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Publisher's version / Version de l'éditeur:
https://doi.org/10.1582/LEUROS.2010.06.03002
Leukos, 6, January 3, pp. 203-225, 2010-01-01

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NRCC-53233

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January 2010

A version of this document is published in / Une version de ce document se trouve dans:
Leukos, 6, (3), January, pp. 203-225, DOI: 10.1582/LEUROS.2010.06.03002

Demand-responsive Lighting – A Field Study

Guy Newsham and Benjamin Birt
National Research Council Institute for Research in Construction (NRC-IRC)
Ottawa, Ontario, Canada

Abstract

Demand-responsive buildings utilize control mechanisms to reduce their electricity use during periods of high grid-wide demand, primarily to aid utilities in maintaining grid stability. Dimming lighting is proposed as one such demand response mechanism, and several laboratory studies have explored the speed and extent of dimming that is either noticeable or acceptable to occupants. We conducted a field study to examine whether these laboratory findings could be applied in real buildings with commercial lighting control systems. The study, conducted during summer months, included an open-plan office with 330 dimmable luminaires, and a college campus with 2300 dimmable luminaires across several buildings. In the office building we conducted two afternoon demand response trials, which dimmed lights by up to 35% over 15-30 minutes. The power reduction achieved was 5.2 kW (23%), and 5.3 kW (24%), respectively. At the campus site we conducted three afternoon demand response trials, which dimmed lights by up to 40% over 1-30 minutes. The power reduction achieved was 15.2 kW (18%), 7.7 kW (14%), and 11.3 kW (15%), respectively. There were no lighting-related complaints to facilities management throughout the afternoons of the trials. Based on prior laboratory studies and this field study we suggest guidelines for dimming lighting as a demand response strategy.

1. Introduction

1.1 Demand response and the potential for lighting

Many jurisdictions in North America, experience a peak demand for electricity on hot summer afternoons. This occurs when an increasing air-conditioning load is added to other loads with (currently) quite constant daytime profiles, such as commercial lighting, and other loads which tend to rise in the late afternoon, such as residential end uses. In such situations utilities must import additional capacity (often at a high cost premium), switch in peak capacity generators, or reduce demand. Failure to match supply and demand through these measures will result in brownouts or blackouts. There might not be the capacity to build additional generation, transmission, and distribution fast enough to accommodate projected demand growth, and the frequency of peak demand problems is expected to grow[1].

As a result of this concern, there is growing interest in addressing this issue, at least partially, on the demand side [Piette et al., 2005; DRCC, 2006; Rowlands, 2005], that is, reducing the peak demand for electricity at critical times by eliminating electricity use, or shifting it to non-peak times, a strategy known as demand response (DR). The most commonly-referenced form of DR utilizes signals from the electric utility based on well-established forecast models of electricity demand, which typically provide market price signals at least three hours ahead [e.g. IESO, 2006]. End-users (or their energy supply company, or both) may receive incentives from the utility to make loads available for such actions. Rosenzweig et al. [2003]

[1] The current economic downturn has substantially reduced peak demand in many jurisdictions, consequently lowering the urgency of addressing peak demand issues. However, peak demand growth is expected to re-emerge in the long-term, as the economy rebounds.

estimated that a reduction of only 2-5% in system-wide demand at peak times could reduce the spot price for electricity by 50% or more.

As significant end-users, it will become increasingly important for buildings to participate in DR[2]. In commercial buildings, which represent 45% or more of the US summer peak electricity demand [Kiliccote et al., 2006; Rubinstein & Kiliccote, 2007], load reduction and shifting can be achieved with a modern energy management and control system (EMCS)[3]. For thermal loads, one strategy is pre-cooling, in which the building is over-cooled in the morning, and the building thermal mass carries some of this "coolth" to the afternoon to delay the need for air-conditioning during the hottest part of the day. Another strategy is simply to raise the thermostat set-point [Piette et al., 2005]. Lighting, which constituted 30% of peak electricity demand in California[4] [Rubinstein & Kiliccote, 2007] can also participate in DR, in which light levels are temporarily reduced. However, use of lighting systems is often not considered because central control systems infrastructure is less common than for thermal control [Rubinstein & Kiliccote, 2007].

By definition, the above DR strategies may cause interior conditions to deviate from recommended temperature and lighting standards [e.g. ASHRAE 2004; IESNA 2000]. This may result in an indoor environment that is uncomfortable to occupants, and might impair their performance. Indeed, Kiliccote et al. [2006] stated that "Occupant comfort under these sequences is still not understood". It would certainly be preferable if DR strategies did not disrupt building occupants. Switching lighting will obviously be noticed by occupants, and may cause dissatisfaction [Boyce, 1984; Piette et al., 2005 p.57]. However, smooth changes in lighting characteristic of dimming systems may be much more acceptable. In general, we need to gain a better understanding of occupant tolerance for the indoor environment changes resulting from DR strategies to better inform the design of DR programs. This paper addresses this challenge for dimming lighting as a DR strategy.

1.2 Prior studies

Several laboratory studies have explored the effects on occupants of changes in lighting conditions similar to the use of dimmable lighting in DR scenarios, for example, Tenner et al. [1997], Kryszczuk and Boyce [2002], Shikakura et al. [2003], Akashi and Neches [2004], Akashi and Neches [2005], Newsham and Mancini [2006], Newsham et al. [2008], and Newsham et al. [2009]. For brevity, we will not describe each of these studies in great detail, Newsham and Mancini [2006] provided such detail on earlier studies in the pages of this journal, and the latter three papers above are widely available.

All of these studies sought to define the speed and level of dimming which would be noticed or be unacceptable to occupants in office-like scenarios, though details of the experimental designs differed between the studies with regard to things like length of total exposure, expectation that dimming might occur, and the presence of a distracting task. To summarize the results, Tenner et al. [1997] allowed participants to set their own preferred level, up to a maximum of 830 lx (desktop). Fifteen minutes after the initial level was set, the light began to dim by 8% every 3 minutes. The participants could intervene at any time, and the point of intervention was defined as the acceptable light level. In trials where daylight was largely excluded, Tenner et al. reported that a mean reduction of around 13% was acceptable.

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[2] Demand reduction strategies may also yield energy savings during non-peak periods.
[3] In practice, there are challenges [Piette et al., 2005].
[4] Air-conditioning represented 32% of peak demand.

Kryszczuk and Boyce [2002] dimmed electric lighting from 1090 lx or 475 lx (desktop) over periods of 3.33 to 120 seconds in a room without daylight. The results showed that 50% of participants detected a 15-20% change in light level. Akashi and Neches [2004] dimmed electric lighting from 500 lx (desktop) over 10 seconds in a room without daylight. The results showed that 50% of participants detected a 15% change in light level, 50% of participants found a reduction in light level of 40% to be acceptable, and 80% of participants found a reduction in light level of 20-30% to be acceptable. Akashi and Neches [2005] performed further studies in the same experimental space, in which electric lighting was dimmed from 500 lx or 300 lx (desktop) over 10 seconds. The results showed that 50% of participants detected a 15-25% change in light level, 50% of participants found a reduction in light level of 55-80% to be acceptable, and 80% of participants found a reduction in light level of 30-50% to be acceptable. Shikakura et al. [2003] dimmed electric lighting from 750 lx (desktop) over periods of up to 16 seconds in a room without daylight. Results showed that 50% of participants detected an 8-20% change in light level. Newsham et al. [2009] showed that dimming of electric lighting from 500 lx (desktop) by 30-60% over 30 minutes, in an office with little daylight, caused little hardship[5]. Newsham et al. [2008] dimmed electric lighting from 400 lx (desktop) over 10 seconds, in an office both with and without substantial daylight. The level of dimming of electric lighting not noticed by occupants was 20% with no daylight, and 40-60% with daylight, whereas the level of acceptable dimming was 40% with no or low daylight, and 80% with high prevailing daylight.

In short, these laboratory studies suggest that substantial dimming over periods that may be useful in DR is possible without causing hardship[6] to occupants. However, publicly-available field studies of this approach are rare and limited in scope. For example, Piette et al. [2005] conducted trials of automated DR infrastructure at several sites in California. Most of these trials involved interventions in the heating, ventilation and air-conditioning (HVAC) system. One site did include dimmable lighting in office spaces, where occupants could individually define the level of acceptable reduction. The total lighting load was reduced by 31% during one event [p. B-26], and the authors noted that no complaints from the occupants regarding this lighting control strategy were registered [p.C-18]. SCE [2005b] and ADM [2007] also report on small-scale trials with dimmable lighting used as a DR strategy in California buildings. In these trials the authors noted potential problems when lighting was dimmed too aggressively.

In this paper we report on a detailed and systematic field study that enacted lighting dimming in accordance with the findings of these earlier studies, to more-fully examine the potential of lighting as a DR strategy.

2. Methods and Procedures

The field study was conducted at two sites, a federal government office building and seven buildings on a college campus, both located in southern Ontario, Canada. Both sites featured central lighting control systems with addressable ballasts, and control software that was modified to allow for the form of DR we wished to explore. Each of these sites is described below.

[5] This study also addressed changes in thermal conditions: ambient air temperature increased by ~1.5 ºC over a 2.5 hour period in the afternoon without causing hardship.

[6] The term "hardship" encompasses a variety of negative effects on occupants, potentially including discomfort, lower environmental satisfaction, and reduced task performance.

2.1 The office building

This building was occupied by Canadian federal government staff. The building layout was predominantly open-plan, with a few private offices and enclosed meeting spaces; this study was exclusive to the open-plan areas. These open-plan areas were in the two storeys above grade, and provided office accommodation for around 200 people. The addressable lighting control system had been in operation at this site since December, 2006.

The ambient lighting was provided by ceiling-recessed parabolic luminaires laid out on a rectangular grid, with no simple assignment of luminaires to individual workstations. Each luminaire featured 3x32W 4100K T8 lamps. Supplementary undershelf task lights were also provided to some individuals who, in the past, had requested them. Perimeter photosensors were installed, and the system was configured to dim luminaires near windows when daylight was available (daylight harvesting). However, photosensors were disabled on the days on which we conducted DR trials. The regular lighting schedule was 6:00am-6.30pm Monday-Friday.

Four lighting zones were independently controlled in this study, these zones are shown in Figure 1. The 1st floor featured a perimeter zone and an internal zone, and the 2nd floor featured a perimeter zone and a larger zone that was mostly internal but included some perimeter space. The total floor area of these four zones was ~ 1470 m^2. There were around 525 luminaires under control at the site, of which around 330 were in the four zones controlled in our DR trials. The normal luminaire output in the four zones during non-DR periods was a 70-84% dimmer setting[7], resulting in a power draw of ~ 22.6 kW; this equates to an operational[8] lighting power density (LPD) of 15.4 W/m^2 (1.43 W/ft^2). For this study, the central control system was configured to record all dimming signals to the four zones; the calculated lighting power draw to each zone was also recorded. Figure 2 shows the cubicle office furniture on the second floor, and the luminaires.

The lighting control system had a DR option, however, it did not provide the functionality required for this controlled study. The manufacturer made a custom modification to the software to allow us to specify the desired dimming time parameters, and to dim to specific dimming percentages.

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[7] Throughout this paper when we refer to a "dimmer setting" or "dimming lights to X%" at the field study sites, we are referring to the central software setting that translated into a signal sent to the ballasts, we are not directly referring to the relative light output of the luminaires. However, Figure 7 shows that, for the dimmer settings we typically used, the relationship between software dimmer setting and light output was close to linear.

[8] In other words, we base LPD on calculated actual power draw in typical operating state. If we simply count lamp labels and add a little for ballasts, and don't account for the fixed dimming less than 100%, then each luminaire is ~100W installed, and the LPD is ~22.4 W/m^2 (2.1 W/ft^2).

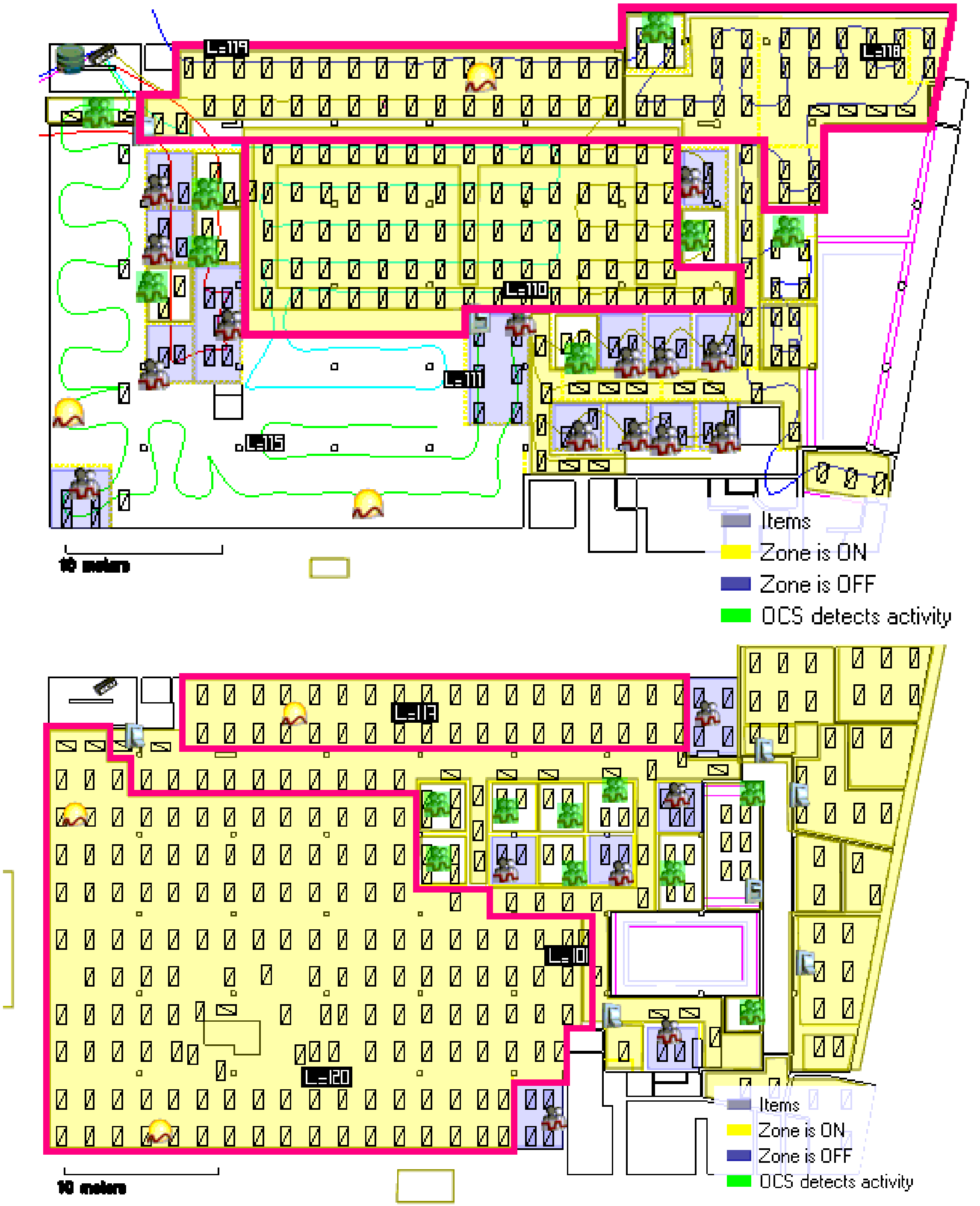

Figure 1. Floor and reflected ceiling plan of 1st (upper) and 2nd (lower) floors of the office building. The pink outlines show the four lighting zones that were independently controlled during the study. The yellow "sun-like" symbols indicate locations of photosensors, which were disabled on DR event days. Black boxes with text beginning "L=" indicate locations of illuminance loggers.

Figure 2. Photograph of the 2nd Floor of the office building, showing furniture and luminaires.

2.2 The college campus

This site included several buildings, occupied throughout the day and early evening by faculty, staff, and full-time and part-time students. The total building population may have been several thousand, depending on time of day and year. The study areas included classrooms, private and shared offices, circulation areas, and other mixed uses, in Buildings A-F and H. The addressable lighting control system had been in operation at this site since October, 2006. Figure 3 shows the campus plan, Figure 4 shows an example private office, and Figure 5 is an example classroom.

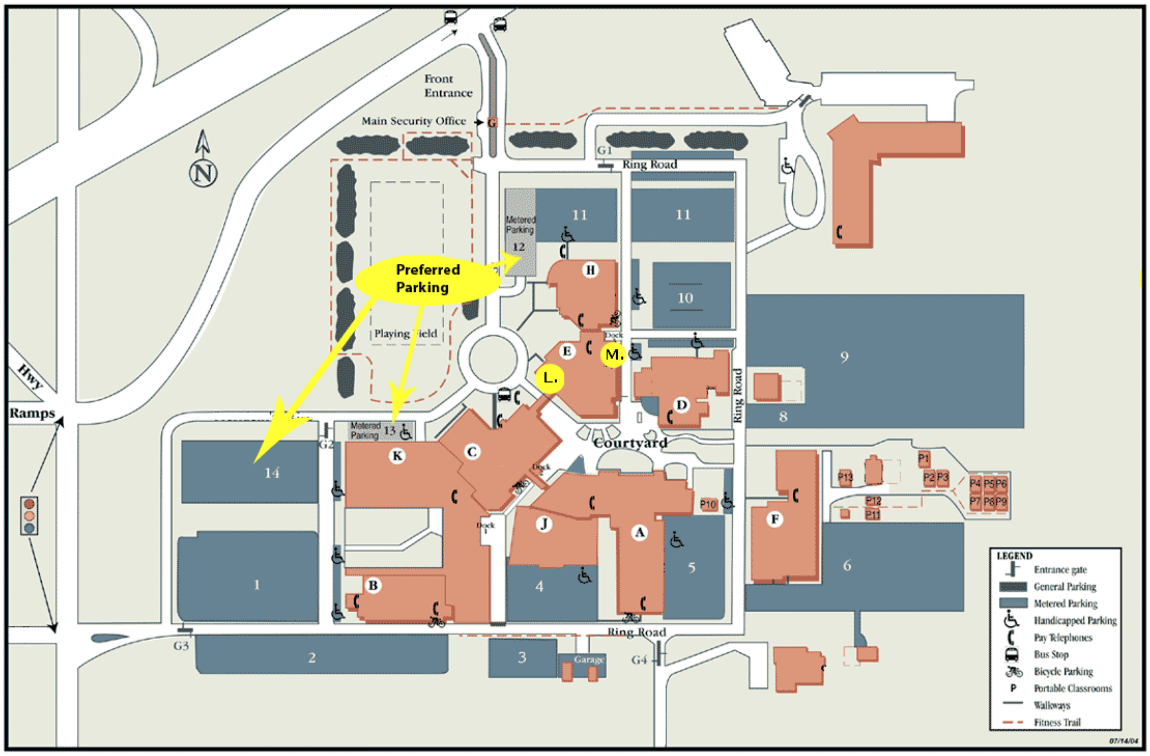

Figure 3. College campus plan

Figure 4. Example private office at the college, showing two-lamp recessed luminaires, and wall switches.

Figure 5. Example classroom at the college, showing two-lamp recessed luminaires.

Ambient lighting in all spaces with the lighting control system was provided by ceiling-recessed, lensed direct-indirect luminaires with two 3500K T5 lamps. In some spaces the lamps were 28 W, and in others they were 54 W high output. Around 50 spaces featured occupancy sensors and photosensors for daylight harvesting, which remained active during the DR trials. Occupants of private offices and classrooms could switch lights on and off, or dim the overhead lighting to their preferred level through a wall switch, as shown in Figure 6.

A central control system recorded all the dimming signals to each luminaire. There were around 2300 luminaires under control at the site, of which 1852 were dimmed on DR trial days. The total floor area serviced by the studied lighting system was ~ 20180 m^2. The normal luminaire output during non-DR periods was an 80% dimmer setting, resulting in a power draw, if all luminaires were on, of ~ 130 kW; this equates to an operational[9] lighting power density of 6.4 W/m^2 (0.60 W/ft^2).

The lighting control system in this building had a DR option, however, it did not provide the functionality required for this controlled study. The manufacturer made a custom modification to the software to allow us to specify a smooth dim down to the specified dimming percentage, over a configurable dimming period. If a particular luminaire in a dimming group was already lower than the specified dimming percentage (due to the operation of other local controls) it would not increase its ouptut but would stay at its lower level. Note, this modification did not allow us to return light levels back to normal after the DR event. Instead, luminaires remained at their lower output levels until they were switched off and switched back on again (most typically the following morning), at which time they would return to their default levels. It remained possible for occupants to use their wall controls to override the DR dimming.

[9] In other words, we base LPD on calculated actual power draw in typical operating state. If we simply count lamp labels and add a little for ballasts, and don't account for the fixed dimming less than 100%, then each 28W luminaire is ~60W installed, each 54W luminaire is ~115W installed, and the LPD is ~8.0 W/m^2 (0.74 W/ft^2).

Figure 6. Wall-mounted personal lighting controller at the college.

2.3 Night time illuminance surveys

We conducted detailed illuminance surveys at both sites. These were conducted at night, to ascertain the illuminance provided by the electric lighting system only. We also derived typical dimming vs. light output curves for the luminaires, and then used this information to chose appropriate dimming levels for the DR trials that balanced the load reduction with acceptable minimum illuminances at each site.

The luminaires in the spaces to be measured were switched on at normal output and allowed to stabilize for at least five minutes (time constraints prevented a longer stabilization periods). Measurements were made horizontally, at a standard height of 800 mm, typical of a desktop surface. In the office building, a measurement was made at the centre of every cubicle, and at select locations in circulation areas. On the college campus, time constraints precluded making a measurement in every space. Instead, we took a measurement in approximately every third space, choosing spaces that were representative of their neighbours. We chose measurement locations near the centre of each space, but not directly below a luminaire, where possible. In representative locations we measured dimmer setting vs. relative light output. Again, measurements were made horizontally in the space at a height of 800 mm. Luminaires were initially switched on at 100% output and allowed to stabilize for five minutes before making the first measurement. Dimmer setting was then decreased in 10% increments; again, we waited for output to stabilize, which took approximately two minutes, before making a measurement (time constraints prevented a longer stabilization periods). The graphs in Figure 7 show consistency within luminaire types, even at the college where the lamp type between luminaires was different. Figure 8 show samples from the illuminance survey.

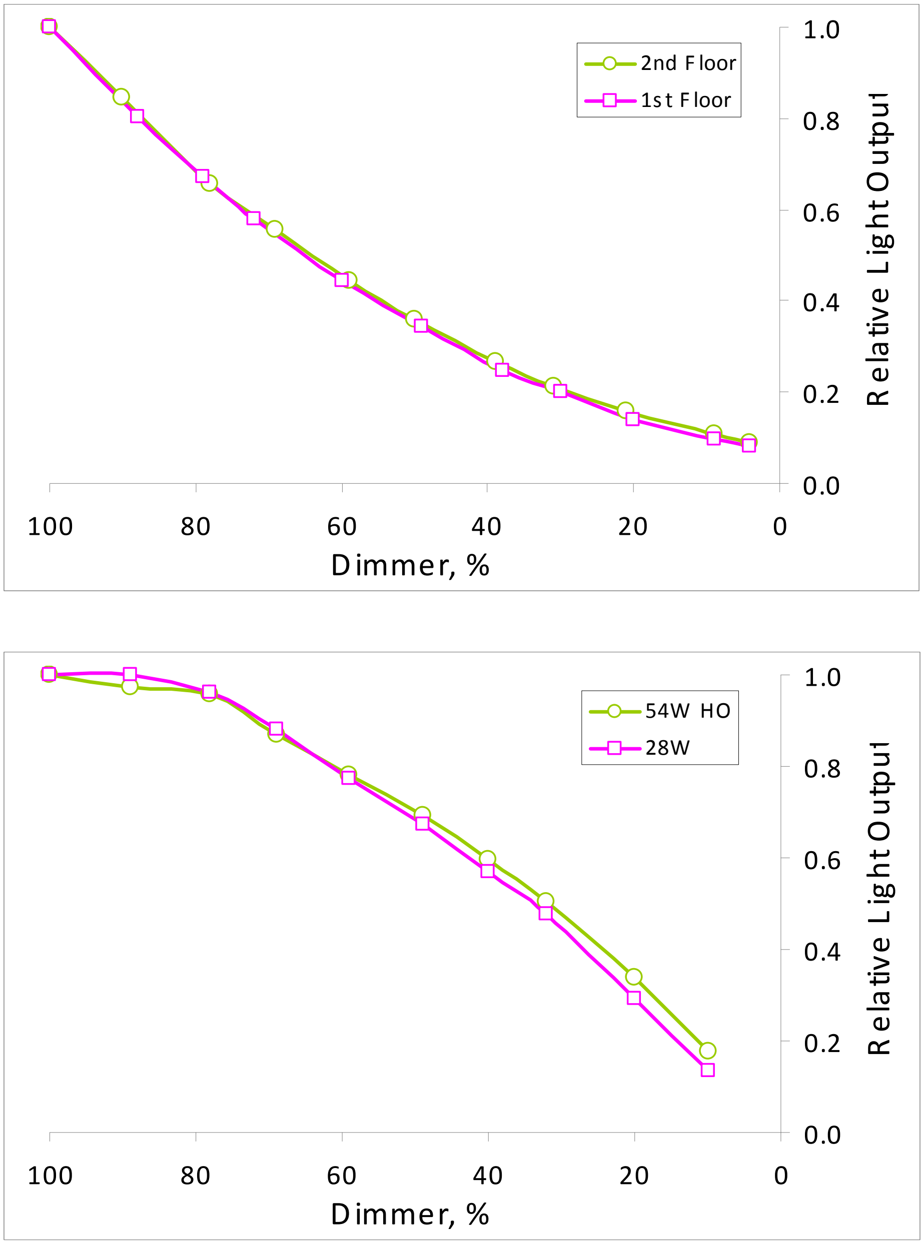

Figure 7. Dimming vs. relative light output curves, as measured at representative locations at the two sites. The upper chart shows data from each floor on the office site, measured under the same luminaire type. The lower chart shows data from the college campus, measured in an office with 54 W HO lamps only, and a classroom with 28 W lamps only.

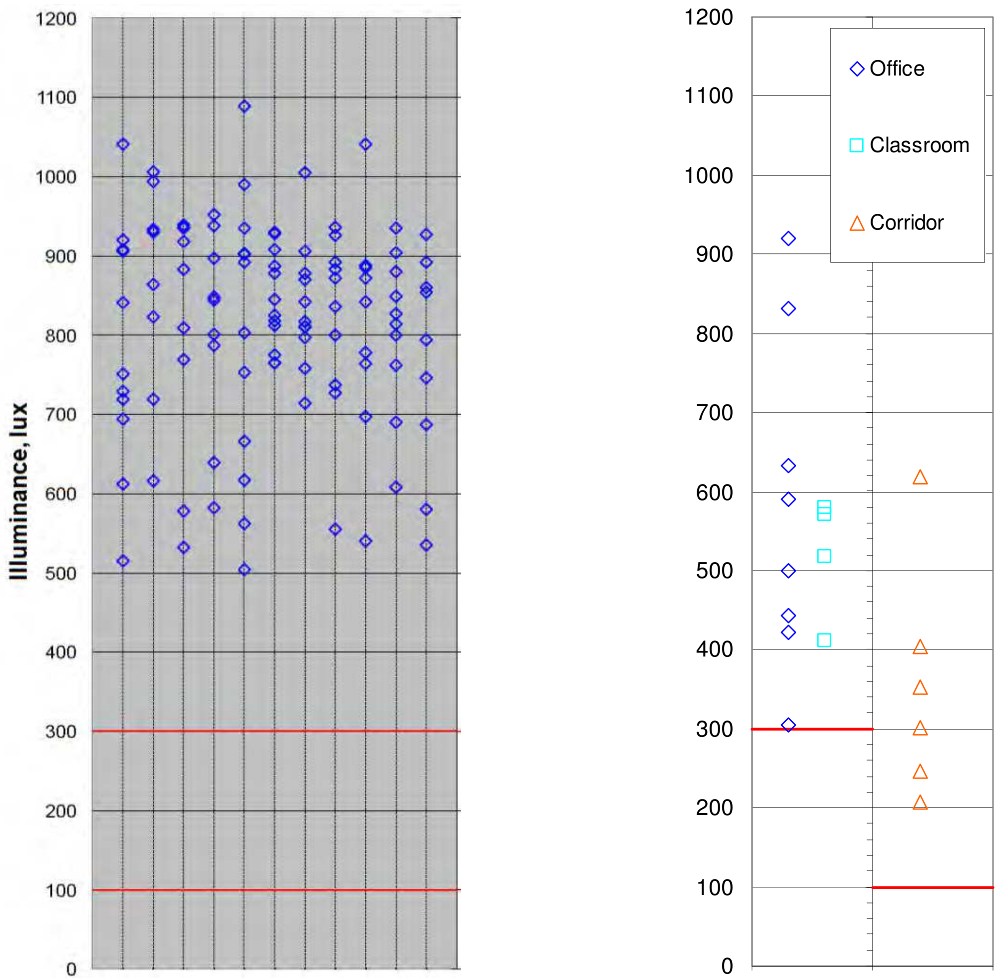

Figure 8. Illuminances measured in each cubicle, on the 2nd floor of the office site (left) and at representative locations in three space types, on the 1st floor of Building C at the college campus site (right). The red lines at 300 lx and 100 lx illustrate the typical minimum recommended illuminance for offices and corridors, respectively, suggested by the IESNA [2004]. For the office site, individual measurements have been divided among several vertical lines to facilitate interpretation of the data.

2.4 Illuminance loggers

We installed illuminance loggers at both sites. The data from the loggers provided long-term information on typical luminous conditions, and also provided a physical confirmation that a scheduled DR event had, in fact, affected the illuminance as expected. The loggers, which consisted of a Licor sensor and a Madgetech logger, recorded horizontal illuminance every 1 minute. We chose representative locations for the loggers that did not interfere with regular operations. The locations of the eight loggers at the open-plan office site are shown in Figure 1; ten loggers were used at the campus site.

2.5 Demand response trials

Trials were conducted during the period May-July, 2008, on chosen afternoons. This schedule was approximately coincident with the typical periods of highest system-wide electricity demand in southern Ontario. However, the days of the trials had to be agreed with each site several days in advance and had to fit the summer schedules of several key individuals, and therefore picking days when actual system-wide demand was unusually high was not possible. Demand response events were configured and initiated manually, unlike the automated trials conducted by Piette et al. [2005]. At both sites, we conducted a trial in a limited area to ensure the procedures worked smoothly, before expanding subsequent trials to the entire site.

At the office site, the trials were conducted by zone. All luminaires in a zone were dimmed to the same level[10]. Based on the outcome of Newsham et al. [2008] laboratory study, some perimeter zones were dimmed by a greater amount than the interior zones. The site-wide trials for the office building are summarized in Table 1.

Table 1. Dimming sequence for DR trials at the office site, for the two completed site-wide events. Shaded rows indicate dimming down, unshaded rows indicate subsequent dimming back up to normal. Note, the starting dimmer setting for each zone indicates the normal output.

Date	Zone	Dimmer	Dim Time Period	Begin
2008-05-09	2nd Floor Perimeter	84-->65%	15 min.	1:03PM
	1st Floor Perimeter	70-->60%	10 min.	1:22PM
	2nd Floor Interior	84-->65%	15 min.	1:34PM
	1st Floor Interior	75-->60%	15 min.	1:52PM
	2nd Floor Perimeter	65-->55%	10 min.	2:08PM
	1st Floor Perimeter	60-->70%	5 min.	2:31PM
	2nd Floor Interior	65-->84%	10 min.	2:40PM
	1st Floor Interior	60-->75%	10 min.	2:54PM
	2nd Floor Perimeter	55-->84%	15 min.	3:05PM
2008-05-23	2nd Floor Perimeter	84-->55%	30 min.	1:19PM
	1st Floor Perimeter	70-->60%		
	2nd Floor Interior	84-->65%		
	1st Floor Interior	75-->60%		
	2nd Floor Perimeter	55-->84%	30 min.	3:18PM
	1st Floor Perimeter	60-->70%		
	2nd Floor Interior	65-->84%		
	1st Floor Interior	60-->75%		

At the campus site, each room was assigned to a DR potential group, based on the data from the illuminance survey and knowledge of the space type. There were three groups: no potential (N=443), low potential (N=514), and medium potential (N=1338). Thus, more dimming was pursued for the medium potential group. The site-wide trials for the campus are summarized in Table 2.

The facility managers at both sites were understandably keen to avoid occupant complaints during the trials. Therefore our dimming choices were conservative, and designed such that there was little risk of even the darkest spaces (as measured during the illuminance survey) dropping below minimum recommended levels.

[10] With the exception of some luminaires which had been switched off due to prior occupant request, and remained off during the DR trials

Table 2. Dimming sequence for DR trials at the campus site. Note, the starting dimmer setting for each group indicates the normal output.

Date	Dimmer	Dim Time Period	Begin	DR potential group
2008-06-04	80-->48%	30 min.	2:30PM	Medium load reduction potential
	80-->68%	30 min.	2:30PM	Low load reduction potential
2008-06-27	80-->48%	15 min.	2:15PM	Medium load reduction potential
	80-->60%	15 min.	2:15PM	Low load reduction potential
2008-07-17	80-->52%	1 min.	1:45PM	Medium load reduction potential
	80-->64%	1 min.	1:45PM	Low load reduction potential

2.6 Measures to address occupant concerns

The protocol for this research was approved by NRC's Research Ethics Board. Following this, we consulted with facilities management, health and safety, and HR representatives at both sites to ensure a process that would meet the scientific goals of the study, the operational requirements of the site, and afford the necessary protections for occupants.

At both sites occupants received an announcement from building management prior to the beginning of the study. The announcement stated the reason for the study, its goals, what occupants could expect in terms of the impact on them, and how to seek resolution of any problems. Occupants were not informed of the specific dates and times of the trials. The mechanisms established for occupants to register any problems with lighting during the study built on the mechanisms already in place to address buildings issues. In the office building, a department intermediary was nominated to collect problems before passing them on to facilities management; in the college campus problems were reported directly to facilities management. Such problems were logged. The plan was to address a low number of complaints on DR days using the normal means employed on all other days. In addition, on the college campus, occupants were able to use the wall switches to override the DR dimming. However, if an unusually high number of complaints was registered during a DR trial, we committed to abandon the trial and restore normal light levels immediately.

Our DR trials were not out of line with other power savings measures already taken by facilities managers at both sites. For example, at the office building during summer 2006 thermostats were set to 26 ºC, compared to the normal 23 ºC. Notably, there was no special accommodation made for people who found this too hot, it was expected that clothing adjustments could be made, and some individuals brought in their own desk fans. Lighting in stairwells and lobby areas was also switched off. Both of these measures were advertised to participants, via e-mail, as summer energy-saving strategies to offset peak demand. Similar measures had been taken by facilities managers at the college campus on occasional days during 2006.

3. Results

In this section we begin by focussing on the realised power reduction of the DR trials. In addition, both sites included photosensors for daylight harvesting; later in the section we will comment on photosensor performance in the context of DR.

3.1 The office building

The lighting system manufacturer ran custom software during the DR trials that reported the power draw of the lighting system by zone. It was not possible to run this software during a large sample of non-DR event days. The reported power draw was calculated from the manufacturer's equation linking the dimming level to the total power draw of all the luminaires in the zone; this equation was not published, and we did not conduct any measurements to verify this relationship.

Figure 9(a) shows the derived power data for all study zones combined, and two example interior illuminance measurements, for the building-wide DR trial on May 9th; Figure 9(b) shows similar data for the trial on May 23rd. Measuring the difference between the power draw just before the DR event, and the minimum power draw during the event, the load reductions were 5.2 kW (23%), and 5.3 kW (24%), respectively.

Illuminance just prior to the DR event on May 9th was around 650 lx at both locations. This might seem high for an office space (typically 500 lx is recommended [IESNA, 2004]), given the small contribution of daylight at these locations. However, these sensors were placed above work surfaces so as not to interfere with normal operations. This meant that they generally showed higher values than if measurements were made on the desktop, both because they were closer to the source of electric light, and because there were fewer obstructions between luminaire and logger. During the DR event illuminance fell to around 470 lx, or about 28% lower than the initial level. Very similar illuminance values were recorded during the trial of May 23rd.

The facility managers did not receive a single lighting-related complaint during these trials.

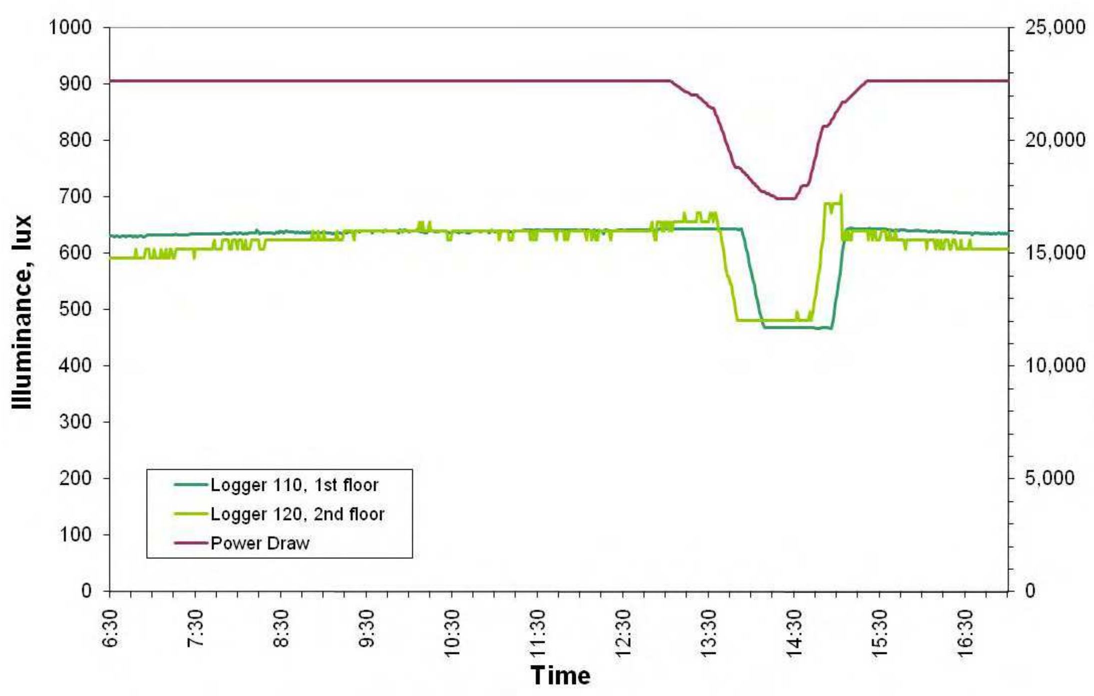

Figure 9(a). Derived power data for all study zones combined, and two example interior illuminance measurements, for the DR trial at the office building on May 9th.

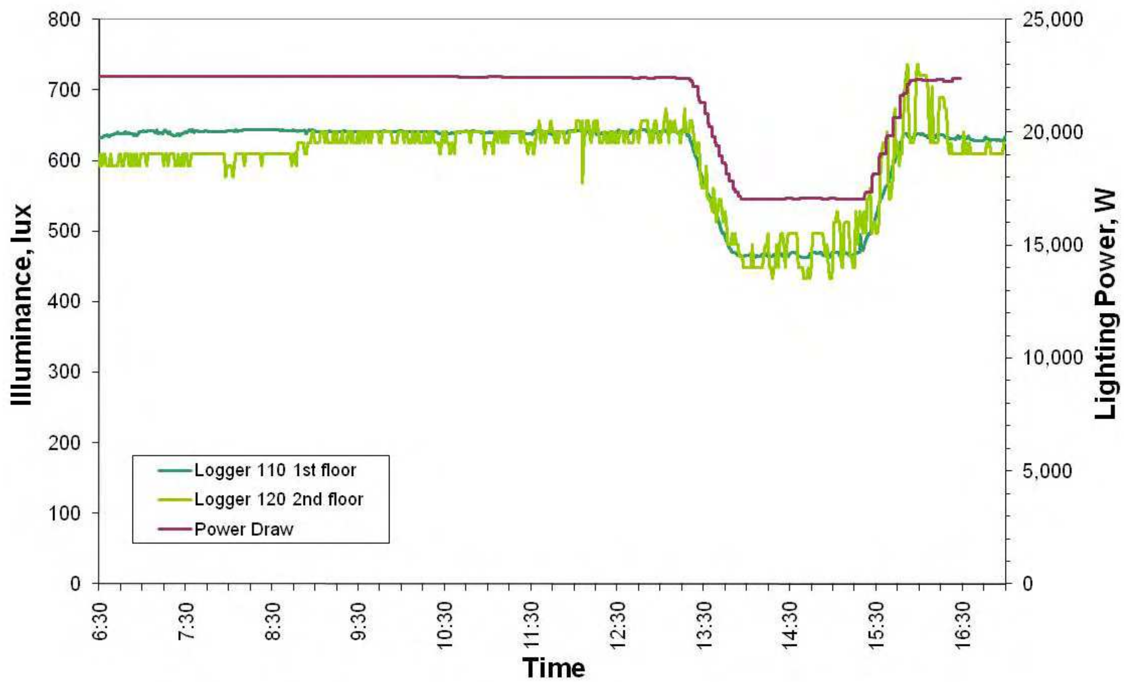

Figure 9(b). Derived power data for all study zones combined, and two example interior illuminance measurements, for the DR trial at the office building on May 23rd.

3.2 The college campus

A much richer dataset was available from the campus lighting system. The system recorded every state change for every ballast on the network on all days. The value recorded was the dimmer setting (0 – 100%), the cause of the state change was not recorded. There were approximately 5.4 million data points recorded over the study period of mid-April to mid-July, 2008. Dimmer value was converted to power draw for each luminaire via equations supplied by the lighting control system manufacturer, and shown graphically in Figure 10; we did not conduct any measurements to verify this relationship. Individual luminaire data was then summed to provide overall performance data by day, room type, building, and campus-wide.

On days without DR the typical weekday peak lighting load was around 80 kW, and tended to decline slightly in July, as might be expected. Therefore, the existing wall switches and dimmers, occupancy sensors and photosensors combined to reduce the lighting load by more than 50 kW (or 38%) on typical days (compared to the 130 kW baseload installed described in Section 2.2). Also as expected, lighting loads were much lower (peaking around 20 kW) on weekends and public holidays.

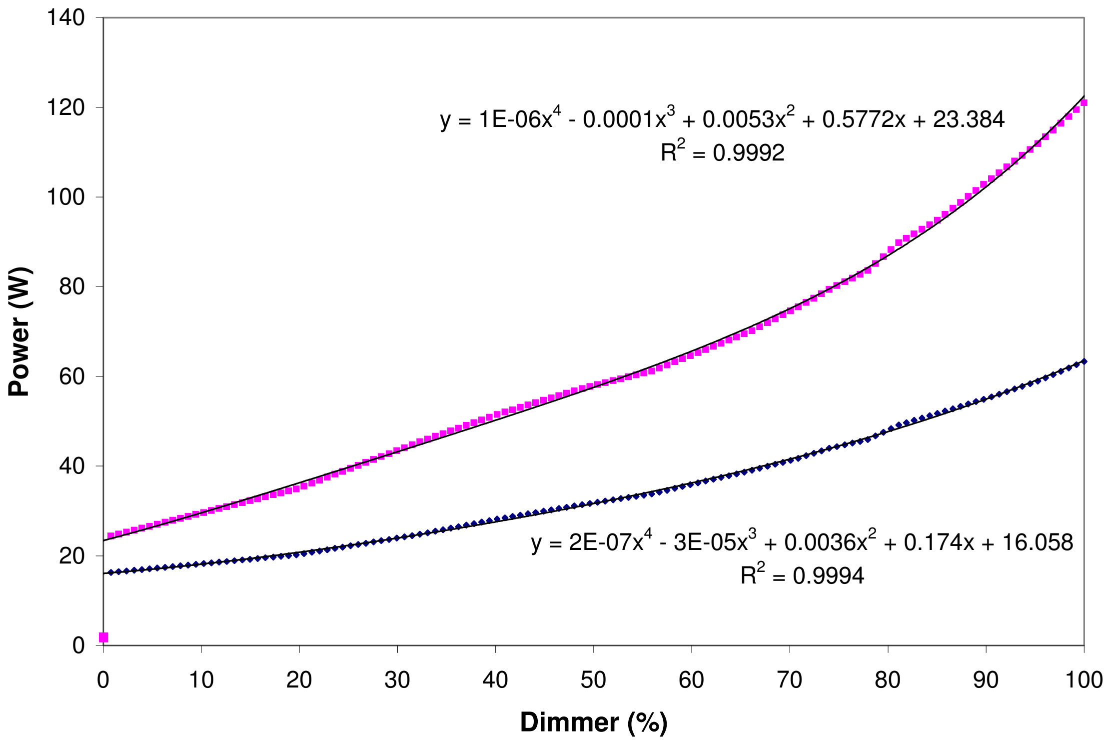

Figure 10. Dimmer/power curve fit to manufacturer's data for the college site; lower curve for 28W lamps, upper curve for 54W HO lamps. Note, the power drawn when the dimmer setting was zero was not continuous with these curves.

The effect of the campus-wide DR events on lighting loads is shown in Figure 11. The minute-by-minute load is shown for all weekdays (excluding public holidays) overlaid on the same graph, with DR days highlighted. A general diurnal load shape is clearly shown. Measuring the difference between the power draw just before and after the DR event, the load reductions were 15.2 kW (18%) on June 4th, and 7.7 kW (14%) on June 27th, and 11.3 kW (15%) on July 17th.

The lighting loads of June 4th and July 17th, before the DR events, were typical of the non-event days of the period. However, Friday June 27th exhibited the lowest load of any weekday of the study period. Fridays in general tended to have lower loads, but this was also a Study Week on the campus, with a consequently lower classroom loading. The following Tuesday was a public holiday, and some staff might have been prompted to begin summer holidays during the Study Week, or to take an extra-long weekend starting on the Friday of the DR trial.

Although the dimming profiles on each of the event days differed, it is generally the case that the lower the initial lighting load the lower the magnitude of the resulting load reduction. This is simply because lights that are already off, or are already dimmed below the target DR level, cannot contribute to the event. Nevertheless, there was still a substantial load reduction on the very low load day of June 27th.

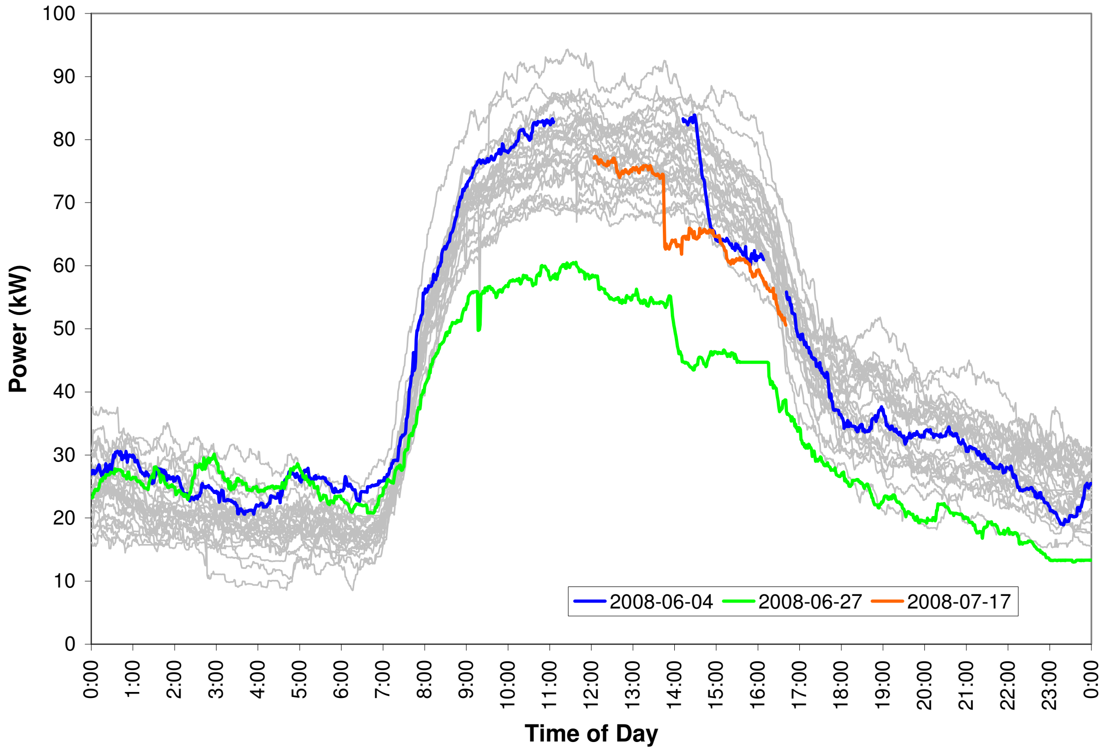

Figure 11. Calculated minute-by-minute lighting power for the campus-wide lighting system, for all weekdays (excluding public holidays). Non-DR days are shown in grey, DR days are shown by individually-coloured, thick lines. Periods of missing data appear as obvious gaps in the trace.

Building-by-building analysis showed that the contribution of each campus building to the total load reduction depended on their balance of space types and occupancy. Individual building load reductions varied between 8-39%.

Figure 12 shows illuminance data recorded by a logger in a reception area with no daylight. The minute-by-minute light level is shown for all weekdays (excluding public holidays), overlaid on the same graph, with DR days highlighted. Illuminance just prior to the DR event on June 4th was around 550 lx. After the event illuminance fell to around 450 lx, or about 18% lower than the initial level. Very similar illuminance values were recorded during the event of July 17th, with the more rapid drop in illuminance concomitant with the more rapid scheduled dimming. Note that the lights were manually switched off soon after this event. On June 27th the lights were manually switched off before the DR event occurred.

The facility managers did not receive a single lighting-related complaint during these DR trials. The other mechanism we had for exploring dissatisfaction with the DR events was to look for instances where the dimmer level for a given ballast increased substantially during or after an event, which might indicate use of the manual wall control to override the event. We scanned all ballasts on event days for evidence of such behaviour. On June 4th there were seven such instances, one occurred during the event, three within two minutes of the end of the event, and three occurred 30 minutes or more after the end of the event. On June 27th there were seven instances, and all occurred 45 minutes or more after the end of the event. On July 17th there were three instances, and all occurred 20 minutes or more after the end of the event. We did not know what the actual motivation for these control actions was. Given that the absolute number of events was very small, there is little evidence that the DR events caused anything other than minimal hardship, at worst.

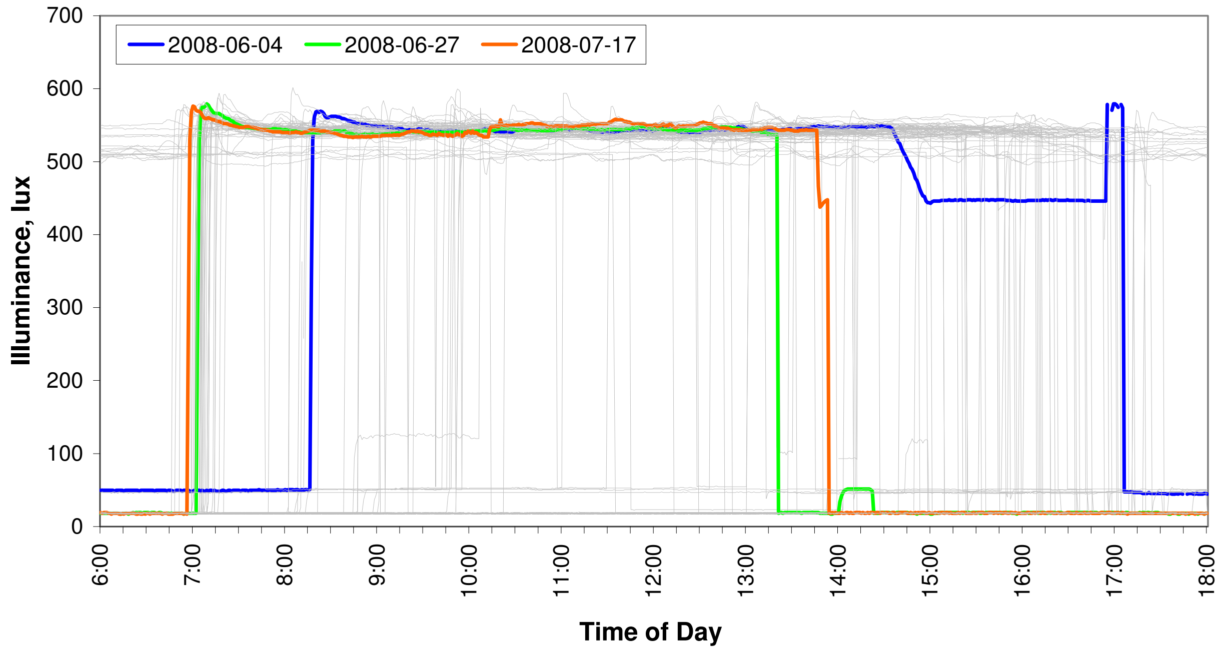

Figure 12. Illuminance data recorded by a logger in a reception area at the college site with no daylight, for all weekdays (excluding public holidays) for which lighting power data was also available. Non-DR days are shown in grey, DR days are shown by individually-coloured, thick lines.

3.3 Photosensor effects

Photosensors enabling daylight harvesting were installed at some locations at both sites. At the office site they were disabled on DR event days, at the campus site they remained functional on all days. In summer peaking locations, the highest demand for electricity tends to occur on hot summer afternoons, this also tends to be a period of high daylight availability. Therefore, photosensors may also contribute to DR. Data was available at both sites with which to examine this contribution.

Figure 13 shows data from the office site, comparing a non-DR event day (May 8th) with photosensors active, and the following DR event day (May 9th) with photosensors disabled. May 8th is the only non-event day for which we had lighting power data, and even on this day data was truncated just after 3 pm. Note that the power reductions attributable to the photosensor system peak at about the same time as the specified DR event reduction. The power reduction attributable to the photosensors was about 3.6 kW (16%). This is a smaller effect than the specific DR event, but the photosensor system may also contribute to savings at other times of the day or year. Figure 13 also suggests that with the photosensor system active, the magnitude of the load reduction attributable to a simultaneous DR event, while maintaining desired illuminance levels, might be reduced[11].

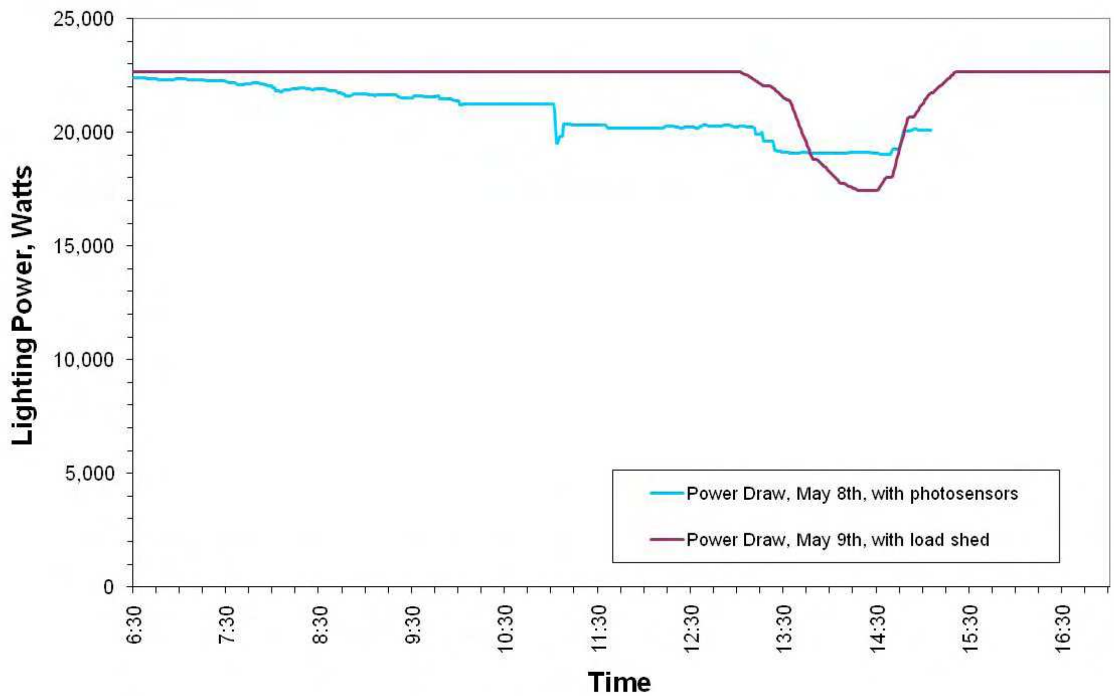

Figure 13. Derived power data at the office site for all study zones combined, for a non-DR day with photosensors active, and for the following DR day with photosensors disabled.

Figure 14 shows data from a single ballast connected to a photosensor in a corridor at the campus site. All normal weekdays (excluding public holidays) are overlaid, with the DR days highlighted. The target minimum power level on event days is indicated by the horizontal parts of the graphs on these days, and was around 35 W. The corridor had east-facing glazing and therefore photosensor-based dimming was greatest in the morning, but output was often still substantially below maximum in the early- and mid-afternoon. Figure 14 shows that DR events resulted in additional dimming beyond that already provided by the photosensors, although on the latter two event days DR contributed far less to the total dimming than the photosensor had already contributed[12]. On June 4th the photosensors had reduced power by 9.6% just prior to the DR event, which produced a further 23% reduction; numbers for the other two events were 21.5% and 11.1%, and 20.5% and 9.4%, respectively.

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[11] Illuminance data from Logger 119, which was placed next to an east-facing window and therefore provides a correlate to general afternoon sky illuminance without direct sun, was >30% higher on May 8th compared to May 9th, suggesting that the contribution of photosensors, had they been active, to an afternoon lighting load reduction on May 9th would not have been as high as it was on May 8th.

[12] It is also noteworthy that for this ballast the DR schedule did not behave as designed. The first two events were scheduled to take place over 30 and 15 minutes, respectively. However, the ballast dropped to the target minimum level within one minute. Tests revealed that they happened for fewer than 10 ballasts campus wide, so the dimming curve was as expected when aggregated over the whole campus, as shown in Figure 11. The second event also appears to have been enacted earlier than scheduled, for which we have no explanation.

Campus-wide there were only 87 ballasts connected to photosensors, less than 4% of all ballasts on the system

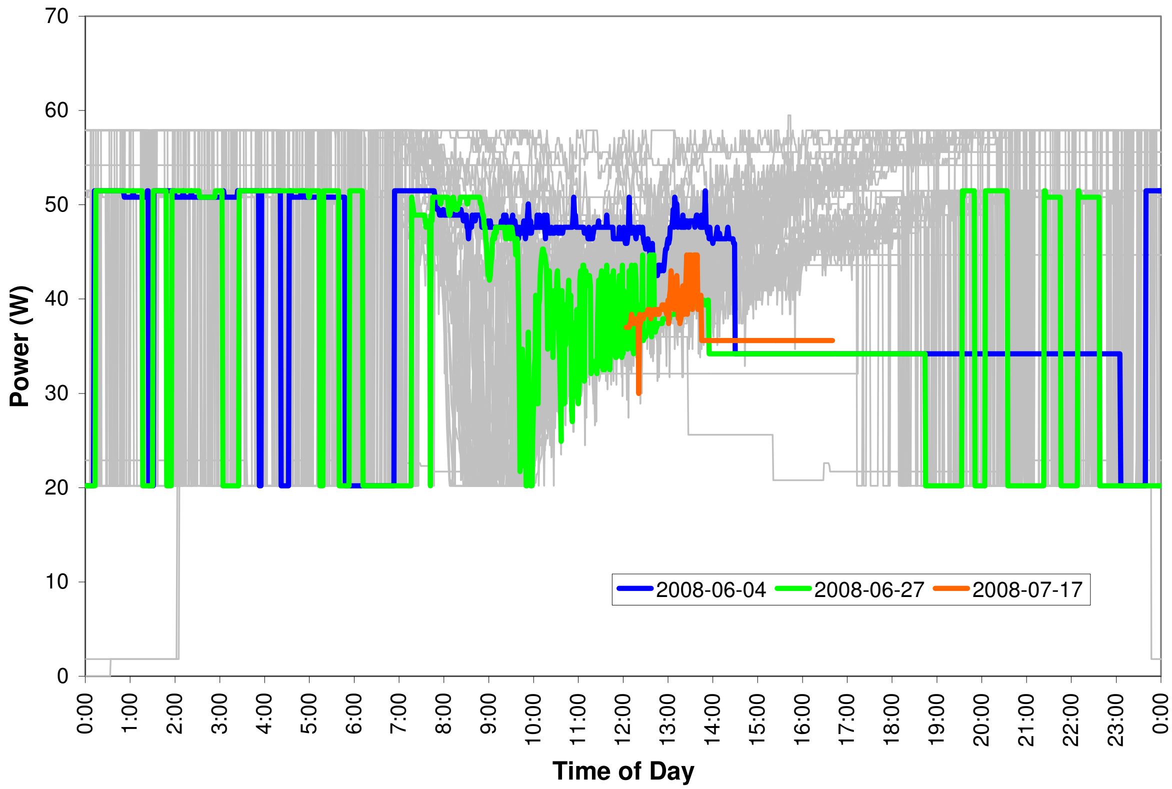

Figure 14. Calculated minute-by-minute lighting power for a single corridor ballast at the campus site, connected to a photosensor, for all normal weekdays (excluding public holidays). Non-DR days are shown in grey, DR days are shown by individually-coloured, thick lines. Periods of missing data appear as obvious gaps in the trace.

4. Discussion

Prior laboratory studies suggested that light levels could be reduced substantially over relatively short periods without substantial hardship for the large majority of occupants. This field study suggests that these laboratory findings can be successfully applied in real workplaces and with commercial lighting systems. However, it is important to note that the field study did not fully explore the envelope of acceptability suggested by the laboratory studies. This was partly because we could not practically conduct enough trials in the field to test all combinations, and partly because we tended towards conservative choices when implementing load reductions in real workplaces. In the laboratory studies, the rate of dimming spanned 10 seconds to 30 minutes, with related acceptable dimming amounts of up to 60%. In the field study, the rate of dimming spanned 1 to 30 minutes, with related acceptable dimming amounts of up to 40%. It seems likely that further dimming could take place in field settings without causing substantial hardship, but full extrapolation to the levels demonstrated in the laboratory should be explored with caution.

Our field study also showed that daylight harvesting systems can also make a substantial contribution to reducing lighting load during afternoon periods of high system-wide demand.

The advantage of photosensors is that they save energy during other periods of daylight too, the disadvantage is that they cannot be relied on to deliver a specific load reduction at a specific time, and can only be applied in daylit zones.

Dimming systems to enable DR are rare in existing office buildings, and dimming ballasts represent only a few percent of all ballasts shipped [Rubinstein & Kiliccote, 2007; AEC, 2002]. The main barrier to market penetration is first cost. Simple energy savings due to daylight harvesting and personal control [Galasiu et al., 2007; Lee and Selkowitz, 2006; Newsham et al., 2004], although substantial, often result in long payback times. However, many utilities now apply charges based on peak demand. In such cases DR dimming may reduce payback times substantially[13].

Nevertheless, the building owner/operator is likely to want to see reduced first costs to stimulate purchase. There are two ways in which this can happen in the short term. First, Lee and Selkowitz [2006] have demonstrated that the cost of dimming ballasts can be substantially reduced if purchased in volume. Second, some utilities offer incentives for lighting systems with dimming ballasts, in recognition of their benefits. For example the National Grid (a utility serving New England states) offered a $40/ballast rebate for dimming ballasts with daylight harvesting controls [National Grid, 2009], and PSE&G (a utility serving New Jersey) offered a $25/fixture rebate for luminaires with daylight harvesting controls [PSEG, 2009]. Incentive schemes could be broadened to fairly recognize the role of DR dimming in offsetting generation costs and grid stabilization.

There are other practical barriers to using lighting as a demand-responsive load. These barriers include how buildings can verify load reductions to the utility, and the certainty that a load such as lighting with large diurnal fluctuations will be available to the utility at sufficient levels when required. Adding equipment to address these issues adds further first costs.

Further, DR incentive programs are typically focussed on load reductions of the order of 100 kW or more, which are most often accessible in large industrial settings. The extensive lighting installation at our campus site realized a reduction of 15.2 kW. Therefore, multiple sites of this size would have to be aggregated, or utilities would have to lower the load threshold for incenting DR. However, a single very large office building may have more than 100 kW of operable lighting load[14].

Another concern is one of liability. Building operators may have contracts that require them to deliver a certain light level, as recommended by the IESNA, local labour codes, or specific tenant standards. It is unlikely that such contracts currently include the possibility for light levels to be temporarily reduced in the manner required by DR.

This research may help overcome some of these barriers. This will be achieved through wide dissemination of results to utilities, the writers of codes and recommended practices, and the manufacturers of lighting control systems. It is also important that this information reaches end-users, enabling them to specify DR capabilities when they procure lighting systems. Demand-responsive lighting systems require dimming systems. Dimmable lighting systems bring other benefits, such as personal control, light level tuning, and daylight harvesting. Green

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[13] In our field study, the need for demand response was placed in the context of price, GHG emissions, and grid stability. We speculate that this context is likely important to the acceptability of DR dimming. People may be more willing to accept the expectation of some degradation of building service to protect grid stability, and less willing just to reduce electricity bills when there is no immediate threat of a blackout. However, this remains to be demonstrated objectively.

[14] A 500,000 ft^2 office tower with a lighting power density of 1 W/ft^2 has 500 kW of installed lighting. If dimming of 30% can be called on, this is 150 kW of operable load.

building rating systems and energy codes are encouraging the use of lighting controls of all kinds. In this context, the use of lighting systems for DR may represent an additional value proposition to an end-user already interested in dimming, particularly if incented by utilities. Granderson & Agogino [2006] present a control algorithm that may facilitate intelligent and simultaneous use of all dimming capabilities.

Finally, there are other electricity demand issues that are important to utilities, and that could benefit from dimmable lighting systems. The first is referred to generally as operating (or "spinning") reserve. Utilities are required to maintain operating reserve so that they can respond to a failure at a generator (or an unusual departure from forecast demand). Typically, this sudden need must be met fully within 10 minutes and maintained for another 20-50 minutes, until other backup supplies can be made available. Operating reserve is normally met on the supply side, however, in principle, it could be met on the demand side [Kirby, 2003]. Dimmable lighting systems might represent a partial operating reserve opportunity by reducing load relatively quickly in response to the loss of supply. In addition, many utilities are aggressively adding renewable generation to their supply portfolios. Renewable supplies are not constant, for example, wind generation may change substantially over a few seconds. Accommodating a large proportion of renewable generation may present problems to utilities in matching supply and demand continuously. Again, dimmable lighting, in principle, could be employed to help in this regard.

The maximum potential for dimmable lighting systems to contribute to the above load management concerns is enormous. Around 66,000 MW [Navigant, 2002][15] are required to supply fluorescent lighting requirements in commercial buildings in the US and Canada. Our research results suggest dimming by 30% is a reasonable estimate of what may be possible in a DR event, implying a potential operable load in dimmable fluorescent lighting systems of 20,000 MW. This is in line with an estimate by Rubinstein & Kiliccote [2007] that the potential DR from lighting in commercial buildings in California is at least 1,000 MW (a figure supported by ADM [2007]). However, these numbers represent maximum potentials only, the actual number of luminaires currently installed with the necessary control gear is very small.

5. Conclusion and Recommendations for Practice

This field study demonstrates that dimmable lighting systems may be successfully utilized in demand response. Groups of luminaires were dimmed by up to 40%, with site-wide lighting load reductions of around 20%, with no reported occupant complaints.

A combination of prior laboratory studies and this field study helps define guidelines for the extent and speed of dimming of lighting as a DR strategy. These guidelines are premised on the desire to limit inconvenience and discomfort to occupants. These guidelines could be included in recommended practice or standards for office lighting, and referenced in utility DR programs.

The first stage of DR should be dimming by amounts that are not even noticed by the large majority of occupants. The second stage of DR, when more load reduction is required, may involve dimming by to light levels that are noticeably lower, but are still acceptable to the

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[15] Table 5-22 states that fluorescent lighting in commercial buildings uses 220.1 TWh of delivered electricity per year. Elsewhere in the report it states that commercial lighting is on ~ 10h/day, therefore, assuming lights are at 100% when on: $220.1 \times 10^{12}/(10 \times 365) = 60{,}000$ MW. Adding 10% for Canada gives a total power demand of 66,000 MW.

large majority of occupants. Inherent in these guidelines is that prior to DR dimming occurring the electric lighting in the space conforms with typical recommended practice (e.g. IESNA [2004]).

The recommended limits of smooth dimming for DR are:

- Stage 1:
  - Rapid response, over as little as 10 seconds, by …
    - 20% with no daylight
    - 40% with low[16] prevailing daylight
    - 60% with high prevailing daylight
  - Slow response, over 30 minutes or more, and with no immediate expectation of dimming occurring, by …
    - 30% with no daylight
    - 60% with high prevailing daylight[17]
- Stage 2:
  - Rapid response, over as little as 10 seconds, by …
    - 40% with no or low daylight
    - 80% with high prevailing daylight
  - Slow response, over 30 minutes or more, and no immediate expectation of dimming occurring, by …
    - 50% with no daylight
    - 80% with high prevailing daylight[18]

It is important to emphasize that DR dimming should only be enacted to alleviate temporary grid stress problems that occur infrequently, and is intended to prevail for a few hours at most, and that light levels should be returned to normal levels thereafter. Our studies do not provide support for these lower light levels becoming the "new normal", applied routinely every day as an energy efficiency measure, although some facility managers may be tempted to do this [Granderson & Agogino, 2006, Table 1]. There is abundant evidence to suggest that the light levels in current IESNA recommended practice [2004] are appropriate to ensure long-term occupant satisfaction [Veitch and Newsham, 1998; Newsham et al., 2004; Newsham et al., 2008].

Acknowledgements

This research was sponsored by the National Research Council Canada (NRC), the Program on Energy Research & Development (administered by Natural Resources Canada), and Public Works & Government Services Canada (PWGSC), and by the Lighting Research Office, Electric Power Research Institute (EPRI) with the support of the J.H. McClung Lighting Research Foundation. We would also like to thank Chantal Arsenault (NRC) for her help with

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[16] Defined in earlier research [Newsham et al., 2008] as <1343 lx on the desktop due to daylight at mid-afternoon

[17] Newsham et al. [2008] did not test a slow dim rate/daylight combination, so this is a conservative choice identical to the rapid response recommendation.

[18] Newsham et al. [2008] did not test a slow dim rate/daylight combination, so this is a conservative choice identical to the rapid response recommendation.

the illuminance monitoring, Emilie Thibault (NRC) preliminary data analysis, and Morad Atif (NRC) for his on-going support.

Of the very generous people who facilitated the demand response trials at the field study sites, we are particularly grateful to: Jeff Choma, Sandy Hancock, Rob Mongrain, Mat Lefler (Georgian College); Chris Rigatti, Chris Ballard, Pekka Hakkarainen (Lutron Electronics Co. Inc.); Phil Santia (e-Lumen International Inc.); Cassandra Howarth, Sal Pace, Cathy Backes (Canada Revenue Agency); Mark Page, John Lalonde, Raymond Lee (SNC - Lavalin ProFac Inc.); Paolo Consoli, Andrew Parker, Terry Mocherniak (Encelium Technologies Inc.); David Faltenhine (PWGSC); Travis Gliedt (University of Waterloo). We also thank all of the building occupants, who accepted our presence in their work/study places.

References

ADM Associates. 2007. Demand Response Technology Evaluation Mackenzie Laboratories. Southern California Edison Report. Available on request from Doug Avery.

AEC. 2002. Architectural Energy Corporation. Demand responsive lighting systems URL: http://www.archenergy.com/lrp/demandresp_lighting.htm (last access: 2009-07-22)

Akashi Y, Neches J. 2004. Detectability and acceptability of illuminance reduction for load shedding. Journal of the Illuminating Engineering Society 33(1): 3-13.

Akashi Y, Neches J. 2005. Potential recommendations for illuminance reductions by load shedding. Lighting Research & Technology 37(2): 133-153.

ASHRAE. 2004. American Society of Heating, Refrigerating and Air-Conditioning Engineers. Thermal environmental conditions for human occupancy. Atlanta (USA). ANSI/ASHRAE Standard 55-2004.

Boyce PR. 1984. Lighting control: the user's point of view. Proceedings of the CEA/DBR Symposium, Ottawa (Canada): 69-85.

DRCC. 2006. United States Demand Response Coordinating Committee. URL: http://www.demandresponsecommittee.org/ (last access: 2009-07-22)

Galasiu AD, Newsham GR, Suvagau C, Sander DM. 2007. Energy saving lighting control systems for open-plan offices: a field study. Leukos 4(1): 7-29. URL: http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/nrcc49498/nrcc49498.pdf (last access: 2009-07-27).

Granderson J, Agogino A. 2006. Intelligent office lighting: demand-responsive conditioning and increased user satisfaction. Leukos 2(3): 185-198. URL: http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/nrcc48678/nrcc48678.pdf (last access: 2009-07-22).

IEA. 2006. International Energy Agency. Light's labour's lost: policies for energy-efficient lighting. Paris (France).

IESNA. 2004. Illuminating Engineering Society of North America. American national standard practice for office lighting. New York (USA). ANSI/IESNA-RP-1-04.

IESO. 2006. Ontario's Independent Electricity System Operator, Emergency Load Reduction Program (ELRP). URL: http://www.ieso.ca/imoweb/elrp/elrp-index.asp (last access: 2009-07-22)

Kiliccote S, Piette MA, Watson DS, Hughes G. 2006. Dynamic controls for energy efficiency and demand response: framework concepts and a new construction study case in New York. Proceedings of ACEEE Summer Study on Energy Efficiency in Buildings (Pacific Grove, CA): 3.172-3.183. URL: http://drrc.lbl.gov/pubs/60615.pdf (last access: 2009-07-22).

Kirby BJ. 2003. Spinning reserve from responsive loads. Oak Ridge National Laboratory. Tennessee (USA). ORNL/TM-2003/19.
URL: http://certs.lbl.gov/pdf/spinning-reserves.pdf (last access: 2006-07-22).

Kryszczuk KM, Boyce PR. 2002. Detection of slow light level reduction. Journal of the Illuminating Engineering Society 31: 3-10.

Lee ES, Selkowitz SE. 2006. The New York Times Headquarters daylighting mockup: monitored performance of the daylighting control system. Energy and Buildings 38(7): 914-928.

National Grid. 2009. National Grid's lighting incentive and eligibility requirements manual for Massachusetts, Rhode Island and Nantucket customers, Design 2000plus Program.
URL: http://www.nationalgridus.com/non_html/shared_energyeff_lighting_newconst.pdf
(last access: 2009-07-27)

Navigant, 2002. U.S. Lighting Market Characterization, Volume I: National Lighting Inventory and Energy Consumption Estimate. Report prepared for U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Building Technologies Program, September
URL: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/lmc_vol1_final.pdf
(last access: 2009-07-22).

Newsham G, Veitch J, Arsenault C, Duval C. 2004. Effect of dimming control on office worker satisfaction and performance. Proceedings of the IESNA Annual Conference, Tampa (USA): 19-41. URL: http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/nrcc47069/nrcc47069.pdf (last access: 2009-07-22).

Newsham GR, Mancini S. 2006. The Potential for demand responsive lighting in non-daylit offices. Leukos 3(2): 105-120.
URL: http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/nrcc48678/nrcc48678.pdf (last access: 2009-07-22).

Newsham GR, Mancini S, Marchand RG. 2008. Detection and acceptance of demand-responsive lighting in offices with and without daylight. Leukos 4(3): 139-156.
URL: http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/nrcc50324/nrcc50324.pdf (last access: 2009-07-22).

Newsham GR, Mancini S, Veitch JA, Marchand RG, Lei W, Charles KE, Arsenault CD. 2009. Control strategies for lighting and ventilation in offices: effects on energy and occupants. Intelligent Buildings International 1(2): 101-121.
URL: http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/nrcc49249/nrcc49249.pdf (last access: 2009-07-22).

Piette MA, Watson DS, Motegi N, Bourassa N. 2005. Findings from the 2004 fully automated demand response tests in large facilities. Report for the PIER Demand Response Research Center. LBNL Report Number 58178.
URL: http://drrc.lbl.gov/pubs/58178.pdf (last access: 2009-07-22)

PSEG. 2009. New Jersey Smart Start Buildings Program.
URL: http://www.njcleanenergy.com/commercial-industrial/programs/nj-smartstart-buildings/tools-and-resources/equipment-incentives/equi (last access: 2009-07-27)

Rosenzweig MB, Fraser H, Falk J, Voll SP. 2003. Market power and demand responsiveness: letting customers protect themselves. The Electricity Journal 16(4): 11-23.

Rowlands IH. 2005. Ontario demand response scenarios. CANMET Energy Technology Centre – Varennes, Natural Resources Canada. CETC 2005-139.
URL: http://cetc-varennes.nrcan.gc.ca/fichier.php/codectec/En/2005-139/2005-139e.pdf
(last access: 2009-07-22).

Rubinstein F, Kiliccote S. 2007. Demand Responsive Lighting: A Scoping Study. LBNL/DRRC Report LBNL-62226.
URL: http://drrc.lbl.gov/pubs/62226.pdf (last access: 2009-07-22).

SCE. 2005b. Demand Response Technology Evaluation Ganahl Lumber. Southern California Edison Report. Available on request from Doug Avery.

Shikakura T, Morikawa H, Nakamura Y. 2003. Perception of lighting fluctuation in office lighting environment. Journal of Light & Visual Environment 27: 15-22.

Tenner AD, Begemann SHA, van den Beld GJ. 1997. Acceptance and preference of illuminance in offices. Lux Europa'97, Proceedings of the 8th European Lighting Conference, Amsterdam (The Netherlands): 131–143.

Veitch JA, Gifford R. 1996. Choice, perceived control, and performance decrements in the physical environment. Journal of Environmental Psychology 16: 269-276.

Veitch JA, Newsham GR. 1998. Lighting quality and energy-efficiency effects on task performance, mood, health, satisfaction and comfort. Journal of the Illuminating Engineering Society 27 (1): 107-129.
URL: http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/nrcc40663.pdf (last access: 2009-07-22).