Daylighting in Wisconsin

A Program Study

June 1997
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Prepared for

ENERGY CENTER OF WISCONSIN

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Objective and Approach

This report develops an approach to a statewide daylighting program to be implemented in Wisconsin. It has been prepared in response to an order by the Public Service Commission of Wisconsin to the utilities in the state to develop such a program. The Commission order states that the program should address:

1. demonstration projects;
2. training for architects and engineers;
3. design assistance; and
4. education for the general public.

The term daylighting means different things to different people. By daylighting we mean the use of natural light in order to supplant the use of electric lighting. This program promotes daylighting that goes beyond traditional, and largely aesthetic, use of daylighting—which does not result in energy savings for lighting—by using automatic lighting controls.

The “we” in this report refers to a working group established to assess the need for—a daylighting program in Wisconsin. The working group was comprised of representatives from Wisconsin utilities, utility intervenor groups, state government, the Public Service Commission, building design professionals, and the Energy Center of Wisconsin.

To prepare this report, we met throughout the latter half of 1996 and the first quarter of 1997 to discuss daylighting issues and possible program activities. We also:

• reviewed literature on daylighting;
• consulted with national daylighting experts;
• conducted two focus groups with Wisconsin architects; and,
• conducted thirty interviews with potential daylighting stakeholders such as lighting designers, facilities managers, and developers.
Results

We found that daylighting in commercial buildings holds significant potential for electricity savings in Wisconsin. In the commercial sector, lighting uses a lot of electricity—daylighting can substantially reduce this use. The cost of automatic lighting controls has come down in recent years, and the payback on lighting controls appears to be reasonable.

Perhaps more importantly, daylighting has several non-energy qualities that, to most people, may well be more attractive than energy savings. Specifically, (1) most people prefer natural light to artificial light; (2) there appears to be a market for (and increased professional interest in) environmentally sustainable buildings; and, (3) a growing list of case studies suggests that people who work in naturally lit buildings are healthier and more productive than those who work in artificially lit environments. Similar findings are also emerging in terms of student test scores in daylit schools, and sales in daylit retail stores. In particular, the health and productivity implications of daylighting have the potential to dramatically alter the economics of daylighting because labor costs—or sales revenues—are far more important to most businesses than are energy costs.

If daylighting is so attractive, why is a statewide program to promote it needed? Our investigations uncovered the following significant market barriers to widespread adoption of daylighting in Wisconsin:

- a lack of awareness and understanding of what daylighting is;
- a perception that daylit buildings are more expensive;
- a lack of awareness of lighting controls and an uncertainty about how much energy daylighting will save;
- a perception among design professionals that daylighting is a complex design add-on that will increase design costs, along with a lack of exposure to design analysis tools;
- a perception that daylit buildings have problems with glare;
- a perception that daylit buildings have higher heating and cooling loads because they have more fenestration; and,
- concerns about the reliability and maintenance costs of lighting controls.

Recommendations

Given these findings, we recommend that a statewide program be implemented to stimulate both demand for daylit buildings and professional capabilities to design and construct them. To overcome the above barriers, we propose that the
program activities in the PSC order be pursued within the context of the following program strategies:

- increase awareness of what daylighting is and how it works;
- promote simple daylighting principles that can readily be integrated into new and retrofit building designs;
- provide practical demonstrations of the energy savings and cost effectiveness of daylighting in Wisconsin;
- provide hands-on training for architects and engineers through design assistance that promotes learning through doing;
- promote a systems approach to daylighting that optimizes lighting and HVAC savings, along with cross-disciplinary coordination;
- promote awareness of daylighting at all phases of building design and construction, from initial architectural design to interior design to proper calibration of lighting controls;
- promote the productivity and ‘green building’ benefits of daylighting.

In order to address the activities delineated in the PSC order, we recommend that the program initially be funded at about $350,000 per year. Our analysis of daylighting technology diffusion in the Wisconsin commercial building market suggests even conservative estimates of the impact of a program funded at this level would be justified in terms of societal benefits. The program should seek to result in a minimum of one square foot of daylit space for each dollar spent on the program.
Introduction

Objective and Approach

In December 1995, the Public Service Commission of Wisconsin directed the utilities in the state to “participate in a collaborative effort to design a coordinated, statewide program to promote the increased use of daylighting.” The Commission’s order states that the daylighting program in Wisconsin should address four areas:

1. demonstration projects;
2. training for architects and engineers;
3. design assistance; and,
4. education for the general public.

The utilities agreed to develop a conceptual proposal for such a program with the help of the Energy Center of Wisconsin. Since fundamental changes are likely to occur in the electric industry in the near future, we were instructed not to make assumptions about who would deliver such a program.

To fulfill this task, we formed a daylighting working group with representatives from the utilities, utility intervenor groups, state government, the PSC, and the Center. We also recruited several knowledgeable people from the commercial design community. In addition to meeting to discuss program design options, we completed the following activities:

1. reviewed daylighting literature;
2. consulted with national and regional daylighting experts;
3. conducted two focus groups with architects who had previously attended Center workshops on daylighting; and,
4. conducted thirty formal telephone interviews with design professionals, developers, and others in Wisconsin who might have a stake in a future daylighting program.

We included the results of these activities in separately-bound contractor reports.
The remainder of this report sets forth what we know about daylighting as an energy efficiency strategy, assesses the market for daylighting in Wisconsin, and defines a broad vision for a program to promote daylighting.

**Scope of the Market for Daylighting**

Our focus in this report is on daylighting in commercial and industrial buildings—the sectors cited as having the most potential for energy savings. There may also be a role for daylighting in homes, but most homes are already adequately daylit, and many people are not home during the day when daylighting would save them the most.

Electric lighting constitutes one of the largest single end-uses of electricity in the commercial sector, and is estimated to make up between a third and one-half of all electricity use in this sector. *(Lighting in Commercial Buildings. Energy Information Administration, DOE/EIA-0555(92)/1. 1992.)* When we consider that the commercial sector itself uses about one-third of all electricity in Wisconsin, the implication is that ten to 15 percent of all electricity used in Wisconsin is for lighting in commercial buildings. This costs Wisconsin businesses about $350 million dollars each year.

Table 1 shows that the commercial sector is expected to grow by more than seven percent over the coming decade, adding about 100 million square feet of floor space and 468 million kWh worth of electrical lighting. Growth is expected to be particularly strong in offices and colleges, two especially attractive and adaptable candidates for daylighting.
Introduction

These statistics show that growth in the commercial sector will offer significant new construction opportunities for daylighting. The numbers also tell that for every new building that is built, there are about a hundred buildings that already exist; a daylighting program must not ignore opportunities to retrofit lighting controls, windows, and skylights in existing buildings.

Table 1: Projected growth of lighting needs in the commercial sector

<table>
<thead>
<tr>
<th>Existing Floor Space (million square feet)</th>
<th>Existing Lighting Electricity Use (million kWh)</th>
<th>Projected growth (1997-2007)</th>
<th>Projected growth Floor Space (million square feet)</th>
<th>Projected growth Lighting Electricity Use (million kWh)</th>
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<tbody>
<tr>
<td>Office 260.6</td>
<td>1347</td>
<td>9.9% 25.74 133</td>
<td>Misc. 266.1</td>
<td>779</td>
</tr>
<tr>
<td>Retail 201.2</td>
<td>911</td>
<td>7.0% 14.09 64</td>
<td>Warehouse 189.4</td>
<td>466</td>
</tr>
<tr>
<td>Health 91.1</td>
<td>665</td>
<td>9.1% 8.29 60</td>
<td>College 79.3</td>
<td>478</td>
</tr>
<tr>
<td>Lodging 55.1</td>
<td>269</td>
<td>9.3% 5.13 25</td>
<td>Restaurant 43.8</td>
<td>279</td>
</tr>
<tr>
<td>School 145.9</td>
<td>530</td>
<td>1.0% 1.5 5</td>
<td>Grocery 26.1</td>
<td>233</td>
</tr>
<tr>
<td>Overall 1358.6</td>
<td>5957</td>
<td>7.7% 104.45 468</td>
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</table>

Sources: Wisconsin Energy Bureau, Energy Information Administration
What Do We Mean By “Daylighting”?  

Early on we found that the word daylighting means different things to different people. For our purposes, “daylighting” means using natural light to supplant electric lights inside a building. Many people wrongly think this means lots of sunlight streaming into a room—it actually takes only about one percent of the total light available from the sun to adequately illuminate an interior space. In fact, good daylighting design avoids the glare, high visual contrasts, and heat gain that come with direct sunshine, preferring diffuse light from the sky or reflected from the ground. For this reason, the north side of a building is considered the easiest source of daylight.

Daylighting strategies that also save energy have two essential aspects: (1) the architectural and interior design features that allow outside light into the building and help it penetrate the interior; and, (2) controls that reduce the use of electric lights when daylight is available.

Architectural Features  

Nearly every building can be daylit to some degree, but the extent to which daylight can penetrate a building is strongly dependent on its basic form and orientation, as well as more specific architectural features. For example, it is easier to daylight a larger percentage of the floor area of a long narrow building than a square or blocky one, because there is a shorter distance from the outside to most points in the interior. And a building that has its long axis oriented east-west is preferable to one that is oriented north-south, for it greatly simplifies glare control.

Because fundamental design decisions such as the orientation and footprint of the building affect the ability to bring daylight into the interior, early integration into the design process is vital for daylighting to be successful.

Buildings can be toplighted by skylights, clerestories, or other features, but it is more common that they be sidelighted via windows. Sidelighting has less inherent ability to penetrate deeply into the interior of a building than toplighting, but toplighting is more problematic in the lower stories of multi-story buildings. Architectural features such as light shelves can be used with sidelighting to cast daylight toward interior ceilings and increase its penetration into the building. Regardless of the ability to implement deep daylighting, most buildings can be daylit on their perimeter through sidelighting.
The interior layout of a building is also important for daylighting. Daylighting works best when the floor plan is fairly open—or at least contains glass in interior partitions—so that daylight can penetrate further into the interior.

Although there are many high-tech ways to daylight buildings—such as light pipes and roof-top devices that collect and concentrate light—we believe that the emphasis of a promotional program should be on simple, intuitive design features to make buildings more daylight friendly.

**Lighting Controls**

Most experts agree that daylit buildings will save little electricity unless automatic lighting controls are used. This is an important point, because while the aesthetic appeal of natural light immediately came up with most of the stakeholders whom we interviewed, the idea of saving electricity by using controls on electric lights did not. If a statewide daylighting program aims to save energy, we need to increase awareness and promote lighting controls.

Daylighting control systems typically use photocells to detect interior light levels and adjust electric lights. The least sophisticated of these simply turn the electric lights on and off in response to ambient light levels. An intermediate level of control allows several levels of electric illumination by turning some lamps on and off. At the most sophisticated, and expensive, end the light output of the electric lights is adjusted continuously in response to the amount of daylight available. Not surprisingly, acceptance of continuous dimming systems, as these are called, is higher than on/off type controls.

While daylighting technology has progressed since the 1980s, and costs have declined, specifying daylighting controls still requires specialized expertise in order to obtain a workable system. The Lighting Research Center in New York has conducted research showing that some combinations of dimmable ballasts and photocell controllers are incompatible. Unfortunately lighting designers are generally unaware of this.

In addition, the performance of daylighting systems greatly depends on where sensors are placed. If interior design is not coordinated with the lighting layout, savings can dramatically fall.

Even with proper sensor placement, there have recently been a number of examples of daylighting projects—including one in Wisconsin—that exhibited no energy savings until researchers went back to calibrate the lighting controls. Clearly, such commissioning of controls is a vital issue that the program should address in order for controls to avoid being the Achilles Heel of daylighting.
What Are the Benefits for Daylighting?

The benefits from daylighting can be put into three categories:

1. energy cost savings for lighting and space cooling;

2. non-energy (but quantifiable) benefits such as increased productivity, reduced absenteeism, higher retail sales, or improved student performance; and,

3. intangible benefits, such as improved aesthetic appeal, an improved corporate image, and concern for the environment.

Energy Savings

The most immediate benefit of daylighting—albeit not the one that is likely to be foremost in the minds of most people—is the energy savings that come from reduced electricity for electric lighting. We found documented cases and estimates of lighting savings from daylighting that range from about 30 percent to 70 percent (see Appendix B). Even the lower end of this range represents a substantial reduction in lighting energy, which typically accounts for 30 to 40 percent of the electricity used in an office building. These savings also coincide with summer peak utility load. From a system planning perspective daylight offers good potential for helping avoid future electric power generation.

Daylighting also brings energy savings through reduced cooling loads. The most efficient lamps only convert 20 to 25 percent of the electricity they use into light; the rest becomes heat, which must be removed by the building’s cooling system much of the year. Diffuse daylight introduces more light per unit of heat (120-140 lumens/watt) than any artificial source, so cooling savings can be substantial in a daylit building. In fact, the size of the cooling system that needs to be installed in the building can be reduced if daylighting is used. We found a case study of an office in Oregon that was able to use chillers that were 31-percent smaller than would otherwise have been required due to the use of daylighting and lighting controls. True, the electric lights help heat the building in winter, but cooling savings generally dominate in commercial buildings, even in a climate like Wisconsin’s.

Productivity and Other Tangible Benefits

What may be much more attractive than energy savings, however, is a growing body of literature suggesting that people who work in naturally lit spaces are more productive than people who work under artificial lights. A 1994 collection of case studies prepared by the Rocky Mountain Institute showed productivity gains from efficient lighting strategies such as daylighting that ranged from six to 16 percent. Daylit buildings have also been associated with lower absenteeism. And retail stores that have piloted daylighting report higher sales
in the daylit areas. We gathered anecdotal reports of the effect of daylighting in retail and found stores increased sales on the order of 15 percent or more. Finally, intriguing studies from North Carolina and Alberta suggest that students in daylit schools have higher test scores.

Although these benefits are tough to quantify, they have dramatic cost-effectiveness implications. A 1990 survey of U.S. office stock estimated workers’ salaries at about $130 per square foot (compared to $1.50 for electricity). Even a small increase in productivity (or sales) would more than offset the entire electricity bill for most businesses, since the cost per square foot to support employees or promote sales is much greater than the cost of electricity for the building.

**Intangible Benefits**

Daylight is what the human eye evolved to respond to, and so it is what most people find to be the most aesthetically pleasing. The color rendition of daylight represents the standard that artificial lights seek to achieve. A generally more pleasing indoor environment was often stated as a primary advantage of daylit buildings by stakeholders with whom we spoke.

Daylighting can also play an image role for some companies. Being seen as environmentally friendly, high tech, or interested in employee comfort are all intangible benefits of daylighting.

**What Are the Costs of Daylighting?**

Daylighting costs are generally categorized as:

1. the cost of lighting controls;
2. increased design costs; and,
3. increased construction cost to accommodate daylighting architectural features.

**Lighting Controls**

Lighting controls represent the most immediate cost for daylighting. Estimates for the cost of controls range from about $0.30 per square foot to about $1.50 per square foot. It is difficult to pin down these numbers, because the technology is changing rapidly, with generally declining costs. We estimate the average current cost of lighting controls at $0.50 per square foot.
Design and Construction Costs

There is no general agreement among daylighting experts about how much higher—if even at all—design and construction costs are for daylit buildings. Certainly daylight is a more complex lighting source than tracts of fluorescent luminaries. However, some argue that most daylighting design issues can be resolved with simple design principles, and that more expensive modeling is rarely needed. Certainly, some daylighting issues can be resolved at a very simple rule-of-thumb level. At an intermediate level, some energy modeling may be needed in order to optimize the trade-offs among lighting and heating and cooling loads. Such modeling may also be needed to lend credibility to claims of the HVAC impacts of daylighting. At the most costly end, larger projects—or those with stringent lighting requirements—may require modeling (computer or physical) to measure or visualize the illuminance characteristics of a space.

The added construction costs of daylighting are also difficult to quantify in the abstract, mainly because good daylighting requires a systems approach to a building, along with architectural decisions that occur at such a fundamental level that it may be difficult to determine the impact on construction costs. Some daylighting experts argue (and some case studies seem to show) that there are no net increased costs for daylighting—properly designed daylit buildings can be built at a cost per square foot that is comparable with other similar buildings in the region. Moreover, reduced consumption by the electric lights may mean that cooling equipment can be downsized with consequent cost savings.

Is Daylighting Cost Effective?

A program to promote daylighting needs to clear two cost-effectiveness hurdles before it would make sense to implement. First, the program needs to promote something that makes economic sense to those whom it seeks to influence. There is no point in promoting a technology that is not an economical option to building owners and occupants. Second, the program itself should not add so much cost to society that the overall benefits are not worth the costs. In the parlance of traditional energy efficiency program planning, these two perspectives are known as the participant and societal perspectives, respectively.

Participant Perspective

For a building owner who pays the utilities, possible dollar benefits from daylighting are:

1. electricity savings for lighting;

2. electricity savings for space cooling; and,
3. employee productivity and attendance gains for offices or, for retail, increased sales.

The costs are:

1. the cost of lighting controls;

2. increased heating costs in the winter to make up for heat once provided by electric lights;

3. possible increased costs to design and construct a daylit building; and,

4. increased heating and cooling costs from having more penetrations in the building shell.

For reasons which we will detail shortly, we’ve largely restricted our analysis to a comparison of the first two items in each list—in other words, a comparison of lighting energy and HVAC impacts to the cost of lighting controls. This approach has an intuitive appeal, since most daylighting experts advised us that while aesthetic and other benefits of daylighting can be had without controls, the controls are needed in order for a daylit building to actually save energy. One way to look at the situation is to postulate that people will seek daylit buildings for aesthetic reasons unrelated to energy but will want a traditional energy economics calculation to justify the installation of lighting controls.

From this perspective, the economics of daylighting appear reasonable. A typical office building in Wisconsin might expect to save 50 percent on lighting energy in daylit spaces, which is worth about 20 cents per square foot in electricity costs. Savings on space cooling and ventilation will add another 4 cents per square foot in electricity savings. If the building is heated with gas, gas costs will increase by about one cent per square foot to make up for heat that used be provided by the lights. Overall, the direct lighting and related heating and cooling savings work out to about 23 cents per square foot.

If the controls cost 50 cents per square foot on average, this represents roughly a 2.2-year simple payback on the controls. The present value of such savings over the life of the controls works out to be in the range of $1.75 to $2.50 per square foot, depending on the assumptions one makes about the discount rate, inflation of electricity prices, and the life of the controls, or a 45 percent rate of return on the investment in the controls over the first ten years after installation.

Adding productivity (or sales) and absenteeism effects to this equation appears to make daylighting an obvious winner. A ten percent gain in productivity in an office with labor at $130 per square foot works out to $13 per square foot annual savings—or about nine times the entire electricity bill for a typical office. Even a gain in productivity of only one percent would result in annual
Results

savings of more than one dollar per square foot, and a net present value of more than seven dollars per square foot.

While these numbers are breathtaking, they have a couple of limiting factors. First, as some of the stakeholders we interviewed pointed out, it is difficult to reliably single out a lighting change such as daylighting as the root cause of a change in productivity, sales, or absenteeism. Skeptics are unlikely to be persuaded to implement daylighting projects on the basis of productivity claims alone.

Second, the link between energy efficiency and productivity roles for daylighting is not a fundamental one. If productivity benefits are all that one is after, then daylit buildings can easily be built without the cost—and associated energy savings—of lighting controls. Similarly, productivity benefits are largely irrelevant in situations where one would consider retrofitting daylighting controls in spaces that already receive adequate daylight.

For these reasons, while we consider these non-energy benefits to be an important driving factor in a program to promote daylighting, we believe it is also important that lighting controls also be justifiable on strictly energy terms as well: the figures above suggest that they are.

Increased design costs for daylit buildings can be real if computer or physical modeling is needed. However, Dr. Donald Aitken, a recognized authority on daylighting advised us to “stop scaring people with modeling.” He emphasized that much can be achieved on a basic level by following simple design principles. The Weidt Group advised us that daylighting modeling might add one-half to three-fourths of a percent to the design cost of a 200,000 square foot building, but later emphasized that these costs tend to decline sharply with design experience. It is helpful here to distinguish between modeling (either physical or by computer) that enables visualization or measurement of the illuminance levels in interior spaces versus energy modeling to evaluate the energy impacts of various strategies. The latter is less costly and time consuming than the former.

As far as construction costs go, some of these costs are wrapped up in the basic orientation, geometry, and architectural features of a building that make it fundamentally daylighting friendly or unfriendly. This makes it difficult to even identify the aspects of a building’s design that are there solely for the sake of achieving daylighting. Moreover, some, if not all of these design decisions may be motivated by an aesthetic desire for natural light in a building, not necessarily by a desire for energy savings.

We also note that if daylighting results in reduced cooling loads on a building, there can be significant first-cost savings from being able to downsize cooling equipment.
Societal Perspective

At the direction of the AP-7 steering committee, we analyzed the societal cost-effectiveness of a daylighting program from two perspectives: (1) a total societal perspective, and (2) a traditional utility revenues requirement test. The former compares the societal benefits from the program to the total costs to implement the program to promote daylighting and to install the daylighting. The latter (which is somewhat mis-named in this context) compares the societal benefits from daylighting to the costs to run the program. In both cases, our analysis (detailed in Appendix C) is based on a typical office building in Wisconsin.

We had to make an assumption for how many daylit buildings would result from a program to promote daylighting in Wisconsin. To do this we propose a goal that each dollar spent on the program result in one square foot of daylit space. The two societal cost effectiveness tests shown in Table 2 indicate that if this goal can be achieved, the program will be cost-effective.

Table 2: Societal cost-effectiveness tests

<table>
<thead>
<tr>
<th>Benefits (per ft²)</th>
<th>Costs (per ft²)</th>
<th>Net Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Societal</td>
<td>$1.84</td>
<td>$1.50</td>
</tr>
<tr>
<td>Utility Revenue Requirement</td>
<td>$1.84</td>
<td>$1.00</td>
</tr>
</tbody>
</table>

Again, if employee productivity is added into the picture, the figures look even better. Even if we assume a minuscule one-tenth of a percent average gain in employee productivity for workers in daylit space, the program net benefits will be boosted by about $1.30 per square foot. A ten-percent gain in productivity adds over $130 in (life cycle) benefits per square foot.

Because one of the aims of the program is to help build demand and daylighting infrastructure for daylighting throughout the state, it is also insightful to speculate how the program might affect the overall market for daylighting. This way of looking at the issue holds that there is some natural diffusion curve for daylighting in Wisconsin that the program seeks to accelerate.
Technological diffusion is often depicted in terms of an S-shaped curve, like that in Figure 1. Early on, penetration is very low, and adoption rates are slow as most of the market is either unaware of the technology or unconvinced of its benefits. Then as awareness and acceptance build, adoption rates increase. Finally, market penetration plateaus at some level determined by the share of the market for which the technology makes economic sense. If daylighting is on a similar trajectory, then a statewide program to promote daylighting might accelerate the adoption curve, or even increase the ultimate penetration rate of the technology.

We created a model of technology diffusion for commercial daylighting in Wisconsin in order to examine the scope of market transformation effects from a daylighting program, and hence its value to society. The assumptions that go into the model are speculative for the most part, because no one can really know what the diffusion curve for daylighting will look like. But the exercise is useful in that it demonstrates that even quite modest assumptions about daylighting market penetration and program impacts result in significant net benefits to society.

The model we created combines assumptions about how a program might affect the diffusion of daylighting into various types of commercial buildings in Wisconsin with projected growth rates in these sectors and estimates of savings from daylighting. Our assumptions about the diffusion curve for daylighting—and the effect of a statewide program—are conservative in a number of ways. Specifically, our model assumes that:
daylighting will never completely penetrate any market in Wisconsin: at most, daylit buildings will ultimately represent 30 percent of new construction;

no more than five percent of existing buildings will ever be retrofitted with daylighting controls, and those controls will affect only about 25 percent of the floor space in the buildings where they are implemented;

it will take something on the order of 40 years for these transformations to take place;

a daylighting program will not affect the ultimate penetration of daylighting in Wisconsin: the only impact of the program will be to accelerate the natural diffusion process by about five years;

we only calculate benefits and costs for the first 13 years of the 40-year diffusion process (the extent of our growth projections); and,

we limit the analysis to lighting energy savings only.

We found that even under these quite modest assumptions, the 1997 value of the net benefits, excluding program costs, are on the order of $2.5 million. If we also assume that new office buildings will experience a modest one-percent increase in productivity, the benefits increase by $3.3 million, making the total benefits almost $6 million.

The above figures probably represent the low end of what might be expected. More aggressive scenarios that assume deeper and faster market penetration of daylighting yield net benefits that are on the order of tens of millions of dollars. It seems clear in this context that there is justification to spend several hundred thousand dollars a year to sponsor a program to promote daylighting in Wisconsin.

What Are the Market Barriers (and Market Drivers) for Daylighting?

A successful campaign to promote daylighting in Wisconsin begins by first understanding how daylighting is perceived in Wisconsin. We were able to get a view through the eyes of stakeholders in the lighting and building construction industries through telephone interviews and focus groups. The telephone interviews with design professionals and other possible daylighting stakeholders in Wisconsin along with architect focus groups, provided insight into the barriers they face, attitudes they hold, and driving factors that might be exploited to increase the penetration of daylighting in Wisconsin.

Below is a summary of the information we gathered. More detailed results of these investigations appear in the contractor reports.
Market Barriers

Some of the most significant barriers that we uncovered in our research include:

- a lack of awareness and understanding of what daylighting is;
- a perception that daylit buildings are more expensive;
- a lack of awareness of lighting controls, and uncertainty about how much energy daylighting will save;
- a perception among design professionals that daylighting is a complex design add-on that will increase design costs, along with a lack of exposure to design analysis tools;
- a perception that daylit buildings have problems with glare;
- a perception that daylit buildings have higher heating and cooling loads because they have more fenestration; and,
- concerns about the reliability and maintenance costs of lighting controls.

Lack of Awareness

Most people intuitively understand that daylighting means using natural light in buildings. Many outside the building industry—like facilities managers and developers—do not associate daylighting with the ability to save energy on lighting. And some confuse daylighting with having a view through a window. Moreover, some design professionals apparently think erroneously that the term daylighting is synonymous with solar heating.

To overcome this barrier, the program will need to clearly and consistently spell out that daylighting means the introduction of diffuse natural light into buildings to save lighting energy.

Perception That Daylit Buildings Are More Expensive

Design professionals, building operators, and developers expressed concerns about anything that increases the cost of a building. The recurrent theme of the interviews and focus groups was that clients and design professionals focus on first costs whether building or remodeling. Energy conservation is at best a secondary consideration for most businesses.

While concern with first cost sets an overall limit on a building, within this constraint there is an endless series of trade-offs of building features. Every building starts out with a wish list of features that is inevitably pared back as the costs go up. These trade-offs involve evaluating the worth of one feature in relation to another.

The program should seek to do three things in this area: (1) promote design principles that can be used to increase the penetration of daylight into buildings
in a relatively cost neutral way; (2) promote a systems optimization to
daylighting that seeks an overall optimal investment in mechanical systems,
glazing, and lighting controls; and, (3) emphasize the aesthetic and productivity
benefits of daylighting in order to increase its perceived value. In addition,
gaining an early commitment to admitting natural light in principle will
influence over-arching design considerations (such as orientation, footprint, and
window placement) that make a building fundamentally either friendly or
unfriendly for daylighting. These decisions largely precede the trade-offs that
occur among the more detailed design features.

Lighting controls will still be left in the mix of features that must compete for
limited funds. In this case, the energy savings payback must be attractive, and
the savings must be seen as relatively risk-free. Inevitably, controls will be
omitted in some cases. Here we would argue that the program should take the
view that a daylit building without lighting controls can always be retrofitted
later, while a building that is fundamentally hostile to daylighting represents a
lost opportunity that will likely never be realized until the structure is razed.

Lack of Awareness of Lighting Controls

Except for lighting designers and electrical contractors, we found widespread
ignorance of automatic lighting controls that save energy by lowering electric
light levels during daylight. Simple education of key interest groups, such as
architects and facility managers, will help remedy this market barrier.

Simply being aware of the existence of lighting controls and dimmable ballasts
is by itself insufficient to lead to widespread adoption of the technology. Most
of the people we spoke with recognized that the amount of daylight varies by
time of day, season, and with weather conditions, and were concerned about
quantifying the savings from lighting controls. Some also made the connection
between daylighting and heating and cooling costs in buildings.

The more benign manifestation of this uncertainty about the savings from
daylighting is a lack of comfort on the part of design professionals who would
like to promote daylighting to clients but feel they don’t have the numbers to
back it up. As one architect put it:

“In reality, the client wants to know ‘what will it cost me per square foot?’
We need to be able to tell them ‘here’s what it costs, here’s what you will
save, here’s how long it will take to pay it back’. I’m not sure we can do
that.”

At the other extreme, a lack of hard numbers is cause for outright skepticism of
the concept. In the words of one design-build firm manager:

“I think it is…cost prohibitive to the point you’re trying to save a penny by
spending a dollar.”
These reactions point to a need to clearly demonstrate the cost-effectiveness of lighting controls. This will be a key role played by the program’s demonstration sites.

**Perception That Daylighting is a Complex Add-on That Will Increase Design Costs**

Architects and others told us that they were reluctant to get into daylighting because it is a complicated, largely unknown, design issue:

“Daylighting is complicated. Complicated means more work, more expenses. It also means more time. Many tenants want to be in their new buildings as soon as possible, and are not willing to slow down the process by considering factors like daylighting.”

Design professionals also expressed a concern that they are under considerable competitive pressure to keep their fees low. This precludes exploring new technologies such as daylighting, especially ones that involve a lot of complicated analysis.

The program can address this barrier in a couple of ways. First it can help stimulate demand for daylit buildings by promoting the benefits of daylighting to those who commission new construction and renovation projects. Many architects and other design professionals enjoy working on projects in which the client can articulate needs and desires such as daylighting.

Second the program should seek to demystify daylighting to design professionals so that it is seen more in terms of simple design principles rather than elaborate computer modeling. Visualization modeling will not be needed on many projects. Energy modeling is likely to be needed to help sell daylighting in traditional energy measure cost effectiveness. We foresee a menu of tools available that are appropriate to the scale of the project. Small projects would be based on simple design guidelines and energy modeling for generic building types. Midsize projects will benefit from more detailed energy modeling. And large projects would be modeled and explored in still more detail. The program should help develop, disseminate, and train designers on tools at all of these levels to help them work through the energy trade-offs associated with daylighting projects.

Finally, by offering direct design assistance, the program will soften the financial impact of the learning curve that design professionals need to go through before they feel they can offer daylighting solutions for competitive fees.
Perception That Daylit Buildings Have Higher Heating and Cooling Loads and Have Glare Problems

The following statement by an architect exemplifies a belief that seems to be held by many design professionals—daylit buildings have higher heating and cooling loads:

“Daylighting does decrease lighting costs, but it increases air conditioning costs in the summer and heating costs in the winter. Although technologies are evolving that keep the heat in or out, you have to ask how much can you use and still save money in the long run, though, if you spend more on HVAC.”

This attitude seems to be based in three beliefs: (1) a perception that daylit buildings have vastly more fenestration than non-daylit buildings; (2) equating daylighting with uncontrolled direct sunshine; and, (3) discounting the heat contribution of electric lights.

The program can address this barrier through education efforts that show that proper architectural daylighting design has more benign heating and cooling impacts than most people think.

More importantly, the program can promote a systems approach to daylighting that takes into account the heating and cooling implications of daylighting designs so that daylighting schemes that have significant adverse heating and cooling impacts simply are not implemented. The goal of good daylighting design should be to go beyond the lighting aspects to offer a solution that is optimal in terms of thermal and visual comfort.

The issue of glare is a vital one to address in an era when nearly every desktop has a computer monitor on it. Daylit buildings with few or no glare problems can be built without a great deal of difficulty. The program needs to provide the proper training and knowledge to design professionals to help them understand and deal with glare issues.

Concerns About the Reliability and Maintenance Costs of Lighting Controls

The issue of the reliability of lighting controls is actually a two-fold one. On the one hand, architects and other “upstream” design professionals perhaps are not concerned about the reliability of these controls. The architects in our focus groups and interviews tended to assume that once the controls were specified, there was little likelihood of problems down the road.

At the other extreme, facility managers were acutely aware of how controls of any kind can have reliability problems that lead to complaints, or can have
maintenance issues not foreseen by designers more removed from the day-to-day operation of a building.

The program can best address these issues by promoting a total-systems approach to daylighting that ensures that workable control systems are specified, that the controls are correctly installed and calibrated, and that the needs of occupants are accounted for. To help achieve this goal the program should document the lessons of daylighting demonstration projects and develop guidelines for specifying, installing, and commissioning these controls.

**Market Drivers**

Obviously, the electricity savings that daylighting offers is one potential market driver. But as many energy efficiency programs have demonstrated, energy efficiency is at best a weak motivator for most business decisions.

Fortunately, daylighting has some non-energy advantages that may be significantly more compelling to most businesses than the prospect of an energy efficiency payback. There are four non-energy driving factors that can help promote daylighting:

- aesthetics
- productivity
- image
- building codes

**Aesthetics**

There is near-universal agreement that natural light is aesthetically preferable to artificial light. Architects told us that they love to work with natural light in a space—so long as their clients allow them to. Developers told us that buildings that have significant naturally lit spaces command a rent premium over those that have little natural lighting—though the concepts of natural light versus windows with a view are often mixed up with one another.

The program should capitalize on this natural driver for daylighting with the message that you can get the natural lighting you really want without a great deal of expensive add-ons—and save energy to boot.

**Productivity and Other Non-Energy Economic Drivers**

It is difficult to anticipate the influence that this angle might have on demand for daylighting. While the people we spoke with generally acknowledged that it is possible that people are healthier and more productive in daylit buildings, they also immediately recognized that these effects are difficult to prove. In our interviews and focus groups, we did not mention specific figures or examples,
so it is hard to know how people react to compelling case studies of productivity improvements, increased test scores for students in daylit schools, and higher sales in daylit retail operations.

Some targeted market research in this area would help us understand how to best promote this potentially important driver. In particular, more investigation is needed into how to play this angle in markets where the company that commissions a project is not the one that occupies the space, such as speculative office developments. The key here is understanding whether, or how, daylighting can add perceived marketability.

At the very least, the productivity aspects of daylighting might be enough to persuade a decision-maker who tends to be amenable to daylighting, but for whom the energy economics do not provide a sufficiently compelling motivator.

For institutional buildings it might be most useful to promote these non-energy benefits more widely. For example, promoting the studies that show higher test scores for students in daylit schools to Wisconsin school boards might result in directives to consider daylighting district-wide.

Green buildings and Other Image Drivers

The architects in our focus groups characterized their clients in one of two camps. First, clients who want to minimize initial costs, realize a quick return on their investment, and who desire to build a quick, easy project that will meet minimum code requirements—or clients who want to minimize long-term operating costs. And second, clients who take a long-term view of their investment, who value such things as “occupant comfort” factors, or who desire to develop a high image, innovative, or “green” building.

“A ‘dark ages’ client is only worried about money and wants the project done as quickly and cheaply as possible. Things like daylighting are the first things to go out the window.”

“An enlightened client is aware of issues like daylighting, is willing to look at innovative things, is sophisticated about energy issues. This kind of client often has more a more sophisticated vision of the needs of their building, and is willing to discuss design options that will help them achieve those needs.”

Architects see clients in the former group—which constitutes the majority—as a hard sell for daylighting, while clients in the latter group are more likely to value the benefits of daylighting.

The program should seek to address the needs of the latter class of clients where an image agenda meshes with daylighting. This might be a desire for a green building to demonstrate environmental commitment, a desire to be seen as high-tech, or a desire to be seen as an employee-friendly place to work. Daylighting
messages can be created to fit all of these desires, and these early adopters will help nurture a daylighting infrastructure that can then move out into the more general market for buildings. It is also important to distinguish between rental space and owner-occupied space. The latter provides a more natural setting for promoting these image drivers, but there may be ways to promote development of “green” speculative developments.

Building Codes

A new commercial building code is set to come into play in Wisconsin in 1997. This code has a several provisions that could act as drivers for stimulating daylighting in Wisconsin:

1. Lighting in daylit areas is required to be separately switched.
2. Spaces with lighting controls receive code credits that can be applied to other areas in the building.
3. The energy requirements of the code can be met through a systems optimization approach that looks at overall energy performance.

The first item removes a barrier to the implementation of lighting controls that arises when lighting circuits include both daylit and non-daylit spaces. However, if designers perceive it to be a costly requirement it could also perversely result in fewer daylit spaces. The second and third items are essentially carrots that encourage daylighting.

It is too early to tell how much effect the code change will have on demand for daylighting and lighting controls. It is, however, an opportune time to promote daylighting, since design professionals will be learning about the new code. The program should take advantage of synergies with code training efforts and develop materials that show how daylighting fits within the new code.
A Program Strategy for Promoting Daylighting in Wisconsin

Overall Strategy
Our proposed overall strategy can be summarized in the following points:

• increase awareness of what daylighting is and how it works;
• promote simple daylighting principles that can readily be integrated into new and retrofit building designs;
• provide practical demonstrations of the energy savings and cost effectiveness of daylighting in Wisconsin;
• provide hands-on training for architects and engineers that promotes learning through doing;
• promote a systems approach to daylighting that optimizes lighting and HVAC savings, along with cross-disciplinary coordination;
• promote awareness of daylighting at all phases of building design and construction, from initial architectural design to interior design, to proper calibration of lighting controls;
• promote the productivity and green building benefits of daylighting.

These strategic elements fit well with the four components proposed by the PSC. We would, however, add one additional program component: market research and evaluation. Market research is needed to better understand what daylighting messages work with which audiences. And evaluation is obviously needed in order to measure the effectiveness of the program.

Demonstration Projects
What we heard over and over from a variety of professionals is that people need to see real-world examples of daylit buildings in Wisconsin in order to be convinced that daylighting is practicable here. Therefore, we believe that an early priority for the program should be to concentrate on developing practical demonstration projects that represent tangible evidence that daylighting can work in Wisconsin. While there are examples of daylit buildings throughout the U.S., few have hard documentation of energy savings; and fewer are located in places with a climate like Wisconsin’s (although some daylighting experts argue that daylighting savings are not very climate sensitive).

In addition to meeting a “show-me” need, starting with demonstration projects will provide good material for later training efforts and yield valuable knowledge to help develop Wisconsin-specific guidelines for implementing...
daylighting. The projects should seek to demonstrate the process of daylighting, not just the end result.

The search for demonstration projects should begin with daylighting installations that are already known to exist in and around Wisconsin. While researching this report, we discovered at least a half dozen existing or planned daylighting projects in Wisconsin and neighboring states. The program should take full advantage of these in addition to seeking to sponsor new daylighting demonstrations.

Architects in our focus groups urged us to make sure that demonstration projects were real-world practical examples of the application of daylighting principles, and not extreme examples of how far you can go with technology. An added bonus would be demonstration projects where it is possible to measure employee productivity effects. We note that Southern California Edison—a leader in the promotion of daylighting—requires access to data such as sales data and employee attendance records as a condition for participating as a demonstration site.

The demonstration projects need to be demonstrably successful, so it will be important for the program to provide substantial expert assistance in the design of the daylighting systems, as well as subsequent commissioning. Some cost sharing may also be needed on incremental costs such as lighting controls in order to offset perceived hassles of participating as a demonstration project.

Although we desire successful demonstration projects, it is imperative that they be assessed in an objective and forthright way. Clients and design professionals need to feel assured that there are not a lot of warts that are being hidden in the interest of promoting daylighting. The program should also fund monitoring of the projects to document energy savings. The write-ups should discuss the lessons that were learned from each project.

The demonstration projects will be useful later for education efforts targeted at design professionals and promotion efforts for building owners and operators. They will also provide good working knowledge on commissioning issues.

The results of the demonstration projects should be prepared in a variety of formats and available at different levels of detail so that the information can meet the needs of various consumers. The materials should range from one-page executive summaries, to more detailed reports, to perhaps a CD-ROM compilation of sites with schematics and other details. A little market research should reveal how the information can best be prepared for those who will use it. Site tours will also be an on-going aspect of the demonstration projects.
Design Assistance

Another hallmark of the program will be to help build professional infrastructure to implement daylighting in Wisconsin. This need will be met in several ways: (1) by providing organized education opportunities for design professionals (discussed below in “Training for Architects and Engineers”), (2) assistance with the design of individual projects, and (3) development and dissemination of design aids such as software to help specify daylighting.

We see the design assistance aspect of the program as an opportunity to provide hands-on training for design professionals involved in their own projects. However, we also recognize that design assistance removes one market barrier mentioned by architects and other design professionals: reluctance to delve into the perceived complexity of daylighting without increased design fees.

We propose that the program implement design assistance at two levels: (1) in-house staff expertise to provide less-detailed consulting on small to medium-sized projects, along with some assistance in projecting the cost-effectiveness of daylighting controls; and, (2) program subsidization for daylighting consulting for larger or more complicated projects. Some mechanism will be needed to tie the level of design assistance to the size of the project; large projects will receive more detailed assistance than small ones.

Our inspiration for maintaining in-house staff for design assistance comes from conversations with staff at the Pacific Gas & Electric Energy Center, who advised us that a half hour of simple consulting early on in a project can avoid many problems down the road.

Providing professional consulting for larger projects is an approach that is currently being employed in a program sponsored by Northern States Power Minnesota. One aspect of this design assistance program offers daylighting consulting services for building projects that are 60,000 square feet or more. Anecdotal reports from this program suggest that the consulting pays off in more ways than one. Design teams that initially were somewhat suspicious of program-sponsored design assistance later went on to implement some of the daylighting concepts on their own in other projects. While the exact mechanism for arranging for this consulting has yet to be worked out, the working group envisions having a pool of qualified consultants on retainer to provide these services.

In addition to design assistance for specific projects, the program should develop and disseminate daylighting design guidelines and tools to help estimate daylighting savings. The former could be couched in terms of general principles and rules of thumb to apply in considering daylighting as a design option. The latter could be off-the-shelf software to help estimate daylighting savings for particular projects. This would help design professionals present their clients with a better case for daylighting.
Market research will be needed to assess whether there is an on-going design assistance function that the program can provide that would be useful in general to the daylighting market in Wisconsin—such as developing software or establishing a simulation facility for testing building models. Utility-sponsored facilities such as this have been constructed in Seattle and San Francisco. The cost-effectiveness of these efforts would need to be established on the basis of market research to gauge the size of the daylighting market and the demand for the facility or product.

**Training for Architects and Engineers**

The program should offer organized efforts to educate design professionals on the topic and techniques of daylighting. We foresee the need for ongoing overview workshops on the topic for architects and other design professionals, along with topically-oriented sessions such as training on software. These would be partially subsidized by the program, with some cost sharing by participants. Our budget is based on four workshops per year.

The training efforts should be implemented in conjunction with the Wisconsin chapters of the American Institute of Architects (AIA) and the Illuminating Engineering Society (IES). We note here that the Center has already conducted two workshops on daylighting, sponsored a speaker on the topic at an IES conference, and sponsored speakers on daylighting as part of training efforts on the coming new commercial code. All of these have been well attended and well received.

In addition to workshops, we recommend that the program seek to sponsor or assist in the development and implementation of longer formal education opportunities such as university extension courses or courses within architectural schools.

**Education and Promotion**

The main emphasis of this aspect of the program will be to:

(a) promote the benefits of daylighting to those who commission buildings and major remodels

(b) apprise non-technical decision-makers of key aspects about daylighting

(c) keep Wisconsin design professionals abreast of national developments in control technologies, analysis software, and other daylighting-related news

Although the PSC order calls for education for the general public, we feel that promotion should be focused on those who have a hand in how buildings are designed and built. Interview and focus group participants echoed these sentiments. Architects, developers, and facility managers are all appropriate—
and readily identifiable—targets for promotion of daylighting, since they all have at least some say in building design early in the process.

Effective promotion of daylighting will require much more than a simple message of saving energy. We expect that the promotion of productivity benefits and a green building environmental message will be prominent driving factors, with energy savings playing a secondary role.

Promotion of daylighting should highlight productivity benefits from daylighting. Even though productivity benefits are difficult to document, this angle offers a more compelling impetus for daylighting than the somewhat shop-worn save energy message. Corporations and institutional organizations are more likely to be receptive to this message, but some developers might also be able to use it to market daylit rental space.

Promotional activities will involve ads and articles placed in strategic publications, daylighting fact sheets for distribution, and a trade-show and convention presence. The demonstration projects will factor prominently in the promotion efforts.

The program can also play a role as an information resource. The program should act to digest the national literature on daylighting for design professionals and distribute this information in the form of a newsletter. Moreover, the program should maintain a good set of reference materials that can be loaned out. It should also have at hand fact sheets and other succinct materials that can be used to address basic or common questions.

Given the growing importance of the Internet as an information source, the program should develop and maintain a web site devoted to information and resources for daylighting.

Finally, the program should serve as a referral service to help put those who desire daylighting services in touch with those who can provide the services. The promotion efforts from the program will generate contacts with people who are interested in finding out more about daylighting and possibly implementing it for specific projects. In the latter case, the program can act as a referral agent to put clients in touch with design professionals who can deliver daylighting services. Additional thought will need to be put into whether architects or others who wish to be listed as daylighting specialists will be required to provide evidence of competency and experience.
**Evaluation and Market Research**

Throughout the program, evaluation and market research will be needed to refine the program approach and revise the overall strategy if necessary. Evaluation will provide feedback on the program’s effectiveness. A market research budget is needed to pre-test promotion messages as well as help identify how and to whom to target these messages.

**A Proposed Program Budget**

Our proposed budget is based less on the societal benefits of daylighting in Wisconsin (which we believe are substantially higher than this) and more on what we believe is a realistic expectation of what a new start-up program could expect to achieve in its first years. Realistically, it will take at least three to five years to fully implement a statewide daylighting program that addresses all of the elements outlined by the Public Service Commission, and it might easily take longer to effect a large-scale transformation of the market. Our budget scenario looks out for three years, at which point we believe that a review of the program should be conducted to gauge its effectiveness and the appropriateness of its focus.

A program budget (Table 3) of about $350,000 per year over a three-year horizon—plus $125,000 in Year 3 for market research and evaluation—will support:

- A full-time professional staff person (plus support) to manage the program and conduct some simple design consulting
- Seven demonstration projects
- Four half-day workshops per year
- Minimal advertising and promotion in the first year, increasing in the second and third years
- Design assistance consulting for about 20 projects
Table 3: Program budget over three years

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<th>Year 1</th>
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<td>Program Staff (salary and benefits)</td>
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<td>Demonstration projects</td>
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<td>Workshops</td>
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<td>40,000</td>
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<tr>
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<td>Develop design guidelines and fact sheet materials</td>
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<tr>
<td>Market research and evaluation</td>
<td>15,000</td>
<td>25,000</td>
<td>125,000</td>
</tr>
<tr>
<td>Program Total</td>
<td>$340,000</td>
<td>$350,000</td>
<td>$475,000</td>
</tr>
</tbody>
</table>

**Program Staff**

The budget for staff assumes that the program will retain one full-time professional person to both manage the other aspects of the program as well as provide some design assistance. Some support budget is also included in this figure (additional support is built into other specific budget areas such as workshops). It is important that the staff person retained for the program be technically proficient in daylighting and have sufficient experience or training in design and construction to have a credible presence with other design professionals.

**Demonstration Projects**

We anticipate two kinds of demonstration projects: development of new demonstration sites and documentation of existing examples of daylit buildings in and around Wisconsin. The cost of new demonstration projects depends on a variety of factors such as how much extra design assistance is required and whether the program needs to partially, or wholly, fund the incremental cost of lighting controls. The cost of documenting existing sites is limited to the cost of monitoring and interviewing participants. Table 4 shows our estimates of typical costs for these activities.
Table 4: Cost of demonstration projects

<table>
<thead>
<tr>
<th></th>
<th>new site</th>
<th>existing site</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Design assistance</td>
<td>15,000</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Incremental cost of controls</td>
<td>10,000</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Monitoring and analysis</td>
<td>8000</td>
<td>8000</td>
<td></td>
</tr>
<tr>
<td>Commissioning assistance</td>
<td>2000</td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>Interviews</td>
<td>1000</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Case study write-up</td>
<td>4000</td>
<td>4000</td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>$40,000</strong></td>
<td><strong>$15,000</strong></td>
<td></td>
</tr>
</tbody>
</table>

We assume that costs for demonstration projects will occur early on, then decline as time goes on. The budget is based on two new demonstration projects and documentation of one existing one in the first year, then one of each in each of the remaining two years.

**Design Assistance (Consulting)**

We assume here that design assistance will require $5000 to $15,000 in consulting costs per project. Our budget assumes that design assistance will become more prominent as the program becomes more known in the professional community.

**Workshops**

The budget for workshops assumes four half-day workshops per year at a cost of about $10,000 each. These costs are based on previous Center-sponsored workshops and assume an average attendance of about 50, with a $100 fee to partially offset workshop costs. We assume that workshop costs will decline somewhat in the second and third years of the program once the materials have been developed and tested.

**Advertising and Promotion**

We assume that promotion activities will increase over time as the other elements of the program are put into place. As a point of reference, the statewide program to promote high efficiency motors spends about $100,000 annually.
Develop Guidelines and Fact Sheets
We assume that these will be developed in the first year, then updated and reprinted in subsequent years.

Daylighting Newsletter
The cost of this item is based on the average per-issue cost of Motoreader, the Center’s newsletter to promote high efficiency motors.

Market Research and Evaluation
Market research will allow the program to better identify specific target markets in which to promote daylighting, pre-test the program messages, and to better understand how the program can meet the needs of clients and design professionals.

We assume that in the third year, the program will be subjected to a comprehensive evaluation that seeks to assess its effectiveness, as well as whether the focus of the program is appropriate.
Appendix A: Literature Review

Summary of Readings Pertaining to Daylighting

• General Daylighting Texts
• Case Studies
• Indirect Benefits
• Publications for Daylighting
• Lighting Controls / Occupancy Sensors
• Utility and Laboratory Information
• Behavior and Monitoring
• History / Market Potential
• Integrated Design / Construction
• Products, Services, Software
• Energy Code

All articles are classified under one of the above ten categories. An overview of the article is provided. Each article will be filed in the order it appears in each category. For those articles which appear in a collection or are otherwise not filed in the order they appear, an indicator “*” will be follow the titles with reference to their location in the overview. These articles will be placed at the end of each section.

There is only one topic listed per entry, reflecting the main subject, though several topics may be discussed in an article. Thus, an integrated design article may cover some aspects of lighting controls, but would not be found in the lighting control category. Utility and Laboratory Information may include aspects of any of the other categories, but due to the information source is separate from the general readings.
General Daylighting Texts


Case Studies


Target Stores are using sun tracking deep daylighting systems to reduce the electric lighting load. The store presented is in Fullerton California and uses different methods of controlling daylight for different zones in the store. The softlines areas used the trackers while the hardlines areas underwent a more standard ballast improvement and bulb changeout. Overall, a 57% reduction in lighting related energy was found.


This article describes the same Target store mentioned above. 42 skylights were installed by Brayer Lighting and supplied by the Natural Lighting Company. A dimming system balances the light levels. A constant 100 foot candles is maintained, day or night. An energy management system is used to control both HVAC and lighting systems. Several other environmentally “benign” technologies are used, including water for a refrigerant, with solar energy heating all the water in the store’s restaurant.
Appendix A: Literature Review


The reasons for the inefficiency of current supermarket lighting techniques is noted. The effect of three lighting scenarios are discussed. The business as usual scenario emphasizes the implementation of more efficient light bulbs and little else. Significant barriers are noted. The smart shelf scenario integrates lighting into product shelving with the Troy, New York prototype supermarket used as an example. The smart shelf provides lighting, product information, ductwork, refrigerant piping and general illumination. The advanced design concepts scenario changes the entire shopping experience, separating the shopping from the warehousing of products. The customer would order basic goods and have them delivered to the shopping area rather than the customer going to the goods.


This is a solar industry magazine that publishes case studies and discusses politics and other factors influencing the solar industry. The Mar/Apr 1996 issue has a case study on a daylit and passively heated University of Northern Iowa building. Daylighting results in savings of 77% (energy) and 64% (demand). The building cost was comparable to other academic buildings in the mid-west.

Lighting Research Center. Delta Portfolio. 1(4).

A case study of a daylit glove factory is presented. The methods of daylighting the offices and work areas are described. The areas are controlled by an EMS. The operation methods for each area is presented.


This case study involves the energy efficient modifications in the UCS’s new offices. The UCS was able to redesigned the entire building though they only were to occupy the top two floors. The various options and problems encountered are described. The offices are daylit. Rough costs and benefits are included.

Aitken, D. An Upper-Story Enterprise.

A description of the daylighting and passive heating strategy of the Western SUN office building. This was an ambitious plan to minimize non-solar energy inputs in Portland, Oregon. This study offers a description of the technology and some innovative ideas as well as the energy and cost savings of the retrofit. A financial agreement with the
owner allowed Western SUN to receive payments for the energy savings compared to other building occupants.


This article discusses the energy efficiency aspects of a new office building in Portland, Oregon. Norm Thompson, the clothier, wanted to create a “green” headquarters, though rent the property. In agreement with the owner, the company was willing to pay an extra $13,000 per year in rent in exchange for energy savings of $22,000 per year. Daylighting was a major factor in the design, with almost 1/3 of the wall surface area as glazing. The key criteria was that the building should cost no more on a square foot basis than a regular office building meeting the Oregon energy code. Major savings came from a reduced chiller (decreased by 50 tons, saved $30,000) and a $50,000 rebate from the utility. Overall the energy efficiency improvements increased costs by only $4 per square foot, over the hypothetical reference design and still below many commercial office buildings in the Portland area.


Very stringent first cost and operational cost criteria were used in the building of the San Hose Federal Office Building. Both form and function issues were closely matched to achieve the optimal design and cost goals. Daylighting was “maximized” while controlling for direct solar gain. A penetration of 30 feet around the perimeter was achieved with standard window and ceiling heights.

Employees Resond to Lockheed Building 157; Case Study: Lockheed Building 157

One year after the construction of a large daylit office building, employee attitudes were surveyed. All were quite pleased with the building design and daylighting effects. It was also found that productivity was up and absenteeism was decreased. In the more extensive case study, energy factors of design and decisions are described. Both perimeter and deep daylighting was utilized. Interior and exterior light shelves were used on the perimeter with literiums used in the center of the building. The HVAC system was integrated with the design, with some emergent problems. Due to non-compliance with California energy codes and large glass surface area, an alternative energy budget approach was used, illustrating that the building would consume only 45% of the allowable amount.
Kroner, W., Stock-Martin, J., and Willemain, T. *Using Advanced Office Technology to Increase Productivity.*

This is a case study of the West Bend building designed with Environmentally Responsive Workstations. An evaluation of the program includes a detailed description of the technology, how it effects the workplace environment and worker response to the system.

Lighting Research Center. *Delta Portfolio*, 1(1).

The first issue of the Delta Portfolio. Described are the lighting changes made during the construction of an A&P grocery store. During the construction process, Connecticut Light and Power encouraged the use of T8 bulbs and electronic ballasts. Several other technologies were used as well. Control methods are described. A blueprint of the store and specs for the lighting zones are provided.


A lighting demonstration project on the 7th floor of the State of Wisconsin Administration Building (SWAB) was conducted during 1993. Photosensors controlled 27 separate zones totaling 120 lighting fixtures. Three of the zones used occupancy sensors. Paybacks for controlled fixtures ranged from 3 to “many” years. Savings of 50% and 60% were realized in the best locations. Some locations had savings of less that 10%. The impact of reflecting surfaces on photosensors revealed that dark surfaces reduced savings, especially in more remote areas away from daylight sources. The importance of placement of photosensors is discussed. It is noted that less than 15% of the savings occurred during operating hours, in part due to high occupant traffic in open areas.


It was found that the annual electric lighting demand for deep interior core areas adjacent to south facing perimeter offices on the top floor of an office building can be reduced from 44 to 66%, depending on the city. Peak demand reductions fell by 6% in part due to decreased chiller size. Low emissive windows reduced heating loads be 30%. Payback times were substantial; 10 years for the Boston or Fort Worth areas and 20 years for Edmonton. The key factor was the capital costs of dimming systems and other advanced daylighting options. A key aspect of the design is a light guide window, located above the perimeter zone. The perimeter area ceilings were effectively used as a
light shelf. Analysis was conducted using the DOE-2 computer simulation program.


The architectural features and lighting practices of an unnamed daylit building are described. An ex-post evaluation of the building’s lighting electrical demand and savings was conducted. Each zone was analyzed. Improvements in lighting control system suggested that the an improved placement of photocells would improve the energy performance.


Simulation by computer and actual measurements were compared for 10 offices in the Government House in Trondeim, Norway. Actual measurements showed a savings potential of 30 percent using a constant lighting system, whereas the simulation showed 40% potential savings using a one year simulation length. When considering occupancy information, 60 savings were estimated for this building.


A fluorescent dimming system linked through daylighting was tested by monitoring, site inspection and interviews with operators for three office buildings. It was found that group control of individual offices presents many difficulties. In Building A, no correlation between available daylight and savings occurred. Deep areas were on the same photo-electric control as perimeter areas. The degree of dimming had been changed to avoid blacking out the deep areas. In Building B, the photo-electrically controlled dimming system had been deactivated. The system was turned back on for one zone to allow comparisons with similar zones. It was found that the percentage reduction in lighting power demand was greater than the percentage contribution of daylighting illumination. In Building C, the operator was interviewed. The dimming system had been deactivated due to interference with renovation and interior design plans and a belief that more energy efficient systems could be used for the interior and perimeter areas.
An elementary school had put in place a dimming system that would respond to daylight. Prior to commissioning the system, lower than expected savings resulted. Post-commissioning resulted in a 27% reduction in lighting power due to dimming. Total savings came to 76%, much of which was due to a switch from magnetic ballasts and T-12 lamps to electronic ballasts and T-8 lamps. If blinds were left open, the dimming savings would have been 36%.

Light pipes are used to daylight 244 m$^2$ in an office complex. Tracking mirrors direct light into eight prism light pipes. Each pipe covers 23 m$^2$. During dark or cloudy times, two metal halide luminaires light the pipes. While economics was not considered in the design, it is expected that mass production will result in a 20% to 57% savings within the decade.

A description of a daylit primary school is described. The building made use of standard construction technology and minimized northern window exposure to maximize the “cold protection - sun collection” goal. Customer satisfaction was positive, especially during the hot season. Some problem with glare was noted; fluorescent lights were used during cloudy weather and during the mornings and late afternoons of autumn and winter.

The ABN AMRO bank’s head office in Amsterdam is profiled. A dimming system was installed throughout the building, with all rooms containing measuring equipment to determine kWh consumption. Simply switching to an electronic ballast saved 20%. Daylight-dependent controls saved between 7 and 47% (over the electronic ballast savings). Savings were greatest for outer wall side of the office. Overall 60% savings resulted on the outer walls and 25% on the inner walls. The payback for outer wall areas was 3.3 years with no subsidy and 1.9 years with a subsidy. The inner wall areas exhibited a payback of 8.7 years with no subsidy and 5.0 years with a subsidy. Information about the subsidy was not available.
Indirect Benefits

Kroner, W., Stark-Martin, J., and Willemain, T. Using Advanced Office Technology to Increase Productivity.

This is a case study of the West Bend building designed with Environmentally Responsive Workstations. An evaluation of the program includes a detailed description of the technology, how it effects the workplace environment and worker response to the system.

Romm, J. J. and Browning, W. D. Greening the Building and the Bottom Line. Rocky Mountain Institute.

This paper documents cases where efficiency improvements in lighting, heating and cooling have measurably increased worker productivity. Other factors related to lighting and decreased defects and mistakes. The disparity between salary costs and energy costs is illustrated, the main point being that changes in productivity far outweigh energy efficiency costs. A variety of industries are considered, including a post office, office buildings, retail store and tool manufacturer. A copy is also available at the ECW library (#4428).


This article explains that there has been a correlation between daylit buildings and consumer buying behavior and workplace productivity. The Eco-WalMart is cited as an example for purchases and the Lockheed building for productivity. Productivity tends to rise by virtue of decreased absenteeism. By decreasing absenteeism, the added costs associated with construction were paid for in one year vs. a four year strictly energy savings payback. Another example is the unusual design of a bank in the Netherlands. No desk is more than 23 feet from a window. Combining energy savings and decreased absenteeism, the added costs were paid for in three months.

IAEEL Newsletter, 14:5. February, 1996.

The energy savings resulting from a daylighting project in several North Carolina schools are presented. Chillers size was reduced by 10% (compared to non-daylit similar buildings). Non energy benefits are also discussed including increased attendance and performance.

The press release describes the findings of two studies of the effects of daylighting on school energy costs and student performance. Tests scores were 5 to 14% higher in daylit schools over non-daylit schools. Energy consumption was between 22 and 64% lower for daylit schools. It was noted that the average middle school will save about $500,000 over ten years, though the higher student performance is more important.

Nickas, M. and Bailey, G. *Analysis of the Performance of Students in Daylit Schools*.

A study of elementary school students attending similar schools in Johnston County, North Carolina was conducted to compare the effects of daylighting. It was found that attendance at daylit schools was 3.2 to 3.8 more days per year and that students were healthier. Higher light levels appeared to reduce library noise levels. The full spectrum light induced a more positive mood in students. The additional vitamin D resulted in nine times less dental decay and an average of 2.1 more centimeters in growth. The above press release refers to this study. To control for selection bias, the relative improvements in test scores was considered rather than average scores between schools. An explanation of the methodology is included in the report.


A building using DDC in West Bend, WI is described. The focus of the article is on productivity increases due to the “intelligent” system. Open office area workers as well as those in closed offices have personal methods to control comfort levels in their airspace. A measure of productivity before and after the move to the new building studied the number of insurance claims filed by each employee. A surprising 16% increase was found and maintained. To test the contribution of the HVAC design, it was disabled during two random two-week time periods. Some employees selected out of the study and demanded that the system be turned back on for them. A decrease of 2% productivity was found, though estimated at 5% if all employees were included. Thus the system contributed to a 2 to 5% productivity increase. During times when employees were not at their desk, the system would turn itself off. The result was an average building temperature higher than normal, resulting in lowered energy costs.

A series of case studies of energy efficiency retrofits is presented. What makes them unique is the fact that productivity gains were unanticipated, though significant. It is noted that yearly energy costs are about $1.37 per sq. ft. while labor costs are about $130 per sq. ft. Thus small change in productivity can have a far greater effect than changes in energy costs. One retrofit resulted in a 540% ROI largely due to improvements in productivity. Energy savings are also discussed.

**Publications for Daylighting**

*Progressive Architect*

Look to new techniques. One issue described the Lockheed Office building. Mixture of form and function.

*Building Operating Management*

Have had previous issues on efficiency in facilities. See March 1996.

*Corporate Report Wisconsin*

Articles on various factors effecting Wisconsin businesses, good and bad. Industry specific special reports as well as general discussion.

*Inland Architecture. The Midwest Magazine of the Building Arts.*

Focus is on MidWest architecture. Discusses general industry issues and particular projects.

*Building Design and Construction*

June ‘96 issue has an article on “green” approaches to office design. Covers a variety of issues affecting the construction industry. Some cross over to architecture.

*Constructor*

Deals with construction management. Appears to focus more on broad issues affecting the construction trade rather than specific projects.

*Buildings*

Covers the construction and management of facilities. Covers issues from optimal roofing to security to space planning and how the worker interacts with the office.
Appendix A: Literature Review

CADDET Energy Efficiency. Centre for the Analysis and Dissemination of Demonstrated Energy Technologies.

Published by the IEA and OECD, CADDET puts out “Maxi Brochures.” Number 01 cover several aspects of daylighting, but also includes information about controls, general energy consumption information, demonstration projects and updates recent technological advances. They also have the CADDET Energy Efficiency Newsletter that offers case studies and recommendations for energy efficient lighting systems.

Building Operating Management

June 1996 has the annual product guide. Editorial of the same issue discusses that productivity is more important than cost reduction. When combined with employee moral, almost twice as many executives are concerned more with those issues than cost reduction.

Engineering News Record

A weekly magazine that discusses current topics and happenings affecting the electric power market. Discusses topics such as accidents, international work, planning and particular buildings.

Architecture

Covers issues related to the whole field of architecture. Greater emphasis seems to be placed on the form of a building, rather than the function.

Wisconsin Architect

Covers the entire architecture filed, with a focus on Wisconsin.

Lighting Controls/Occupancy Sensors


The well studied Lockheed office building in Sunnydale, CA is described. The background, project design process, performance studies and lighting control retrofits are presented. Changes in photosensor location were found to have a major impact on improving the lighting system.


It is noted that the cost of the actual dimming ballasts is not the main cost of a dimming project. Rather, the new wiring which must be put in contributes the largest amount of costs. Thus, despite manufacturer’s
efforts at reducing the cost of dimming ballasts, the cost of dimming is not expected to go down in the near future.


This publication presents an overview of the operations of fluorescent lamps. A worksheet is presented that allows for information from ballast manufacturers to be recorded and compared.


A brief abstract that describes various aspects of dimmable ballasts. These include the purpose, technological overview, methods and results. Positives and negatives are discussed with brevity.


This article offers a concise history of changes in the DSM market. One section focuses on dimming controls for controlling lights. It is noted that dimming was not cost effective until recently. Additionally, labor costs are decreasing, especially in retrofits, due to improved design and familiarity with the technology. The importance of creative savings arrangements for leased properties and the link with productivity gains is noted.

Energy Efficient Procurement Collaborative. Lighting Controls.

A list and description of databases for information on energy efficient lighting control manufacturers and purchases is offered. The databases cover information from technical to economic factors.


The author is an employee of Johnson Controls, Inc. Discusses various factors to be weighted when making decisions about lighting controls. He points out that the public does not feel responsible for lights in public areas. Thus they will not turn them on and off. However, responsibility is felt towards private areas such as offices.

Beck, P. Lighting Controls Offer a Wide Range of Options. Electrical Design.

The various options for lighting controls are discussed. It is noted that switching fluorescent lights on and off shortens lamp life. Thus occupancy sensors should not be used in areas with steady streams of people going in and out.

The cost and performance of various lighting techniques are discussed. The authors consider six control strategies and study the subsequent energy savings from each. Non-tangible benefits are not considered.


This study reviews current control technologies and strategies in the U.S. and Europe. A survey of utilities, manufacturers and specifiers is discussed. A few case studies are included. Recommendations are made as are the steps to take when implementing the recommendations.


An annotated bibliography to the above study.


The authors discuss the belief that automatic lighting controls with appropriate manual overrides offer opportunities for increased energy efficiency, occupant satisfaction and improved productivity. The key to a successful design is understanding how people react to and make decisions about lighting. Greater energy wastage and lower satisfaction were found for lighting controls in areas where people had little or no control. The needs for different users of the space should be considered as well. A cleaning crew may have very different lighting control requirements than office workers. Several levels of lighting interfaces may be appropriate. Key is the context under which people may expect control due to “perceived ownership.”


This issue covers the broad topic of daylighting technologies and practices. Controls, including dimmable ballasts and sun pipes are described. The benefits of daylighting are discussed, including aesthetics, health and productivity, color rendering and energy savings.

A $500,000 lighting control system was installed in an office building in Australia. The controls included continuous dimming ballasts. A laptop computer can be used to fine tune the controls. In the evening, lights are automatically turned off just after a 10 minute warning period when the lights go to full brightness. Pushing a button keeps the lights on for an additional two hours and allow for manual turn off. An immediate 50% reduction in electricity use was found for the controlled areas. Total savings for areas with and without the special controls was 35%. Benefits of reduced A/C costs, reduced harmonic interference and improved lighting power factors (from 0.85 to 0.95) were not included. ECW #937.1


The authors note that while the energy savings potential of daylighting has been well studied, the use of control systems, particularly compatibility, have been studied in a limited fashion. The interactions between components and overall system performance can seriously affect the savings potential. It was found that the high voltage class of dimming ballasts maintain efficacy over wider range of dimming than did lower voltage dimming ballasts. Additionally, it was found that dimming effects were often non-linear with some control range areas having almost no effect on the light output levels. The study also found that certain photo-sensors and ballasts did not always perform well in a lumen maintenance application.


This article discusses key aspects of a successful daylighting effort. The positioning of computer monitors, lighting levels and furniture arrangements are discussed. Issues concerning lighting controls (automatic vs. manual) are presented, though no absolute conclusions are made. ECW# 937.1
Utility and Laboratory Information


Substantial changes have occurred in the window market since the 1970s. Shading coefficients have increased while U-values have decreased. A detailed analysis of the factors that within windows that influence solar gain and heating losses is discussed. Building orientation, position relative to the window sash and transmittance factors make up part of the analysis. Other factors include multi-glaze spacing and gas-fills. Daylighting is the most recent concern, with the factors influenced by glass types. The importance of considering window selection as part of the larger building design criteria is noted.


A brief description of daylighting issues and methods. Also includes and excellent literature guide for more detailed information. Advantages and disadvantages, methods of transmitting daylight, methods of integrating controls and daylighting technologies are covered.


It is noted that a tradeoff exists between increasing the penetration of perimeter based light and the solar gain energy consumption. In order to overcome this, the use of light shelves, light pipes and skylights was evaluated. All technologies were found to be useful for getting daylight to the back of the rooms. The light pipe was more variant than the light shelf, and obvious limitations on skylight placements were noted.


A broad overview of past research provides information about thermal losses due to various window and wall types. A description of other program aspects such as technology transfer, simulation studies and others is provided.
Windows and Daylighting Group, Lawrence Berkeley Laboratory. 1995 (May). 
Publication.

Organized chronologically, all the reports and publications containing those reports are presented. Broken down by broad subject categories, this bibliography illustrates the range and depth of study of daylighting and windows at LBL.

The PG&E Energy Center, Pacific Gas and Electric Company. 
http://www.pge.com/pec/inftoc/daypho.htm,
http://www.pge.com/pec/progtoc/dayelec.htm,
http://www.pge.com/pec/progtoc/daymodlw.htm

Three internet sites covering many facets of improving energy use. The addresses will take one directly to a daylighting page. Resources provided by PG&E are included as well as a list of issues covering the modeling of daylighting projects is included in the first site. The second web page covers issues related to electricity and daylighting. The last site describes a class offered by PG&E on learning daylighting techniques

http://solstice.crest.org/environment/gotwh/general/lbl-daylight/index.html

This site presents general daylighting information including an introduction, why using daylighting can be beneficial and how to use daylighting.

Daylighting Example.

A general example of daylighting techniques using the Monte Carlo method of ray tracing.


A description of the use of daylighting for greenhouses. The holograms are used to redirect sunlight.


A number of factors influencing energy flows are discussed. How they were put into a data base of design tools is also included. These factors are: spatial distribution of skylight light, skylight area, transmission of visible light, well factor, illumination setpoint, interior partitions, ceiling height, and glazing characteristics. ECW library # 2267 (Daylighting Materials).

The impact of daylighting on a building designed for maximizing daylighting impact in California is discussed. If the potential were reached, the southern half of the building would use 44% of electric light capacity, while the northern half would use only 31%. However, it was found that actual lighting power was 75% for the South and 50% for the North. This was due to poor tuning of the electric light system, illustrating the importance of maintenance and monitoring. ECW library # 2267 (Daylighting Materials).


The impact of glazing with optical switching properties can impact the solar gain and subsequent chiller size requirements of a building. Implications and measurements are presented. ECW library # 2267 (Daylighting Materials).


A look back at past lighting philosophies and their impact on daylighting are used as a backdrop to discussing the history of modern daylighting techniques. A wide variety of subjects are covered, including glazing effects and simulation laboratories. ECW library # 2267 (Daylighting Materials).


Using 16 US cities, the authors tested the effect of daylighting with over 5000 parametric simulations. The interaction between daylighting and HVAC demand are included in the demand reduction calculations. It was found that chiller size increased with aperture size, though a total minimum demand was found. Where building lighting power intensity is 1.7 W/sq ft, moderate to large apertures realized a 14 to 15% reduction in peak demand. ECW library # 2267 (Daylighting Materials).


These nomographs are designed to aid in the initial assessment of a daylighting project for designers. Alternative designs can be compared rapidly. Detailed solutions can not be derived. Instructions are included. ECW library # 2267 (Daylighting Materials).

It was found that low-E glass can provide both heating and cooling energy savings to these buildings. Between K values of 0.5 and 1.0 (visible transmittance to shading coefficient), savings increased. ECW library # 2267 (Daylighting Materials).


This book covers many aspects of lighting in buildings. A description of the various electric light technologies make up the bulk. Also included are descriptions of computer aided design, retrofit technologies, occupant sensors and daylighting.

**Behavior and Monitoring**


The costs and advantages/disadvantages of six methods of monitoring lighting use are presented. Switching retrofits were made to four buildings to encourage decreased lighting usage with improvements in all, though to different degrees.


Determinants of lighting use are discussed. Predictions are based on a probit model utilizing the minimum daylight illuminance in the working area and subsequent probability of turning on the light. A mathematical model is presented and tested. A difficulty in repeatability hampered the study.


This study observed the energy usage and acceptability of light switch reminders. It was found that the reminders (placed over the switches) had a payback time of 10 weeks and was viewed positively by the office staff. It is interesting to note that lighting reductions were found in offices with no stickers, suggesting an influence that stickers had on visitors to areas with stickers. 26% of office workers who were aware of the purpose for a light auditor felt that its presence influenced their lighting decisions.

The methodology of a rudimentary light monitoring study is presented. A movie camera with wide angle lens was used to monitor an open classroom. An analog watch was dangled in front of the camera. Frames were taken every six minutes. A comparison of occupancy and lighting levels could be made.


The authors note the difficulty of obtaining reliable occupancy data concerning lighting. Five techniques are compared against actual occupancy information. Cost comparisons and the accuracy of each method is discussed.


The probability of switching on lights is compared to the amount of daylight entering an area. Based on the type of occupancy, a recommendation is made for the type of control that would minimize the chance of a light being on.

Rea, M.S. *Window Blind Occlusion: a Pilot Study*.

The use of window blinds and their effect on daylighting is discussed. Based on the time of day, and building face, one could determine the level of window blinds. The pitch of the blinds was not included as observations were taken from ground level, influencing the appearance of pitch. Not a strong study, but contains useful information about the interactions between time of day, and orientation.

**History/Market Potential**


The editor notes the gap between university based building research and practical application. Attention is paid to the lack of training and European vs U.S. technological breakthroughs. One reason U.S. architects cannot use many European technologies is due to cheap energy and building codes.
Daylighting in Wisconsin


A description of the ideas, specifications, applications, availability, cost and customer benefits. Customer acceptance is noted to have been generally favorable, with greater impact in new rather than old buildings.


The history of daylighting goes back as far as building technology. A history of its use is several eras is documented and illustrated. Only since the introduction of the electric light has daylighting suffered a setback. The use of modern technology as an end rather than a means to an end and the effect on daylighting is discussed.


Utilizing a growth model to predict the total commercial and industrial building stock, the authors use several energy efficiency models to illustrate the benefits of lighting controls on the new buildings. The perspectives of various stakeholders are taken into consideration, including end users, utilities, the lighting industry and the national economy.


A history of daylighting a solar positions through the year are presented. Examples of daylit buildings and the considerations of building orientation are included. Properties of glass and the interactions with solar angles are also covered.


The use of model energy efficient lighting designs, or lighting patterns to accelerate the implementation of energy efficient lighting is discussed. It was found that lighting designers have very little influence over the lighting decisions people make. Also noted is that most lighting case studies have focussed on expensive or monumental buildings, or fail to provide information in sufficient quantity or quality. The criteria of successful patterns for specific and generic patterns are critical. Specific patterns are for actual case studies whereas generic patterns are for buildings that have not yet been built.
Appendix A: Literature Review


The authors use data taken from hundreds of energy audits. The audits had mention of specific measures which could be taken. The clients were later contacted to see if they had implemented the suggestions. A systematic response was not found so statistical measure were taken to determine what situations resulted in what types of rejections. The nature of the suggestion, the amount of energy the company used and the type of industry were important factors. Simple payback and first cost were not found to be significant reasons for rejection. However, the authors cannot be sure that these factors don’t matter as concern over statistical noise and small sample size may be influencing the numbers. Many managers were found to demand paybacks of one to two years.


The impact of programs in other states is discussed. Also included is a rough estimate of the impact of a daylighting program in Wisconsin. Broad concepts of daylighting are also presented. ECW library # 2267 (Daylighting Materials).

**Integrated Design/Construction**


A philosophical discourse into true integrated design - integrating our buildings and products into the earth’s natural system. Offers a framework to evaluate one’s own decisions and some ideas on how to keep “non-natural”, hazardous materials from interfering with non-man made systems. Good reading.


This paper addresses the development and changes that will occur throughout building construction. A matrix of the tasks involved in construction and the personnel’s degree of involvement (DOI) illustrates who is in charge of what and what they can influence during the construction process. Of particular interest is that designers and other “externals” play a small role in all tasks during the construction process. Implications for daylighting are that once a building is under
construction it may be exceedingly difficult to make changes in plans that emphasize daylighting. In follow-up discussion, it is noted that as a project’s expense increases, the DOI of externals increases as well.


A comprehensive book on daylighting nuts and bolts. Basic fundamentals, integration with electric lighting, design tools, case studies and a technical appendix cover the range of daylighting aspects. More than just a how to manual, this book offers the reader an opportunity to fully understand and appreciate daylighting as both a technical issue and art.


The broad subject of energy in office buildings is discussed from the design phase to use of the building. Chapter Seven deals with electric light and daylighting. Three strategies are presented to decrease lighting energy use. Five control strategies and four strategies to bring light into the offices are discussed. Heating and cooling considerations are included.


This article discusses the tradeoff between reducing solar gain to reduce cooling demand while maintaining the visual transmission of light to capture daylight savings. Electrochromic glass may offer the best long term potential for dynamic, real time controls. One can also use an automated blind system to achieve a similar effect. In order to realize the maximum savings, the authors believe that it is important to package an integrated system that takes into account all the factors.


This article illustrates the basic mathematics behind daylighting practices. The gist of the article is to be able to model the effect of window area on the transmittance of light energy and energy consumption for lighting. One is able to determine the tradeoff between greater window area and increased heat losses in order that a minimal energy usage point be determined.
Appendix A: Literature Review


This article discusses the key components of a successful daylighting project. The importance of daylighting interactions with HVAC and other building energy systems is noted.

American Institute of Architects. 1993 (Jan 14). *Building Connections*.

A number of topics are covered. Three case studies of successful daylit/energy efficient buildings are described. These include the “Way Station’, NMB Bank and Rocky Mountain Institute. An extensive section discusses the design tools and technologies aimed at different levels of understanding, but overall aimed at architects and engineers. Regulatory aspects and information sources are also included.


It is noted that buildings in the U.S. consume twice as much energy as could be cost-effectively be reduced. A description of several software packages is included. These deal with building life cycle information, chiller commissioning and performance evaluation and tracking.


A method of considering the overall energy savings, human factors and daylighting is presented. The type of lighting requirements and interactions between potential daylight and electric light are charted. Focused on qualitative descriptions, though some quantitative criteria are presented.


A brief editorial on the benefits of integrating the various stakeholders into the building design process.


This article points out that “most daylighting analysis ignores HVAC effects, despite obvious interactions between windows, heat form lights and thermal loads. The value of integrating these aspects is discussed. It is noted that when properly scaled, the reduction in lighting and cooling for lights electric use is greater than the cooling required for daylighting. A brief cost calculation is offered. An important use of an EMS is discussed.

The importance of building design on the use of daylighting is discussed. An office building similar to the Lockheed offices is used as an example. The impact of North vs South offices, distance from the windows or atrium and time of day are illustrated. A brief cost breakdown with savings is included.


This section of the report describes the Seattle Lighting Design Lab. The lab focuses on lighting energy efficiency. The facilities and operations are presented.


The conditions of daylighting under which energy consumption may be increased or decreased are discussed. Wall and fenestration factors that combine to minimize energy requirements are discussed, based on the climate and orientation of the building. ECW library # 2267 (Daylighting Materials).


After studying hundreds of daylit buildings in the U.S., the author concludes that attempts at daylighting have resulted in a net increase in energy consumption. These causes are: visual desensitization, inadequate control of artificial lighting, irrational window treatment, and lack of effective shading and thermal shutters. The author is optimistic for the future as substantial analytical tools have been developed that will aid in the pre-construction design and assumptions. ECW library # 2267 (Daylighting Materials).

**Products, Services, Software**

*AIA Continuing Education System.*

This packet of information includes a registration form and description of the American Institute of Architects training program. A large number of topics and areas of interest are available for participants.

A review of the Energy-10 software program. This program is designed for small commercial buildings, though can be used for single family homes. An advantage over other programs includes the use of real weather information spaced at 15 minute intervals, its graphics capabilities and its ability to calculate the effects of insolation, a rarity among small desktop programs. Its accuracy was comparable with other desktop building energy modeling programs. This article highlights some of the plusses and minuses of the software, as well as how to contact the publisher.


Using the software program, WANDSIM, the authors discuss the simulation of transparent insulation materials (TIM) on window energy flux. Three systems can model the impact of TIM. These are within window glazing, transparently insulated masonry and transparently insulated glass wall. Each of these three have impacts related to passive heating and daylighting. Simulation results obtained for two days in Feb. is included for each of the three TIM applications. Simulation for a year’s energy flows are computes as well, both with favorable results for TIM. TIM’s impact on architectural choices and implications for window area are discussed.

**BEEM. Building Energy Estimation Module: Daylighting and Other Fenestration Effects.**

This software is designed to predict the daylighting and window impacts on building energy economics. Paybacks, peak usage and other factors are included. This does not predict values for an entire building, only window related energy and demand factors. Additionally, BEEM does not report glare, comfort, daylight spatial distribution or hourly solar profiles. A sample output is included.

**Superlite 2.0.**

A software program designed to predict illuminance levels inside complex building spaces. Daylighting and electric lighting are factored in. One can integrate daylighting and electric lights or choose to model them separately. Predicts the light levels on surfaces. Designed for researchers and lighting designers.

**Solatube** (advertisement).

The solatube is a roof mounted reflector with a long tube that reaches into living spaces. The tube is made of highly reflective aluminum and
is hermetically sealed with a dual glazed diffuser to improve insulation value.

*Window 4.0.*

Not the well known operating system. This program allows one to generate the U-value, solar heat gain coefficient, shading coefficient and visible transmittance of a window. Uses the rating procedure developed by the National Fenestration Rating Council.

*Suspended film and low-E glass.*

Describes a glazing system that improves window R values up to 7. This is found on the flip side of the Window 4.0 description.


This article notes that the assumption that window space = heat greater heat loss does not necessarily hold true with modern windows. With the new technologies one can also reduce heating loads. The use of photochromic glass and electrochromic glazings are discussed. Primarily focuses on electrochromic glazing.

*Active Daylighting Systems. So-Luminaire.*

An advertisement for So-Luminaire’ Active Daylighting Systems. Pictures of this technology at work in a grocery store, class room and factory floor are included.


This article describes the past contractual arrangements energy service companies (ESCOs) have had for different services. The private sector demands shorter payback and prefers more control whereas the public sector may be willing to enter into long term contracts. The implication for which type of energy efficiency options then become clear. Generally. Lighting companies have operated on short, two year contracts. Thus the terms of the contracts are critical.


The authors note that most daylighting simulation software is targeted to experts. Thus the architect must delegate part of the design process, decreasing efficiency. The relevancy of the daylighting strategy may be lost as the initial design phase (sketches) would move ahead without daylighting considerations. The key is to design a software package...
that requires minimal software learning and matches the architects' intuition and ways of working. This software is being developed.

**Energy Code**


This article describes aspects of the Wisconsin Building Code to be implemented on April 1, 1997. It is noted that the "new code decreases lighting power allowances and requires more switches and controls, especially for daylit areas." Windows will be graded on their heat loss and gain factors, the shading coefficient and U-value. No difference is made for the orientation of the window, a major factor affecting heat gain and loss.

Building code rules won't take effect next month. *Wisconsin State Journal*, page 7B.

A new energy code, set to be brought into effect on April 1 of 1996 was delayed for one year. Concerns of small contractors and construction companies are given as reasons.


This article discusses DSM programs in general, commenting on the importance of utility support of energy code requirements and improvements. It is also noted that in the absence of codes, utility programs can play an important role as a second best alternative.
Appendix B: Compiled Estimates of Savings from Daylighting

Table B-1 shows the energy and demand savings of daylighting, as found in the daylighting literature. The savings represent the decrease in electrical demand and use for lighting, not the whole electrical load. Unless noted, the savings do not represent HVAC impacts of daylighting. Additionally, if an Energy Center of Wisconsin library code number (ECW#) is not included, the materials can be found at ECW in the daylighting folder.

The range of lighting energy savings appears to be between 25 percent and 75 percent. Lighting energy savings of 50 percent appears to be the norm. Demand savings are less predictable, with proper commissioning being the primary factor. In cases where actual buildings are studied, the time of year and length of the study may influence savings. In simulation studies, the program and programmer assumptions will influence the amount of savings. Savings coming from actual building measurements and not computer models or other estimating tools are in boldface type.

Table B-1: Daylighting savings estimates

<table>
<thead>
<tr>
<th>Energy Savings</th>
<th>Demand Savings</th>
<th>Notes</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA</td>
<td>44% (south) &amp; 31% (north) vs. 75% (south) &amp; 50% (north)</td>
<td>The lower values for demand savings represent the actual findings for a poorly controlled daylit building. The higher values were the expected savings.</td>
<td>A Field Evaluation of Daylighting System Performance. LBL, July 1986. Benton, et al. Daylighting Material, ECW #2267, p.i.</td>
</tr>
<tr>
<td>60 - 70%</td>
<td>90%, 100% (both on sunny summer days)</td>
<td>60% energy savings is for a standard Wisconsin office building, whereas 70% is for a one-story Wisconsin office building. 90% demand savings are for dimming controls that dim to 90%. 100% is possible for an on-off system.</td>
<td>Wisconsin Public Service Commission. Docket No. 6690-UR-107. Prepared Testimony of Steven E. Selkowitz. Daylighting Material, ECW #2267, pp.8-9.</td>
</tr>
</tbody>
</table>
Table B-1: Daylighting savings estimates (continued)

<table>
<thead>
<tr>
<th>Energy Savings</th>
<th>Demand Savings</th>
<th>Notes</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>80%</td>
<td>80%</td>
<td>80% savings refers to the Union of Concerned Scientists office building.</td>
<td>Wisconsin Public Service Commission Advance Plan 7. Prepared Testimony of Donald W. Aiken, Ph.D. Background Materials for the AP-7 Daylighting Subgroup.</td>
</tr>
<tr>
<td>2.0 kWh/sq ft</td>
<td>16%</td>
<td>Dimming over non-dimming zones in a daylit building, the difference in power savings reflects the time of day.</td>
<td>Daylighting. Heating/Piping/Air Conditioning, April 1987. Yellott, John I. p. 63.</td>
</tr>
<tr>
<td>5.0 kWh/sq ft</td>
<td>38%</td>
<td>In sum, dimming contributed only 27% (with entire new system) of the demand savings, though this was due to poor commissioning.</td>
<td>Field Commissioning of a Daylight Dimming Lighting System. 3rd European Conference on Energy Efficient Lighting. Volume 1, Presented Papers. Floyd, D. and Parker, D.</td>
</tr>
<tr>
<td>NA</td>
<td>50% to 70%</td>
<td>In sum, dimming contributed only 27% (with entire new system) of the demand savings, though this was due to poor commissioning.</td>
<td>Field Performance of Daylighting Systems with Photoelectric Controls. 3rd European Conference on Energy Efficient Lighting. Volume 1, Presented Papers. Love, James. p. 77.</td>
</tr>
<tr>
<td>NA</td>
<td>36% (dimming alone). 76% (with total new lighting system.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75%</td>
<td>64%</td>
<td>Savings are for a passively daylit and heated academic building at the University of Northern Iowa. Heating demand savings are 1% and cooling demand savings are an additional 53% from a reference building.</td>
<td>A Passive Solar University Center. Solar Today, March/April 1996. Theyer, Burke Miller, p. 37.</td>
</tr>
<tr>
<td>NA</td>
<td>0.31 W/sq ft. (office) 0.8 W/sq ft. (factory floor)</td>
<td>Values are actual lighting densities, not savings. ASHRAE code is 2.3 W/ sq ft. for offices and 2.5 W/ sq ft. for factory floors.</td>
<td>Lighting Case Studies, Delta Portfolio, 1(4). Lighting Research Center, p.9.</td>
</tr>
</tbody>
</table>
## Appendix B: Compiled Estimates of Savings from Daylighting

Table B-1: Daylighting savings estimates (continued)

<table>
<thead>
<tr>
<th>Energy Savings</th>
<th>Demand Savings</th>
<th>Notes</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA</td>
<td>66%</td>
<td></td>
<td>The Union of Concerned Scientists’ New Energy Efficient, Daylit Office Building in Cambridge, Massachusetts. Aitken, Donald W. and Ris, Howard. p. 5.</td>
</tr>
</tbody>
</table>
### Appendix C: Cost-Benefit Analysis and Market Transformation
Model Assumptions and Results

#### Cost-Benefit Analysis

Table C-1: Life cycle benefit cost analysis (per square foot of daylit space)

<table>
<thead>
<tr>
<th>PERSPECTIVE COMPONENTS COSTS</th>
<th>Total Societal</th>
<th>Traditional URR</th>
<th>End-User/Customer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Program costs - direct variable</td>
<td>$1.00</td>
<td>$1.00</td>
<td>N/A</td>
</tr>
<tr>
<td>2 Program costs - administrative</td>
<td></td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>3 Program Equipment Costs - capital and O&amp;M</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>4 Program Rebates and Incentives to customers</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>5 Customer Energy Bill Increase (interfuel substitution)</td>
<td>N/A</td>
<td>N/A</td>
<td>0.11</td>
</tr>
<tr>
<td>6 Customer Equipment Costs - capital and O&amp;M</td>
<td>0.50</td>
<td>N/A</td>
<td>0.50</td>
</tr>
<tr>
<td><strong>TOTAL COSTS</strong></td>
<td>$1.50</td>
<td>$1.00</td>
<td>$0.61</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BENEFITS</th>
<th>Total Societal</th>
<th>Traditional URR</th>
<th>End-User/Customer</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 Electric Fuel Savings with GHG included</td>
<td>$1.45</td>
<td>$1.45</td>
<td>N/A</td>
</tr>
<tr>
<td>8 Other Fuel Savings</td>
<td>-0.10</td>
<td>-0.10</td>
<td>N/A</td>
</tr>
<tr>
<td>9 Electric Generation Savings</td>
<td>0.45</td>
<td>0.45</td>
<td>N/A</td>
</tr>
<tr>
<td>10 Electric T&amp;D Savings (Included in 9)</td>
<td>0.04</td>
<td>0.04</td>
<td>N/A</td>
</tr>
<tr>
<td>11 Customer Electric and/or Other Fuel Bill Decrease</td>
<td>N/A</td>
<td>N/A</td>
<td>2.35</td>
</tr>
<tr>
<td>12 Customer Rebates and Incentives</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL BENEFITS</strong></td>
<td>$1.84</td>
<td>$1.84</td>
<td>$2.35</td>
</tr>
<tr>
<td><strong>NET BENEFITS</strong></td>
<td>$0.34</td>
<td>$0.84</td>
<td>$1.74</td>
</tr>
<tr>
<td><strong>CUSTOMER PAYBACK (Years)</strong></td>
<td></td>
<td></td>
<td>2.2</td>
</tr>
</tbody>
</table>

Line 1: Assumes that program will result in at least one square foot of daylit space for each dollar spent
Lines 5 and 8: Gas heating penalty from reduced lighting usage
Line 6: Assumes that cost of lighting controls is the only significant capital cost
Lines 7, 9, 10, and 11: Savings are direct lighting savings, plus HVAC cooling and fan savings
Table C-1: Life cycle benefit cost analysis (continued)

<table>
<thead>
<tr>
<th>Assumptions</th>
<th>value</th>
<th>units</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>life-cycle measure life</td>
<td>15</td>
<td>years</td>
<td></td>
</tr>
<tr>
<td>discount rate</td>
<td>5.50%</td>
<td></td>
<td>a</td>
</tr>
<tr>
<td>present worth factor</td>
<td>10.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>energy costs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>customer electricity cost</td>
<td>0.0455</td>
<td>$/kWh</td>
<td>b</td>
</tr>
<tr>
<td>customer demand charge</td>
<td>100</td>
<td>$/kW</td>
<td></td>
</tr>
<tr>
<td>customer gas cost</td>
<td>0.4</td>
<td>$/therm</td>
<td>b</td>
</tr>
<tr>
<td>societal avoided cost of electricity (w/ GHG and SO2)</td>
<td>0.0451</td>
<td>$/kWh</td>
<td>c</td>
</tr>
<tr>
<td>societal avoided cost of electric capacity</td>
<td>50</td>
<td>$/kW</td>
<td>d</td>
</tr>
<tr>
<td>societal T&amp;D savings</td>
<td>5</td>
<td>$/kW</td>
<td>e</td>
</tr>
<tr>
<td>societal avoided cost of gas</td>
<td>0.36</td>
<td>$/therm</td>
<td>f</td>
</tr>
<tr>
<td>energy use</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>typical office lighting energy use</td>
<td>5.4</td>
<td>kWh/sf/yr</td>
<td></td>
</tr>
<tr>
<td>typical office lighting demand</td>
<td>1.5</td>
<td>Watts/sf</td>
<td></td>
</tr>
<tr>
<td>energy savings</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>lighting energy savings</td>
<td>50%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>lighting demand savings</td>
<td>50%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HVAC cooling savings</td>
<td>13%</td>
<td></td>
<td>g</td>
</tr>
<tr>
<td>HVAC fan savings</td>
<td>6%</td>
<td></td>
<td>g</td>
</tr>
<tr>
<td>HVAC heating impact</td>
<td>-30%</td>
<td></td>
<td>g</td>
</tr>
<tr>
<td>daylighting cost</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cost of controls</td>
<td>0.5</td>
<td>$/sf</td>
<td></td>
</tr>
<tr>
<td>program costs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>overall program cost</td>
<td>1.00</td>
<td>$/sf</td>
<td></td>
</tr>
</tbody>
</table>

a from STEP report
b from 1996 Wis. Energy Statistics, Wis. Energy Bureau
c weighted average energy cost assuming that all savings are on-peak, with the following seasonal distribution: 20% winter, 30% summer, 50% spring and fall. Energy costs from STEP report
d AP-7 steering committee estimate
e estimated as 10% of generation avoided cost
f assumed to be 90% of retail price of gas
g estimates are given as a percent of lighting kWh savings; based on a compilation of DOE-2 simulations done by the Weidt group for daylighting projects in the upper midwest.
Market Transformation Model

How the diffusion model works:

(1) estimate a natural (i.e., no statewide program) penetration curve for daylighting into the commercial sector in Wisconsin;

(2) combine (1) with estimates of total floor space and projected growth years, estimate the amount of floor space that will be daylit over some future period;

(3) estimate the discounted present value of lifetime lighting energy savings from the daylit floor space in (2) using societal avoided costs for energy and electricity capacity;

(4) obtain the net benefits by subtracting off the present value of the costs to implement the daylighting from the benefits in (3);

(5) postulate how a statewide program to promote daylighting might change the diffusion curve in (1), and then repeat (2) through (4) to get net benefits that would accrue under the influence of a program; and,

(6) look at the difference in net benefits with and without a program to get an estimate of the impact of the program.

Diffusion Model

Penetration in Year $t = \frac{P_{max}}{1 + \exp(-g^*(t-t_{1/2}))}$

Example:

<table>
<thead>
<tr>
<th></th>
<th>maximum penetration ($P_{max}$)</th>
<th>mid-point year ($t_{1/2}$)</th>
<th>growth parameter (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>0.3</td>
<td>2017</td>
<td>0.200</td>
</tr>
<tr>
<td>Program</td>
<td>0.3</td>
<td>2012</td>
<td>0.266</td>
</tr>
</tbody>
</table>
Figure C-1: Technological diffusion

Table C-2: Diffusion assumptions (all sectors):

<table>
<thead>
<tr>
<th></th>
<th>Perimeter Daylighting</th>
<th>Deep Daylighting</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max Market Penetration ($P_{max}$)</td>
<td>MidPoint Year ($t_{1/2}$)</td>
</tr>
<tr>
<td>Retrofit, Base Case</td>
<td>5%</td>
<td>2017</td>
</tr>
<tr>
<td>Retrofit, Program</td>
<td>5%</td>
<td>2012</td>
</tr>
<tr>
<td>New Construction, Base Case</td>
<td>30%</td>
<td>2017</td>
</tr>
<tr>
<td>New Construction, Program</td>
<td>30%</td>
<td>2012</td>
</tr>
</tbody>
</table>
Table C-3: Savings and affected square footage assumptions:

<table>
<thead>
<tr>
<th>Sector</th>
<th>Energy Savings (%)</th>
<th>Demand Savings (%)</th>
<th>Affected Square Footage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Perimeter</td>
<td>Deep</td>
<td>Perimeter</td>
</tr>
<tr>
<td>Office, Retro</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Office, New</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>School, Retro</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>School, New</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Health, Retro</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Health, New</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Warehouse, Retro</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Warehouse, New</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>College, Retro</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>College, New</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Grocery, Retro</td>
<td>25%</td>
<td>25%</td>
<td>25%</td>
</tr>
<tr>
<td>Grocery, New</td>
<td>25%</td>
<td>25%</td>
<td>25%</td>
</tr>
<tr>
<td>Retail, Retro</td>
<td>30%</td>
<td>30%</td>
<td>30%</td>
</tr>
<tr>
<td>Retail, New</td>
<td>30%</td>
<td>30%</td>
<td>30%</td>
</tr>
</tbody>
</table>
### Table C-4: Lighting energy use and building retirement assumptions:

<table>
<thead>
<tr>
<th></th>
<th>New Construction</th>
<th>Existing (Retrofit)</th>
<th>Annual Building Retirement Rate</th>
<th>Weekly Operating Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kWh/sf/yr</td>
<td>watts/sf</td>
<td>kWh/sf/yr</td>
<td>watts/sf</td>
</tr>
<tr>
<td>Office</td>
<td>5.40</td>
<td>1.50</td>
<td>6.49</td>
<td>1.80</td>
</tr>
<tr>
<td>School</td>
<td>5.75</td>
<td>1.80</td>
<td>6.07</td>
<td>1.90</td>
</tr>
<tr>
<td>Health</td>
<td>7.82</td>
<td>1.50</td>
<td>9.39</td>
<td>1.80</td>
</tr>
<tr>
<td>Warehouse</td>
<td>3.08</td>
<td>0.80</td>
<td>3.08</td>
<td>0.80</td>
</tr>
<tr>
<td>College</td>
<td>5.75</td>
<td>1.80</td>
<td>6.07</td>
<td>1.90</td>
</tr>
<tr>
<td>Grocery</td>
<td>11.03</td>
<td>1.80</td>
<td>12.25</td>
<td>2.00</td>
</tr>
<tr>
<td>Retail</td>
<td>8.12</td>
<td>2.00</td>
<td>8.94</td>
<td>2.20</td>
</tr>
</tbody>
</table>

### Table C-5: Electricity avoided cost assumptions:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy ($/kWh)</td>
<td>0.045</td>
</tr>
<tr>
<td>Demand ($/kW)</td>
<td>55</td>
</tr>
</tbody>
</table>

### Table C-6: Daylighting cost assumptions:

<table>
<thead>
<tr>
<th></th>
<th>New Construction ($/sq. ft)</th>
<th>Retrofit ($/sq. ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perimeter</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Deep</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Annual Deflator</td>
<td>2%</td>
<td>2%</td>
</tr>
</tbody>
</table>
Appendix C: Cost-Benefit Analysis

Table C-7: Life cycle cost assumptions:

<table>
<thead>
<tr>
<th></th>
<th>Discount Rate</th>
<th>Fuel Inflation</th>
<th>Capacity Inflation</th>
<th>Present Year</th>
<th>Years of Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.055</td>
<td>0</td>
<td>0</td>
<td>1997</td>
<td>15</td>
</tr>
</tbody>
</table>

Table C-8: Model output—total benefits from lighting energy savings

<table>
<thead>
<tr>
<th></th>
<th>New Construction</th>
<th>Retrofit</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Program</td>
<td>No Program</td>
<td>Net</td>
</tr>
<tr>
<td>Office</td>
<td>$1,009,104</td>
<td>$610,161</td>
<td>$398,943</td>
</tr>
<tr>
<td>School</td>
<td>$110,712</td>
<td>$69,016</td>
<td>$41,696</td>
</tr>
<tr>
<td>Health</td>
<td>$145,691</td>
<td>$92,751</td>
<td>$52,940</td>
</tr>
<tr>
<td>Warehouse</td>
<td>$445,052</td>
<td>$257,570</td>
<td>$187,482</td>
</tr>
<tr>
<td>College</td>
<td>$345,671</td>
<td>$216,542</td>
<td>$129,129</td>
</tr>
<tr>
<td>Grocery</td>
<td>$36,363</td>
<td>$21,599</td>
<td>$14,764</td>
</tr>
<tr>
<td>Retail</td>
<td>$739,872</td>
<td>$428,037</td>
<td>$311,835</td>
</tr>
<tr>
<td>Total</td>
<td>$2,832,465</td>
<td>$1,695,677</td>
<td>$1,136,788</td>
</tr>
</tbody>
</table>
### Table C-9: Model output—total costs to implement daylighting

<table>
<thead>
<tr>
<th></th>
<th>New Construction</th>
<th>Retrofit</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Program</td>
<td>No Program</td>
<td>Net</td>
</tr>
<tr>
<td>Office</td>
<td>$303,430</td>
<td>$185,671</td>
<td>$117,759</td>
</tr>
<tr>
<td>School</td>
<td>$27,741</td>
<td>$17,631</td>
<td>$10,110</td>
</tr>
<tr>
<td>Health</td>
<td>$31,155</td>
<td>$20,119</td>
<td>$11,037</td>
</tr>
<tr>
<td>Warehouse</td>
<td>$280,207</td>
<td>$83,510</td>
<td>$196,697</td>
</tr>
<tr>
<td>College</td>
<td>$89,370</td>
<td>$56,744</td>
<td>$32,627</td>
</tr>
<tr>
<td>Grocery</td>
<td>$17,015</td>
<td>$10,230</td>
<td>$6,785</td>
</tr>
<tr>
<td>Retail</td>
<td>$297,956</td>
<td>$174,046</td>
<td>$123,910</td>
</tr>
<tr>
<td>Total</td>
<td>$1,046,875</td>
<td>$547,950</td>
<td>$498,925</td>
</tr>
</tbody>
</table>

### Table C-10: Model output—net benefits (benefits-costs)

<table>
<thead>
<tr>
<th></th>
<th>New Construction</th>
<th>Retrofit</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Program</td>
<td>No Program</td>
<td>Net</td>
</tr>
<tr>
<td>Office</td>
<td>$705,674</td>
<td>$424,490</td>
<td>$281,184</td>
</tr>
<tr>
<td>School</td>
<td>$82,971</td>
<td>$51,385</td>
<td>$31,585</td>
</tr>
<tr>
<td>Health</td>
<td>$114,536</td>
<td>$72,632</td>
<td>$41,903</td>
</tr>
<tr>
<td>Warehouse</td>
<td>$164,845</td>
<td>$174,060</td>
<td>($9,215)</td>
</tr>
<tr>
<td>College</td>
<td>$256,301</td>
<td>$159,798</td>
<td>$96,503</td>
</tr>
<tr>
<td>Grocery</td>
<td>$19,348</td>
<td>$11,370</td>
<td>$7,978</td>
</tr>
<tr>
<td>Retail</td>
<td>$441,916</td>
<td>$253,991</td>
<td>$187,925</td>
</tr>
<tr>
<td>Total</td>
<td>$1,785,590</td>
<td>$1,147,726</td>
<td>$637,863</td>
</tr>
</tbody>
</table>
## Table C-11: Model output—daylit square footage (million square feet)

<table>
<thead>
<tr>
<th>Type</th>
<th>New Construction</th>
<th>Retrofit</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Program</td>
<td>No Program</td>
<td>Net</td>
</tr>
<tr>
<td>Office</td>
<td>1.119</td>
<td>0.658</td>
<td>0.461</td>
</tr>
<tr>
<td>School</td>
<td>0.113</td>
<td>0.067</td>
<td>0.045</td>
</tr>
<tr>
<td>Health</td>
<td>0.111</td>
<td>0.068</td>
<td>0.043</td>
</tr>
<tr>
<td>Warehouse</td>
<td>0.952</td>
<td>0.539</td>
<td>0.412</td>
</tr>
<tr>
<td>College</td>
<td>0.337</td>
<td>0.204</td>
<td>0.133</td>
</tr>
<tr>
<td>Grocery</td>
<td>0.046</td>
<td>0.026</td>
<td>0.019</td>
</tr>
<tr>
<td>Retail</td>
<td>1.012</td>
<td>0.574</td>
<td>0.439</td>
</tr>
</tbody>
</table>