles and diffusers can be controlled by limiting air velocity as described above.

Other Design Issues

Pay special attention to the duct branch with the greatest pressure drop: either the longest branch or the one with the most constricted turns. To achieve proper air flow with longer branches, either a larger duct size or low-loss duct transitions will be required.

Do not place balancing dampers directly behind diffusers. If they are necessary, then locate dampers as close to the fan as possible to minimize noise and to avoid air leakage in the supply duct due to backpressure.

Connections to ceiling diffusers should have two diameters of straight duct leading into the diffuser. Otherwise noise and pressure drop can increase significantly.

Think twice before placing ducts in a hot attic. The roof can reach 150°F on a sunny day and the radiant heat load on the duct is significant. If ducts are above the ceiling, then insulation must be installed on or under the roof or a radiant barrier must be installed under the roof deck.

In many cases, if the pressure loss in the air distribution system can be reduced by as little as 0.15 in. w.c., then fan speed can be reduced and fan power decreases significantly. In the case of a 3-ton rooftop packaged unit, energy savings can be $200 to $300 over a 10-year period. Manufacturer's data for a typical 3-ton unit shows that the fan can supply 1100 cfm at 0.80 in. w.c. external static pressure if the fan is set to high speed. The fan can provide the same air flow at 0.65 in. w.c. at medium speed. Therefore, if the duct system is carefully designed and installed it may be possible to run at medium speed. The fan power then drops from 590 watts to 445 watts. For typical operating hours and electricity rates, the savings are about $30 per year.

Operation and Maintenance Issues

Filters must be replaced regularly to maintain air flow and to prevent filter housings from collapsing and allowing air to bypass the filter.

Commissioning

Measure supply air flow and external static pressure to compare to design values. If air flow is low, take measures to reduce restrictions in duct system rather than increasing fan speed. If airflow is higher than necessary, then reduce fan speed rather than closing down balancing dampers.

Utility Programs

Check with the local electric utility to see if custom incentives are available for high efficiency duct systems.

Resources

Advanced VAV System Design Guide, New Buildings Institute, www.newbuildings.org.

ASHRAE *Fundamentals Handbook* (Atlanta, GA: American Society of Heating, Refrigeration and Air Conditioning Engineers, 1997). Web site: www.ashrae.org.

HVAC Systems — Duct Design (Chantilly, VA: Sheet Metal and Air Conditioning Contractors National Association, 1990). Web site: www.smacna.org.

Efficient Chilled Water Distribution

Recommendation

Utilize variable-flow chilled water distribution when a central plant is needed, and consider using a primary-only pumping system for greater energy savings.

Description

Chilled water distribution is a big energy end use in Hawaii due to year-round cooling loads. Older chilled water plant designs circulate a constant volume of chilled water through the chillers and the building, no matter if the cooling load is large or small. If loads are small, the constant volume of chilled water is diverted around the cooling coils by three-way valves. As a result, energy consumption is higher than necessary, and variable-flow systems have emerged. The energy savings can be captured cost effectively using modern control systems and variable speed drives.

There are several different strategies to variable flow chilled water system design. One common option is the primary/secondary system, where flow through the chiller is maintained relatively constant while flow through the cooling coils is varied according to demand for cooling. The other option that is somewhat more efficient and becoming increasingly popular is the variable-primary system, where flow through the chiller is also varied.

Regardless of pumping system configuration, chilled water pipe insulation is a critical concern in Hawaii. Due to the moist climate, condensation will form on poorly insulated pipes and can cause damage. Condensation can be minimized when pipes are adequately insulated and insulation is protected with a vapor barrier. When dealing with condensation problems in existing systems, it is important to repair damaged vapor barriers and insulation rather than increase the chilled water temperature setpoint to avoid condensation. If the chilled water temperature is increased, then it is likely that the cooling coils will not provide adequate dehumidification.

Applicability

Applicable whenever a significant amount of chilled water is required.

Applicable Codes and Standards

The energy code includes several requirements related to chilled water distribution systems. Insulation is required on chilled water pipes. Variable flow systems are required for pumping systems that include control valves that are designed to modulate flow based on load and that have pumps larger than 25 hp. This requirement covers most large chilled water cooling systems and essentially requires the use of two-way valves rather than three-way valves that bypass unneeded chilled water around the cooling coil.

Benefits

An efficient chilled water distribution system can have a significant impact on a building's total energy consumption.

Integrated Design Implications

Choices regarding chilled water distribution are intimately related to the entire chilled water plant.

The possibility of condensation should be considered when routing chilled water pipes. It is best to avoid areas where moisture could cause structural damage or mold growth, especially if access for maintenance is difficult.

Design Details

This section provides a brief overview of two options for variable-flow chilled water distribution design. For much more detail, see the *CoolTools Energy Efficiency Chilled Water Plant Design and Performance Guide*.[6]

Primary-Only Variable Flow Design

Figure 6 shows the piping arrangement for a typical primary-only system, in this case with a single chiller serving multiple cooling coils. Each of the coils has a two-way valve that modulates flow through the coil according to demand. A bypass line with control valve diverts water from the supply into the return piping to maintain a minimum flow through the chiller or chillers. A variable speed drive on the pump is controlled from a remote differential pressure controller or cooling coil valve position.

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[6] Available at www.hvacexchange.com/cooltools.

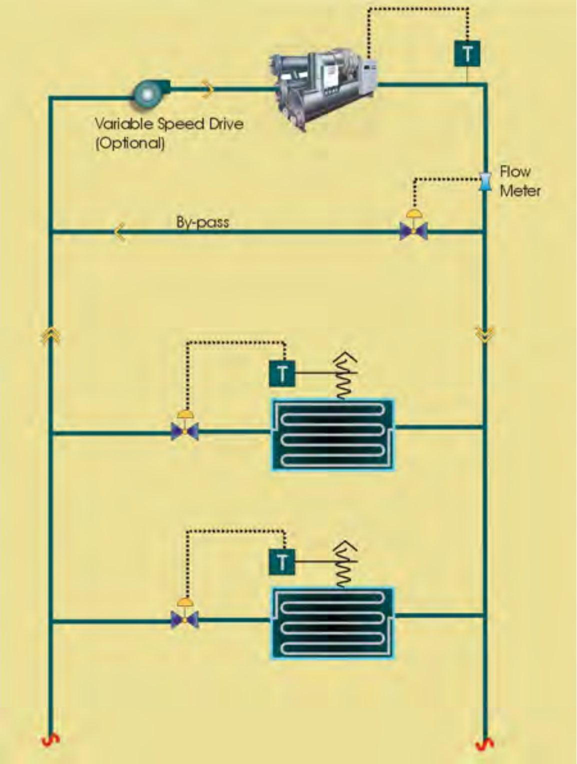


Figure 6 — Primary-only variable flow piping, single chiller, multiple coils.

Source: CoolTools

Engineers have traditionally avoided variable flow through chillers, but flow in the evaporator can be dynamically varied to a greater extent than in the past due to advances in chiller controls. If a chiller is operating in a stable condition and flow in the evaporator is reduced, the leaving chilled water temperature will drop. If the flow reduction occurs slowly, the controls will have adequate time to respond and the system will remain stable. But a rapid change in flow will cause the leaving water temperature to drop quickly. If the controls react too slowly the chiller may shut down on low temperature safety. This is a significant nuisance since someone must manually reset the safety control and the chiller must remain off for a minimum period of time before restarting. Most manufacturers (although not all) have adopted modern controls that account for the rate at which the leaving chilled water temperature drops. These controls will prevent inadvertent shutdown of the chiller.

Another issue in primary-only plant design is avoiding laminar flow in the evaporator tube. A fluid velocity of at least 3 feet per second is recommended to maintain good heat transfer. In chilled water plants with higher delta-Ts (lower flow rates), the variation between the design flow and the minimum flow may be limited. Given the fluctuations and accuracy of controls, a good designer will choose a minimum flow rate that is not too close to the published minimum. Consult the manufacturer's literature for maximum and minimum flow rates.

Primary/Secondary Variable Flow Design

This is the standard design for central chilled water plants with multiple chillers and multiple cooling loads (Figure 7). The beauty of the primary/secondary variable flow design is that the piping loop for chillers (the primary loop) is hydraulically independent (decoupled) from the piping loop for the system (the secondary loop). The key to this design is that two independent piping loops share a small section of piping called the "common pipe."

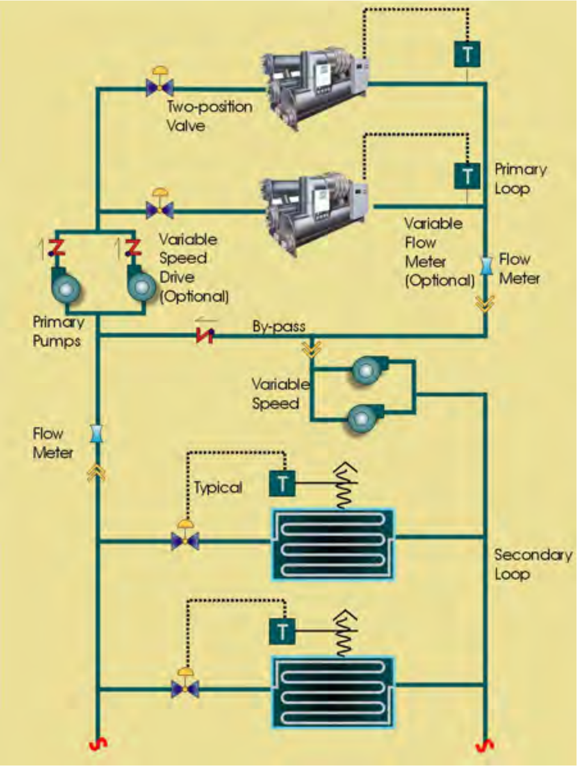
When the primary and secondary pipe loops operate at the same flow rate, there is no flow in the common pipe. Depending on which loop has the greater flow rate, the flow direction in the common pipe is subject to change. Typically, the number and flow rates of the primary pumps match each chiller. The primary pumps are typically constant volume, low head pumps intended to provide a constant flow through the chiller's evaporator. The secondary pumps deliver the chilled water from the common pipe to coils then back to the common pipe. These pumps are variable-speed pumps controlled from differential pressure sensors located remotely in the system or from cooling coil valve position.

Normally it is desirable to have the flow rate in the primary loop equal to or greater than the flow rate in the secondary loop. This means that some of the cold supply water is bypassed through the common pipe to the return side. The cold bypass water mixes with the return water from the secondary system, dropping the temperature accordingly. This water is then pumped back into the chiller. When the secondary flow exceeds the primary, return water from the system flows back through the common pipe and mixes with the supply water from the chillers. This increases the temperature of the supply water to the secondary system, sometimes with dire consequences. The warmer supply temperature causes the two-way valves at each cooling coil to open even more, creating an ever-increasing demand for secondary system flow. To address this problem, controls turn on chillers so that the primary flow is always equal to or greater than the secondary flow.

If the secondary system return-water temperature is lower than the design temperature, the chillers cannot be loaded to their maximum capacity. This is called “low delta-T syndrome” and it results in greater pump, chiller, and cooling tower energy consumption, as well as a reduction in cooling plant capacity. In most cases, the capacity control and control valve of the air handling units are the cause of low delta-T.

Figure 7– Primary/secondary variable flow piping, multiple chillers, multiple coils.

Source: CoolTools.



Design and Analysis Tools

Software is available that assists engineers in sizing pipes, pumps and fittings and can be used to compare the performance of alternative designs. Energy simulation programs such as DOE2 can be used to estimate the energy consumption for different control options, comparing constant flow systems to variable flow systems and comparing primary only systems to primary/secondary systems.

Cost Effectiveness

The cost of a primary-only system will generally be lower than a primary/secondary system because fewer pumps are usually required. Variable flow systems generally cost more than a constant flow system due to the variable speed controls on the pump. However, the energy savings in the variable flow system generally provide a quick payback.

In some cases, choosing a larger size pipe will be cost effective due to reduced pressure drop.

Operations and Maintenance

Periodic pump maintenance should check vibration, bearing temperature, noise, entrapped air, pressure, current, bearing wear, impeller and casing wear, and signs of cavitation.

The air release valve automatically ejects unwanted air to the atmosphere. Air inside the system contributes to corrosion and unnecessary energy usage. Periodically check for and purge entrapped air. Check for water leaks.

The air and dirt separators extract air from chilled water systems. Dirt inside the systems is trapped and expelled by the use of a blowdown valve to maintain a clean system. The air and dirt separators contribute in keeping the systems operating at peak efficiency and also, prolong the life expectancy of pumps, coils, valves, and piping

Pipe insulation damage is common. Visually inspect for damage. Missing insulation on chilled water pipes can lead to condensation and moisture damage.

Also inspect for leaks.

Commissioning

Commissioning of pumping control systems is critically important. Calibration of flow and temperature sensors is important. In addition, operation must be verified over the full range of operation, from minimum to maximum flow.

Utility Programs

The utilities that serve Oahu, Maui, Molokai, Lanai, and the Big Island (HECO, MECO, and HELCO) have a rebate program called the Commercial and Industrial Customized Rebate (CICR) program. Under this program innovative technologies that save energy and demand would qualify for a rebate based on $125/kW of peak demand reduction and $0.05/kWh for a year of energy savings. Rebates are based on engineering estimates of energy and demand savings. In the case of unproven technologies the rebate may be paid over a period of 5 years based on metered savings.

The Kauai Island Utility Cooperative's "Energy Wise Program" offers incentives for Kauai commercial buildings (phone 808-246-8275).

Case Study

Variable-flow primary-only systems have been installed in several Hawaiian facilities. The DFS Galleria in Waikiki installed two 750-ton variable-flow chillers with primary-only chilled water loop as part of a renovation and expansion. Other examples include the Ala Moana Hotel and the U.S. Postal Service Airport P&DC.

Resources

CoolTools Energy Efficiency Chilled Water Plant Design and Performance Guide, Pacific Gas & Electric. www.hvacexchange.com/cooltools.

www.griswoldcontrols.com

www.taco--hvac.com

Single-zone DX AC System

Recommendation

If choosing a single-zone direct-expansion (DX) system, be sure to properly size the system for good dehumidification performance and consider including refrigerant subcooling to increase the latent capacity.

Description

Two possible equipment choices when specifying a single-zone DX system are packaged rooftop and split system. A packaged rooftop system is fully self contained and consists of a supply fan, direct expansion cooling coil, filters, compressors, condenser coils and condenser fans. Units are typically mounted on roof curbs but can be also mounted on structural supports or on grade. Packaged rooftop single-zone units are typically controlled from a single space thermostat with one unit provided for each zone. Supply air and return air ducts connect to the bottom (vertical discharge) or side (horizontal discharge) of the unit.

A ductless split system consists of two matched pieces of equipment: an indoor fan coil unit and an outdoor condenser and compressor unit. The two are connected by refrigerant tubing and control wiring that run through the wall or roof. The indoor unit contains a cooling coil, fan and filter. The outdoor unit includes a compressor or compressors, condenser coil, and condenser fans. In its simplest form, a ductless split system recycles 100% indoor air. However, on many units ventilation air can be supplied with an optional duct attachment that passes through the wall.

Applicability

Packaged rooftop units are available in capacities from two tons to more than 100 tons and can be used for single zones from 600 ft^2 to more than 30,000 ft^2.

A ductless split system can serve spaces up to about 1,000 ft^2, or perhaps 2,000 ft^2 if multiple units are installed. They are most useful for buildings with indoor and/or outdoor space constraints, where rooftop space is unavailable or space for ducts is limited. This system is also applicable for retrofits where ducts do not currently exist.

Due to the constant volume fan, packaged single-zone systems are usually not the best choice when humidity control is important.

Applicable Codes and Standards

Federal regulations require a SEER value of 10.0 for both split and packaged rooftop systems smaller than 65,000 Btu/h.

The Hawaii energy codes set efficiency requirements for packaged air conditioners larger than 65,000 Btu/h. (The latent cooling capacity of AC systems is often sacrificed in order to meet Federal regulations. This is obviously unfortunate for tropical climates such as Hawaii.)

Integrated Design Implications

Rooftop units can have a significant visual impact. Consider their location early in the architectural design process to allow for efficient duct layout. In addition, consider the location of ducts and supply registers when making lighting system decisions.

Specify system controls so that they integrate with natural ventilation design. Use automatic interlock controls to shut off the system when windows are opened or allow manual fan shutoff.

Try to place ducts within the conditioned envelope as much as possible to minimize the impact of leakage and conduction losses (which can be very significant). When ducts are located above the ceiling, then insulate under the roof deck rather than on top of a suspended ceiling.

Costs

The overall cost for a packaged rooftop system can be as low as $10 per square foot (installed cost, including ductwork and controls).

Cost of the unit alone ranges from about $1,500 for a 2-ton unit to around $2,000 for a 5-ton unit. High efficiency package units (when available) cost about 10% more than standard efficiency models and have paybacks of around 3 to 4 years in warm climates such as Hawaii.

The price for a typical 2-ton split system unit is $4,000 to $5,000.

Cost Effectiveness

Packaged rooftop systems are often the lowest cost alternative. However, they are relatively costly to maintain and energy costs are higher than average. Due to the extra cost, a ductless split system will probably be cost effective only where space constraints prohibit the use of ducted system types.

Design Details

This section lists a number of design considerations.

- It is important to look at the psychrometrics of the actual zone loads and to realize that most packaged systems are not designed for the latent loads experienced in the Hawaiian climate. Specify high efficiency units if they provide adequate dehumidification performance.
- Look for packaged equipment that is specially designed for humid climates and has a high latent (moisture removing) cooling capacity. Increased dehumidification can be achieved by further subcooling the hot liquid refrigerant leaving the condenser coil. The package consists of a subcooling coil located on the leaving-air side of the evaporator coil. Refrigerant passes through this subcooling coil before it enters the evaporator. Therefore, air passing through the evaporator is cooled to a lower temperature than in a normal system and more moisture is extracted. Then this cool supply air is reheated somewhat when it passes through the subcooling coil. This arrangement greatly enhances the latent capacity of the system.
- The incremental equipment cost for packaged rooftop equipment is not too large to increase size from say, two to four tons. Therefore, the temptation is strong to specify the larger unit for safety's sake. However, there are performance penalties for oversized systems. Bigger is not always better. Do not rely on rules of thumb to select air flow, cooling capacity or heating capacity. See the Sizing AC Systems section for a discussion of load calculations and the impact of cooling capacity oversizing.
- In order to avoid excessive cycling, be very careful not to oversize the unit, which reduces humidity control, reduces reliability, and irritates occupants. Manufacturers even recommend choosing a system slightly smaller than peak load for these reasons.
- Consider using packaged AC units in a dual-path arrangement as described in the Dehumidification chapter. For example, one unit can be dedicated to cooling outdoor ventilation air and run continuously. Additional units can cool recirculated air as necessary to maintain space temperature at a comfortable setpoint.

- Most packaged systems have several fan speed options that can be selected in the field when the unit is installed. Careful design of the air distribution system can reduce pressure drop and provide significant savings if the fan is wired for low or medium speed
- Variable-speed fans are becoming more commonly available and should be considered in order to minimize cycling and reduce noise.
- Pay attention to security, noise and ambient temperature when positioning the outdoor unit.
- Specify low-noise units.
- Demand control ventilation is an option available on many units, employing CO2 measurements manage ventilation loads.
- Specify coated fins to maintain efficiencies and extend life of packaged rooftop AC units.
- Specify thicker fins with wider spacing when available.
- Ultraviolet germicidal irradiation (UVGI) lamps are available as options from some manufacturers. See the section *Ultraviolet Germicidal Irradiation* for more details.
- Water may condense on the indoor cooling coil. Therefore, a condensate pump may be required to remove water from the condensate drain pan to an approved receptacle. Overflow from the drain pan must be routed to a visible location.
- For ductless split systems, place the indoor unit on an external wall for ventilation air access and for minimum distance to the outdoor unit. Follow the manufacturer's recommendations for positioning the indoor unit to provide maximum air distribution and to avoid drafts.
- The indoor unit of ductless split systems are available in several forms: high wall mount, ceiling mount, and above-ceiling mounting. The high wall mount may be least costly but is usually limited in peak capacity to about two tons. Capacities up to five tons are available with suspended ceiling units. The above-ceiling units typical fit in a 2 ft x 2 ft suspended ceiling system and resemble a typical supply diffuser from below.
- Ductless split systems are available that allow two indoor units to be connected to a single outdoor unit.

- For split systems insulate suction and liquid refrigerant lines separately during installation. Otherwise one heats the other, causing capacity and efficiency loss.

Operation and Maintenance Issues

Maintenance requirements for a packaged rooftop system are very similar to other system types. Recommended maintenance tasks include:

- Replace filters regularly.
- Clean coils regularly (indoor and outdoor). Be careful regarding the type and application of coil cleaners employed to ensure that they will not damage the fins.
- Check refrigerant charge.
- Clean cooling coil condensate pan and drain.
- Lubricate and adjust fan as recommended by manufacturer.
- Clean UVGI lamps if installed. Replace lamps if necessary.

Commissioning

Measure total supply air flow with a flow hood or comparable measuring device. Make sure that air flow is within 10% of design value. If air flow is low, then check ducts for constrictions and check that filters and coils are free of obstructions. Larger ducts or shorter duct runs may be necessary. Reduce the number of duct turns to a minimum. If air flow is high, then reduce fan speed if possible according to manufacturer’s instructions.

Verify proper multiple fan speed control operation and thermostat operation.

Utility Programs

Hawaiian Electric Company and Maui Electric Company offer rebates for energy efficient packaged and split system air conditioners. The Kauai Island Utility Cooperative's "Energy Wise Program" offers incentives for Kauai commercial buildings (phone 808-246-8275).

Case Study

Marco’s Southside Grill won a MECO 2001 Energy Project of the Year award, partly for the use of a 5-ton Thermoplus "WaterWise" air conditioner that provides space cooling as well as virtually all of the hot water for the kitchen. The unit recovers waste heat from the air conditioner to provide the facility with hot water.

Products

Carrier's packaged systems with the MoistureMi$er dehumidification package provide increased latent capacity through refrigerant subcooling. www.commercial.carrier.com.

WaterWise by Thermoplus Air Inc. is a packaged air conditioner that recovers condenser heat to preheat hot water for domestic or industrial uses. www.thermoplus.com.

Lennox provides an optional dehumidification system for their packaged systems that uses hot gas reheat for humidity control called Humiditrol. www.lennox.com.

Resources

Small Commercial HVAC System Design Guide, New Buildings Institute. www.newbuildings.org.

Heat Pump Water Heating and Heat Recovery

Recommendation

Install heat pump water heating (HPWH) systems in spaces such as restaurant kitchens, commercial and coin-operated laundries, and hotels. Take advantage of the space cooling opportunity provided by the system.

Description

A heat pump water heating (HPWH) system consists of an evaporator, condenser, compressor, expansion valve, hot water circulating pump and controls. Generally, additional water storage capacity is also used to minimize the heat pump size while providing satisfactory water delivery capacity. The system is essentially a refrigeration loop in reverse. Heat is removed from either air or water, and transferred to the water. Transporting the heat from one place to another also provides for a cooling opportunity. This can be used to cool a space, such as a kitchen or elevator machine room, or to enhance chiller efficiency.

Heat recovery for service water heating can be categorized as either heat recovered from condenser water or heat recovered from the refrigerant. Recovery systems that extract heat from the condenser water include simple double-walled (required by health codes) heat exchangers and separate HPWH. Desuperheaters and double-bundle (also known as “side-arm” arrangement) chillers are two examples of systems that recover heat from the refrigerant. A desuperheater is a refrigerant-to-water heat exchanger located between the compressor and condenser. As it name suggests, it extracts heat from the superheated refrigerant vapor. Double-bundle chillers have two possible pathways for extracting heat. One pathway is a conventional cooling tower. The other pathway is heat recovery for space service water heating.

Applicability

Applicable in all building types requiring a significant amount of service hot water. Both HPWH and heat recovery systems are most applicable in spaces where the hot water demand coincides with a cooling demand. These spaces include restaurant kitchens, commercial and coin-operated laundries, and hotels. Another application is spaces where additional spot cooling is desired but where it would be difficult to run ducting or refrigerant lines.

Applicable Codes and Standards

The Hawaii energy codes require heat recovery in certain buildings that have both space cooling and water heating loads.

> *Condenser heat recovery from air conditioning or refrigeration equipment is required for any single cooling system larger than 10 tons of cooling capacity or compressor size of greater than 15 hp for buildings with service hot water heaters with more than 75,000 Btu/h or 12 kW input rating, unless the system can be shown to be not cost effective over its anticipated service life*

Benefits

Heat pump water heaters can provide the following benefits:

- Able to provide space cooling as well as water heating.
- More efficient than electrical resistance water heating by a factor of 3.5 to 4.5.
- Can be used to improve chiller efficiency. The combined chiller-heat pump system can reach COPs between 8 and 10.

Integrated Design Implications

It is important to integrate the design of heat pump water heaters with the air conditioning system to capture full savings.

- The various components of the HPWH system should be placed wisely. The evaporator should be placed in, or near, areas providing significant amounts of waste heat, or needing additional cooling.
- Double-bundle, or “side-arm” arrangement, condensers have applications in large heat pumps systems. They have two water tube bundles enclosed in the shell. High-pressure refrigerant gases are released in to the shell. As they condense, heat is released. The cooling tower water is pumped through the "summer-bundle," carrying off any excess heat beyond that needed for domestic hot water.
- Hot drain heat pumps use hot drain water as its source. Typical applications include commercial laundries and conveyor dishwashers. The recovered heat preheats fresh water before it goes in the domestic hot water tank — reducing the energy needed to heat it to the required temperature.

- Depending upon the hot water demand schedule, one application of a HPWH system is to preheat water for a gas or electric unit, especially when water temperature in excess of 140°F is required.
- A HPWH system can be integrated with a chiller to enhance the overall efficiency of the system.
- HPWHs are most efficient during long run times versus cyclic operation.

Design Details

- Screw compressor heat pumps have been replacing reciprocating compressors in larger sizes. Scroll heat pumps are often used in small HPWHs and multiple scroll compressors are used for sizes that can exceed 20 tons in heating capacity.
- The system will run more efficiently (highest COP) if the coldest water from the storage tanks is introduced to the water side of the condenser. This is accomplished through stratification of the storage tanks and other techniques. In a large installation, it is easier to use several smaller tanks piped together rather than one large tank.
- Install the unit next to equipment that produces waste heat, such as dryers, boilers or furnaces.
- Provide a drainage outlet for condensation in air-cooled heat pumps.
- For each kilowatt of electric power input, a typical air-source HPWH with COP of 2.93 operating at normal ambient conditions delivers about 10,000 Btu/h of water heating and 6,600 Btu/h of cooling and dehumidification.
- Performance: About 15 gallons of water can be heated per hour through a temperature change of 80°F with a HPWH rated for 10,000 Btu/h heating.
- System sizing depends on peak hot water demand, hourly hot water demand, cooling demand, and space available for storage tanks.
- Systems generally have two controls: an aquastat and a time clock. The aquastat monitors the storage tank temperature and shuts off the HPWH when the setpoint is reached. The time clock can be used to limit the operation of the system to times when it is needed.

- Service water temperatures of 140°F are attainable with the aforementioned systems, but the system as a whole will run more efficiently if used for preheating and limited to temperatures below 110°F. In Hawaii, R134a heat pumps are commonplace at 140°F while R22 systems are limited to 120°F operation.
- HPWH is most efficient during long run times.
- Hot water temperature is now recommended to be maintained above 135°F while in distribution and storage systems to avoid the threat of Legionnaires disease.

Design and Analysis Tools

Software is available from manufacturers such as Colmac (HPAPro) and ETech.

Costs

The initial cost of HPWH systems is always higher than that of a conventional water heater. Installed systems cost between $90 to $130 per gallon per hour. Insulated storage tanks cost from $4 to $10 per gallon. Fiberglass-reinforced-plastic (FRP) tanks are well-suited to the Hawaii climate.

Cost Effectiveness

Energy economics in Hawaii make HPWH an attractive option. Combine the high price of gas with the inefficiency of electric water heaters and HPWH systems become a very viable option, especially when their cooling ability is taken advantage of. Hawaii leads the nation in the implementation of HPWH systems.

In cases where the cooling opportunity is captured, payback can be as little as one year.

Operations and Maintenance

Air source systems require maintenance similar to that for air conditioners. The water side requires standard heat exchanger and hydronic system-type maintenance to ensure pumps are functioning and to avoid a decrease in heat transfer from fouling/scaling.

Commissioning

Heat pump water heating systems should be tested following installation to ensure that they are providing expected performance.

Utility Programs

The utilities that serve Oahu, Maui, Molokai, Lanai and the Big Island (HECO, MECO, and HELCO) have a rebate program called the Commercial and Industrial Customized Rebate (CICR) program. Under this program innovative technologies that save energy and demand would qualify for a rebate based on $125/kW of peak demand reduction and $0.05/kWh for a year of energy savings. Rebates are based on engineering estimates of energy and demand savings. In the case of unproven technologies the rebate may be paid over a period of 5 years based on metered savings.

The Kauai Island Utility Cooperative's "Energy Wise Program" offers incentives for Kauai commercial buildings (phone 808-246-8275).

Case Study

The Coasters Restaurant in Honolulu uses two E-Tech Model 400 Heat pumps and 400 gallon tank.

Honolulu Park Place Spa and Restaurant replaced its electrical resistance water heating with HPWH system. They achieved a simple payback period of 2.8 years on the incremental cost of premium efficiency equipment and saved $1200 per year on their electricity bill.

The largest commercial heat pump water heater in Hawaii was installed at the Sheraton Waikiki hotel in 1994.

The Ala Moana Hotel operated a McQuay Templifier HPWH since 1984, saving over $300,000 per year with a 1.2 year payback. The system was replaced in 2001 with a Carrier screw compressor HPWH.

The Grand Wailea Hotel on Maui uses two York heat pumps.

Resources

EPRI Commercial HPWH Applications Handbook, D.W. Abrams and Associates.

EPRI Report on Heat Pump Water Heaters (CU-2020R.1.90)

Hawaiian Electric Company Guide to HPWH For Condominiums and Commercial Facilities.

EPRI Report on Heat Recovery Heat Pumps (BR-020250)

Hawaiian Electric Company Report, “How Do You Define a Heat Pump”.

Contact HECO’s Energy Services Department at (808) 543-4756 to obtain HPWH publications and assistance.

Energy Management System

Recommendation

Use an energy management system (EMS) to integrate multiple components of HVAC equipment and provide detailed monitoring to aid in commissioning and performance maintenance.

Description

An EMS is an automatic control system that can serve a range of functions, from simple on/off time-of-day control to more complex optimization of equipment staging. Typically, an EMS consists of a programmable controller connected to sensors and actuators. In larger systems, the central computer will be connected via a network to a number of programmable controllers, which in turn are connected to a set of sensors and actuators. The sensors measure quantities such as temperature and flow, and the actuators are devices like motorized valves and dampers. The central computer usually has a graphic interface for operator control.

There are a number of other names used for energy management systems such as facility management system (FMS), building automation system (BAS), and energy management and control system (EMCS). Sometimes the name DDC (direct digital control) system is also used to refer to the overall energy management system.

Figure 8 – Energy Management System User Interface

Applicability

Most applicable in situations requiring complex HVAC systems that are exposed to a variety of load requirements and have operations and maintenance (O&M) staff with adequate training.

Applicable Codes and Standards

An EMS is not required by the energy code, but there are a number of required functions that can be implemented with an EMS. Among those requirements include off-hour controls and system temperature reset controls.

Benefits

A properly installed and maintained EMS provides the following benefits:

- Significant energy savings due to the ability to monitor and maintain equipment efficiency.
- Increased comfort through smaller variations in thermal conditions.
- Peak electric demand savings when load management controls are implemented.
- Remote monitoring and control can help to reduce the time spent on maintenance calls.

Costs

Overall cost is \$0.50 to\$1.50/ft^2 or roughly \$300 to \$500 per input or output "point." Special O&M training is required to operate, maintain and troubleshoot EMS systems. Periodic recalibration or replacement of sensors is required for precise and proper control. Software upgrades are periodically required and the life expectancy of major system components may be as low as 8 to 10 years due to the rapid pace of development of computer control technologies.

Cost Effectiveness

Simple paybacks for EMS systems range from 4 to 15 years based upon energy and maintenance related savings. The system must be programmed carefully, checked out thoroughly, and maintained actively. If O&M personnel are comfortable with the system, it is less likely to be bypassed, and thus sufficient training is always critical. Often the greatest benefit of EMS systems is as a maintenance tool, allowing remote adjustment and troubleshooting of equipment.

Integrated Design Implications

Coordination between mechanical and electrical consultants is necessary for supplying power to EMS systems. If the system is to integrate control of lighting and other building systems, significantly greater coordination will be required between the mechanical and controls contractors. These decisions must be made early in the design phase to allow for coordination throughout the design.

Design Details

- Keep controls as simple as possible for a particular function. They will generally be operated (or bypassed) to the lowest level of understanding of any of the O&M personnel responsible for the HVAC system.

- Rooftop units are often available with optional factory installed control modules that will interface with the EMS as an independent "node" allowing a high level of monitoring and control. Make sure that these modules interface satisfactorily with the chosen EMS.
- Specify a graphics-based user interface where desired; some users prefer a simple text-based interface.
- Discharge air temperature sensors are necessary for troubleshooting, even if not required for control.
- Specify thermostats with adjustable set point to give occupants control within a reasonable range.
- Specify training. Since O&M personnel will "inherit" the system, and its performance will ultimately depend on them, involve them as much as possible in design decisions.
- Specify at least a 1-year warranty, including all programming changes.
- By specifying the configuration of specific data trend logs (not just the capability to collect them) and submittal of them for review & approval at system completion, some system commissioning may be accomplished by the design engineer and/or other owner's representatives.
- Specify all software necessary for efficient system operation by O&M personnel to be provided as part of the system installation.
- For hotels, consider a system that controls guest room conditions and can set back conditions when a room is not occupied.
- Local EMS contractors will usually be willing to provide design assistance or even a "complete" design package. Great care should be taken in such collaboration, for it is unlikely that thorough engineering will be applied to the design. The control system should be carefully specified by the design engineer, and details left up to the installing contractor only after careful consideration.
- Control algorithms that may be specified to increase energy efficiency include: optimal start time calculation based on learned building behavior; operation of central equipment based on zone demand, including supply air temperature or pressure reset; heating and cooling system lockouts based on current or predicted outside air temperature; or heating and cooling lockout when windows or doors are opened for natural ventilation (using security system sensor switches).

- Specify submittal of control wiring diagrams as part of the design drawing package.

Design and Analysis Tools

Control systems manufacturers and their representatives are usually able to assist with the design process. This resource should be used with care; it is important not to overlook the design engineers' responsibility to specify a well-engineered system. Close attention to development of the sequence of operation is always worthwhile. Software to chart sequences of operation in block diagrams or flow charts is available commercially and from control manufacturers.

Energy simulation software can predict savings for many control sequences. Savings can be compared to additional cost to judge if an extra investment is justified. DOE-2 is an example of applicable software.

Operations and Maintenance

Calibration of critical points is required annually or semi-annually. Alternation of redundant or lead/lag equipment for even wear may be triggered automatically or manually. Operation and maintenance requires special training, particularly in the case of software; therefore consistency with existing systems may be desirable. Access to make permanent software changes should be carefully limited. Periodic checkout is necessary. A procedure to re-install up-to-date control software including databases must be established.

Commissioning

Careful commissioning is critical for success of EMS installations, and proper control operation is necessary for proper equipment operation. Since EMS software may be somewhat esoteric, lack of commissioning may mean that this important aspect of the contractor’s work may never be inspected and therefore may never be finished to the desired level. Therefore it is a very good idea to provide for some commissioning of the control system by an independent party or organization representing the owner’s interests and/or by the people who will maintain and operate the building systems.

Submittal and review of contractor’s input and output point verification test documentation should be required. Field calibration of any temperature sensors that must be accurate for proper control is necessary (for example, sensors for chilled water systems, boilers, etc.). Factory calibration is adequate only for non-critical sensors, such as room temperatures with adjustable set points.

One minimal but effective commissioning method is to specify submittal of trend data logs showing system operation in specified modes, for review by the design engineer. User interfaces including graphics (when specified) should also be reviewed.

Utility Programs

Contact the local utility to find out if customized incentives are available for installation of an EMS or for upgrades to EMS capability.

Case Study

The headquarters of the Hawaii Medical Service Association (HMSA) in Honolulu contains an EMS that controls lighting, air conditioning, building maintenance, security, and fire protection. The additional cost of the system was roughly 2.5% of the total building cost.

The Moana Surfrider (Sheraton) Hotel in Waikiki is an example of an EMS used to help monitor system performance and reduce time required for maintenance.

Products

There are many control system vendors. An important consideration in choosing specific products is the communication protocol used to transfer information between devices. Some systems use proprietary protocols. Some follow a protocol developed by ASHRAE called BACnet.

Resources

The Iowa Energy Center sponsors an excellent website that includes general information about control systems as well as summaries of the capabilities of specific products. See www.ddconline.com.

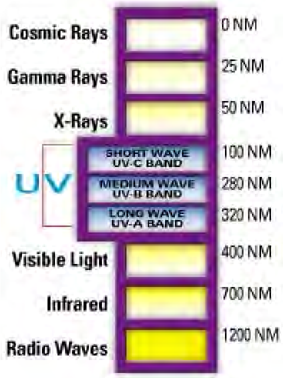
Ultraviolet Light Germicidal Irradiation

Recommendation

Use ultraviolet (UV) light systems in air handling equipment to improve indoor air quality, control biological growth, and maintain system efficiency.

Description

Ultraviolet light has been used since the turn of the 20th century to combat germs and other pathogens. Though originally developed to treat water, UV light can also be used to effectively purify air and clean air handling equipment. The industry name for this process is ultraviolet germicidal irradiation (UVGI). Wavelengths of visible light range from about 400 to 700 nanometers. Ultraviolet wavelengths range from about 1



to 400 nanometers and are beyond the range of visible light.

Ultraviolet rays with wavelengths shorter than 300 nanometers are effective in killing bacteria and viruses. The most effective sterilizing range for UV is within the C bandwidth (UVC). This range is called the germicidal bandwidth.

Though unable to penetrate the dead outer layer of skin on humans, UVC light can penetrate germ cells and destroy DNA information. This renders germ and mold cells unable to reproduce.

UVGI systems have been used to control the spread of infectious disease in places such as hospitals and shelters for 50 years. In Hawaii, notable examples include Queen’s Medical Center and Iolani School. UVC has been used in hospitals for decades to sterilize surgical instruments, water, and the air in operating rooms. Many food and drug companies use germicidal lamps to disinfect various types of products and their containers. More recently these systems have been used to avoid "sick building syndrome" by controlling the quantity of bio-aerosols arising from air handling equipment. Aside from the benefits of better indoor air quality and increased human productivity, UVGI systems can also decrease the required cleaning maintenance of air handlers by preventing mold growth and help maintain system efficiency.

Applicability

Systems designed to control the spread of infectious disease are most applicable in hospitals, clinics, and shelters where controlling the spread of disease is of the utmost importance. Less powerful systems designed to control biological growth and the dispersion of allergens are applicable in any situation where moisture may be present.

Applicable Codes and Standards

ARI Standard 850-93 “Commercial and Industrial Air Filter Equipment.”

Benefits

- Use of UVGI systems can result in the elimination or drastic reduction in cooling coil and pan cleaning maintenance. This provides not only economic benefits but also environmental benefits due to the elimination of toxic chemicals normally employed for this purpose.

- Bio-film and slime can reduce coil heat transfer by up to 30%. UVGI systems help to maintain system efficiency by keeping the coils clean, allowing them to perform at original operating conditions. Clean coils offer less obstruction to air flow, and lower pressure loss means that less fan energy is required compared to systems that are only manually cleaned a few times per year.
- Keeping the air handling unit mold- and pathogen-free results in a healthier environment for the building occupants. This can result in lower absenteeism and improved productivity.

Integrated Design Implications

UVGI systems affect choices regarding air handling equipment. To optimize operation, consider both systems simultaneously. It is important to consider the affects of the UVGI system on pressure drop and cooling load. A UVGI system should not completely take the place of filtration. For healthcare applications, the Center for Disease Control (CDC) recommends that high efficiency particulate air (HEPA) filters be used with the system. A properly configured system will enhance indoor air quality and maintain system efficiency.

Design Details

The design and effectiveness of UVGI systems depends on several factors. The most important are the intended application (bio-growth or infectious disease control), characteristics of the air flow, and the air handling equipment being treated.

- *Mold vs. infectious disease.* The choice between mold control and infectious disease control will determine the required dosage. The dosage is determined by the radiation intensity and the time of exposure. This is a function of the lamp power, distance from lamps, reflectivity of surrounding surfaces, and characteristics of the air flow.

- *Air flow characteristics.* Important air flow characteristics include relative humidity, temperature, velocity, and presence of particulates. Increased RH is believed to decrease decay rates under UV exposure though studies regarding this topic are currently incomplete. Air temperature can affect the power output of the UV lamps if it is outside the range of design values. UVGI lamps are optimized for specific temperature ranges (consult manufacturer). Air velocity should be high enough to ensure complete mixing. The typical UVGI system is designed for a similar air velocity as filter banks, about 400 ft/s. The presence of particulates and dust can decrease the system's effectiveness by providing shelter for pathogens and fouling lamp surfaces.
- *Air handling equipment.* Though UVGI systems can easily be installed into existing air handling systems, their effectiveness and ease of installation is enhanced when the air handling system is designed with them in mind. The use of highly reflective materials can be an economical way of increasing the effectiveness of UVGI systems. Be sure the material reflects UV radiation. Polished aluminum works well for this, but copper does not reflect UV light.

UVGI systems are rarely placed in outside air supply ducts. Spores from the outdoors are more efficiently removed by filtration alone. Since UV-C energy requires a finite amount of time to effect a kill, it’s ideally suited to treat static contaminated surfaces - like the damp cooling coil and condensate pan inside an HVAC unit.

The best location for the lamps is on the downstream side of the coil, evenly spaced across the coil, within 13 to 16 in. of the target surface(s). The downstream location is selected because the downstream side is the wettest portion of the coil and typically the largest portion of the drain pan is on this side of the coil. HVAC units using evaporator coils that are very deep may require lamps installed on both sides of the coil for best effectiveness.

As a general rule, use 24 in. of UVC lamp length for every 4 ft^2 of coil face area. For infectious disease application, the ratio should be greater.

Be sure to shield any wiring that may be susceptible to UV light with foil tape or metal conduit because UV light degrades rubber, plastic and similar materials.

Used lamps are hazardous materials and should be treated as such. Used lamps should be disposed of properly.

Design and Analysis Tools

Contact UV product suppliers for design guidance.

Costs

The cost of UVGI systems depends on the application. In facilities such as hospitals and shelters, where controlling the spread of infectious is the focus, UVGI systems will be more expensive than for mold-control applications. Equipment and installation costs roughly $100/ton for mold control and $200/ton for infectious disease control. Operation and maintenance costs are roughly $40/ton per year including an annual lamp change.

Cost Effectiveness

Combining savings from decreased cleaning maintenance and more energy-efficient operation leads to a payback period of one to two years. This does not include the expected external benefits such as increased worker productivity, which are significant. Researchers at Lawrence Berkeley National Laboratory have estimated that companies could save up to $58 billion a year by preventing so called "sick building syndrome" and an additional $200 billion by improving worker productivity through better indoor air quality. A project at Queen’s Medical Center that employed both UVGI and variable air volume control dramatically improved indoor air quality in the area.

Operations and Maintenance

These systems are fairly easy to install even in retrofit situations. Sensors can be used to determine when bulbs should be changed.

Bulbs should be cleaned with each filter change. Dust settling on light bulbs can reduce effectiveness.

Properly designed high output lamps last about 9000 hours (just over one year of continuous use).

The “glass” portion of the bulb is heavy wall 100% quartz and should not be touched by unprotected human hands. Handle the bulb with the same caution as a quartz halogen automotive headlamp bulb using clean gloves or other suitable protection.

It is recommended that the UV-C lamps are “ON” at all times and not cycle with the fan or the HVAC system. The most opportune time for growth of fungi and mold is when the air is still (the fan is “OFF”); therefore it is important to irradiate the surface at all times. The energy consumed is only 70-75 watts per lamp.

Commissioning

Controls for UVGI systems should be verified. In most cases it is desirable for the lamps to remain on 24 hours per day even if the fan is off.

Utility Programs

Since UVGI light systems provide relatively little energy savings, and may increase energy use due to the electricity consumption of the lamps, there may not be utility incentives available.

Case Study

The Iolani School in Honolulu pioneered the installation of UVGI systems in a project involving the Hawaiian Electric Company (HECO) and Steril-Aire Corporation. The tightly constructed, 32,000-ft^{2}facility uses a high percentage of recirculated air, resulting in indoor air quality concerns. The project involved an initial installation of UVGI lamps in a 16-ton unit and was later extended to four other units. Tests performed on the initial system showed a 98% drop in colony-forming units per millimeter (a mold indicator), and inspection revealed a cooling coil that looked "factory clean." Maintenance cost savings were $8,000 per year for coil and pan cleaning.

The Queens Medical Center in Honolulu has UVGI systems in three facilities. The center is a 530-bed acute care facility located in the heart of the city. UVGI systems were installed in a project involving HECO, the Electric Power Research Institute, Commercial Lighting Design, and Steril-Aire Corporation. A total of 50 lamps were installed in three air handling units sized between 20 and 30 tons. The systems were oversized by 15% to account for high Hawaiian humidity levels. Annual cleaning of the coils and pans has been eliminated. In addition, ceiling and wall-mounted UVGI fixtures were installed to further protect workers in clinic and emergency room areas.

Products

The most common UVGI system places a UVC lamp on the discharge side of the cooling coil, mounted to expose both the coil surface and drain pan to as much light as possible, and positioned a foot from the coil surface.

Another UVGI configuration is the patient-room wall or ceiling-mounted unit. In this application, the UV light source is directed into the room to kill organisms floating in the air. The efficacy varies widely depending on ventilation rate, activity in the room, room bioburden loading, and other factors.

Resources

Commercial Lighting Design Inc. / Lumalier, www.lumalier.com

Island Controls. Steril-Aire representative.

Island Air Filters. Steril-Aire representative.

Kowalski and Bahnfleth, *UVGI Design Basics for Air and Surface Disinfection,* HPAC Engineering, January 2000.

Lawrence Berkeley National Laboratory, www.lbnl.gov

Penn State University:
http://www.engr.psu.edu/ae/wjk/uvhpac.html

Steril-Aire, www.steril-aire-usa.com

Kitchen Exhaust Makeup

Recommendation

Install kitchen exhaust systems that avoid the conditioning of makeup air. Spot cooling provides the most beneficial cooling for kitchen workers.

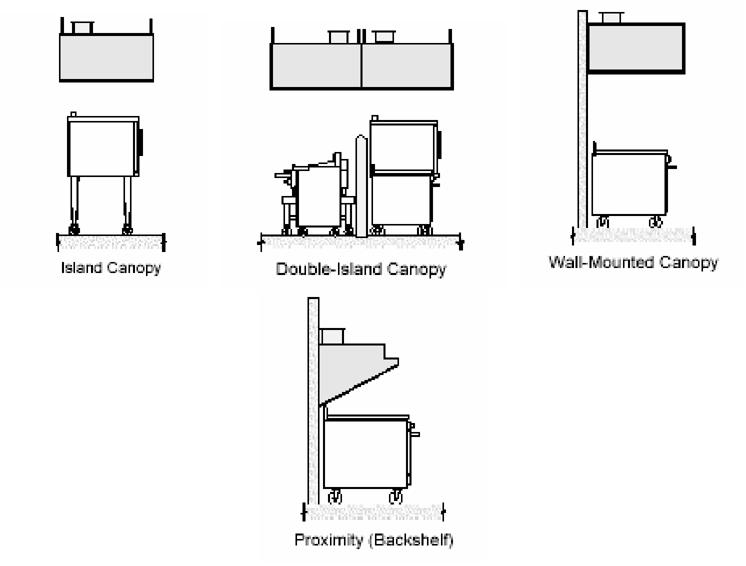
Description

Commercial kitchen ventilation systems account for upward of 20% of the total energy consumed in a restaurant. Unfortunately, these systems are generally designed with only indoor air quality in mind. Several measures can be taken to conserve energy while maintaining proper indoor air quality.

Kitchen exhaust makeup refers to air replacing the air exhausted to remove cooking effluents. Common kitchen exhaust systems include wall-mounted canopy hoods, island (single or double) canopy hoods, and proximity (backshelf, pass-over, or eyebrow) hoods. Each hood type has a different capture area and is mounted at a different height relative to the cooking equipment.

Figure 9 – Kitchen Exhaust Hood Configurations

Source: California Energy Commission



There are also several options for delivery of makeup air.

Backwall Supply (Rear Discharge)

Lab testing has shown that the backwall supply can be an effective strategy for introducing MUA. However, the discharge area of the backwall supply should be at least 12 inches below the cooking surfaces of the appliances to prevent the relative high velocity introduction of MUA from interfering with gas burners and pilot lights. As with other local MUA strategies, the quantity of air introduced through the backwall supply should be no more than 60% of the hood's exhaust flow.

Short-Circuit Supply (Internal Makeup Air)

These internal makeup air hoods were developed as a strategy to reduce the amount of conditioned air required by an exhaust system. By introducing a portion of the required makeup air in an untempered condition directly into the exhaust hood reservoir, the net amount of conditioned air exhausted from the kitchen is reduced. Research has shown however, that in the cases tested, internal MUA cannot be introduced at a rate that is more than 15% of the threshold exhaust rate without causing spillage.

Air Curtain Supply

Introducing MUA through an air curtain is a risky design option and most hood manufacturers recommend limiting the percentage of MUA supplied through an air-curtain to less than 20% of the hood's exhaust flow. An air curtain (by itself, or in combination with another pathway) is not recommended, unless velocities are kept to a minimum. It is too easy for the as-installed system to oversupply, creating higher discharge velocities that cause cooking effluent to spill into the kitchen.

Front Face Supply

Supplying air through the front face of the hood is a configuration that has been recommended by many hood manufacturers. However, a front face discharge, with louvers or perforated face, can perform poorly if its design does not consider discharge air velocity and direction. Not all face discharge systems share the same design; internal baffling and/or a double layer of perforated plates improve the uniformity of flow. Face discharge velocities should not exceed 150 fpm and should exit the front face in a horizontal direction. Greater distance between the lower capture edge of the hood and the bottom of the face discharge area may decrease the tendency of the MUA supply to interfere with hood capture and containment.

Perforated Perimeter Supply

Perforated supply plenums (with perforated face diffuser) are similar to a front face supply, but the air is directed downward toward the hood capture area. This may be advantageous under some conditions, since the air is directed downward into the hood capture zone. Face discharge velocities should not exceed 150 fpm from any section of the diffuser and the distance to lower edge of the hood should be no less than 18 inches (or the system begins to act like an air curtain). Widening the plenum will lower the discharge velocity for a given flow of MUA and reduce the chance of the supply air affecting exhaust.

Four-Way Ceiling Diffusers

Four-way diffusers located close to kitchen exhaust hoods can have a detrimental affect on hood performance, particularly when the flow through the diffuser approaches its design limit. Air from a diffuser within the vicinity of the hood should not be directed toward the hood. Discharge velocity at the diffuser face should be set at a design value such that the terminal velocity does not exceed 50 fpm at the edge of the hood capture area. It is recommended that only perforated plate ceiling diffusers be used in the vicinity of the hood.

Displacement Diffusers

Supplying makeup air through displacement diffusers at a good distance away from the hood is an effective strategy for introducing replacement air. It is analogous to low-velocity "transfer air" from the dining room. However, the diffusers require floor or wall space that is usually a premium in the commercial kitchen. A couple of remote displacement diffusers (built into a corner) could help diversify the introduction of makeup air into the kitchen when transfer air is not viable.

Applicability

Applicable in all buildings with commercial-style kitchen equipment such as restaurants and school cafeterias.

Applicable Codes and Standards

The Honolulu energy code requires that individual kitchen exhaust hoods larger than 5000 cfm (2500 L/s) be provided with make-up air sized for at least 50% of exhaust air volume that is uncooled or cooled without the use of mechanical cooling.

ASTM Standard 1704-99, 99 *Standard Test Method for the Performance of Commercial Kitchen Ventilation Systems*. ASTM International. West Conshohocken, PA

UL Standard 710. UL 710, *Exhaust Hoods for Commercial Cooking Equipment*. Underwriters Laboratories

Benefits

Proper design of kitchen exhaust makeup can enhance indoor air quality and thermal comfort while also saving energy.

Integrated Design Implications

Kitchen hood systems should be installed with the makeup air system integrated with the exhaust hood operation. A portion of the makeup air may come from adjacent dining areas, and in those cases the control of the dining room ventilation system needs to be integrated with the kitchen system.

Design Details

The strategy used to introduce replacement (makeup) air can significantly impact hood performance and should be a key factor in the design of kitchen ventilation systems. Makeup air introduced close to the hood's capture zone may create local air velocities and turbulence that result in periodic or sustained failures in thermal plume capture and containment. Furthermore, the more makeup air supplied (expressed as a percentage of the total replacement air requirement), the more dramatic the negative effect.

The following design suggestions come from the California Energy Commission's *Design Guide: Improving Commercial*

Kitchen Ventilation System Performance (see Resources) and can improve the energy efficiency and performance of commercial kitchen ventilation systems:

- Group appliances according to effluent production and associated ventilation requirements. Specify different ventilation rates for hoods or hood sections over the different duty classification of appliances. Where practical, place heavy-duty appliances such as charbroilers in the center of a hood section, rather than at the end.
- Use UL Listed proximity type hoods where applicable.
- Hood construction details (such as interior angles and flanges along the edge) or high-velocity jets can promote capture and containment at lower exhaust rates.
- Install side and/or back panels on canopy hoods to minimize cross drafts and reduce heat gain.
- Integrate the kitchen ventilation with the building HVAC system (i.e., use dining room outdoor air as makeup air for the hood).
- Maximize transfer air and minimize direct makeup air.
- Do not use short-circuit hoods. Use caution with air-curtain designs.
- Avoid 4-way or slot ceiling diffusers in the kitchen, especially near hoods.
- Diversify makeup air pathways (use combination of backwall supply, perforated perimeter supply, face supply, displacement diffusers, etc.).
- Minimize makeup air velocity near the hood; it should be less than 75 fpm.
- Consider variable or 2-speed exhaust fan control for operations with high diversity of appliances and/or schedule of use.
- Provide air balance requirements to avoid over- or under-supply of makeup air.
- Locate vent canopy on a wall to minimize the required air flow. Wall-mounted canopy hoods function effectively with a lower exhaust flow rate than the single-island hoods.
- If an island canopy is required, place a partition at the back of a row of cooking equipment or between a double row of equipment to improve efficiency.

- Locate kitchen exhaust away from the HVAC fresh air intake.
- Install spot cooling equipment (or radiant ceiling panels) to provide thermal comfort for the kitchen staff.

Design and Analysis Tools

There is a public-domain software program described in the following ASHRAE paper that provides engineers with a more sophisticated hour-by-hour simulation of commercial kitchen ventilation systems. The software illustrates the impact of makeup air set point and geographic location on outdoor air load.

- Donald Fisher, P.Eng, Ferdinand Schmid and Anthony J. Spata. "Estimating the Energy-Saving Benefit of Reduced-Flow and/or Multi-Speed Commercial Kitchen Ventilation Systems," Publication. CH-99-20-3. Available from ASHRAE: www.ashrae.org.

The Outdoor Airload Calculator (OAC) software quickly estimates the energy use for different commercial kitchen ventilation design and operating strategies. The software is available free at www.archenergy.com/ckv/oac.

Cost Effectiveness

A well-designed kitchen exhaust system can reduce both fan energy and conditioned air, and thereby improve the efficiency of the kitchen ventilation system up to 50%. This translates into energy savings of $1,000 - $2,000 per hood per year in any given kitchen. A typical payback ranges from one to three years. The exact savings depend on variables such as hours of operation, cost of energy, size of hood and fans, and nature of cooking load.

Operations and Maintenance

Regularly clean filters and oil traps.

Commissioning

Building air balancing and system commissioning should be required as part of the construction requirements.

Utility Programs

The utilities that serve Oahu, Maui, Molokai, Lanai and the Big Island (HECO, MECO, and HELCO) have a rebate program called the Commercial and Industrial Customized Rebate (CICR) program. Under this program innovative technologies that save energy and demand would qualify for a rebate based on $125/kW of peak demand reduction and $0.05/kWh for a year of energy savings. Rebates are based on engineering estimates of energy and demand savings. In the case of unproven technologies the rebate may be paid over a period of 5 years based on metered savings.

The Kauai Island Utility Cooperative's "Energy Wise Program" offers incentives for Kauai commercial buildings (phone 808-246-8275).

Products

Melink Intelli-Hood Plant, 5508 Fair Lane, Cincinnati, OH 45227 Ph. 513-527-7020, /www.melinkcorp.com.

Resources

California Energy Commission, *Design Guide: Improving Commercial Kitchen Ventilation System Performance*, publication # 500-03-034F. www.energy.ca.gov.

Demand-controlled Ventilation

Recommendation

Specify controls to adjust ventilation rate for spaces with varying occupancy to prevent unnecessary cooling of large quantities of outside air, and ensure that adequate ventilation is provided when needed.

Description

Many spaces — such as auditoriums and theaters — require high ventilation rates due to dense “design” occupancy, but experience this occupancy level only sporadically. The outdoor air required can represent a very large cooling load, especially in subtropical climates such as Hawaii. Therefore substantial amounts of energy and wear on equipment may be saved by reducing the amount of ventilation during those times the space is partly occupied or unoccupied but temperature needs to be maintained. This may be accomplished using occupancy sensors or air quality (CO_2 concentration) sensors to control the quantity of ventilation air. This may be done either in conjunction with a EMS system or by independent controls. Many packaged air conditioning systems now offer demand control ventilation (DCV) controls either standard or as an option.

Applicability

DCV controls have the biggest impact in spaces with intermittent, high-density occupancy such as theaters, cafeterias, and conference rooms. These spaces need to be designed with ventilation adequate to meet the full occupancy rates but don’t need full ventilation during unoccupied periods.

In Hawaii, due to the humidity load caused by outdoor air ventilation, DCV controls can also be used in any spaces that have intermittent occupancy such as offices.

DCV controls based on CO2 measurement are usually not applicable for spaces that have high pollution loads that are independent of human occupancy. Examples of these building types include retail stores where off-gassing from products affects air quality or healthcare and laboratory buildings.

Applicable Codes and Standards

Ventilation systems should be designed to meet the requirements of ASHRAE Standard 62.

Benefits

The benefits of DCV systems include reduced energy consumption, reduced wear on equipment, and confirmed/documented interior air quality

Integrated Design Implications

To ensure good air quality when DCV is used, it is important to minimize indoor pollution sources. One source of pollution is emissions from materials such as carpets, ceilings, and furnishes. Cleaning chemicals and procedures also have an impact on indoor air quality.

Design Details

Demand-controlled ventilation responds to human occupancy only. Other sources of internal pollutants must be addressed with per-area baseline ventilation, targeted ventilation, or other methods. Demand-controlled ventilation should be considered very carefully before being applied, especially for classrooms where various odor sources may occur. Logic dictates that demand-controlled ventilation results in worse interior air quality than a properly adjusted system constantly delivering ventilation for rated occupancy; however, DCV can provide significant energy savings.

CO_2 sensor-based ventilation control uses the measured CO_2 level as an indicator of the current occupancy level, so the ventilation rate may be adjusted accordingly. This is an important difference from using the CO_2 sensor as a direct indication of air quality.

For multiple zone AC systems, the CO_2 sensor used for DCV must be located directly in the space. Otherwise, if a single sensor is located in a common return duct, the system will not be able to detect significant differences in CO_2 between spaces.

In areas where the outside air CO_2 concentration is relatively constant, ventilation may be controlled by a single return air sensor to maintain a fixed CO_2 limit. Otherwise, outdoor and return air sensors should be used.

The setpoint must be calculated based on occupancy and activity level. For example, the CO_2 concentration for an office space designed at 15 cfm per person (sedentary adult) can be calculated at 700 ppm above ambient.

Design and Analysis Tools

Energy simulation programs such as DOE2 can be used to estimate the impact of reducing ventilation air volume.

Costs

Each CO_2 sensor costs from $500 to $1,000. Installation, testing and adjustment cost from $500 to $1,500 per system. Annual calibration is necessary and recommended (follow manufacturer recommendations). The cost for a handheld CO_2 sensor for calibration is about $500.

Cost Effectiveness

Generally, the cost effectiveness for occupancy sensor-based control will be very high for larger systems. For CO_2 sensor-based control, it will depend on the climate being “severe” enough, and the required ventilation rate being large enough so that the cooling load reduction saves enough energy costs to offset the first cost of the CO_2-sensing equipment. In Hawaii, ventilation cooling loads can easily justify DCV.

Operations and Maintenance

Calibration is required. Trend logs of CO_2 measurements should be reviewed periodically to ensure that the system is providing adequate ventilation.

Commissioning

Review system operation under varying occupancy. Correlate with balance report data for minimum and maximum outside air damper positions. Verify acceptable levels of CO_2 concentration in space when occupied using hand held sensor. Perform all testing in non-economizer mode.

Utility Programs

The utilities that serve Oahu, Maui, Molokai, Lanai and the Big Island (HECO, MECO, and HELCO) have a rebate program called the Commercial and Industrial Customized Rebate (CICR) program. Under this program innovative technologies that save energy and demand would qualify for a rebate based on $125/kW of peak demand reduction and $0.05/kWh for a year of energy savings. Rebates are based on engineering estimates of energy and demand savings. In the case of unproven technologies the rebate may be paid over a period of 5 years based on metered savings.

The Kauai Island Utility Cooperative's "Energy Wise Program" offers incentives for Kauai commercial buildings (phone 808-246-8275).

Resources

ASHRAE Standard 62

"Interpretation of Ventilation Standard IC-62-1989-27," *ASHRAE Journal* (April 1997).

Mumma, Stanley, "Is CO2 Demand-Controlled Ventilation the Answer?", Engineered Systems, May 2002

9. BUILDING COOLING, HEATING AND POWER GENERATION SYSTEMS

Recommendation

Consider an integrated cooling, heating and power generation system for buildings with both significant cooling loads and heating loads. Appropriate heating loads are usually domestic hot water or swimming pools. Building cooling, heating and power (BCHP) systems are most cost effective for facilities operated continuously such as hotels, hospitals or high-rise residential buildings.

Description

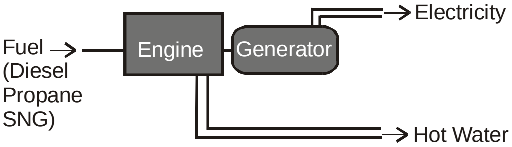
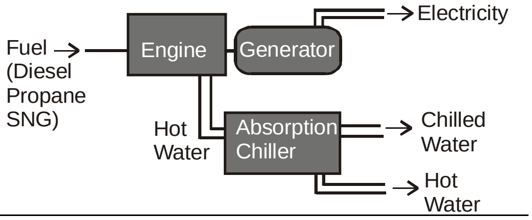
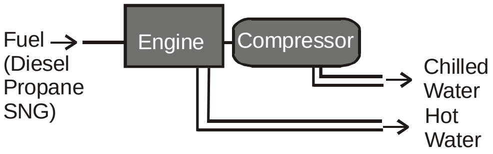
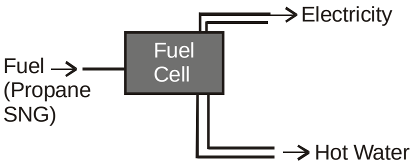
The term BCHP covers a range of system types and is sometimes defined as *Building Combined Heating and Power* and other times as *Building Cooling, Heating and Power*. The common elements are usually electricity generation and recovery of waste heat from the generation process (also called *cogeneration*). The “optional” element is space cooling — either using the waste heat to feed absorption cooling equipment or using the electricity to run an electric chiller. A variation on BCHP systems actually has no generator; it uses an engine-driven chiller for cooling and recovers the waste heat from the engine for water heating. BCHP systems include at least two of the following components:

- **Power Components.** Turbines, engines, fuel cells or micro-turbines.
- **Cooling Components.** Engine-driven chillers, electric chillers, and/or absorption chillers.
- **Heating Components.** Domestic water heating, pool heating, desiccant regenerators, and/or reheat for humidity control.

In Hawaii, the waste heat is most often used to produce domestic hot water for hotels, hospitals or high-rise residential buildings. In some cases, it is also used for swimming pool heating. For dehumidification applications, the waste heat from the power generation can be used for reheat in conventional mechanical cooling systems, or can be used to regenerate desiccants in desiccant-based cooling systems. See the Dehumidification Guidelines.

There are many possible BCHP system configurations. Table 9-1 illustrates some basic options. In each case, a fuel is consumed as input and the system produces electricity, hot water and/or chilled water.

Table 9-1. Basic BCHP configurations.

System Description	**System Configuration**
Engine-driven generator produces electricity, and heat from the engine jacket and exhaust is recovered for water heating. As an alternative, a turbine or microturbine could be used in place of the engine.	
An absorption chiller is added to the first system to produce chilled water using the recovered heat.	
An engine-driven compressor (chiller) produces cold water and heat from the engine jacket and exhaust is recovered for water heating. No electricity is produced in this configuration.	
A less common configuration includes a fuel cell that produces electricity as well as heat that can be recovered for hot water. The fuel cell runs on hydrogen, so propane or SNG must be processed to extract the hydrogen prior to use.	

Notes: SNG=synthetic natural gas

Applicability

In Hawaii, BCHP systems are applicable in buildings with significant and relatively constant hot water demand. Good examples include hotels and high-rise residences with swimming pools. In those facilities, the waste heat can produce domestic hot water that is used for washing and showers and can then provide pool heating. Hospitals can also be appropriate applications because they may have a relatively large and constant hot water load.

Installation of a BCHP system is most likely to be cost effective in a new construction project or as part of a major renovation. Among existing buildings, good candidates include hotels with aging and inefficient chilled water and hot water plants.

BCHP systems are less likely to be cost effective in general commercial buildings such as offices or stores because they have relatively small heating requirements and may not have 24-hour electricity demand. They are also less cost effective in facilities with widely fluctuating heat demands. In those cases, large storage tanks would be required, which would add cost to the system.

Regulatory Issues

BCHP systems face a number of regulatory issues that should be considered as early as possible in the planning phase.

Hawaii State Department of Health — Clean Air Branch

Hawaii clean air regulations are essentially equal to the U.S. Environmental Protection Agency regulations and are administered by the Clean Air Branch of the Hawaii State Department of Health (telephone 808/586-4200). Fuel-burning equipment such as BCHP units require a permit, but there are a number of specific exemptions:

- Equipment with less than 1 MBtu/hr heat input.
- Equipment with emissions of less than one ton per year of regulated pollutants.
- Equipment with emissions of less than 0.1 ton per year of hazardous pollutants
- Other specific exemptions.
- Discretionary exemptions from the Clean Air Branch.

The actual requirements for permitted equipment will be project specific but may include a requirement for best available control technology. The Clean Air Branch may perform a modeling assessment of pollutant impact to determine appropriate measures.

For exempt systems it is not necessary to contact the Clean Air Branch for a determination, but it may be a good idea, especially for a system that is close to the emissions limit. Information submitted with a permit application includes equipment specifications, fuel type and location.

Local City and County

Permits are required from the local Building Division to cover electrical, mechanical, plumbing and structural work.

Zoning regulations set noise limits that vary depending on location. Residential zones have lower allowances.

Utilities

Utilities set interconnection requirements to maintain power quality on the electricity distribution grid. Due to the potentially high cost of connection equipment, it is critical to discuss requirements with the utility early in the planning process. The U.S. Department of Energy is working on a nationwide standard, IEEE 1547, for interconnection of distributed generation, but each utility company still sets its own requirements.

Some electric utilities also impose standby charges for on-site generation equipment. These charges account for the fact that the utility may have to provide power at short notice if the on-site generator fails. These charges can have a significant impact on project feasibility and should be identified at the beginning of project planning.

Fuel suppliers may offer special rates for cogeneration facilities. It is important to identify the appropriate fuel prices when evaluating project feasibility.

Water

A water permit may be required for an existing facility if the new system will increase water consumption. For example, if an absorption chiller is installed to replace an electric chiller, the heat rejection load will increase and cause higher cooling tower water consumption.

Benefits

Under the right conditions, BCHP systems reduce air pollutant emissions and increase energy efficiency. BCHP produces both electric or shaft power and usable thermal energy on site or near site, converting as much as 80% of the fuel into usable energy.

- BCHP systems reduce energy costs if properly applied and operated.
- On-site generation reduces electricity transmission losses.
- Engine-driven generators are relatively efficient, converting up to 40% of the fuel energy into electric energy.

- Utilization of waste heat improves overall energy conversion efficiency to as high as 80% or 90% if the heating requirements are well matched to the availability of waste heat.
- If appropriate redundancy is provided, BCHP systems can improve electrical grid reliability (by reducing the potential for peak-time blackouts).
- BCHP systems can be used as a load management tool to reduce peak demand on the electric utility.
- They are easier to site relative to new central power plants that face greater regulatory hurdles.
- They form an effective foundation for district energy plants.
- BCHP systems may get credits toward Leadership in Energy and Environmental Design (LEED) green building certification from the U.S. Green Building Council.

Costs

An engine-driven generator and heat recovery equipment costs roughly $1,000 to $1,500 per kilowatt of electric power capacity. Several factors can lead to significant variability in price:

- Interconnection equipment may be costly and is critical to the economics of a BCHP project.
- Wiring from the generator to the point of utility connection costs about $1,000 per foot. Therefore, location within the site is an important factor.
- In some cases, emission control equipment may be needed and may add extra cost.
- Costs in Hawaii are about 40% higher than on the mainland due to higher labor rates.

Chilled water system costs are additional. Absorption chillers cost roughly $700 to $1,000 per ton to install. Electric chiller systems are less expensive, typically in the range of $500 to $700 per ton.

Maintenance costs can be significant for BCHP systems and must be considered in a lifecycle cost analysis. Check with manufacturers for recommended service and replacement intervals.

Check to see if tax credits or utility incentives are available.

Design Considerations

Professional Design Assistance

BCHP systems are complex, and it is recommended that mechanical and electrical engineers with extensive BCHP experience be selected. It is also critical that contractors and operators have experience with BCHP systems.

Grid-connected vs. Stand-alone Systems

A BCHP system may be connected to the electricity grid, or it may remain independent. A grid-connected system offers the advantage of utility backup in case the BCHP system fails or needs to be shut down for maintenance. In some areas it is possible to sell excess electricity back to the utility (net metering). But grid connection also requires relatively expensive interconnect equipment. And grid-connected systems may be subject to standby charges from the utility. Standby charges account for the fact the utility may be required to take on the facility's electrical load if the BCHP system shuts down.

A stand-alone BCHP system avoids the cost and complexity of grid connection, but requires equipment redundancy to provide reliable power. Stand-alone systems are most applicable in locations without existing utility service or where adding utility capacity would be too expensive.

Even in a grid-connected system, redundant generators are likely to be necessary to achieve the full demand reduction (and corresponding utility bill savings). In estimating the cost effectiveness of the system, it is important to realize that even a short system shut down, when utility backup is required, can lead to high peak electric demand charges and offset much of the savings.

Emergency and Standby Generation Issues

Some facilities such as hospitals require emergency generators to keep critical equipment running when the electric grid fails. Other buildings have standby generators that provide tenants with power in the case of an electricity outage. Ideally, a BCHP generator would be able to take the place of these emergency and standby generators in order to offset part of the construction cost. However, there are several issues to consider.

- The emergency generator must be large enough to meet the load of critical systems, while a BCHP generator should be sized based on the facility's thermal load. Therefore, it is possible that the emergency generation requirement is larger than the appropriate BCHP capacity.
- BCHP equipment is typically more expensive than standby equipment because BCHP units are designed for continuous operation.

- On-site fuel storage may be required by code for some emergency generator systems, limiting the fuel options and affecting operating cost.

A thorough review of code requirements is recommended before choosing to use a BCHP system for emergency power.

Engine-driven Systems

The most common BCHP system type in Hawaii includes an internal combustion engine-driven generator, running on either diesel or propane fuel. In a typical engine, heat is dumped through the radiator and out the engine exhaust. In a cogeneration engine, heat exchangers are used to capture this heat. They typically produce water at about 200ºF, and are available in a wide range of sizes, from as small as 25 kW up to 5 MW. Issues to consider with engine-driven systems include:

- They are relatively efficient, reaching 40% electric generation efficiency.
- Engine emissions can be controlled through several means including catalytic converters, spark retard ignition, and water injection.
- Propane engines require a special design to account for the variability of the fuel’s heating value. Otherwise they may suffer reliability problems.

Microturbine Systems

Microturbines are newer and less common than engine-driven BCHP systems. These work like a jet engine except that the hot combustion exhaust spins a turbine to produce electricity rather than to propel an aircraft. Heat is recovered from the hot exhaust air after it passes through the turbine. Here are some issues to consider with microturbine systems:

- They are available in sizes of 30 kW to 100 kW.
- Efficiency is moderate, typically around 30%.
- Precooling of inlet air to about 59ºF improves efficiency and reduces emissions.
- Maintenance requirements should be lower than engines due to air bearings and fewer moving parts.
- Current microturbine systems need to be rebuilt after about 1,500 starts and may not be desirable in applications with intermittent operation.

Fuel Cell Systems

Fuel cells use an entirely different means, similar to a battery, to produce electricity. They consist of two electrodes sandwiched around a catalyst and electrolyte. Hydrogen and oxygen are fed to either side of the "sandwich" and the catalyst causes the hydrogen to split into an electron and a proton. The proton passes through the electrolyte and the electron travels through an external wire (providing the fuel cell output). The proton and electron join with the oxygen on the other side to produce water. Hydrogen is typically created from natural gas in a fuel reformer. When a fuel cell is used as part of a BCHP system, waste heat is recovered to meet heating loads.

System Sizing

BCHP system capacity is usually selected based on the facility's heating requirements. Otherwise, if the heat output is larger than necessary the system must either be throttled back to reduce output or excess heat must be dumped (via a radiator or cooling tower). And when the system is not operating at full capacity, more time is required to recover the installation cost.

In an existing facility, accurate measurements of actual electrical load, heating load and cooling load are necessary. The BCHP system should then be designed to satisfy most or all of the heating load, as long as the resulting generation capacity does not exceed the building's electric demand. Typically, if a BCHP system also provides cooling, it will only satisfy a portion of the total load and additional cooling equipment will be required.

For new buildings, simulation programs can be used to estimate the expected loads and choose an appropriate system size.

Heat Recovery Applications

Waste heat from BCHP systems may be used for a wide variety of applications. The most common application in Hawaii is domestic water heating for uses such as showers, kitchens and laundries.

To achieve the greatest overall system efficiency, a BCHP system will supply a cascading set of heating loads where each load can be satisfied with a lower water temperature. A swimming pool is a good example of a low-temperature load that can help utilize the maximum amount of waste heat.

Dehumidification is also a potential use for waste heat in facilities where there are special humidity control requirements, such as hospitals and some laboratories. The waste heat from the power generation process can be used to reheat overcooled air in conventional mechanical cooling systems, or to dry desiccants for desiccant-based dehumidification systems. For more information, see the Dehumidification Guidelines.

Integration with Chilled Water Systems

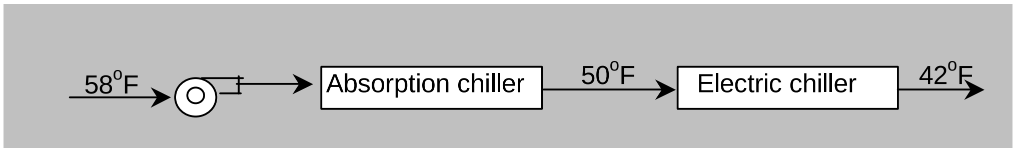
As mentioned at the beginning of this chapter, cooling is an optional element of a BCHP system. Most commonly, BCHP systems provide only electricity and heat. However, BCHP systems can and do provide chilled water through several different configurations:

- Electricity produced by the generator powers a standard electric chiller.
- Waste heat drives an absorption chiller.
- An engine drives the chiller directly.
- A combination of two of the above (for example, the generator powers an electric chiller and also drives an absorption chiller with waste heat).

Electric and absorption or engine-driven chillers can be configured in several different ways to take advantage of the best characteristics of each machine.

Chillers connected in series (Figure 9-1) can be used in high delta-T chiller plants. This arrangement takes advantage of the high temperature preferences of absorption chillers and the low temperature capabilities of vapor compression chillers. The disadvantage of this arrangement is the potential for high pressure loss in the chilled water loop, resulting in higher pumping energy requirements.

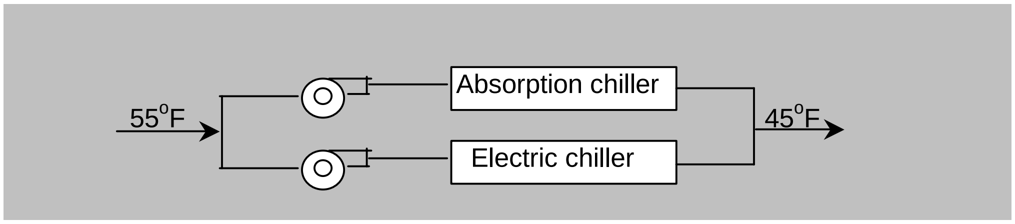
Figure 9-1. Chillers connected in series.



A more common arrangement for plants with two or more chillers is to have chillers connected in parallel (Figure 9-2). This arrangement is simple and reduces chilled water loop pressure drop and pumping power, but does not always have the flexibility to preferentially load a specific chiller to manage utility costs.

Thermal Energy Storage

Figure 9-2. Chillers connected in parallel.



Thermal energy storage usually adds to system cost, but it increases utilization of electricity production or recovered heat. The demand for heating or cooling is seldom perfectly constant; loads usually vary over the course of a day. A thermal energy storage system allows excess production of heat or cooling during part of the day to be used later when demand exceeds capacity.

Heat storage simply consists of a large storage tank in a typical system. Cooling can be stored in several forms, either as chilled water, ice, chilled brine or a phase-change material.

Other Design Considerations

- Induction generators need some power from the grid to get started.
- Space requirements are an important consideration.
- Noise and potential odors should be taken into account.
- Factory-integrated BCHP systems may be available that can be delivered as a package to simplify installation.
- Landfill and sewer gas can be used as a fuel source.
- Solar heat can drive an absorption chiller and provide heating needs as well.
- Space for fuel storage is necessary for diesel systems and for propane systems in many locations.
- Existing electrical systems should be carefully inspected rather than relying on "as-built" plans to be accurate.

Design and Analysis Tools

There are no specific tools for design and analysis of BCHP systems. The building energy simulation tools DOE-2.1E and EnergyPlus, and the transient systems simulation program TRNSYS may be used in an energy analysis of BCHP systems. Details of DOE-2.1E and EnergyPlus are available at Lawrence Berkeley National Laboratory's Web site, http://gundog.lbl.gov. Information about TRNSYS is available at http://sel.me.wisc.edu/trnsys.

Operation and Maintenance

BCHP systems should be operated as continuously as possible to improve energy efficiency and reduce maintenance costs. Here are some operation and maintenance considerations:

- Experienced or trained operators are needed to operate BCHP systems.
- BCHP systems typically operate about 90% of the time. Downtime occurs as a result of planned maintenance and unscheduled outages.
- Frequent starting and stopping of BCHP system operations increase costs of operation and maintenance significantly.
- Maintenance costs for gas engine generators are in the range of \$0.0075 to \$0.0100 per kWh. Costs for microturbine maintenance are potentially lower, ranging from \$0.002 to \$0.010 per kWh.[1]

Case Studies

Wilcox Hospital on Kauai installed five, 400-ton diesel engine-driven chillers (made by Caterpillar) for a total of 2000 tons of cooling capacity. The waste heat is used for domestic water heating. In this case, the BCHP system does not generate electricity, but provides both heating and cooling and offsets the need for electricity.

The Orchid at Mauna Lani Hotel installed four 220-kW synchronous generators (propane engines) and one 240-ton absorption chiller. The waste heat is used for hot water for most guest rooms.

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[1] Source: *Combined Heat and Power: A Federal Manager's Resource Guide*, U.S. Department of Energy, March 2000.

Figure 9-3. Propane-fueled generators at The Orchid at Mauna Lani Hotel.

The Pohai Nani assisted living facility in Kaneohe uses one 100-kW propane engine generator (made by Hess Microgen) that provides heat for two 10-ton absorption chillers, domestic hot water and a swimming pool.

The Hale Poahi Towers in Honolulu provides hot water for 500 apartments with a 140-kW generator. Hot water is heated to 190ºF and stored in two 2600-gallon tanks.

Products

BCHP products are available from a variety of manufacturers including Honeywell, Trane, York, Carrier, Caterpillar and Hess Microgen. In Hawaii, Hess Microgen provides propane engine units in sizes ranging from 85kW to 220kW. Caterpillar produces propane units from 200 kW and up and diesel units from 265 kW.

Resources

The following Web sites provide useful information on BCHP systems:

- ACEEE Combined Heat and Power, www.aceee.org/chp
- Building Energy Solution Center, www.agcc.org/bchp.cfm
- Cooling, Heating and Power for Buildings, www.bchp.org
- U.S. Department of Energy CHP Program, www.eren.doe.gov/der/chp

- University of Maryland, Center for Environmental Energy Engineering, www.enme.umd.edu/ceee/bchp