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Energy Efficiency Package for Tenant Fit-Out: Laboratory Testing and Validation of Energy Savings and Indoor Environmental Quality

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Abstract: Approximately 40% of the total U.S. office floor space of 1.5 billion sq.m (16 billion sq.ft.) is leased space occupied by tenants. Tenant fit-out presents a key opportunity to incorporate energy efficiency within the real estate business cycle. We designed a package of energy efficiency measures tailored to the scope of a tenant fit-out. This tenant fit-out package (TFP) includes advanced lighting and heating, ventilating and air-conditioning (HVAC) controls as core measures, with ceiling fans, automated shading, and plug load controls as additional optional measures. We conducted laboratory testing of six configurations of the package to evaluate energy savings, indoor environmental quality, and identify installation, commissioning, and operational issues. Combined savings for HVAC, lighting, and plug loads ranged from 33–40%. Lighting savings ranged from 69–83%, and HVAC savings from 20–40%. The laboratory testing also revealed some minor but tractable challenges with installation and commissioning of HVAC controls. Overall, the results demonstrate that significant savings can be realized in existing office buildings by incorporating relatively low-risk, proven measures at the time of a tenant fit-out.

Keywords: tenant fit-out; energy efficiency; office buildings; ASHRAE Guideline 36; HVAC controls; lighting controls

1. Introduction

1.1. Motivation and Context

Office buildings are one of the most significant sectors of non-residential building energy use in the U.S., with 1.3 Exajoules (1241 TBtu) of total energy use and total floor area of 1.5 billion sq.m (16 billion sq.ft.) [1], approximately 40% of which is estimated to be leased space [2]. Various market studies over the last decade have shown significant potential for energy savings from retrofits of commercial buildings [3–8]. A number of retrofit case studies have documented energy savings up to 25% using no/low-cost measures and up to 50% or more using deeper retrofit measures [9–12]. There are an array of technologies and strategies to implement energy efficiency retrofits in office buildings, including advanced lighting systems, high efficiency heating, ventilating and air-conditioning (HVAC) equipment and controls, and plug load controls. Major retrofits may also include envelope upgrades, although these are less common. Lighting upgrades are the most common retrofit measure in commercial buildings, largely due to their cost-effectiveness and ease of implementation [13]. A number of tools and guides have been developed to assist building owners, designers and other stakeholders [9,14–16]. However, studies show that the overall retrofit rate is still relatively low, at only about 2.2% of total floor space annually in the U.S. [3]. For leased buildings, tenant fit-outs at the time of lease turnover or renewal present a key intervention point and opportunity to implement energy efficiency, for primarily two reasons: (1) they minimize or eliminate any additional disruption to occupants and business function beyond what is already happening due to the tenant fit-out; and (2) they improve the cost effectiveness of energy efficiency measures because some of the costs are borne by the base tenant fit-out itself, reducing the incremental cost for efficiency measures.

In the building energy efficiency literature, there appear to be very few publications that address energy efficiency in the context of real estate life-cycle events in office buildings. Energy efficiency in existing buildings is typically implemented via dedicated standalone projects, rather than integrated with real estate events, such as tenant fit-outs and building renovations. While there are numerous publications, guides, and tools on how to implement energy efficiency in existing buildings, they generally do not address the interplay with real estate life-cycle events. Our review found a few publications that directly address this issue, including: steps and strategies for building portfolios to achieve net zero energy goals over time by aligning energy efficiency, energy storage and renewable energy with building purchase, renovation, and sale [17]; a ten-step process to include energy efficiency in a lease fit-out [18]; guidance on how to incorporate energy efficiency into lease agreements [19]; a process for leasing net zero buildings [20]; resources to fold energy efficiency into leasing, property management agreements, tenant improvements, and underwriting standards [21]; case studies of energy efficiency in leased spaces [22]; a survey of various real estate stakeholders and the challenges and opportunities for incorporating energy efficiency in five real estate lifecycle events—purchase/sale, tenant fit-out, renovation, equipment replacement, and refinance [23]. Feedback from the stakeholders clearly point to the value of packaged energy efficiency measures, with well-vetted savings, aligned with the scope of these real estate events.

This paper describes the development and laboratory testing of a package of energy efficiency measures for a tenant fit-out. The next section describes the package itself. Following that, we describe the objectives and methods for laboratory testing. We then present and discuss the results of laboratory testing, including energy savings, indoor environmental quality, and installation, commissioning, and operational experience.

1.2. The Tenant Fit-Out Package (TFP)

We used a three-step process to determine a set of efficiency measures for the tenant fit-out package (TFP). First, we developed an expansive list of efficiency measures for consideration, based on commercially available technologies. We then screened for measures that are likely applicable for the scope of a tenant fit-out. The scope of tenant fit-outs can vary considerably. At the minimal end of the spectrum, the scope may be limited to furnishings and finishes. At the other end of the spectrum, it could entail a major renovation with changes down to the structure of the building. We focused on medium-to-larger scale fit-outs in which scope included lighting and HVAC controls that are within the tenant's purview. Prior research has shown that integrated approaches that address multiple end uses have the potential to create deeper savings than component-based approaches (see, for example, Reference [11,24]). Finally, we screened the measures for the extent to which they could be standardized and likely adopted. We excluded measures that inherently require a lot of customization (e.g., variable refrigerant flow cooling system retrofits). Table 1 lists the resulting set of measures. It includes lighting and HVAC controls as core elements. Optionally it could also include plug loads controls, interior shading, and ceiling fans. The package also includes continuous metering and monitoring as a core element.

Table 1. List of measures in the tenant fit-out package.

Measure	● Core ○ Optional
Lighting	
LED Fixtures	●
Occupancy-based controls	●
Daylight dimming controls	●
Network lighting controls system	○
HVAC	
ASHRAE Guideline 36 Controls (trim & respond for supply air temp and duct static pressure, demand-controlled ventilation, intermittent ventilation, VAV box retuning)	●
Ceiling fans w/2.2 °C (4 F) cooling setback	○
Other	
Automated interior Shades	○
Plug load controls	○
Metering & monitoring	●

The individual measures themselves are generally proven, commercially available technologies and strategies. Lighting includes high-efficacy dimmable LED lighting with both occupancy and daylight controls, which have shown significant savings [25–28]. The controls may be achieved through individual fixture-integrated sensors or a separate sensor network. In either case the network lighting controls systems (NLCS) can network room or fixture controllers and system sensors on a single network platform with a graphical front-end from which the user can implement and manage lighting controls strategies, including scheduling, occupancy and daylight sensing and task tuning to reduce maximum intensity if light levels at full output exceed design criteria. ASHRAE Guideline 36 includes a detailed set of best-in-class control sequences [29]. It covers zone sequences, intermittent ventilation, demand-controlled ventilation, and trim-and-respond sequences for resetting supply air temperature and duct static pressure. Ceiling fans can save energy by allowing for higher cooling set-points while keeping occupants comfortable [30,31]. Automated interior shades are an option that can be used to provide optimal daylight conditions for daylight dimming of lights, and also to reduce envelope thermal loads. Tenant-level metering and performance monitoring allows for ongoing measurement and verification of energy performance.

2. Methods

2.1. Objectives of Laboratory Testing

There are broadly three approaches to evaluate building energy efficiency: (a) energy simulation; (b) laboratory testing; and (c) field testing in occupied buildings. Simulation allows for a wide range of parametric analyses at lower effort than laboratory and field testing, but it does not provide measured empirical data. Field testing provides empirical data from real buildings with actual occupants. But field testing can be disruptive to building occupants and logistically challenging. Furthermore, it is difficult to get true counter-factual data for baselines and alternatives. Laboratory testing provides measured empirical data under controlled conditions and can provide true counterfactual data. However, it does not account for the stochastic aspects of actual occupants. Thus, each of these approaches has complementary strengths and limitations.

Laboratory testing was conducted to evaluate the following aspects of the TFP:

- energy savings;
- thermal and visual comfort;
- technology integration, installation and commissioning procedures.

The laboratory tests enable evaluation and validation of these aspects under a wide range of controlled conditions. This helps to "de-risk" the package, making it more acceptable to building owners, managers and occupants before field installation. The laboratory testing was not suitable for evaluating implementation cost, although we were able to identify issues related to installation, commissioning and operation.

2.2. Laboratory Test Facility

Laboratory testing to validate performance of the tenant fit-out package (TFP) involves side-by-side operation of a 'reference case' and a 'test case' in a test facility specifically intended for testing the performance of integrated systems [32]. The reference case represents a baseline existing building, while the test case represents the TFP applied to the baseline. There are a wide range of different existing building conditions. The U.S. Department of Energy (DOE) reference models [33] have three vintages: pre-1980, post-1980, and new construction (which corresponds to ASHRAE standard 90.1-2004 [34]). Since it was beyond the scope of this effort to model the full range of existing building conditions, we chose the post-1980 model as the reference case as it corresponds to the middle level of efficiency. We modeled two versions of the TFP: The Core version includes all the core measures indicated in Table 1, while the CorePlus includes the core and optional measures. The Core version we tested also included the NLCS.

The reference and test cases are set up in laboratory cells that are identical in spatial dimensions, construction attributes (e.g., window type and performance, wall construction and thermal resistance, infiltration, etc.), HVAC system, furniture layout, surface finishes, and occupant and equipment loads. The only difference between the cells is the implementation of the TFP in the test cell. For example, for the lighting system, the test cell has LED fixtures with integrated sensors and controls in place of fluorescent fixtures on simple scheduled control in the reference cell.

The lab cells are operated in parallel in the manner of a typical office over the course of days or weeks, as well as at different times of year to capture seasonal effects of daylight availability and outdoor temperature. All aspects of operation are monitored through time, so that performance can be compared cell-to-cell, such as energy usage and intensity, thermal conditions and comfort, and visual parameters, such as illuminance and glare.

2.3. Test Conditions for Reference and Test Cases

The Core and CorePlus TFPs were designed for implementation in commercial office spaces, so the layout of the test space was configured as an open office plan with six cubicle-style workstations in the 56 sq.m (600 ft^2) of cell floor area, which also includes hallways along the perimeter walls and rear of the cell. 1.5 m (5 ft) high cubicle partitions separated work stations across from one another and 1 m (3.5 ft) high partitions separated adjacent workstations (longitudinal with respect to the window-wall). This open office layout design concept accommodates separation of work spaces while allowing daylight penetration deeper into the zone. The lighting plan was a typical general lighting scheme with 0.6 × 1.2 m (2′ × 4′) recessed troffers over the desks spaced at 2.4 × 3.0 m (8′ × 10′) on center.

Because the test space is not used by actual occupants in the way a real office space would be, occupancy thermal loads are emulated by thermal generators that emit heat equivalent to a human body. These are placed at each workstation and turned on and off based on daily occupancy profiles described later. Additionally, each workstation includes a desktop computer and monitor to add realistic plug loads to the space. The computers are programmed to turn on when the respective workstation is first occupied in the morning and off when it is vacated for the last time at the end of the workday. Plug load was set to approximately 100 W per workstation, resulting in an installed plug load density of 10.8 W/sq.m (1 W/ft^2) when all workstation computers were on. Table 2 below details the equipment used and performance criteria per system and feature.

Table 2. System features in reference and test cells.

System	Feature	Reference Cell	Test Cell: Core	Test Cell: CorePlus
Lighting	Fixtures	3-lamp T8 fluorescent troffer	LED troffer with integrated sensors and controls	LED troffer with integrated sensors and controls
	Controls	Scheduled on/off (6 a.m. to 8 p.m.)	Fixture-level occupancy-based dimming, afterhours shut off, fixture-level daylight dimming. Occupancy data shared with HVAC via API.	Fixture-level occupancy-based dimming, afterhours shut off, fixture-level daylight dimming. Occupancy data shared with HVAC via API.
HVAC	System type	VAV Air handling unit with hydronic cooling and heating; VAV with hydronic reheat (emulated)	same	same
	Heating and cooling setpoints, schedule	Occupied: 21.1 °C/23.3 °C (70 F/74 F) (hours: 7 a.m.–7 p.m.) Unoccupied setback: 15.6 °C/29.4 °C (60 F/85 F) 2-h morning warmup or cooldown based on t-stat and setpoints.	Same heating and cooling setpoints. Same schedule. Morning warmup/cooldown (varies by season: 0.5 h for summer, 1 h for spring/fall, and 1.5 h for winter, conditioning based on t-stat and setpoints).	Same heating and cooling setpoints. Same schedule. Morning warmup/cooldown (varies by season: 0.5 h for summer, 1 h for spring/fall, and 1.5 h for winter, conditioning based on t-stat and setpoints). Automated ceiling fans (on once zone in cooling mode for 1 h, cooling setpoint setback of 2.2 °C (4 F))
	Supply air temp (SAT), VAV min flow	Cooling SAT: 55 F (12.8 °C) (no reset). VAV minimum flow set to 30%, 106 l/s (225 cfm).	SAT reset per ASHRAE Guideline 36, (“trim and respond”). VAV min flow tuned to 15%, 57 l/s (120 cfm).	SAT reset per ASHRAE Guideline 36, (“trim and respond”). VAV min flow tuned to 15%, 57 l/s (120 cfm).
	Ventilation	Standard ventilation amount per ASHRAE Standard 62-2016. Does not turn off after hours; outside air damper maintains same position as occupied condition	Standard ventilation amount per ASHRAE Standard 62-2016. Demand controlled ventilation per ASHRAE Guideline 36, based on occupancy % for zone, calculated from lighting system data. Can turn down to zero flow off hours. Intermittent ventilation: 15 min ‘on’ as min supply period, cycles on/off when in minimum flow to provide overall total vent amount needed.	Standard ventilation amount per ASHRAE Standard 62-2016. Demand controlled ventilation per ASHRAE Guideline 36, based on occupancy % for zone, calculated from lighting system data. Can turn down to zero flow off hours. Intermittent ventilation: 15 min ‘on’ as min supply period, cycles on/off when in minimum flow to provide overall total vent amount needed.
	Economizer	Temp based, with 18.3 °C (65 F) high limit cutoff. No econ prior to 28 September 2019.	Operation per ASHRAE Guideline 36; outside air high limit cutoff 23.9 °C (75 F).	Operation per ASHRAE Guideline 36; outside air high limit cutoff 23.9 °C (75 F).

Table 2. *Cont.*

System	Feature	Reference Cell	Test Cell: Core	Test Cell: CorePlus
Plug Loads	Wattage and operation	Approx. 100 W per workstation (CPU and monitor) on during workday	Same	Same
	Controls	None	None	Occupancy—based turn off of monitor after 5 min timeout for occupancy sensor
Windows	Glazing	Double-pane tinted U-value of 0.594, SHGC 0.41, vis trans 0.276	Same	Same
	Shading	Venetian blinds, seasonally adjusted louver angle adjustment	Venetian blinds, seasonally adjusted louver angle adjustment	Automated rollershades controlled based on solar position and sky condition
Exterior Walls	Wall insulation	Metal stud with R-19 batt insulation and drywall, exterior has cementitious board.	Same	Same

As mentioned earlier, the reference cell lighting and HVAC systems are based on the post-1980s vintage DOE reference building. Light fixtures were standard three-lamp fluorescent T8 troffers, with simple scheduled on/off control. The installed lighting power density (LPD) of this system was around 9.7 W/sq.m (0.9 W/ft^2). The reference HVAC condition is a multi-zone variable air volume (VAV) system with reheat. The cooling and heating setpoints and night setback, economizer operation and other features of the HVAC system are detailed above in Table 2. The window configuration for the cell included tinted double-pane insulated glazing units (IGUs) with performance characteristics also detailed in Table 2. Standard venetian blinds are used as the shading system for the windows, and the angle of the louvers is adjusted seasonally to prevent direct sunlight at workstations. The seasonal adjustment schedule is based on research showing that manual shade devices in offices are typically adjusted infrequently based on longer-term solar trends rather than daily solar conditions.

Figure 1 shows the test cell layout and Figure 2 shows an interior view. The TFP for Core and CorePlus configurations includes 2′ × 4′ LED troffer fixtures with efficacy around 114 lumens per Watt (LPW) and total output of 5000 lumens (CRI of 90, and CCT of 4000 K). The lighting power density (LPD) of this system at full power was around 4.7 W/sq.m (0.44 W/ft^2). The LED fixtures included luminaire-level sensors and controls for occupancy-based dimming and daylight dimming.

For HVAC, the primary efficiency measure is implementation of ASHRAE Guideline 36 control sequences, which include:

- supply air temperature (SAT) and duct static pressure reset (“trim and respond”);
- intermittent ventilation;
- economizing, with an outside air high-limit set to 23.9 °C (75 F);
- VAV minimum flow rate re-tuned, from 30% to around 15% (56.6 l/s (120 cfm));
- demand controlled ventilation based on occupancy status relayed by the lighting controls system.

Additional measures were implemented for the CorePlus test configurations, including automated ceiling fans with setback of cooling setpoint. Fans turn on when HVAC system is in cooling mode for longer than one hour, with cooling setpoint increased by 2.2 °C (4 F). Additionally, for CorePlus, automated rollershades (dark grey fabric with 3% openness factor) were implemented, with position controlled based on solar modeling and local sensor inputs (the system uses a solar position model to determine shade position with the intention of blocking direct solar penetration deeper than 0.9 m (3′)

into the space based on the building geometry, orientation, and latitude, using the ASHRAE clear-sky model to predict hourly solar radiation). Finally, the CorePlus package included plug load controls to turn off desktop monitors when occupants were not present.

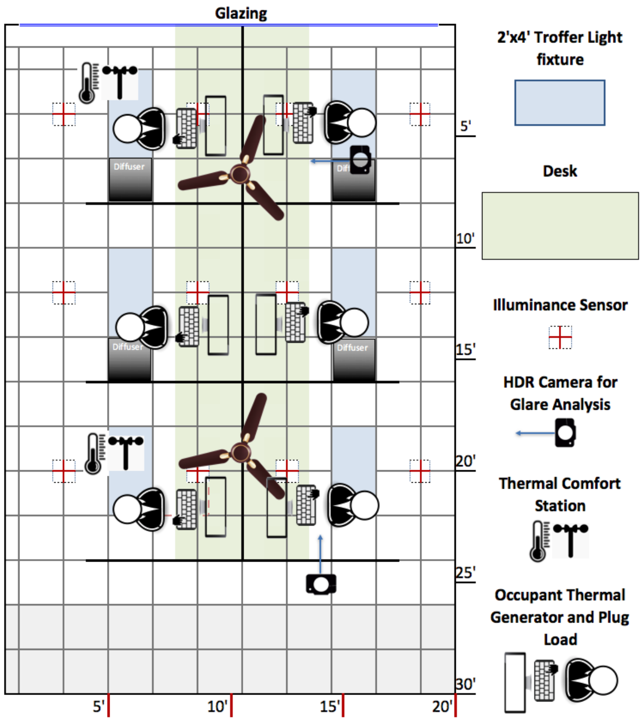

Figure 1. Test cell layout.

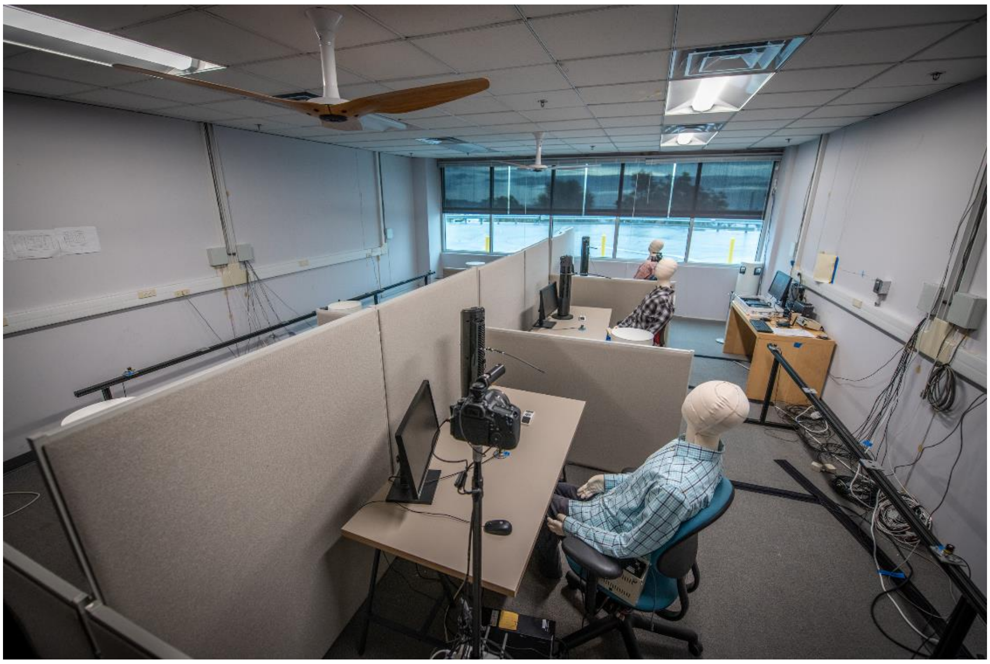

Figure 2. Interior view of test cell setup. Visible in the photograph are the LED fixtures with integrated sensors and controls, automated shades deployed across the windows, occupant thermal generators (mannequins with electric resistance heat tape), the occupancy trigger mechanisms (oscillating tower fan cylinders with heating elements to emulate occupant motion) for pyroelectric infrared (PIR)-based lighting controls and plug load control, automated ceiling fans, and measurement equipment, including high dynamic range (HDR) cameras for glare analysis and illuminance sensors on the desks and rails.

The lighting system in the TFP is occupancy-responsive, as is the demand-controlled ventilation control strategy that relies on occupancy data from the lighting system. The plug load controls in the CorePlus package are also based on occupancy sensors. Occupant loads are also important in terms of contributing to the zone's overall HVAC load. Therefore, emulating occupancy patterns and loads for each occupant in the space was important.

Plausible schedules of occupancy and vacancy were established for each occupant in the zone, based on an agent-based occupancy simulation tool [35]. The zone total occupancy hour by hour and over the course of the day was reasonably representative of an open office environment. Occupancy control for lighting, and when applicable, plug loads, was based on PIR (pyroelectric infrared) sensor technology. Occupant sensor triggering mechanisms were used to emulate occupancy for the sake of occupancy-based controls (lighting and HVAC for Core, and lighting, HVAC, and plug load for CorePlus). These mechanisms pass a small heated element through the PIR sensor field of view which reads as occupancy to the sensor; when an occupant was not present the mechanism remained still and the heated element was deenergized. The specific recurring (daily) occupancy schedules for each of the six occupants are shown in Figure 3, as well as the sum of the six schedules, in terms of percentage occupied for the entire open office zone.

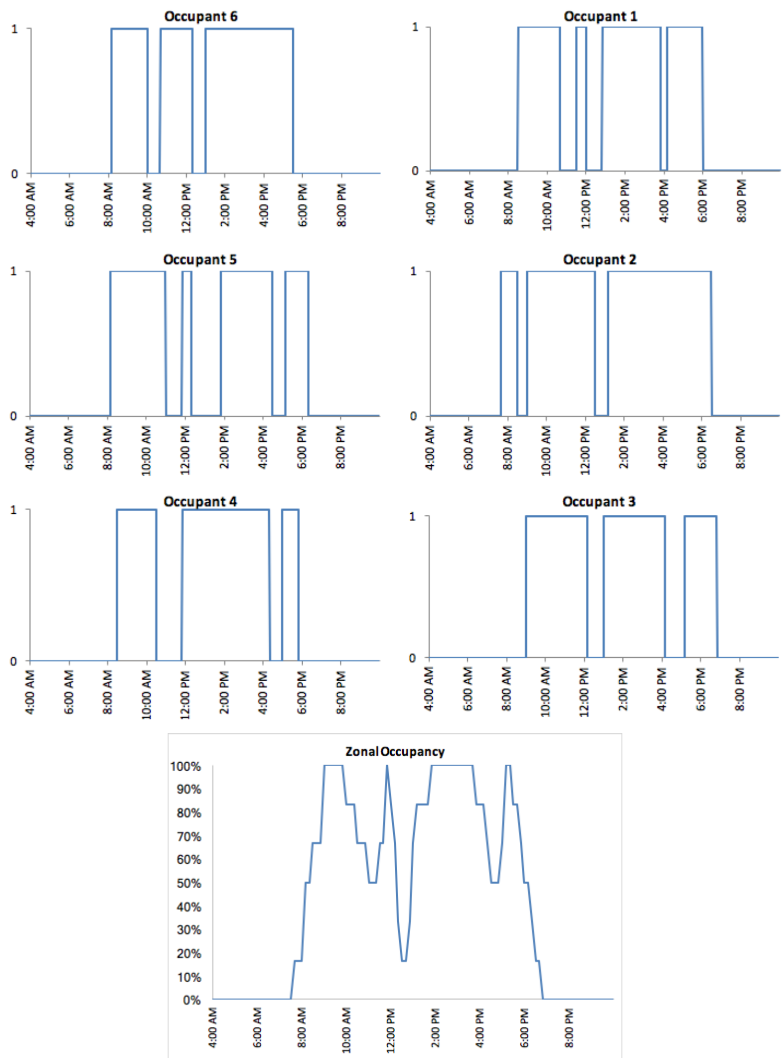

Figure 3. Daily occupancy patterns for each workstation, and summed occupancy fraction for the entire zone (bottom). Patterns of occupancy (1) and vacancy (0) frequency and duration for each workstation show daily routines that sum to a zonal occupancy pattern of build-up in the morning, a lunch dip, and gradual zone vacancy at the end of the workday.

2.4. Sensors and Measurements

The laboratory cells are heavily instrumented with measurement devices to capture conditions at high spatial and temporal resolution, typically recorded at one-minute intervals. The electrical characteristics of all loads (current, voltage, power factor) are individually monitored. Thermal parameters in the cell, such as temperature in conditioned space, above the plenum, and in the slab, are monitored, along with HVAC parameters, such as air flow, damper positions, and air handler fan power. Air-side and hydronic-side measurements (flow rate through heating and cooling coil, and temperature change) capture the thermal load conditions in each cell on an ongoing basis.

For lighting experiments, visual parameters are also monitored at high temporal resolution, including illuminance at a one-minute interval. Desk level illuminance was monitored by two sensors per workstation: one on each desk and one on a rail behind the desk at equal height and equal distance from the overhead fixtures.

Glare, visual discomfort caused by high luminance contrast in the field of view, is another important consideration for electric lighting and daylighting systems. Glare was measured using digital cameras and processors to take hemispherical field-of-view luminance measurements based on high resolution high dynamic range (HDR) images compiled from multiple bracketed images at different exposure settings and pixels converted to photometric data. HDR images are processed to provide daylight glare probability (DGP) at a five-minute interval. The DGP index estimates the probability that glare would be perceived at a location, with an established range from imperceptible (<0.35; glare not noticed) to intolerable (>0.45, glare bad enough to preclude working). One HDR package was situated at the eye level of the seated occupant in a desk nearest the window, facing in the direction of the workstation computer monitor (Figure 4). The other glare measurement location was in the rear of the zone, facing the window wall, and at standing height (see again Figure 1).

Figure 4. Photograph of window-adjacent workstation in test cell. This photograph shows the desktop illuminance sensor, as well as the HDR camera for sensing glare in the occupant field of view. The CorePlus automated shades are in use and, likely due to the cloudy sky condition, are retracted halfway to allow daylight into the space.

To monitor parameters associated with thermal comfort, two thermal comfort stations were located in the reference cell and in the test cells, one on a front desk and one on a desk in the rear of the cell. Each station measures air temperature, mean radiant temperature, and air velocity.

2.5. Configurations Tested

The experiment was carried out in a testbed which is capable of being rotated nearly 360 degrees, such that the window-wall can face different directions to evaluate daylighting and thermal load conditions for different building orientations. Configuration variables included three zone types with differing daylighting and solar load characteristics—south-facing perimeter zone, west-facing perimeter zone, and interior zone (for the interior zone configuration, the windows were covered with insulated panels)—and two tenant fit-out package types—Core and CorePlus—for a total of six unique configurations, identified in Table 3 below. For each configuration, the reference and test cells were operated for several consecutive days and all relevant performance data was collected for analysis. Table 4 shows the number of test days per configuration for each month from August of 2019 through January of 2020 and total days per configuration. Note that, for the south and west perimeter configurations, where seasonal variations in daylight availability and solar load are important, testing was conducted over ranges of days covering summer, fall, and winter conditions, to the extent possible.

Table 3. Tenant fit-out configurations tested.

Configuration ID	Configuration Details
Core-S	Core measures only, south-facing window wall
Core-W	Core measures only, west-facing window wall
Core-I	Core measures only, interior zone (no window wall)
CorePlus-S	Core measures plus optional measures, south-facing window wall
CorePlus-W	Core measures plus optional measures, west-facing window wall
CorePlus-I	Core measures plus optional measures, interior zone (no window wall)

Table 4. Days of test data per configuration. This excludes days for which test facility had operational issues and the data were not usable.

Config	Days per Month per Configuration						Total Days
	Aug	Sep	Oct	Nov	Dec	Jan	
Core-S	1	9	2			4	16
Core-W	4	5	2			7	18
Core-I				4	5		9
CorePlus-S	4 *	6	4		6	7	27
CorePlus-W		4	5			6	15
CorePlus-I				6	5		11

* Lighting only (HVAC systems not functioning).

3. Results and Discussion

3.1. Energy Savings

3.1.1. Lighting

We computed hourly and daily energy savings for each configuration. The savings vary based on a number of factors, some of which vary predictably by season (daylight availability, solar altitude which affects shade deployment), and some that vary stochastically (cloud cover). The test period covered a range of these parameters.

Figure 5 shows the savings percentage for CorePlus-S, as an example. Interestingly, there is not a significant difference in savings between the August/September test period and the December/January test period. We found this to be the case for the other configurations, as well (detailed results on all configurations are available as indicated in the "Supplementary Materials" section. For brevity, we only present selected results here.). It is likely that daily stochastic variations in cloud cover are a more significant driver of savings than seasonal factors. As a case in point, note the difference in daily savings 22–24 January. Upon closer investigation, we found that this was due to differences in shade deployment driven by solar conditions. Due to shade deployment on clear days with low sun angles in winter, clear days yield lower savings than cloudy days.

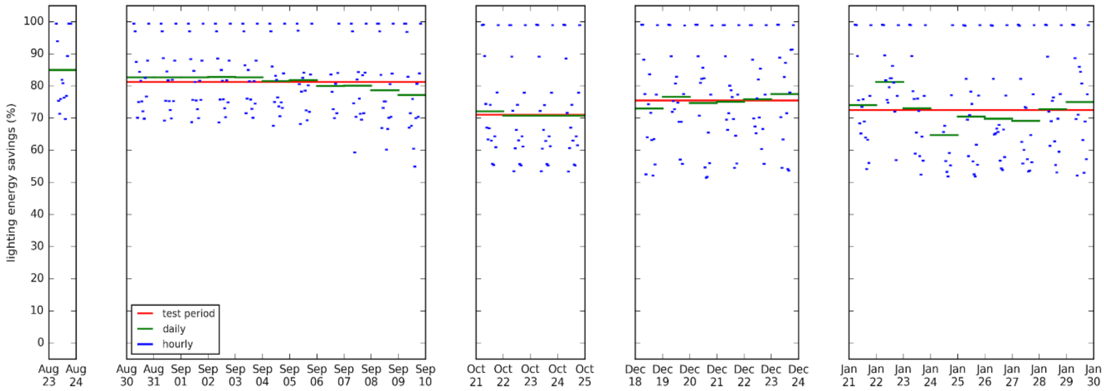

Figure 5. Lighting energy percentage savings for CorePlus-S configuration.

Figure 6 shows the range of daily energy savings as percentage for the six configurations. Note that the interior configuration median savings is just under 70%, while the median savings for the south and west configurations range from about 75–85%. This suggests that daylighting adds about 5–15% energy savings.

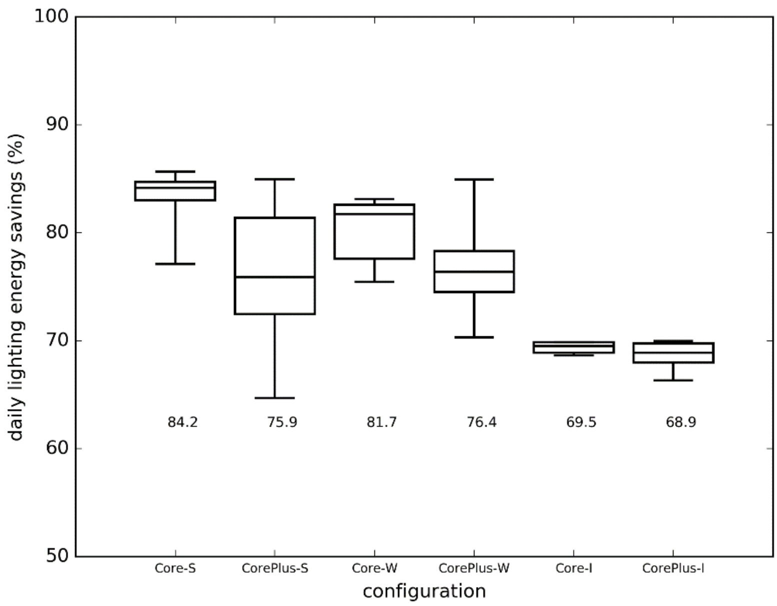

Figure 6. Daily lighting energy savings (%) for each configuration over the test period.

Figure 7 shows the average lighting power density (LPD) over occupied hours for the reference and test cases for each configuration. The reference case (which has no daylighting or occupancy controls) is constant at 9.7 W/sq.m (0.9 W/sf). The test case median LPD for interior configurations—which have no daylight—is 3 W/sq.m (0.28 W/sf). There was not a notable difference between south and west configurations. Interestingly, the Core configurations show lower average LPD (1.5–1.7 W/sq.m, 0.14–0.16 W/sf) than the CorePlus (2.3–2.4 W/sq.m, 0.21–0.22 W/sf) which has automated shading. This suggests that the assumption used for operation of manual shades in effect allowed for more daylight admittance than the automated shade.

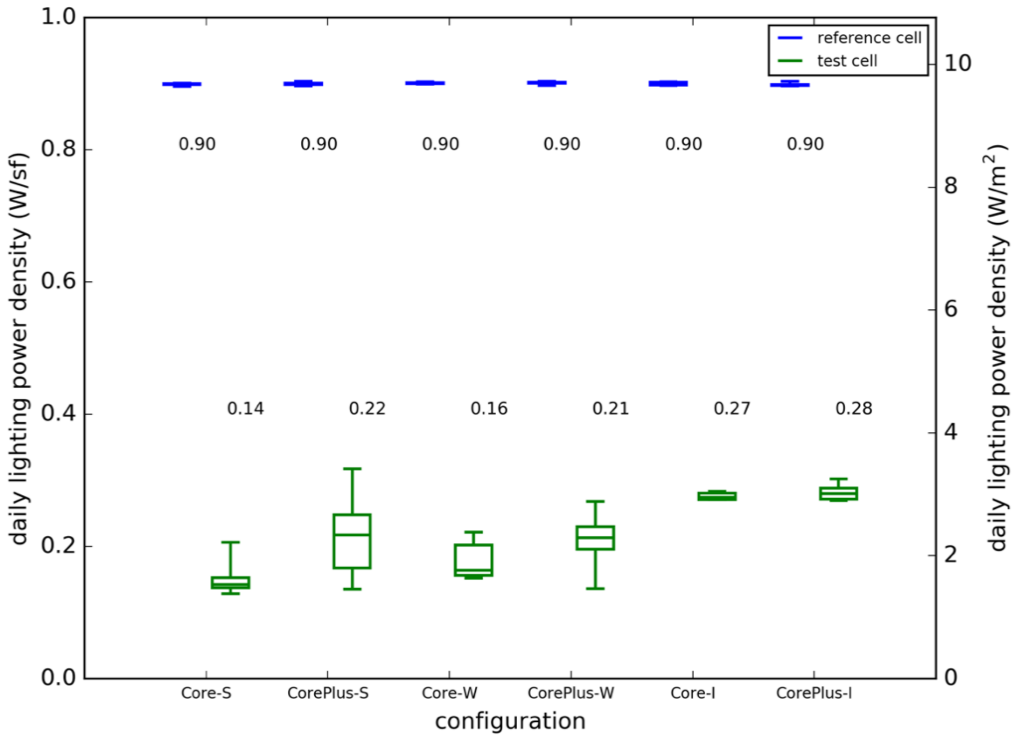

Figure 7. Average lighting power density (W/sf) during occupied hours for reference and test cases for each configuration. (Numbers inside the chart are median values in W/sf).

3.1.2. HVAC

We calculated savings for HVAC cooling and heating load, as well as HVAC energy use. For HVAC load, we computed the hourly and daily cooling load and heating load for each test day from the minutely load profiles. As an example, Figure 8 shows the daily heating and cooling load for Core-S. Values below zero are cooling loads and values above zero are heating loads. The figure shows that both heating and cooling loads are lower in the test cell, with a few exceptions. For diagnostic purposes, we also analyzed the relationship between hourly load and outdoor air temperature for each configuration. Figure 9 shows the results for hourly cooling load for Core-S, again showing lower cooling load in the test cell compared to the reference cell. These overall trends were similar for the other configurations (again, see "Supplementary Materials" for detailed results for all configurations) and follow expected patterns, i.e., cooling loads increase with increase in outdoor air temperature, with some scatter due to other factors, such as solar loads; cooling loads generally do not occur below about 10 °C.

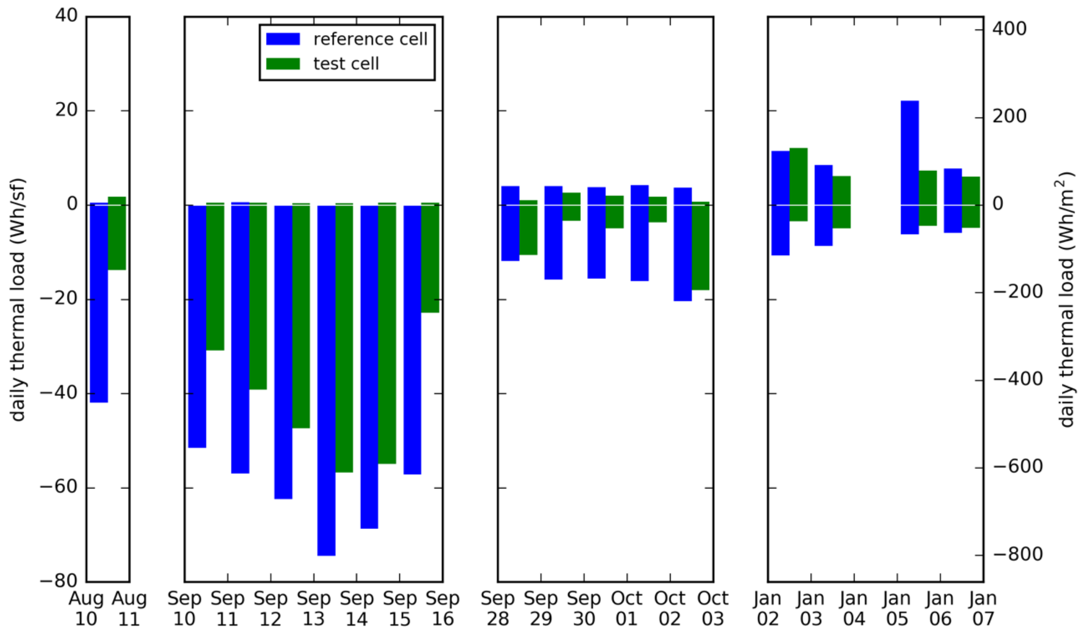

Figure 8. Daily thermal loads for test and reference cells for test days in the Core-S configuration. Values below zero are cooling loads. Values above zero are heating loads.

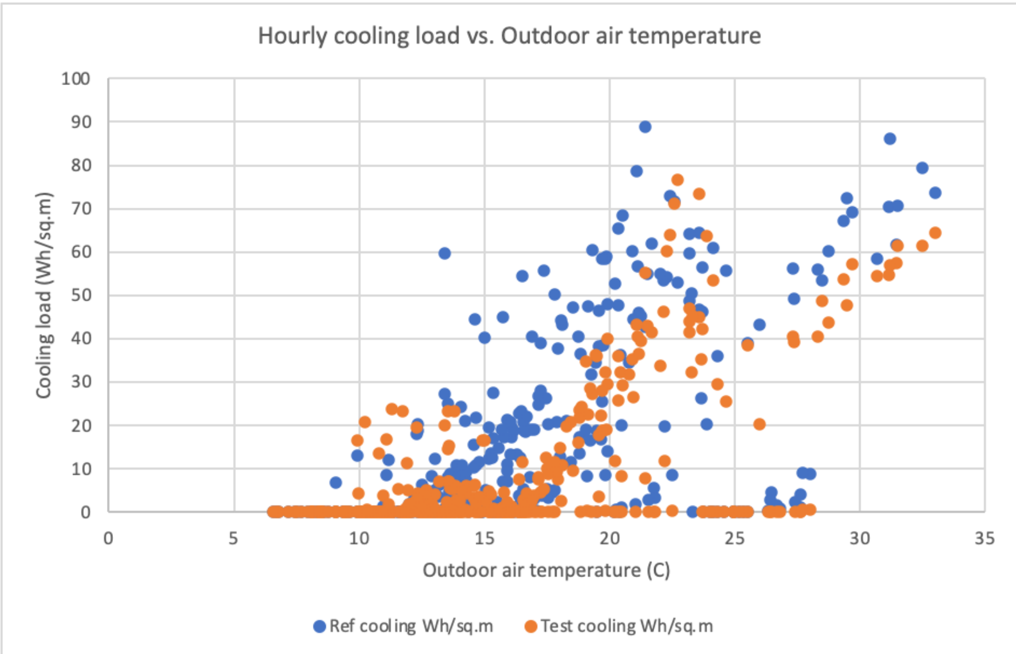

Figure 9. Cooling load vs. outdoor air temperature for Core-S for test and reference cells.

HVAC energy includes the energy used for the chiller system, boiler system and air handler. The chiller and boiler energy use were calculated from the cooling and heating loads using conversion factors for a central chiller plant and boiler for a representative office building. We decided to use these representative conversion factors rather than the actual energy use of the test facility chiller and boiler system because the test facility system is sized for a single zone and would not be as representative of a normal building-scale system. Figure 10 shows the daily HVAC energy for Core-S.

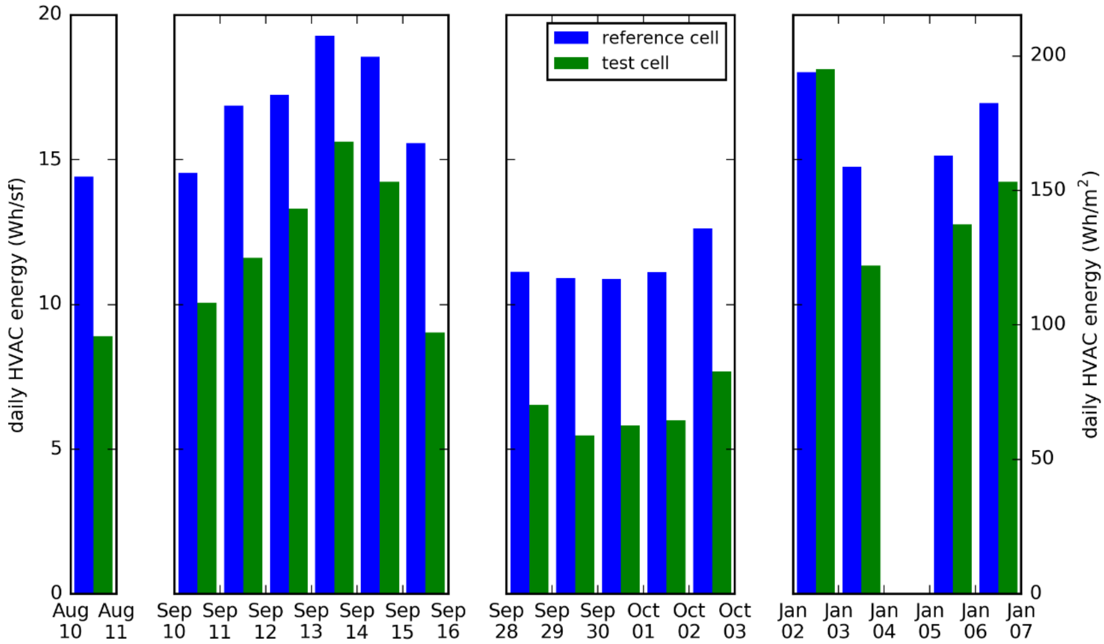

Figure 10. Daily HVAC energy (including chiller system, boiler system, air handlers) for test and reference cells for test days in the Core-S configuration.

Figure 11 shows the HVAC energy savings percentage for each configuration, broken out by chiller system, boiler system and air handler. Table 5 summarizes the thermal load and energy savings for all six configurations over their respective test periods.

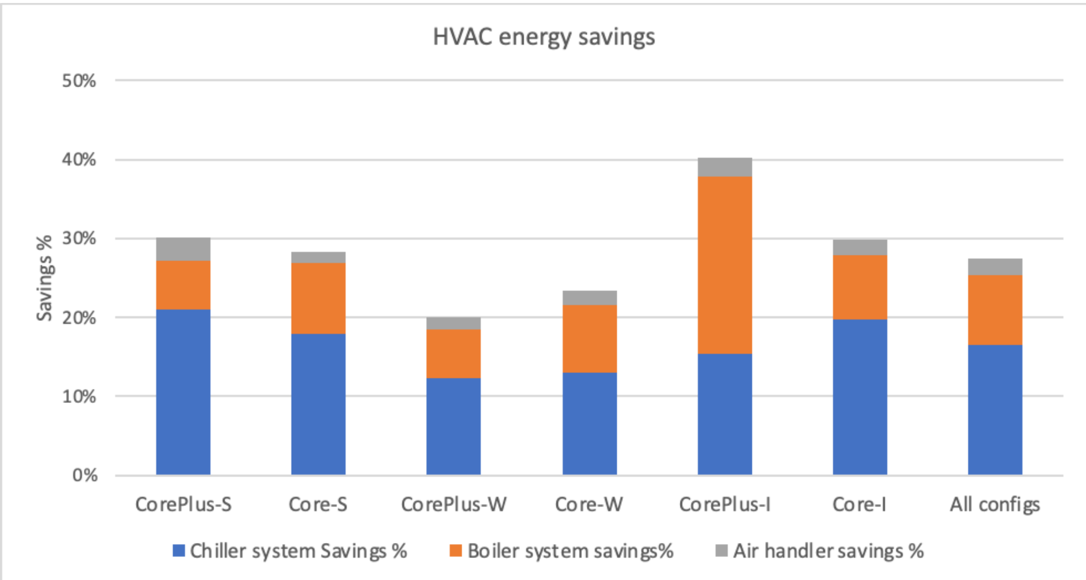

Figure 11. HVAC energy savings for each configuration, broken out by chiller system, boiler system and air handler.

Table 5. Thermal load and HVAC energy savings for each configuration.

Configuration	Cooling Load Savings %	Heating Load Savings %	HVAC Energy Use Savings %
CorePlus-S	54%	25%	30%
Core-S	38%	37%	28%
CorePlus-W	52%	4%	20%
Core-W	42%	10%	23%
CorePlus-I	47%	54%	40%
Core-I	62%	32%	30%
All configs	48%	23%	27%

The results show substantial thermal load reductions and HVAC energy savings in all configurations. Overall savings for the entire test period for all configurations shows a total of 48% cooling load savings, 23% heating load savings, and 27% HVAC energy savings. As Figure 11 indicates, HVAC energy savings are mostly from the cooling system. Air handler savings were a relatively small component of total HVAC energy savings. The savings vary considerably across different configurations: 38–62% for cooling load, 4–54% for heating load, and 20–40% for HVAC energy. The CorePlus configuration shows higher HVAC energy savings than Core for the south and interior orientations, but not for the west orientation; and it shows higher cooling load savings for south and west orientations, but not for interior. In effect, it is likely that the variations in weather for the different test periods for each configuration mask the incremental effect of the CorePlus features. Therefore, it is not possible based on these test data alone to assess the incremental savings from the CorePlus over the Core configuration. Future analysis that normalizes for weather may be able to address this. In addition, in future it would probably be more beneficial to have fewer testing scenarios and longer testing periods per scenario.

3.1.3. Plug Loads

Figure 12 shows the hourly profile of plug load wattage per unit area for the test cell, without plug load control (Core) and with plug load controls applied (CorePlus), as well as the difference. This amounts to a total plug load energy savings of just 3.8 Wh/sq.m/day (0.35 Wh/ft^2/day), which is 3% of total plug load. Note that the savings do not vary by orientation.

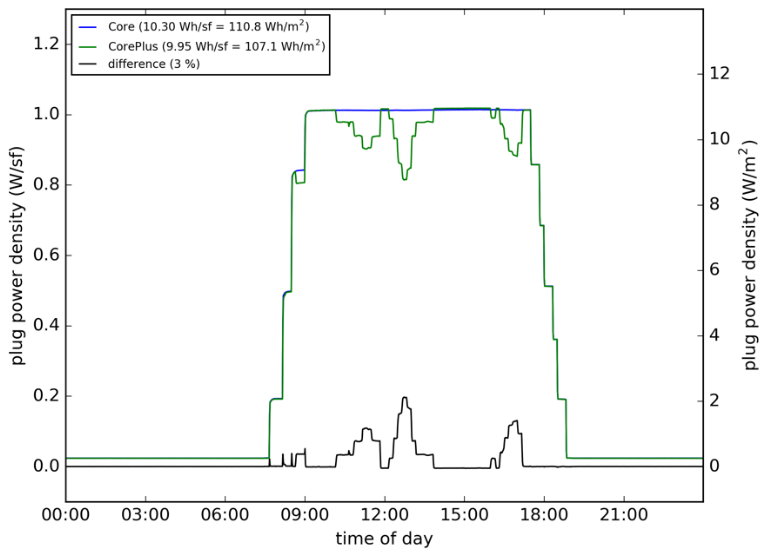

Figure 12. Hourly profile of plug loads with plug load controls (CorePlus) and without (Core). The difference is also shown.

3.1.4. Combined Savings Estimates

Table 6 and Figure 13 below show the combined savings from HVAC, lighting and plug loads over the test period for each configuration, as well as the breakout of savings by end use.

Table 6. End use and combined energy savings percentages for each configuration.

Configuration	Lighting Energy Savings (% of All Three End Uses)	HVAC Energy Savings (% of All Three End Uses)	Plug Load Energy Savings (% of All Three End Uses)	Combined Energy Savings (% of All Three End Uses)
CorePlus-S	26%	11%	1%	37%
Core-S	28%	11%	0%	39%
CorePlus-W	24%	9%	1%	33%
Core-W	26%	10%	0%	36%
CorePlus-I	25%	14%	1%	40%
Core-I	26%	9%	0%	36%
All configs	26%	10%	0%	37%

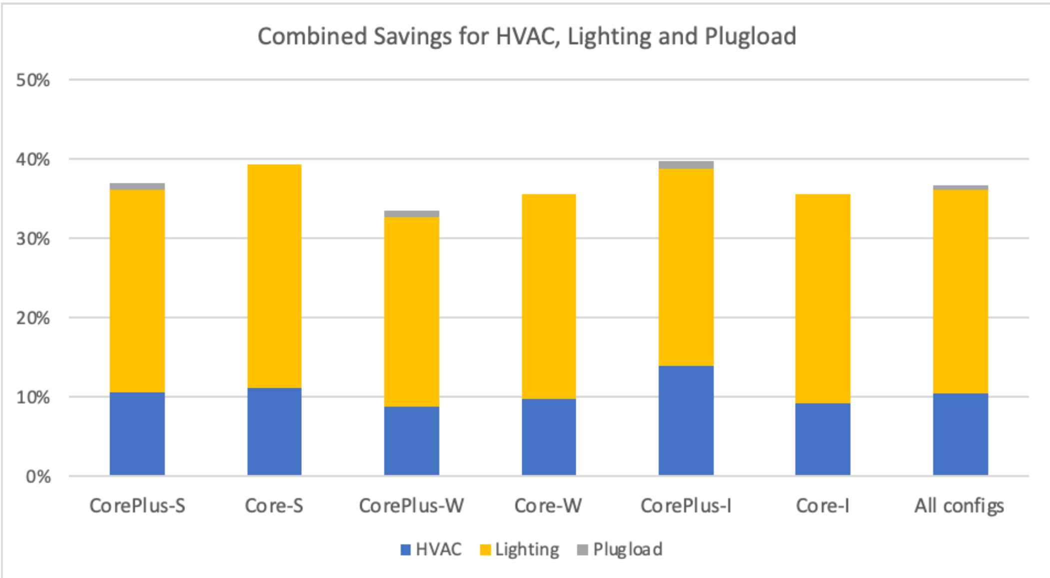

Figure 13. Combined savings breakout for HVAC, lighting and plug loads.

These results show that the TFP yields combined savings of 37% across the entire test period for all configurations, with a range from 33–40% across the six configurations. These are considerable savings especially considering that it is limited to the scope of a tenant fit-out and does not include any HVAC equipment or envelope retrofits.

About two-thirds of the savings are due to lighting and the remaining from HVAC. Although HVAC is the largest component of the combined energy use in the reference case, the percentage reductions in lighting were much higher than HVAC. Plug load savings were negligible in the CorePlus configurations (and not applicable in the Core configurations).

Whole building energy savings for the ISP will depend on several factors: the relative proportion of perimeter and interior zones, ratio of office spaces to other space types in the building, and any ancillary end uses, such as bathroom exhausts, exterior lighting, etc. This is beyond the scope of laboratory testing of the packages, since it was limited to office spaces for south, west and interior configurations. Separately, we are conducting simulations, as well as field demonstrations, that will provide whole building savings estimates (initial results from the simulation studies using the DOE prototype models [36] for medium and large office show savings of 23% to 38% whole building energy savings across four different climate zones for Core and CorePlus configurations. These estimates are consistent with the laboratory results).

3.2. Indoor Environmental Quality

The primary objective of the ISPs is to reduce energy use while maintaining or improving indoor environmental quality (IEQ) relative to the baseline. Toward that end, we measured three IEQ metrics: illuminance, daylight glare probability, and mean radiant temperature.

3.2.1. Illuminance

Figure 14 shows the illuminance levels during occupied hours for the front, middle and rear rows of workstations, for Core and CorePlus for south and west orientations. As expected, illuminance levels are higher for the front workstations which are close to the window. The front workstations also show a much higher range of illuminance, due to the impact of daylight and direct solar radiation in particular.

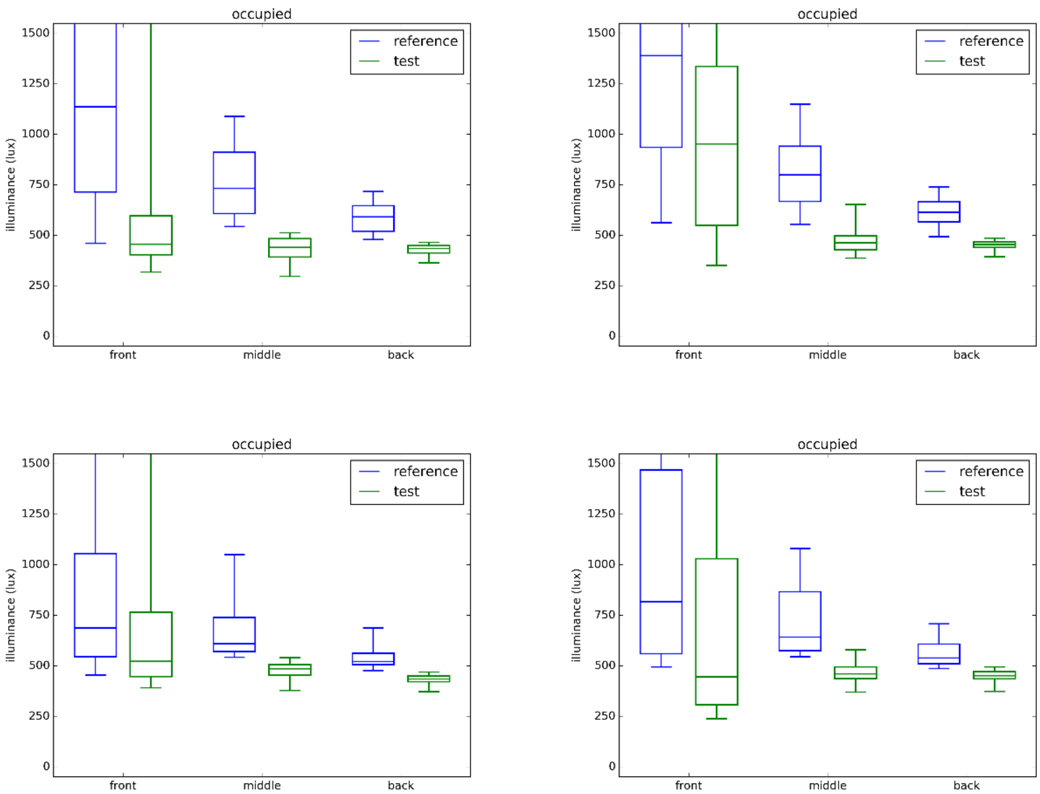

Figure 14. Illuminance levels for Core-S (**top right**), Core-W (**bottom right**), and CorePlus-S (**top left**), CorePlus-W (**bottom left**) for front middle and back rows of workstations during occupied hours.

Illuminance levels in the test case are much closer to the setpoint of 500 lux due to implementation of lower-wattage LED fixtures specified for the design target and due to fixture-level photosensors and dimming based on daylight availability. The test case fixtures' photosensors auto calibrate to maintain the light levels with all lights turned on, excluding daylight, and then dim based on daylighting conditions.

Throughout the day, fixtures also dim to a minimum setting when a workstation is unoccupied, resulting in values lower than the 500-lux design target, which is only intended for occupied periods. Accordingly, we filtered lighting data for each desk to only include data when that desk is occupied. Note however that, while a given desk's overhead fixture contributes the most to its total light levels, light from adjacent fixtures also contributes to that total to a lesser extent. At some times, when a desk is occupied and its lighting data included in the analysis, adjacent desks are unoccupied and associated fixtures dimmed to minimum level. For those times, the occupied desk receives less light contribution from adjacent fixtures and may not meet the 500-lux design target that is achieved with all lights on. This fixture-level occupancy-based dimming behavior explains why the median values of some desks are slightly below 500 lux.

3.2.2. Daylight Glare Probability (DGP)

Daylight glare was assessed from two positions, as described earlier. Figure 15 shows the percentage of time DGP was in different ranges, for CorePlus-S and CorePlus-W. In general, DGP is almost always in the imperceptible range. We found this to be the case for other configurations, as well. In short, daylight glare was not an issue.

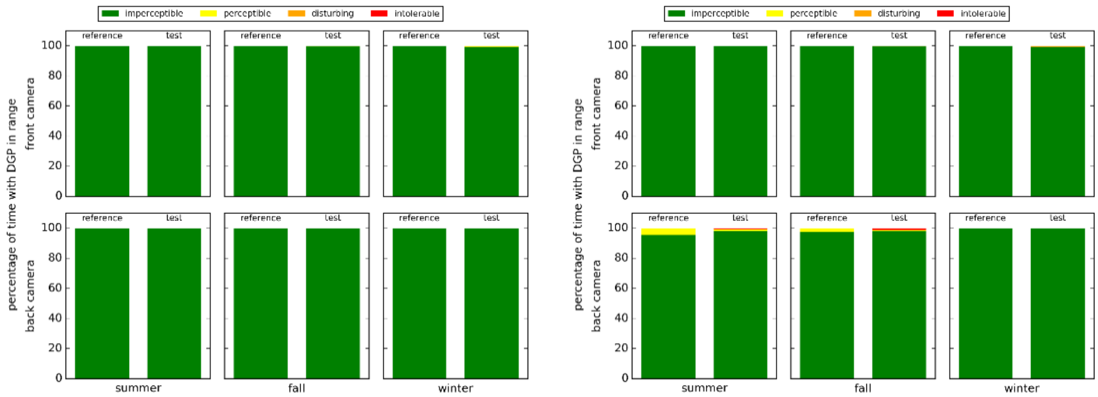

Figure 15. Daylight glare probability (DGP) for CorePlus-S (**left**) and CorePlus-W (**right**).

3.2.3. Mean Radiant Temperature

We measured the mean radiant temperature (MRT) at two locations: at the perimeter about 1.5 m (5 ft) from the window ("front") and in the interior about 6 m (20 ft) from the window ("back"). In all configurations, the temperatures in the test cell were slightly higher than the baseline. As an example, Figure 16 shows the MRT for Core-S and Core-W. Closer examination of the data showed that in the test cell HVAC controls were such that temperatures were at or slightly above setpoint for cooling. There were no significant differences between the front and the rear, indicating that window effects on MRT were minimal.

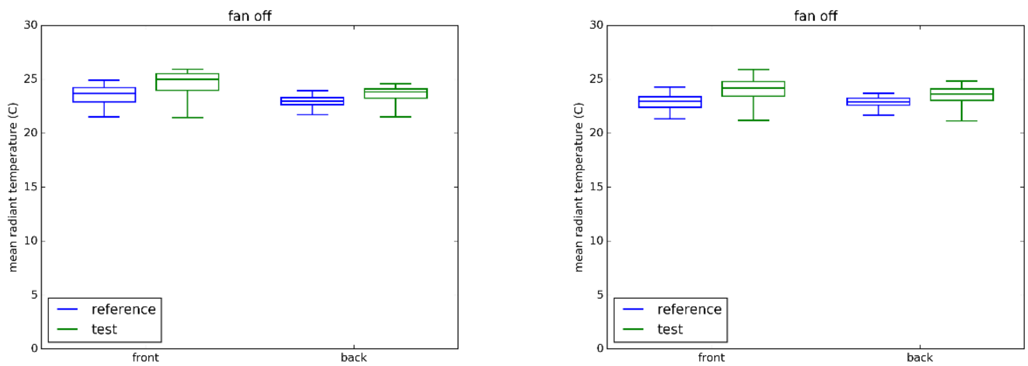

Figure 16. Mean radiant temperature (MRT) in Core-S (**left**) and Core-W (**right**) configurations.

3.3. Installation, Commissioning and Operation

As mentioned earlier, a secondary objective of laboratory testing was to identify any issues with the installation, commissioning and operation of the package. In particular, we sought to identify unanticipated skill, effort, or time requirements. Below, we summarize the key issues we identified.

3.3.1. Lighting and HVAC Integration

Implementation of this measure required additional commissioning procedures with a wireless configuration tool used to program controls features like occupancy zones, configuring the lighting network, and pairing the network to the wireless gateway and control server. There were some challenges commissioning the lighting system to report discrete occupancy statuses per fixture (essentially zoning each fixture independently) and connecting the wireless gateway and Linux-based controls box to the lighting network, which required technical support with the controls manufacturer. Otherwise, the reliability and stability of the data exchange was good throughout the test. While these are not intractable issues per se, they may impact the quality of commissioning in actual buildings, especially under schedule and budget constraints. This, in turn, may reduce the savings.

3.3.2. ASHRAE G36 Controls

In its present form, Guideline 36-2018 is not easy to implement and leaves considerable decision making to the programmer; thus, the guideline requires a fairly experienced programmer to ensure proper implementation. For example, generally more than one PI (proportional integral) control loop is shown on each graph with little detail about where each start and end. The guideline could be improved by including programming recommendations that apply to common building management systems.

Commissioning also can be a challenge, as this is a fairly complex rules-based algorithm and understanding what the correct operation should be is sometimes difficult. For example, economizer operation at the start of each day is not explicitly addressed and should be reset to "no economizer" overnight unless morning cooldown is called for. Omitting this can lead to overcooling the space in the morning after the occupied state changes, which then requires heating to compensate. A simulation-based approach can be used to evaluate the inherent uncertainty in controls components on the performance of HVAC systems programmed with Guideline 36 controls [37].

3.3.3. Ceiling Fan Controls Integration

The ceiling fans standalone controls worked as expected in and of itself. However, the package required integration with the HVAC controls to actuate the ceiling fan based on cooling mode. This integration required customized "patching" between the ceiling fan and HVAC controls, which was a non-trivial effort.

3.3.4. Plug Load Controls

Implementation of this measure involved pairing wireless self-powered occupancy sensors with controlled outlets, and commissioning all controlled outlets through a central server with radio and browser-based user interface. Sensor placement and load disaggregation (monitors vs. CPUs, for example) are important implementation features to ensure that critical loads are switched properly, i.e., monitors being powered whenever occupants are present and CPUs not being de-energized due to vacancy. There were some challenges with time-out operation for the occupancy sensors (a built-in sensor-level time-out inadvertently added to controls system time-out settings), leading to longer time-outs than desired, which, in turn, can negatively impact energy savings potential. We were able to address this, and the system operation was stable throughout the test process. This level of effort should be carefully weighed against the savings from plug load controls. Our results showed minimal savings from control of desktop monitors. Plug load controls may only be worthwhile for larger intermittently used loads, such as printers, plug-in heaters, etc.

4. Conclusions

This paper presented the design and performance of a package of energy efficiency measures that can be applied at the time of a tenant fit-out. The tenant fit-out package (TFP) includes LED lighting with daylighting and occupancy controls, ASHRAE Guideline 36 HVAC control sequences, and, optionally, ceiling fans, automated window shades, and occupancy-based plug load controls. We conducted laboratory testing of the package to evaluate energy savings, thermal comfort, and visual comfort relative to an existing building baseline. Testing was conducted for three orientations (south, west, interior) and TFP versions (with and without optional measures). The results show significant lighting energy savings ranging from 69–83% and HVAC energy savings from 20–40%. Plug load savings were minimal, at just 3%. The combined savings from all measures ranged from 33–40%. The laboratory testing also revealed some minor but tractable challenges with installation and commissioning of HVAC controls. In summary, the results demonstrate that significant savings can be realized in existing office buildings by incorporating relatively low-risk, proven measures at the time of a tenant fit-out. These could be incorporated into the standard fit-out specifications used by landlords and tenants. We discussed these results with several building owners and operators, who generally affirmed the value of these results to help them "make the case" for implementing the TFP. Contractually, this would take the form of an "add alternate" to the baseline tenant fit-out scope of work. However, field validation during actual tenant fit-outs in real buildings is necessary to provide further evidence for real estate stakeholders to adopt this approach at scale. Even if they are convinced of the savings and technical feasibility, stakeholders need to be reassured that it these measures will not overly complicate their conventional practice or add risk to schedule and budget. The building industry is especially risk-averse, and stakeholders have a strong bias for real-world evidence from peers. In particular, field validation is necessary to evaluate the incremental cost and effort relative to a conventional fit-out. We are currently in the process of doing field demonstration in a small office building in the southeastern U.S. and expect to conduct additional field demonstrations in other U.S. locations to assess these factors.

Supplementary Materials: Detailed results for all configurations tested are available on GitHub at https://tinyurl.com/y47sld6y. The detailed time-series data for specific metrics, configurations, and test periods are also available from the corresponding author upon reasonable request.

Author Contributions: Conceptualization P.M. and C.R.; methodology, P.M., C.R. and J.S.; formal analysis, T.W., J.S., C.R., P.M.; writing—original draft preparation, P.M. and J.S.; writing—review and editing, P.M., J.S., T.W.; visualization, T.W. and P.M.; supervision, P.M.; project administration, P.M.; funding acquisition, P.M. All authors have read and agreed to the published version of the manuscript.

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