Title

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Authors

Lee, Eleanor S
Selkowitz, Stephen E
Levi, Mark S
et al.

Publication Date

2002-06-01

ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

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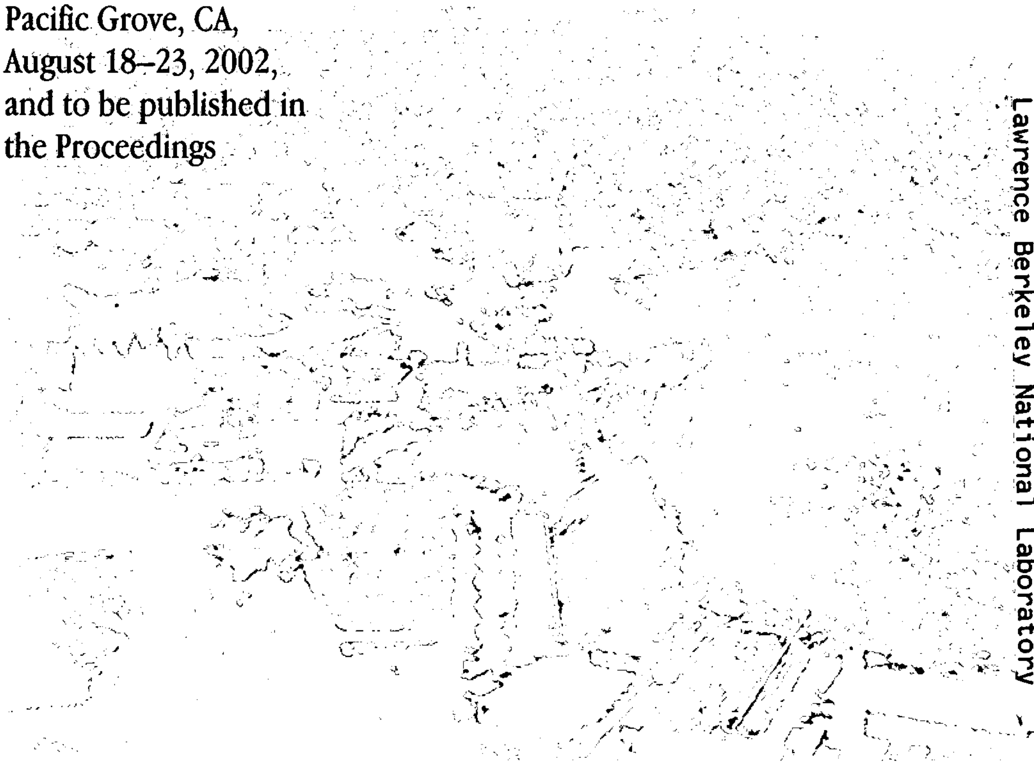
Eleanor S. Lee, Stephen E. Selkowitz, Mark S. Levi,
Steven L. Blanc, Erin McConahey, Maurya McClintock,
Pekka Hakkarainen, Neil L. Sbar, and Michael P. Myser

Environmental Energy Technologies Division

June 2002

To be presented at the
ACEEE 2002 Summer Study on Energy Efficiency
in Buildings: Teaming for Efficiency,
Pacific Grove, CA,
August 18–23, 2002,
and to be published in
the Proceedings



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LBNL-50855
DA-450

Accepted for presentation and to be published in *Proceedings from the ACEEE 2002 Summer Study on Energy Efficiency in Buildings: Teaming for Efficiency,* August 18-23, 2002, Asilomar, Pacific Grove, CA. Washington, D.C.: American Council for an Energy-Efficient Economy.

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Eleanor S. Lee, Lawrence Berkeley National Laboratory
Stephen E. Selkowitz, Lawrence Berkeley National Laboratory
Mark S. Levi, US General Services Administration
Steven L. Blanc, Pacific Gas and Electric
Erin McConahey, Ove Arup and Partners California
Maurya McClintock, Ove Arup and Partners California
Pekka Hakkarainen, Lutron Electronics Co., Inc.
Neil L. Sbar, SAGE Electrochromics, Inc.
Michael P. Myser, SAGE Electrochromics, Inc.

Windows and Daylighting Group
Building Technologies Program
Environmental Energy Technologies Division
Ernest Orlando Lawrence Berkeley National Laboratory
University of California
Berkeley, California 94720

June 2002

This work was supported by the California Energy Commission through its Public Interest Energy Research Program, by Southern California Edison through the California Institute of Energy Efficiency, and by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State and Community Programs, Office of Building Research and Standards of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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ABSTRACT

Advanced window wall systems have the potential to provide demand response by reducing peak electric loads by 20-30% in many commercial buildings through the active control of motorized shading systems, switchable window coatings, operable windows, and ventilated double-skin facade systems. These window strategies involve balancing daylighting and solar heat gains, heat rejection through ventilation, and night-time natural ventilation to achieve space-conditioning and lighting energy use reductions without the negative impacts on occupants associated with other demand responsive (DR) strategies.

This paper explores conceptually how advanced window systems fit into the context of active load management programs, which cause customers to directly experience the time-varying costs of their consumption decisions. Technological options are suggested. We present pragmatic criteria that building owners use to determine whether to deploy such strategies. A utility's perspective is given. Industry also provides their perspectives on where the technology is today and what needs to happen to implement such strategies more broadly in the US.

While there is significant potential for these advanced window concepts, widespread deployment is unlikely to occur with business-as-usual practice. Technologically, integrated window-lighting-HVAC products are underdeveloped. Implementation is hindered by fragmented labor practices, non-standard communication protocols, and lack of technical expertise. Design tools and information products that quantify energy performance, occupant impacts, reliability, and other pragmatic concerns are not available. Interest within the building industry in sustainability, energy-efficiency, and increased occupant amenity, comfort, and productivity will be the driving factors for these advanced facades in the near term – at least until the dust settles on the deregulated electricity market.

Introduction

Over the last twenty-five years the Department of Energy (DOE), in partnership with the window industry has revolutionized the window products available to consumers and specifiers. Low-E coated glass, unknown in the 1970s, is now used in over 40% of all residential windows sold in the US. The heating cost savings in the residential sector already amount to over $1.5B with a lifetime energy savings from windows sold to date of $30B, all from an original federal R&D investment of less than $10M. This initial work was further extended with the development of spectrally selective glazings that save energy in the Sunbelt, where cooling is the key energy end-use. Both conventional low-E and spectrally selective glazings are now beginning to penetrate the commercial sector as well. In both cases these are literally invisible technologies whose function cannot be directly seen. Thus a crucial element to the market success of these new technologies has been the creation of a level playing field for selecting and specifying windows in the marketplace. DOE has helped transform the market by providing tools and applications data for manufacturers, by conducting lab and field tests of emerging products, and most recently by working with the National Fenestration Rating Council to develop ratings and labels to assist in the specification of better windows. These information products provide the credibility and technical underpinnings for the Energy Star Window program and the Efficient Window Collaborative.

Despite the impressive savings, windows still make a large contribution to the US annual building energy consumption of $240B in 2000. Further penetration of existing technologies will increase energy savings but will begin to have diminishing returns. DOE has recently worked with members of the window industry to create a roadmap that helps define the technologies and tools that will be needed to create and sell the next generation of windows in the 21st century. Window industry executives identified a new generation of dynamic, responsive "Smart Windows" as a key need. The emerging concept of the window will be more as a multi-functional "appliance-in-the-wall" rather than simply a static piece of coated glass. Interestingly, these smart windows are also the technologies that are likely to capture the next large energy and demand savings once the market potential of the current generation of static windows is achieved.

Integrated façade systems can include smart windows and shading systems with optical and thermal properties that can be dynamically changed in response to climate, occupant preferences and building energy management control system (EMCS) requirements. These include motorized shades, switchable electrochromic or gasochromic window coatings, and double-envelope window-wall systems. By actively managing lighting and cooling, "smart windows" could reduce peak electric loads by 20-30% in many commercial buildings and increase daylighting benefits throughout the US, as well as improve comfort and potentially enhance productivity in our homes and offices. These technologies can provide maximum flexibility in aggressively managing demand and energy use in buildings in the emerging deregulated utility environment and can move the building community towards a goal of producing advanced buildings with minimal impact on the nation's energy resources. Customer choice and options will be further enhanced if they have the flexibility to dynamically control envelope-driven cooling loads and lighting loads.

This paper takes a broad view of how integrated facades systems can be applied to commercial buildings to provide demand-side responsiveness in a changing regulatory environment. We explain how such systems can allow building owners to shed electric load through the control of window systems whose response is dependent on its synergistic relationship with the electric lighting and heating, ventilating, air-conditioning (HVAC) systems. Short-term and long-term technological options are presented followed by a discussion of how such systems can be implemented to meet the pragmatic requirements of the building owner and to meet active load management goals. The perspectives of individuals representing California utilities, building owners, architecture-engineering (A/E) firms, and window and lighting manufacturers are folded into this discussion.

Quotes from individual authors are given in some cases to properly relay the tenor of the issues they are presenting.

Opportunities in a Changing Electricity Market

A variety of different strategies have been implemented by utilities and other customers in attempts to manage and reduce electric load. Most have been voluntary, with various economic incentives associated with the strategies. Demand responsive programs provide a means to economically incent customer's participation to shed load or use alternate energy sources during critical periods of high demand. In the recent context of the 2000-2001 California energy crises, the emphasis of such programs has been on a near immediate response to curtail energy loads to avoid impending electricity outages. In the long-term, there is a need to increase customer participation in managing finite regional and nationwide energy resources to reduce price volatility and improve system reliability (Kueck et al. 2001). Demand responsive programs and utility rate structures such as time-of-use (TOU) and real-time pricing (RTP) schedules cause customers to directly experience the time-varying costs of their consumption decisions and therefore act as an incentive for customers to actively manage their loads.

Many of the simple curtailment strategies utilized in California during the past summer enabled customers to shed load without incurring additional capital costs for existing as-is facilities. However, in some cases, these strategies significantly impacted the comfort and potentially the health and productivity of the building tenants. Strategies included increasing temperature set points in occupied spaces, reducing fan speed or run-time, switching off lighting, reducing outside air intake volume, and pre-cooling the building during off-peak hours. Drawbacks of such strategies include thermal and visual discomfort; potential increases in CO_2 levels, and possible degradation of indoor air quality depending on the severity of the load response required. Preferable strategies are those that can provide significant load shed with minimum negative impacts to building tenants.

Utility load management programs have historically been aimed at reducing demand during critical times (such as summer or winter peak) using either direct load control (utility operates customer's equipment) or interruptible load programs (customer implements method of load shed). The critical summer peak for the commercial sector occurs in the afternoon and is driven predominantly by weather: hot temperatures and high solar gains. For example, the California statewide commercial building sector peaked at 23,000 MW at 2 PM, an increase of 15,000 MW from nighttime usage. Together, interior lighting and air-conditioning in the commercial sector make up 25% or 12,476 MW of the total 1999 California statewide peak load for all electricity use sectors (Brown & Koomey 2002). Cooling loads are dominant in all large commercial building types and more than one-third is due to lighting and another one-third to solar heat gains through windows (Franconi & Huang 1996).

Therefore, for interruptible load programs, strategies involving daylighting and window solar heat gain management offer significant demand reduction potential without the negative drawbacks of occupant discomfort. Peak daylight availability coincides with summer peak periods enabling reduction of lighting and cooling demand, given careful control of solar heat gains in perimeter zones. This is a *critical* concept associated with the strategies listed in the next section. Many people recognize that control of solar heat gains during peak periods can be accomplished by simply blocking all solar radiation before or just after it enters the window. People also recognize that admitting daylight (solar radiation) reduces the need for electric lighting. Determining the optimum energy balance between solar heat gains (increased cooling) and daylight (decreased lighting and cooling) is a critical issue and is key to optimizing window and lighting peak demand reductions during the summer. Other long-term opportunities not normally associated with window systems are those that allow windows to become part of the space-conditioning solution. Natural ventilation, heat extraction, and nighttime cooling strategies using operable windows reduce a building's dependence on mechanical cooling or shifts the load to off-peak hours.

Technological Options

Demand responsive (DR) strategies below have been loosely defined as solutions that provide a 1-2 hour response or a 24-hour response to requests for load shed. Short-term solutions are those that can be implemented within existing buildings. Long-term solutions are those that are more cost-effective and practical to implement in new buildings or in buildings that are being extensively renovated.

Short-term strategies for existing buildings

A. Occupants voluntarily close interior shades on all windows. Lighting is curtailed. Request is made over a central public address system or by email notification system. Flyers distributed before event could explain manual strategy. 1-2 hour notification.

B. Motorized interior or exterior shades are closed automatically by the facility manager during a load shed event. Lighting is curtailed. 1-2 hour notification.

Long-term strategies for new or renovated buildings

C. Automated exterior or interior shading systems combined with daylighting controls to reduce cooling and lighting loads. 1-2 hour notification.

D. Automated switchable windows controls (e.g., electrochromics) combined with daylighting to reduce cooling and lighting loads. 1-2 hour notification.

E. Heat extraction double-envelope facades with automated venting during peak periods to reduce cooling loads. Lighting loads could also be reduced with daylighting controls. 1-2 hour notification.

F. Pre-cooling of thermal mass using nighttime natural or mechanical ventilation through windows. 24-hour notification.

Strategy A involves a request to all building personnel via email notification, flyers, or the public address system to voluntarily close their window shades so that the entire window surface is blocked. If the shade allows one to modulate daylight (such as Venetian blinds or louvers), the occupant is asked to tilt the blind angle so that incoming daylight is sufficient to meet task lighting levels. Occupants near windows are also asked to switch off unnecessary lighting. This strategy can be applied to most commercial buildings without additional expenditures. Its effectiveness is dependent on the level of voluntary cooperation. Effectiveness is also dependent on baseline shade usage, shade type and reflectance, properties of existing window glazing, and window size and orientation. For example, white shades can reflect solar radiation back through the window if the window glazing has a high transmittance. Impacts on occupants are limited to annoyance at the disruption. Impacts on demand can be as much as 3 W/ft^2 (Figure 1) in perimeter zones. If two- or three-stage fluorescent light switching exists in the building, demand reductions may be less.

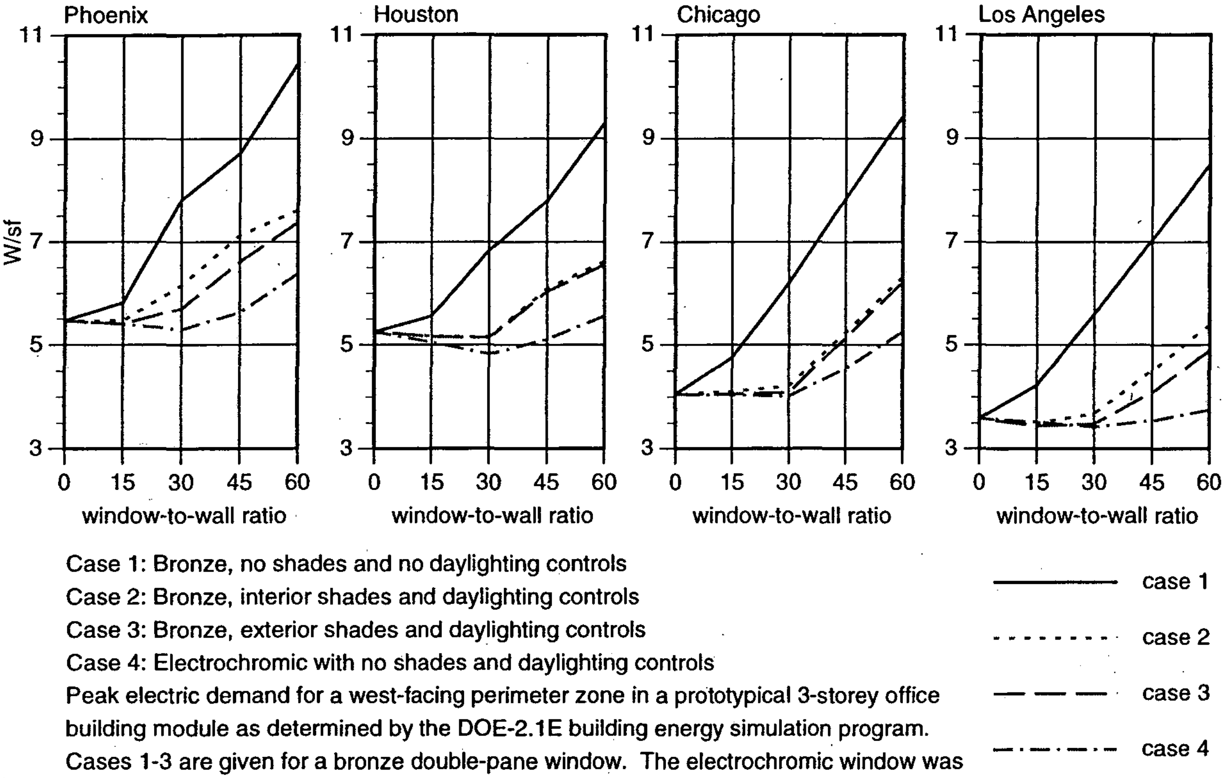
Strategies B and C are similar to A in that interior or exterior shades are used to reduce solar heat gains and manage daylight admission during critical peak periods. In this case, it is assumed that the facility manager through a central control system deploys the shades automatically. Lighting is curtailed either manually or automatically. Strategy B assumes that such a system exists within the building, which is admittedly unlikely for the majority of the commercial building stock. Retrofitting motors to existing static shades is costly. Strategy C assumes that new motorized shades are installed in new or existing buildings. If the building is new, the shades could be coupled to work with dimmable lighting using an integrated control system to achieve better reliability and energy efficiency. With existing buildings, switchable or dimmable lighting would need to be installed. Impacts on demand are similar to strategy A: as much as 3.5 W/ft^2 in perimeter zones (Figure 1). Occupant disruption is likely as well; however, occupant override should be allowed during non-critical peak periods.

Strategy D uses low-maintenance, non-mechanical means to regulate solar heat gains and daylight. Switchable windows include electrochromic or gasochromic glazings, which can be modulated from a clear to a dark tinted state (similar to switchable sunglasses) with either a small-applied voltage (3-5V DC) or a minute influx of gas (e.g., hydrogen). Electrochromic glazings are commercially available in Germany. US products are anticipated to enter the market in 2003. Gasochromic glazings are still under development. Competitively priced products are dependent on volume and on how quickly products get adopted into the marketplace. Electrochromic windows with dimmable daylighting controls regulate peak demand in a similar fashion to strategy C and are slated for new construction. Demand reductions can be as much as 4.75 W/ft^2 in the perimeter zone (Figure 1).

Heat extraction double-skin facades (strategy E) rely on sun shading located in the intermediate space between the exterior glass façade and interior façade to control solar loads. The concept is similar to exterior shading systems in that direct solar radiation loads are blocked before entering the building, except that heat absorbed by the between-pane shading system is released within the intermediate space then drawn off by ventilative means. Cooling load demands are diminished with this strategy. During peak conditions, mechanical ventilation can be used to extract heat if natural means (via thermal buoyancy or stack ventilation) are insufficient. Impacts on peak demand are difficult to quantify due to the complexity of the heat exchange. Occupant impacts are minimal; again, override on shade use should be allowed during noncritical periods. Thermal comfort may be improved, compared to some façade systems, due to a reduction in the interior window surface temperature if designed correctly.

During the summer and in the some climates where there is sufficient variation in diurnal outdoor temperatures, nighttime ventilation (strategy F) can be used to cool down the thermal mass of the building interior and reduce air-conditioning loads. Heat gains generated during the day are absorbed by furnishings, walls, floors, and other building surfaces then released over a period of time in proportion to the thermal capacity of the material. Removal of these accumulated heat loads can be achieved with a variety of cross-ventilation schemes that rely on wind-induced flow, stack effect, sand/or mechanical ventilation. Deployment of such a strategy for peak demand reductions must be implemented given a 24-hour notification. In recent years, the concept of radiant cooling has been coupled with traditional cross ventilation schemes. For some climates and building types, this strategy can be used to completely eliminate the need for mechanical air-conditioning. Heavy-

Figure 1. Peak electric demand (W/ft^2) for a west-facing perimeter zone



Case 1: Bronze, no shades and no daylighting controls
Case 2: Bronze, interior shades and daylighting controls
Case 3: Bronze, exterior shades and daylighting controls
Case 4: Electrochromic with no shades and daylighting controls
Peak electric demand for a west-facing perimeter zone in a prototypical 3-storey office building module as determined by the DOE-2.1E building energy simulation program. Cases 1-3 are given for a bronze double-pane window. The electrochromic window was controlled to maintain an illuminance level of 50 fc (538 lux). All systems use continuous dimming daylight controls and a lighting power density of 1.5 W/sq.ft (16.1 W/sq.m).

weight thermal mass is strategically located in exposed concrete ceilings. This mass is "activated" or cooled at night using outdoor air directed to flow over its unobstructed surface. During the day, occupants exposed to this chilled thermal mass perceive a cooler environment due to a radiative exchange with the low surface temperature of this thermal mass. Peak demand reductions can be significant particularly if all central cooling requirements are eliminated and if rules for proper daylighting are observed (see strategy C).

Utility and Building Owner Perspectives

A critical examination of all the above strategies reveals that for all practical purposes, the widespread deployment of such strategies to achieve a significant demand response across the commercial sector is well off in the future if building owners base their investment strictly on the DR programs aimed at curtailment and ensuring grid reliability. Programmatic rules and regulations for monitoring and verifying demand response (DR) would have to change in order to obtain "credit" for strategies involving windows. For example, baseline peak demand performance with which to verify and determine demand credits and charges (average of previous 10-day peaks) does not currently factor in weather-sensitive peaks – which is key for solar and daylighting DR strategies – and can negatively influence operating strategies (in order to drive up peaks for later qualification). TOU and RTP programs provide much greater incentives to building owners to invest in advanced window systems.

Broader than these programmatic details is the overarching issue of whether demand-responsive programs are here to stay. This uncertainty causes building owners to delay investments in DR technologies. After the excessive price volatility in the 2001 California retail electricity market, news reports indicate that there is potential for more energy cost stability. This volatility has a history of coming in waves. Low prices inhibit infrastructure investment creating shortages, high prices and expansion, similar to the retail commercial rental market. The "waves" exist on diurnal, seasonal and political time frames. The first two are rational and predictable; the last is not. Some feel that there will always be some degree of uncertainty – the never-really-deregulated market may devolve into a state-created monopoly. One way the building-related industry can plan to address this uncertain market is to provide the maximum amount of operational flexibility that reasonable installation costs and maintenance and operation (M&O) constraints will allow.

From the building owner's perspective, the decision to implement window-lighting DR strategies is based on the same pragmatic criteria as any other project: economics, impacts on tenants, and impacts on M&O (long-term ease of use, adaptability to new systems, like controls, and most of all long-term physical reliability). The up-front capital investment is a significant barrier for window-lighting systems if based solely on its DR potential. For example, raising the HVAC temperature set point requires a modest capital investment to reprogram controls and is considered to produce minimal disruption to occupants. The building drifts slowly up from 72°F to 78°F and is felt only in the late afternoon when most people are leaving. Over a hot summer, this strategy may be deployed only three to four times. With the larger capital investment needed to install DR window-lighting systems, project economics are not as compelling if activated occasionally, particularly given the uncertainty of the electricity market. Energy-efficiency and occupant benefits that are gained over the course of the year must be considered in a life-cycle cost analysis.

DR window-lighting systems might also raise special concerns over the impact on the appearance of the building, close exposure to occupants (i.e., unlike HVAC, individual occupants can "get at" the blinds) and ability to make changes in the future as required by tenant alterations and relocations. Occupant acceptance and satisfaction is also very important, particularly with automated blinds. Most building owners feel that it is imperative to grant user autonomy to keep tenants satisfied and to avoid having tenants obtain control through inappropriate means. During the well-publicized California energy crisis, tenants were willing to accept some inconvenience to help prevent blackouts. As the residual problems from this crisis look more and more like the result of regulatory mismanagement (and fraud) than a resource shortage, occupants will become less tolerant. Therefore, it is important in the long run to install systems which are energy efficient but do not compromise the occupants' working environment.

The suggested DR strategies (except possibly that involving natural ventilation) can be designed to not only optimize energy efficiency and comfort conditions during a curtailment event but also during the remainder of the year as well. During non-critical periods, the occupant can tailor the operation of the window and lighting system to suit their particular needs. Definition of "critical" periods can be worked out between the facility manager and the tenants. Blanc of the Pacific, Gas, and Electric Company worked with real-time pricing (RTP) technologies in the commercial buildings (Kammerud, Blanc & Kane 1996). For DR window-lighting systems, he reinforces this notion of shared control. "RTP inputs are easy to use to create open-loop control for any system, but one must temper this ease with the notion that this may not provide optimal solutions, particularly for the people subjected to the actions of the controlled systems. My idea is to integrate system actions at the local level and manage these actions with the pricing input. That way you can temper open-loop control with comfort and productivity needs. Window systems must be coordinated at the zone level and zones must be mapped to provide the maximum fit for lighting, HVAC, and fenestration."

The majority of the DR strategies suggested above involve building automation. Building owners feel that there needs to be increased knowledge of these systems among A/E firms, since window and blind systems in particular are inevitably going to be much more economical in new construction than in retrofits. Robust (low maintenance) well-integrated systems are needed that use open protocol communications to prevent vendor lock-in concerns. Having dealt extensively with building automated systems (BAS), Levi of the US General Services Administration points to specific design details for automated blinds and some fairly generic problems in the controls industry: "Automated blind systems must be occupant friendly and allow occupants to do what they want within reasonable bounds. Lighting systems must be easily adjustable – it must be a simple matter to increase the light level of a fixture in response to a complaint or to adjust lighting for a cubicle being located under what was once circulation space. For both lighting and blind systems, parts must be readily available and maintenance must be inexpensive and reasonable for building maintenance staff. Routine dependence on an outside vendor or dealer for adjustments and minor repairs will generally not be acceptable.

"Two critical issues have been the cost and quality of vendor and dealer support, and the ability of building staff to maintain, operate and to some extent optimize the system. Both have been problems in some regards. Programming talent for BAS tends to be somewhat scarce. At times there have been problems with vendor and dealer support of some systems with regards to basic competence, cost and project management (i.e., organization of effort). It has been difficult to develop the level of maintenance staff necessary to make the best use of the various systems and to do troubleshooting without having to rely on outside vendor and dealer support. It is also necessary to watch carefully for various vendor lock-in strategies, some of which are not obvious (for example, embedding point identification data entirely within the vendor's graphics without any underlying data structure or filling in BACnet optional description fields, thus making the "open" communications only really open through the vendor's front-end software without laborious point description identification)."

What Needs to Happen Technologically?

Automated Shading Systems with Daylighting Controls

With Venetian blinds, the modes of operation include tilt angle and retraction (up, down), which satisfies the criteria needed for both solar heat gain control and daylighting. With roller shades, one controls the degree of shade retraction, which can block view and daylight when providing solar heat gain control. Commercially available products now offer several methods of control. Simple manually operated keypads have tilt open/close as well as up/down options. With DC motor systems, presets are also available. Keypads can be wall mounted with hard-wired connections or be packaged with hand-held remote controllers which communicate via radio frequency or infrared. Centralized control of roller shades has been implemented in many buildings since the late 1970s, typically in public spaces such as museums and libraries or open-plan offices. Proprietary computer interfaces allow group control, as well as facility-wide time scheduling or demand-responsive control, provided the logic has been worked out.

Lutron Electronics Co., Inc. offers an automated roller shade system compatible with their suite of automated lighting control systems. MechoShade Systems monitor sunlight availability on the roof and determines how to actuate roller shades based on these data. SOMFY Systems offer an array of sophisticated products for automated shades. Some products have been applied for innovative uses such as creating a pattern across the entire building façade for signage purposes. Exterior louvers are used commonly in Europe and have been engineered for durability. Many of these European systems have been applied in commercial buildings for active control of daylighting, solar heat gain, and for heat extraction purposes.

Current US software and user interface developments focus on convenience of operation and ease of use for the occupant and building owner. Optimization for energy conservation is typically not done. Sensors are not widely used today. Manufacturers agree with building owners: with automated systems, an override capability is almost always required by tenants. It is not used very often, but when it is used, it is an absolute requirement, mostly for reasons of occupant comfort. Lack of override control quickly results in complaints. Overall energy efficiency is not affected greatly, because the controls are not used continuously to override the central system.

Open protocols have started to penetrate shade and lighting control markets. There are several protocols and they all appear more or less equally suited for the task, so a winner, if one appears, may be based on market factors as much as technological capability. Facility-centralized monitoring and diagnostics tools are also being developed and improved. Manufacturers feel that these systems can be easily integrated with existing building systems, provided that industry standard protocols are used (e.g., BACnet, LonWorks, OPC, etc.).

Many American products are derived from European products, meaning that European components are quite readily available in the market. Product service, however, is provided by the local manufacturer. There is some technician expertise available on the US market to install and program automated blind systems, but it needs to improve. This is definitely a business opportunity for locally operating dealers and installers. To ensure proper operations, large systems are typically factory commissioned. The dealer may commission smaller system. The installer would need to check operations on a zone-by-zone basis and program the specific location of individual components into the central control system for ease of maintenance and operations. Daylighting controls would also need to be commissioned to respond to the specific daylighting signature of the zone. System reliability is typically quite good, especially with DC motor systems. They have more intelligence built in, and include self-diagnostics as well as some self-correction features. AC motors are also fairly reliable, but can suffer from mechanical wear, or overheating. Limits may also shift in time with AC motor systems and may have to be reset occasionally. Some manufacturers offer limited 8-year warranties. Other required maintenance would be cleaning of the shading system.

Costs vary so widely depending on size and type of fabric/finish that manufacturers find that defining costs is not possible to answer easily or concisely. Hakkarainen of Lutron Electronics, Inc. states: “The bottom line is that energy savings alone do not justify the purchase of these products. Other factors, such as user comfort and convenience, have to be evaluated and appreciated in order for the owner to buy the system.”

To reduce costs and address other practical concerns, the Lawrence Berkeley National Labo-

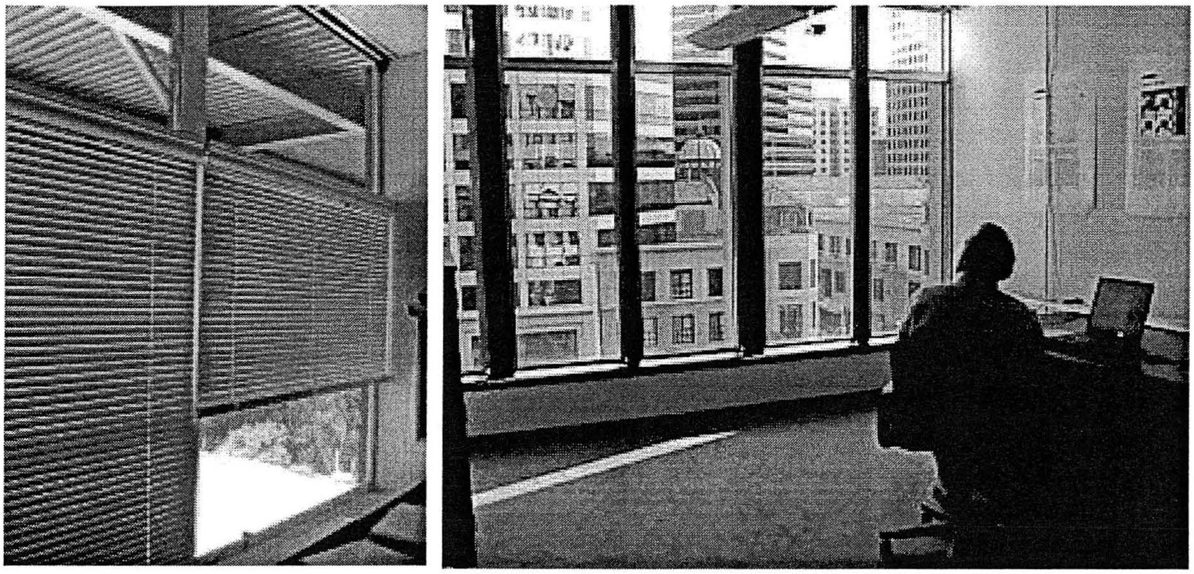


Figure 2. Automated Venetian Blind System based on Dallas Semiconductor 1-Wire® (left) and Large-Area Electrochromic Windows in Oakland Federal Building with Windows in Bleached on Top and Colored State on Bottom (right).

ratory (LBNL) has been involved in various aspects of automated shade design and control. One aspect involves quiet tilt action of an interior Venetian blind. AC- and DC-motors are typically used in shade products offered for both exterior and interior applications. Low-voltage DC motors can provide a more acceptable quality of operation. Software refinements can been made to achieve precise, quiet tilt action of DC-motorized blinds (Lee et al. 1998). To keep costs down, a single transformer is usually dedicated to a group of DC-motorized shades. To reduce costs further, sequential control of shades is cheaper than simultaneous control of an entire bank of shades on a single transformer.

Most products provide simultaneous group control of multiple shades to reduce control costs. Individual control of a single blind or shade is highly desirable for user acceptance and is not necessarily prevented with group control. LBNL has prototyped a supervisory control system (Figure 2) which allows individual control of 8 to 16 Venetian blinds (number dictated by practical wiring lengths of less than 100 ft) for a cost of $5-20 per blind (OEM controls only). The concept is based on Dallas Semiconductor 1-Wire® and has been prototyped for dimmable electronic ballasts and a California Title-24 compliant wall switch (Rubinstein, Pettler & Jennings 2002). A virtual instrument panel on a standard computer enables an occupant to have direct control over individual blinds and light fixtures. Web-based control architecture has also been prototyped and tested.

Software to optimize trade-offs between solar heat gain and daylight has been developed for Venetian blinds and dimmable fluorescent lighting at LBNL. This software has been tested in a full-scale private office over several years and has been shown to meet control objectives for at least 90% of the time (Lee et al. 1998). The system relies on a single photosensor and simple photodiode at the window plane to achieve integrated control between the window and lighting system. Direct sun control and glare control are accommodated in the control algorithm. Self-commissioning procedures have been kept deliberately simple. The system can be overridden by the occupant.

Electrochromic (EC) Windows with Daylighting Controls

Unlike automated shading systems, switchable window coatings are an emerging technology and have not been used extensively in the market. Limited field tests and building demonstrations have been occurring over the past five years. Some manufacturers are or will be offering initial products to niche residential or commercial building markets (e.g., SAGE Electrochromics Inc., Flabeg GmbH, Research Frontiers, Inc.). As the market matures and costs are reduced, application is projected to be broad, following the trend of low-E coatings. EC windows can be applied to any commercial or residential building in the US.

The electrochromic device (Figure 2) is typically deposited as a microscopic multi-layer coating on the inboard side of the exterior glass layer of a standard insulating glass unit (IGU). For some products, the EC is laminated to form the exterior glass layer. Currently, solid-state EC windows can be produced with dimensions of ~20x40 inches; however, there is no fundamental restriction to fabricating EC windows in sizes for most residential and commercial applications. Flabeg produces a laminated EC window that is 35x79 inches and can be cut to size.

The switching range can be quite broad. For example, an EC double-pane window with clear glazing layers can have a center-of-glass visible transmittance that varies continuously from 0.56 to 0.02 and a solar heat gain coefficient that varies from 0.42 to 0.09. U-value does not vary appreciably. Switching speed depends on the area of the window and on temperature. Switching speed for a 20x40 inch window is ~5 min at 21°C and ~25 min for a 24x69 inch window at 12°C. Color switches from a neutral gray or a slight yellow (depending on the EC coating) to blue-green.

The coating is switched with a small (3-5 V) applied DC voltage. For some products, the EC has an open circuit memory – drifting less than 1-2% in transmission over several days without applied voltage. For other products, the EC must be constantly pulsed to maintain a given state. Energy use for "leaky" devices is small: if a 20x40 inch EC window is switched 10 times per day, the daily energy use for switching and holding is ~5.8 Wh or 1 Wh/ft^2-glass. Each EC window has a primary controller. Similar to motorized shades, EC windows can be activated from a touch pad, via a wireless remote, or be fully integrated with HVAC and lighting systems.

Currently, there is no centralized software programs offered to control EC windows automatically. Some manufacturers have developed centralized diagnostic tools to help facility managers troubleshoot problems with individual window units within the building. Prototype software programs have been developed at the local scale for EC windows that have been tested on large-area devices (Lee, DiBartolomeo & Selkowitz 2000) that could be ported to the building-wide level for DR systems. User feedback could be used to commission automated EC window-lighting systems. Most EC manufacturers envision that control will be shared between the facility manager and the occupant.

There have been few full-scale applications of EC windows in commercial buildings so there are no data that quantifies the operational life of such systems with respect to wiring durability. One would expect that if the curtain wall is detailed to protect the low-voltage wiring from thermal stress, moisture, and movement similar to that done for smoke and ventilation dampers, photovoltaic (PV) systems, or other such mechanized components, EC wiring durability and life would be comparable. The EC windows are not wired in series but in parallel, therefore, a single non-functioning unit does not compromise the operations of other windows nor does it impose an electrical drag on the system. If a group of EC windows is affected by a lightning storm or other such catastrophic event, the EC windows may either be static at a partial switched state or will gradually "rest" at the clear state. EC windows will most probably be exterior glazed to accommodate wiring through the framing, so change out of dysfunctional units must occur from the outside (similar to most curtain wall applications). EC windows are compatible with the voltage and power output of PV cells, and prototype systems have been fabricated with PV-powered, totally self-contained EC windows. Such products could be particularly useful for the retrofit market.

There are many unique issues related to the use and handling of EC windows: packing and shipping to window manufacturing, handling and framing EC IGUs, re-packaging and warehousing of units, shipping to construction sites, on-site storage, handling, installation, hook up and testing of installed units, and user tests that include facility managers, occupants, customers and maintenance crews. All these issues have yet to be worked out and tested in the field. Façade engineers anticipate that significant time will be needed to commission and debug the system.

EC coating reliability depends on the EC device construction and the window sealing or laminating system. Sbar at SAGE Electrochromics, Inc. states that: "Solid-state inorganic devices have demonstrated outstanding durability. Such devices were tested by the National Renewable Energy Laboratory per ASTM standard E2141-01 for absorptive electrochromic coatings in sealed IGUs. Test conditions were simulated solar irradiation of 1.2-1.5 sun at elevated temperatures (83-95°C). The EC samples were switched 70,000 times with no significant change in performance or appearance. Polymer-based systems are less durable because of the instability of polymers to sunlight. Solid-state EC windows constructed with state-of- the-art sealing systems show the same long-term reliability as high quality static window IGUs. Both ASTM and P1 tests indicate predicted lifetimes of over 20 years normal use."

Estimates for product costs vary widely depending on volume and level of product maturity. Prototype windows at the early stages of this emerging market can cost up to \$100/ft^2-glass without the controls. Sbar at SAGE Electrochromics anticipates that: "At maturity, EC window costs will be \$6-8/ft^2-glass for an IGU and primary controls will be \$15 per window. The first costs for EC windows will be higher than static windows, however, building energy performance modeling (DOE-2) has been used to demonstrate that the energy costs for buildings with EC windows will be lower. Commercial building energy savings of 26-40% will be achieved with EC windows and peak load reductions of 15-24% can be attained. Solid-state, inorganic EC glazing systems in an IGU with a state-of-the-art sealing system will result in a payback of excess first costs in one to three years. In addition to the energy savings, cost savings for EC systems will be achieved through reductions in building maintenance and HVAC equipment costs."

A three-year collaborative field test program supported by DOE, the California Energy Commission, and the Department of Housing and Urban Development has recently been launched to quantify and verify the savings potential of EC windows in commercial and residential buildings. In Europe, a collaborative research program initiated in 1999 called "Switchable Façade Technology" or SWIFT is focused on providing a scientific and commercial basis for implementing European switchable window products. Both research programs will address many of the concerns and issues raised above.

Night-time Natural Ventilation and Heat Extraction Double-Envelope Facades

For night purge of structural heat, low outdoor air temperature and sufficient volume of the air – either natural or mechanically induced – must be available during the summer. Therefore, this technique of load management is limited to certain geographic locations and building types/shapes.

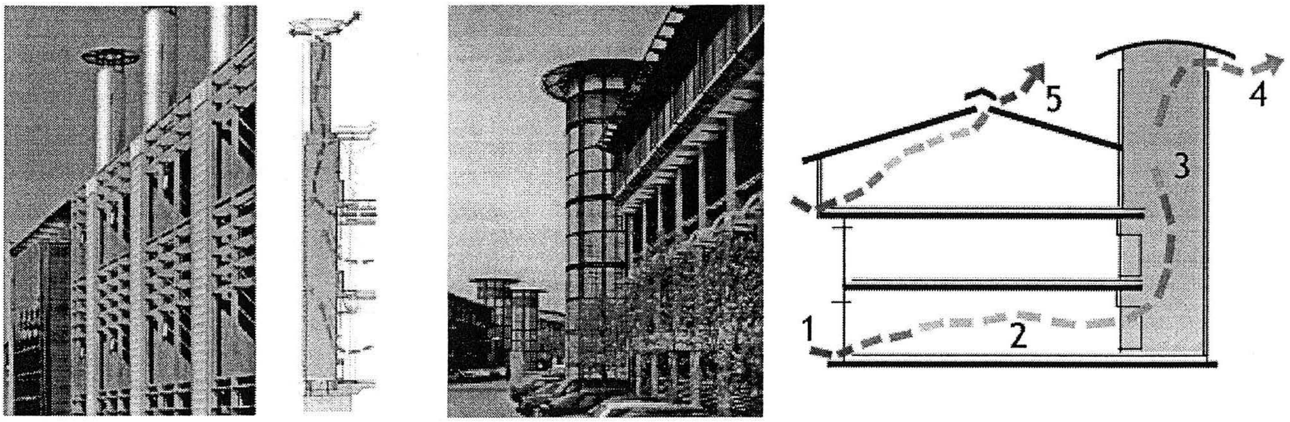


Figure 3. Heat Extraction and Stack Ventilation System in the Environmental Building, Building Research Establishment, Garston, UK (2 left figures) and the Inland Revenue Headquarters, Nottingham, UK (2 right figures)

McConahey of Ove Arup and Partners California, who has been engineering the new San Francisco Federal Building (McConahey, Haves & Christ 2002), notes that the manipulation of thermal mass in air-conditioned/mixed mode buildings is quite tricky: "With regards to night-time ventilation, it is important to remember that the diurnal manipulation of thermal mass requires a clearly "unoccupied" 12-hour stretch that corresponds to the free cooling at night. Additionally, the manipulation of thermal mass can occasionally work against total energy use in air-conditioned buildings. To be most effective, first of all, the thermal mass needs to be insulated from the outside, so that the building management system is controlling the charging and discharging of the mass, not external effects on the backside of the mass. Secondly, if the mass is cooled overnight, one must be sure that the indoor conditions are not too cold in the morning. The worst thing that can happen is that the heating systems kick in when people enter and one depletes the mass's charge prior to the afternoon, just to keep morning comfort conditions. Lastly, we have found in certain case studies that if you are in a climate condition that you know will require the air-conditioning mode in the following afternoon, it can actually be better for total energy use to run the air-conditioning systems at a minimum during the night to keep the indoor conditions constant instead of manipulating the mass. Peak afternoon demand can go up if you are not only carrying your peak instantaneous loads, but also having to carry the beginning of the heat rejection mode of the mass that has been spent in the "too-hot" morning hours. There is no way to model thermal mass except dynamically with the building systems and control sequences accurately modeled."

Automated control systems for night-purge systems are not commercially available. The barriers to "canned" software products include the unique geometries of the particular building, local wind regimes and how much wind mitigation is required, security concerns, etc. Normal temperature sensors can provide feedback on indoor conditions. Additionally, if wind-based or rain-based decisions are made about windows usage, differential pressure sensors and rain gauges may be appropriate feedback signals. Once a building management system is involved, user-override controls are not difficult to incorporate. Giving tenants override ability on motorized windows, however, adds cost to the project in the form of override keypads and may lead to the windows being used inappropriately if the motorized windows are to be serving a large shared space. It may be possible to provide temporary local overrides when excessive wind, rain or security conditions exist.

For occupied periods when non-DR conditions apply and when outdoor temperatures are comfortable (typically during “swing” spring and fall seasons), windows can be operated in a natural ventilation mode. However, there is no commercially available software to control motorized natural ventilation windows for thermal comfort. Such software would be appropriate to maintain “baseline” indoor temperature conditions when the building is unoccupied or if multiple occupants in a space do not have direct access to the operable window. Here, the key to successful natural ventilation control schemes is to allow the user as much control as possible over manipulating their personal environment and to maximize the use of the thermal potential outside to make themselves comfortable. Unlike central air-conditioning systems, which require little input from the occupant, successful natural ventilation schemes require the occupant to be engaged in regulating their own comfort by changing clothing type, adjusting body posture, opening windows, or temporarily adjusting work schedule or task type. The occupant’s personal control will usually be the optimal setting for comfort, as there is a direct biological feedback control loop.

Night-purge schemes rely on motorized window actuators, which tilt open hopper- or awning-type windows to admit outdoor air. Although there are window actuators available on the market, they are primarily marketed to address the concerns of the Americans with Disabilities Act (ADA). Most window actuators could be fitted with control contacts that would allow integration with EMCS products. Installation is usually done under the curtain wall or window installer’s scope of work. Programming the building management system typically comes under the scope of the controls contractor. Commissioning includes ensuring that each manual window could be opened with ADA forces and that motorized windows react appropriately to their input signals.

There are currently many manual natural ventilation systems in older buildings and residences throughout the US. Failure modes include leaking windows (both water and air), installation of full-height partitions in locations that block air flow, windows that are not easily opened or maintained to ensure operability, lack of window security when in the open position, blinds that interfere with opening the window, etc. There are also many mechanical ventilation schemes, especially in areas with temperate climates. In these cases, there are the usual fan-related failures, and the systems often have little user input. As there are few motorized window installations and each is unique, it is currently difficult to assess reliability. This is an area that bears further research.

Cost-effectiveness of these schemes will depend on the locality’s climate, energy rates, and building configuration. The quickest return on investment occurs if natural ventilation can provide all cooling for the building for the entire year, thereby avoiding the installation of a refrigeration plant. Mixed-mode systems that require the installation of two systems (refrigeration plant and window system) will need to be evaluated on a case-by-case basis with a life-cycle cost analysis.

Comparable issues apply to heat-extraction double-skin facades. The façade consists of a single exterior layer of heat-strengthened safety glass or laminated safety glass, with exterior air inlet and outlet openings controlled with automatic throttling flaps. The second interior façade layer consists of fixed or operable, double- or single-pane windows. Within the intermediate space between the two glazing layers, which can be 2-36+ inches wide, are retractable or fixed, automated Venetian blinds or roller shades. The vertical height of this space can be single- or multiple-story. For systems relying on thermal buoyancy, the vertical height of the stack tends to be two to three stories. During DR cooling conditions, the shade cover the full height of the façade and in the case of blinds, are tilted to block direct sun. Tilt angle can be optimized for interior daylighting to obtain lighting energy reductions as well. Absorbed solar radiation is either convected within the intermediate space or re-radiated to the exterior or interior. Low-emittance coatings on the interior glass façade reduce radiative heat gains to the interior. If operable, the interior windows are closed. Convection within the intermediate cavity can occur either through thermal buoyancy or be wind driven.

The effectiveness of this strategy is dependent on the local climate (starting temperature at entry), height of the effective stack (impacts what the temperatures are at or near the top of the stack), width of the void (impacts laminar and turbulent airflow), and size of the openings at the intake and exhaust (and their relevant size in relation to each other). These combined factors influence the velocity of air within the shaft, how much heat the shaft contains, and how much heat is extracted over the course of a day. Design tools to predict façade performance are not routinely available.

Like the night-time purge systems, canned BMS control software is not available for heat-extraction facades. Functional limits on intake and exhaust throttling flap actuators and fans are similar to those for mechanical systems. Failure modes for the motorized shade are similar to those discussed above. Inlet and outlet vents have reportedly been blocked by insect and bird nests. Condensation with the interior vented cavity also causes problems with maintenance and occupant satisfaction.

Natural ventilation and double-skin facades have been of considerable architectural interest over the past 10 years in Europe (EU) and are now being implemented in the US. Adequate third-party façade system and building performance data are not routinely available; these needs are only starting to be addressed by the buildings industry. A pilot study was conducted by LBNL to better understand this architectural trend and the information products needed to assist the building industry to design and evaluate such systems (completed in June 2002). The International Energy Agency (IEA) Task 27 is developing and verifying the modeling algorithms needed to assess the energy performance of these complex systems. Research to better understand thermal comfort associated with natural ventilation is being conducted at the University of California at Berkeley. Monitoring of occupant satisfaction (IEA Task 31) and thermal performance is also occurring collaboratively between private engineering firms, academic institutions, and research laboratories world-wide.

Changes in Business Practices

In order to adopt and widely implement the technological options discussed in this paper, there needs to be several fundamental changes to the way industry, A/E firms, and building owners approach the design and engineering of integrated window-lighting-HVAC systems. Within industry, there needs to be a shift in how technology gets marketed and deployed. The building industry – by virtue of trades, products, and design approach – is fragmented. One critical aspect of integrating advanced facades into building designs is that they maintain a similar construction interface as traditional systems, so that specialists aren't relied on to complete construction as well as installation. Hakkarainen of Lutron Electronics, Inc. states that: "We need to develop specifiers and installers who have interest and capability in multiple disciplines. Window treatments are specified in the Construction Specifications Institute (CSI) Section 12 and lighting controls in Section 16. Section 17 specifications need to become widely used. The barrier is that manufacturers have to reach the owners or at least the architects to be able to sell their products, because the specifiers and installers are not easily motivated by the idea of integration. Additionally, the integration capability requires that choices be made during the commissioning process to determine what the system functionality is. This, too, requires the building owner to be involved."

On the design and engineering front, decision-making based on short-term economics must fundamentally change. McClintock of Ove Arup and Partners California states that: "To become business as usual, the A/E community would have to present an effective case for return of investment to building owners that shifts the focus from the traditional one of a five to ten year payback period versus up front cost. The case to owners needs to change their perceptions from this shorter payback period to one that is around 20-25 years, which has started to become accepted in Europe."

Building codes and regulations also need to catch up to the latest architectural trends. The National Fenestration Rating Council's (NFRC) standards for quantifying and certifying the thermal properties of windows are applicable to primarily conventional windows. ASHRAE 90.1-1999 now requires that window properties are determined using NFRC ratings. Many building codes also require NFRC certification. Variances are required to accommodate the systems discussed here, which cost time and effort to obtain.

Conclusions

The changing electricity sector offers new opportunities and challenges to building owners and the building industry (architects, engineers, manufacturers, etc.). Achieving demand responsive window-lighting-HVAC solutions could yield significant benefits to utilities since these end-uses contribute significantly (40-50%) to summer peak demand. Positive impacts on occupants' visual and thermal comfort are expected.

Technologically, widespread deployment of such systems is not likely in the immediate future. Operable shade technology is available but underdeveloped and not integrated with other building systems except as prototypes. Electrochromic and other switchable window technologies have significant potential, but integrated product development is in its earliest stages. Natural ventilation and heat extraction façade systems also have significant potential and are projected to deliver improved indoor air quality and occupant amenity as well.

These systems performance potentials cannot be achieved with business-as-usual practice. Significant changes to the business and regulatory environment must be made to adopt such systems routinely. Traditional division of labor and specifications must be worked out between façade and electrical systems. Simulation tools are needed to facilitate analysis of peak demand impacts and to help the building owner make cost-effective decisions when implementing a demand response. If we look toward future building trends, we see that Europe has already successfully deployed such complex systems in many highly acclaimed buildings, proving that the process at least is achievable. Performance impacts are as yet unknown.

Extensive further development of tools, technology integration, standards, etc. is required if widespread deployment of such advanced window systems is desired for the purposes of demand response or for other less urgent needs such as sustainability, energy-efficiency, optimized systems efficiency, and improved environmental quality for occupants.

Acknowledgments

This work was supported by the California Energy Commission through its Public Interest Energy Research Program, by Southern California Edison through the California Institute of Energy Efficiency, and by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of

Building Technology, State and Community Programs, Office of Building Research and Standards of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY
ONE CYCLOTRON ROAD | BERKELEY, CALIFORNIA 94720

Prepared for the U.S. Department of Energy under Contract No. DE-AC03-76SF00098