Leading in Los Angeles: Demonstrating scalable emerging energy efficient technologies for integrated façade, lighting, and plug loads

INTER System FLEXLAB Test Report

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DISCLAIMER

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Introduction

This report is a part of the California Energy Commission (Energy Commission) EPIC study *Leading in Los Angeles: Demonstrating scalable emerging energy efficient technologies for integrated façade, lighting, and HVAC*. The set of technologies are called the Integrated Technologies for Energy-efficient Retrofits (INTER) and are comprised of automated shading products and LED lighting systems with networked luminaire-level sensors and controls. In addition, the project will include control modifications and assessments of HVAC savings. This document includes the test plan and test results for the FLEXLAB® testing of the shading and lighting INTER system and related energy use impact. The test plan describes the test objectives and features, test cases, schedule, and measurements. The test results cover system performance in the lab; including lighting and HVAC energy, visual comfort, and thermal comfort.

Objectives

The two main objectives of the FLEXLAB testing were to 1) evaluate the energy performance of the INTER shading and daylighting control system (determine energy savings compared to 'typical' existing baseline as well as code baseline; disaggregate lighting and HVAC energy savings), and 2) evaluate the visual and thermal comfort performance of the INTER shading and daylighting control system. The INTER system was tested over three seasons (summer, fall, winter) in parallel to two alternating baseline configurations:

1. Existing building baseline with manually operated venetian blinds and fluorescent lighting with no daylight-based dimming.
2. California Title 24 code-compliant baseline with manually operated venetian blinds and lower-wattage fluorescent lighting with zonal daylight-based dimming.

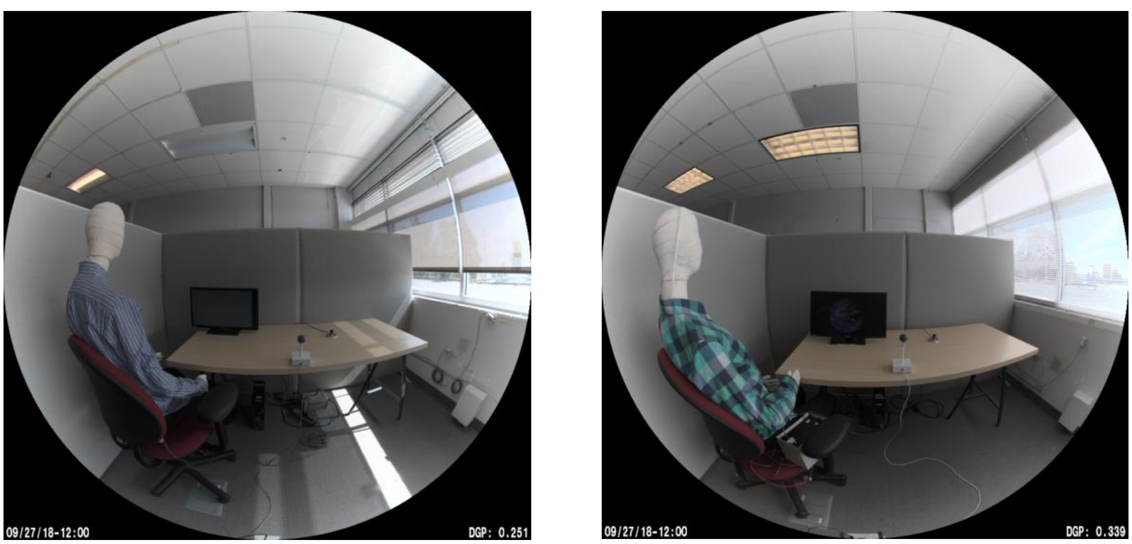


Figure 1. Side-by-side view of baseline (right) and retrofit test configurations (left)

In addition, the testing was meant to provide feedback and lessons learned on the installation, commissioning, and operation of the INTER shading and daylighting control system, especially aspects that affect operations and maintenance, savings persistence, or user acceptance. The side-by-side photographs above from the high dynamic range (HDR) glare sensors shows the basic configuration of the baseline (right) and retrofit (left) cells; visible are the shading systems, electric lights (note daylight dimming in left photo of retrofit), cubicle layout, and light and mean radiant temperature sensors (on the desk). Table 1 provides the details for the Baseline and the Retrofit test cell configuration and include an existing building and a Title 24 code-compliant baseline with the glazing area as a 'Full-window' and with the introduction of physical cover such as cardboard to simulate a "Mid-window" size area.

Table 1. Test Cell Configurations

Abbr.	Description (Abbr. in column to the left)	Both Cells	Baseline Cell			Retrofit Cell		
		Window-to-Wall Ratio	Lighting System	Lighting Dimming Controls	Shading System	Lighting System	Lighting Dimming Controls	Shading System*
FWEB	Full-window, **existing building** baseline	~ 0.50	Fluorescent: 3-lamp T8 troffers	No daylight-based dimming	Manually operated venetian blinds	LED troffers	Fixture-level daylight dimming	Automated roller-shades and daylight redirecting louvers
MWEB	Mid-window, **existing building** baseline	~ 0.40						
FWTB	Full-window, **Title 24 code-compliant** baseline	~ 0.50	Fluorescent: 2-lamp T5 troffers	Stepped dimming near windows				
MWTB	Mid-window, **Title 24 code-compliant** baseline	~ 0.40						

* At the time of this lab evaluation, automated solar tracking controls were not commercially available, but scheduled operation of the shades and blinds via smartphone app and Wi-Fi hub was.

Results

With the retrofit to the INTER system of automated shading products and LED dimmable lighting with daylight controls, the lighting energy savings relative to an **existing building baseline** of non-dimmable fluorescent fixtures on scheduled operation ranged from **62% in winter** (less daylight dimming possible) to **76% in summer** (more daylight dimming). Relative to a **Title 24 baseline** lighting system equipped with dimmable fluorescents and stepped dimming for fixtures near the windows, lighting energy savings were naturally reduced, but will ranged from **49% in winter to 62% in summer**. Table 2 below provides details on the savings from baseline to retrofit for the configurations and per season. These are savings measured from one configuration (baseline) to an alternate (retrofit) and are not annual whole buildings estimates.

Table 2. Energy savings per test case and season (Wh/ft²/day, %)

Savings Type	Test Configuration		Season		
			Summer	Fall	Winter
Lighting Energy	Full Window	Existing Building	10.8 (76%)	10.4 (73%)	9.0 (62%)
Cooling Load	Full Window	Existing Building	11.0 (36%)	10.9 (28%)	(no cooling)
Heating Load	Full Window	Existing Building	-1.9 (%n/a)	-1.2 (%n/a)	-2.3 (-17%)
Lighting Energy	Mid Window	Existing Building	10.6 (75%)	10.1 (71%)	9.2 (63%)
Cooling Load	Mid Window	Existing Building	11.3 (38%)	13.9 (43%)	1.1 (100%)
Heating Load	Mid Window	Existing Building	-1.3 (-44%)	-1.6 (-53%)	-2.7 (-27%)
Lighting Energy	Full Window	Title 24 Building	5.3 (62%)	5.0 (57%)	5.0 (50%)
Cooling Load	Full Window	Title 24 Building	6.0 (19%)	6.5 (15%)	5.9 (26%)
Heating Load	Full Window	Title 24 Building	-0.6 (-18%)	-0.2 (-8%)	-0.3 (-5%)
Lighting Energy	Mid Window	Title 24 Building	5.6 (61%)	4.9 (56%)	5.5 (49%)
Cooling Load	Mid Window	Title 24 Building	6.7 (25%)	8.8 (24%)	4.3 (76%)
Heating Load	Mid Window	Title 24 Building	-0.8 (-24%)	-0.2 (-6%)	-1.4 (-16%)

HVAC load savings were found for all configurations when in cooling mode, with HVAC cooling load savings being very close to lighting energy savings, indicating that **the majority of the HVAC load difference is due to the lower-wattage electric lighting in the retrofit case** (lower wattage lighting results in less heat added to the space). Summer and fall HVAC cooling load savings were consistently higher than energy savings from lighting alone, indicating **that the INTER automated shading also contributed energy savings, potentially due to solar heat gain reductions from the shades**. Some HVAC load penalty (**negative savings) was observed while in heating mode**, as expected. However, little time was spent in heating due to the test site's climate so the results are less robust. For **thermal comfort near the window wall, no meaningful difference was measured between mean radiant temperature in the baseline and retrofit cells for most cases** (differences typically between less than 0.5 degree F to slightly over 1 degree F).

Table 3 below details the measured light levels in the baseline and retrofit cells during the various test configurations. With some minor adjustments to increase lighting power and light levels to ensure maintained illuminance was at or above the design criterion (500 lux, at Desk 2), the illuminance design criterion was met in the baseline and retrofit condition. Visual comfort was also evaluated in terms of glare, and **the daylight glare probability analysis from test data showed that glare was adequately controlled for all test periods in the baseline case** (venetian blinds across window with louvre angle adjusted seasonally to block direct sun) **and the retrofit case** (rollershade and redirecting blind angle set seasonally to avoid direct sun).

Table 3. Desk 2 illuminance results (median lux per test period)

Test Configuration		**Test Season**					
Window Height	Building Type	Summer		Fall		Winter	
		Base.	Retro.	Base.	Retro.	Base.	Retro.
Full Window	Existing Building	773	589	772	562	656	545
Mid Window	Existing Building	767	598	739	558	670	504
Full Window	Title 24 Building	532	589	558	574	552	547
Mid Window	Title 24 Building	521	604	545	542	520	542

In addition to the energy and illuminance findings above factors regarding the installation and commissioning of the INTER shading system were also evaluated with the following results:

- The INTER shading system is powered by rechargeable batteries and integrated photovoltaic chargers, which functioned as intended during the test (autonomous with no need for hardwired power).
- The shade controller Wi-Fi hub was successfully programmed to discover and control the blinds and shade motors. The wireless battery-powered remote control was also easily commissioned and used to adjust shade height and blind angle.
- Automation of blind tilting through scheduled actions was not effective due to minor mechanical issues (deflection of the rod holding the louvers up), so blinds tilt angle was controlled in-person by remote control or smartphone and then fine scale adjustments were made manually.
- At the time of deployment for FLEXLAB testing, there was no commercial control server or software that could implement automated blinds and shades operation based on a solar model for predicting solar angles through time.
- The ability of the reflective louvers to direct sunlight onto the ceiling deeper into the test cell was confirmed visually and through photographs for different tilt angles.

Introduction

This report is a part of the California Energy Commission (Energy Commission) EPIC study *Leading in Los Angeles: Demonstrating scalable emerging energy efficient technologies for integrated façade, lighting, and HVAC*. The project launched in June 2017 and is a 3-year research study involving bench and laboratory testing, field demonstration, performance measurement and verification, and market assessment and connection efforts to move an integrated set of emerging commercial retrofit technologies into wider adoption. The set of technologies are called the Integrated Technologies for Energy-efficient Retrofits (INTER) and are comprised of automated shading products and LED lighting systems with networked luminaire-level sensors and controls. In addition, the project team will demonstrate metering and measurement and verification (M&V) and make controls and commissioning adjustments to further the energy savings potential in the retrofit demonstrations. The project prime contractor is New Buildings Institute (NBI) and key team members are TRC Companies, Inc. and Lawrence Berkeley National Laboratory (LBNL).

This document includes the test plan and test results for the FLEXLAB testing of two key components of the INTER system from mid-2018 through spring 2019: the shading system and the lighting system. The test plan describes the test objectives and features, test cases, schedule, and the measurements. The test results cover system performance in the lab; including lighting and HVAC energy, visual comfort, and thermal comfort.

Test Objectives and Features

The two main objectives of the FLEXLAB testing were to:

1. Evaluate the energy performance of the INTER shading and daylighting control system.
    a. Determine energy savings compared to 'typical' existing baseline as well as code baseline;
    b. Disaggregate lighting and HVAC energy savings.
2. Evaluate visual and thermal comfort performance of the INTER shading and daylighting control system.

In addition, the testing was meant to provide feedback and lessons learned on the installation, commissioning, and operation of the INTER shading and daylighting control system, especially aspects that affect the operations and maintenance, savings persistence, or user acceptance.

Key features of the tests include:

- Three rounds of seasonal testing consisting of three weeks total each round (including setup/takedown time). The first round of testing includes feedback on system integration and controls algorithm performance.
- The full package of integrated system elements to test consists of:
    - Rollease automated roller shade
    - Rollease automated light redirecting louver

    - Enlighted dimmable lighting system and LED fixtures
- Key test fixed conditions:
    - Configuration (open office only)
    - Orientation (South only)
    - Occupant and Plug loads
- Key test condition variables:
    - Window lintel height:
        - Ceiling level (window-to-wall ratio of ~0.50) and
        - 12” lower than ceiling (window-to-wall ratio of ~0.40)
    - Baseline cases:
        - ‘Typical’ (scheduled on/off operation of 3-lamp T8 fluorescent light fixtures), and
        - Title 24 condition (scheduled on/off operation of 2-lamp T5 fluorescent fixtures with stepped daylight dimming of primary and secondary zones only).
- Key performance metrics:
    - Lighting energy savings
    - HVAC thermal load savings
    - Illuminance distribution in the test space
    - Daylight glare probability
    - Indoor air temperature and mean radiant temperature
- Additional diagnostic testing conducted to evaluate and analyze daylight penetration with all lights turned off.
- Daily checks of data logging and any operational issues associated with the system.

Approach

LBNL’s FLEXLAB test facility allows building systems to be tested individually or as an integrated system, under real-world conditions. FLEXLAB test beds can test HVAC, lighting, windows, building envelope, control systems, and plug loads, in any combination.

<u>Side-by-side testing:</u> The test case (i.e. automated shading integrated with efficient LED lighting and daylight dimming) and the baseline cases were tested at the same time under identical conditions using the two cells of the FLEXLAB testbed. The baseline cases were:

- Existing building with manually operated venetian blinds and fluorescent lighting with no daylight-based dimming
- Code compliant case with manually operated venetian blinds and fluorescent lighting with zonal daylight-based dimming)

Figures Figure 2 and Figure 3 show the floor plan and external view of FLEXLAB testbeds. Each test cell is approximately 20’ wide and 30’ deep.

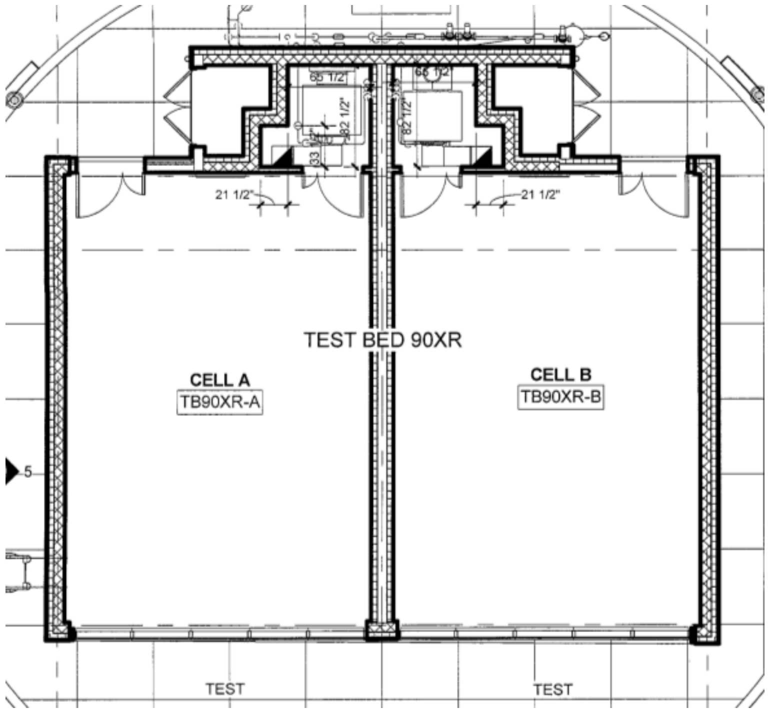


Figure 2 . Floor plan of FLEXLAB testbed showing side by side test cells

Figure 3. External view of a FLEXLAB testbed

Figure 4. Internal view of FLEXLAB testbed with INTER shading system installed

Figure 5. External view of FLEXLAB testbed with INTER shading system installed

Test Cases

Table 4 lists and describes the features of each test case. The main test cases are FWEB, MWEB, FWTB, and MWTB. Test case LOFF is only for diagnostic testing of daylighting with the lights turned off.

Table 4. Test case descriptions

ID	Test	Days/ cycle	Cell B – Test Case	Cell A - Baseline
0	Setup/ Commission	2	N/A	N/A

FWEB	Existing building baseline, full window height (to lintel), 5ft partitions	5	• Orientation: South
			• HVAC: VAV
			• Façade:
			  ○ WWR ~0.50
			  ○ Lintel to underside of ceiling
			  ○ Single-pane window w/ thermally broken (single break) aluminum frame
			  ○ metal stud wall w/ R-19 batt cavity insulation
			• Shading: Rollease automated shade and automated light redirecting louver w/integrated PV and battery
			• Interior partition: 5ft high
			• Lighting: 0.40 W/ft^2, LED 2x4 troffer tuned to 500lux output, occ. sensing, daylight dimming (Enlighted), tuned for 500 lux at workplane
			• Plug loads: 0.5 W/ft^2 scheduled to represent plug load profile for heat output only (will not be testing integrated occupancy controls w/Enlighted system)
				• Orientation: South
				• HVAC: VAV
				• Façade:
				  ○ WWR ~0.50
				  ○ Lintel to underside of ceiling
				  ○ Single-pane window w/ thermally broken (single break) aluminum frame
				  ○ metal stud wall w/ R-19 batt cavity insulation
				• Shading: Manually adjusted horizontal venetian blind. Adjusted seasonally to sun-blocking angle. No daily adjustments.
				• Interior partition: 5ft high
				• Lighting: 1.0 W/ft^2, 3-lamp T8 2x4 troffer, no automated controls, timeclock only
				• Plug loads: 0.5 W/ft^2, scheduled to represent plug load profile for heat output only

MWEB	Existing building baseline, mid window height (lower false lintel), 5ft partition	5	• Façade:
			  ○ WWR ~0.40
			  ○ Lintel stops 12" from underside of ceiling
			• All else same as FWEB
				• Façade:
				  ○ WWR ~0.40
				  ○ Window head stops 12" from underside of ceiling
				• All else same as FWEB

FWTB	Title 24 compliant building baseline (2016), full window height (to	5	• Orientation: South
			• HVAC: VAV
			• Façade:
			  ○ WWR ~0.50
			  ○ Lintel to underside of ceiling
			  ○ Single-pane window w/
				• Orientation: South
				• HVAC: VAV
				• Façade:
				  ○ WWR ~0.50
				  ○ Lintel to underside of ceiling
				  ○ Single-pane window w/

ID	Test	Days/ cycle	Cell B – Test Case	Cell A - Baseline
	lintel), 5ft partitions		thermally broken (single break) aluminum frame ○ Metal stud wall w/ R-19 batt cavity insulation ● Shading: Rollease automated shade and automated light redirecting louver w/integrated PV and battery ● Interior partition: 5ft high ● Lighting: 0.40 W/ft^2, LED 2x4 troffer tuned to 500lux output, occ. sensing, daylight dimming (Enlighted), tuned for 500 lux at workplane ● Plug loads: 0.5 W/ft^2 scheduled to represent plug load profile for heat output only (will not be testing integrated occupancy controls w/Enlighted system)	thermally broken (single break) aluminum frame ○ Metal stud wall w/ R-19 batt cavity insulation ● Shading: Manually adjusted horizontal venetian blinds ● Interior partition: 5ft high ● Lighting: 0.69 W/ft^2,(0.75 W/sf is baseline per 2016 CA T24, Table 140.6-C, area category method for offices >250sf), 2-lamp T5 2x4 troffer, occ. sensing, daylight dimming (per Table 130.1-A, for Linear fluorescent and U-bent fluorescent > 13 watts, stepped dimming), timeclock, no tuning (lights will be operated at the output installed, not tuned). Only rows within 2 x ceiling height from window will have stepped dimming control. Calibrate the photocell for 150% of target illuminance minimum approach in the primary and secondary sidelit daylit zones. ● Plug loads: 0.5 W/ft^2, scheduled to represent plug load profile for heat output only.
MWTB	Title 24 compliant building baseline, mid window height (lower false lintel), 5ft partition	5	● Façade: ○ WWR ~0.40 ○ Lintel stops 12” from underside of ceiling ● All else same as FWTB	● Façade: ○ WWR ~0.40 ○ Lintel stops 12” from underside of ceiling ● All else same as FWTB
LOFF	Lights off	1	Same as FWEB, with all lights turned off	Same as FWEB, with all lights turned off.

Test Set Up

Furniture Plan and Cell Layout

The furniture plan consisted of an open office layout with cubicle partitions of 5' height and three total work spaces in the 600 ft^2 test cells: Desk 1 being adjacent to the south, window wall; Desk 2 in the middle of the cell and separated from the first work space by a hallway; and Desk 3 being the most interior workspace. The area of each work space was 80 ft^2 with hallways on either side. This configuration was meant to represent a sample of work spaces in an open office environment at different depths from the windows. Total effective illuminated space in the test cell for lighting power density calculations was 520 ft^2 (excludes 1' of perimeter floor area along the sides and rear of cell), while the space conditioned by the HVAC system for HVAC load calculations was the full 600 ft^2 of the test cells. The locations of the desks, light fixtures, illuminance sensors, and glare sensors are illustrated in Figure 6. The configuration of the retrofit cell is shown in Figure 7.

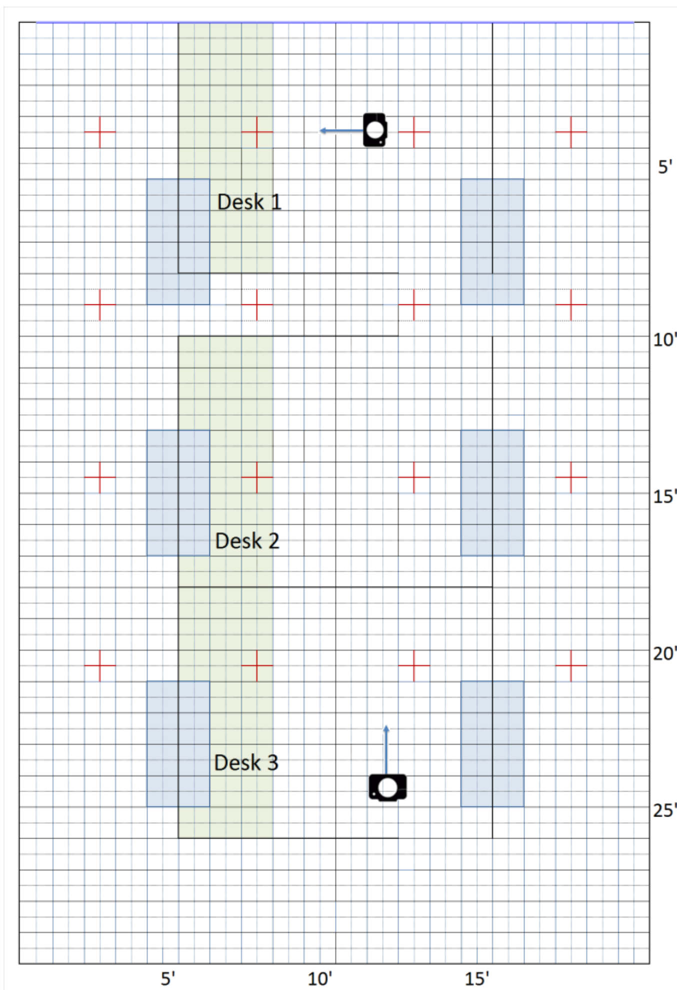


Figure 6. Cell configuration (black lines are partitions, desk locations indicated by green area, light fixtures by blue area, light sensors by red hatch marks, and glare sensors by camera icons).

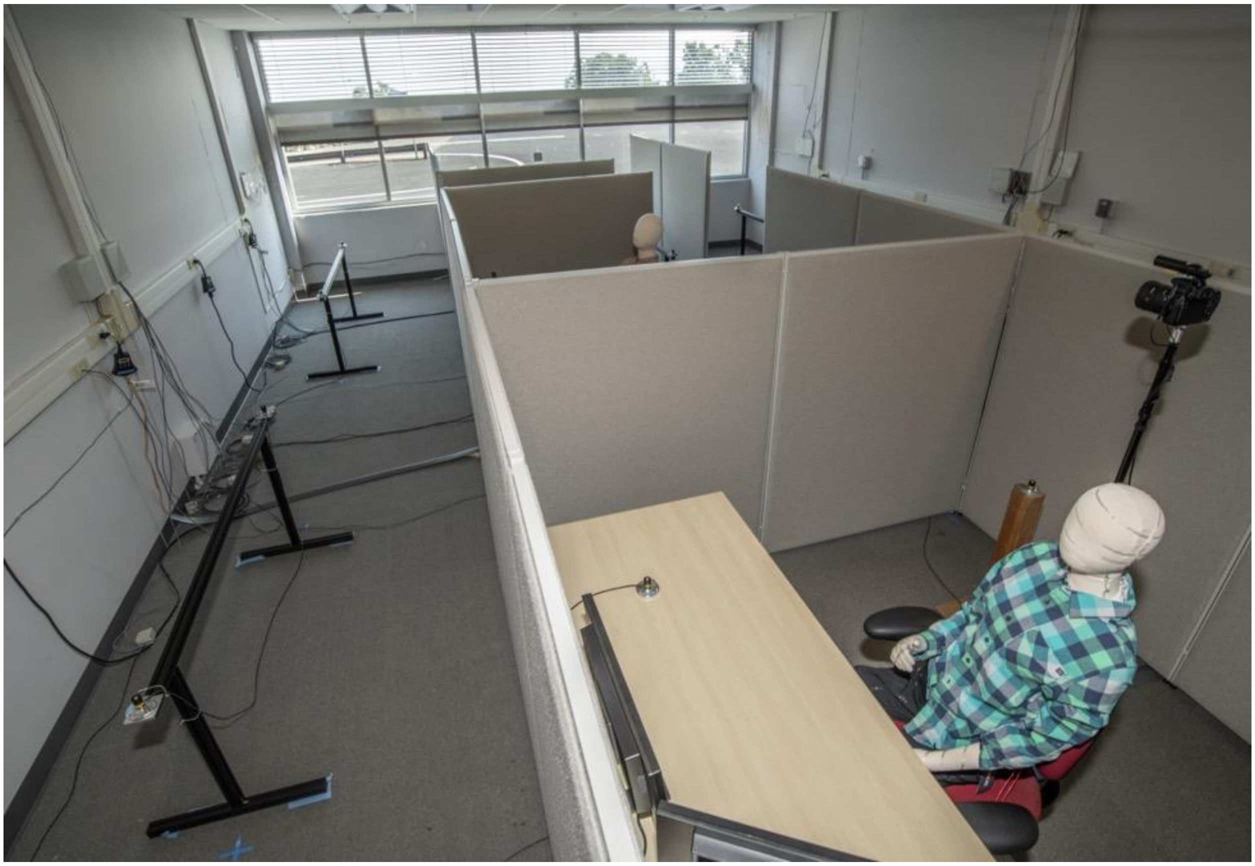


Figure 7. Photograph of retrofit cell layout. Automated blinds are set to a neutral angle (0^o) and automated rollershades are deployed at a length of approximately 10 inches.

Each of the three desks had emulated thermal loads typical of a real office, including plug loads comprised of a desktop computer and monitor on a daily schedule of operation and a heat-generating mannequin with the thermal load profile of an actual occupant also on a daily schedule. These loads are illustrated in Figure 8 below. The plug load wattage ranged from 60 to 100W per computer and monitor combination, with one desk having two computers and monitors, and plug loads totaling around 0.5 W/ft^2, which was set to be equivalent in the baseline and retrofit cells. The wattage per mannequin was around 77W, for around 0.4 W/ft^2 of occupant thermal load, which was also set to be equivalent in the baseline and retrofit cells.

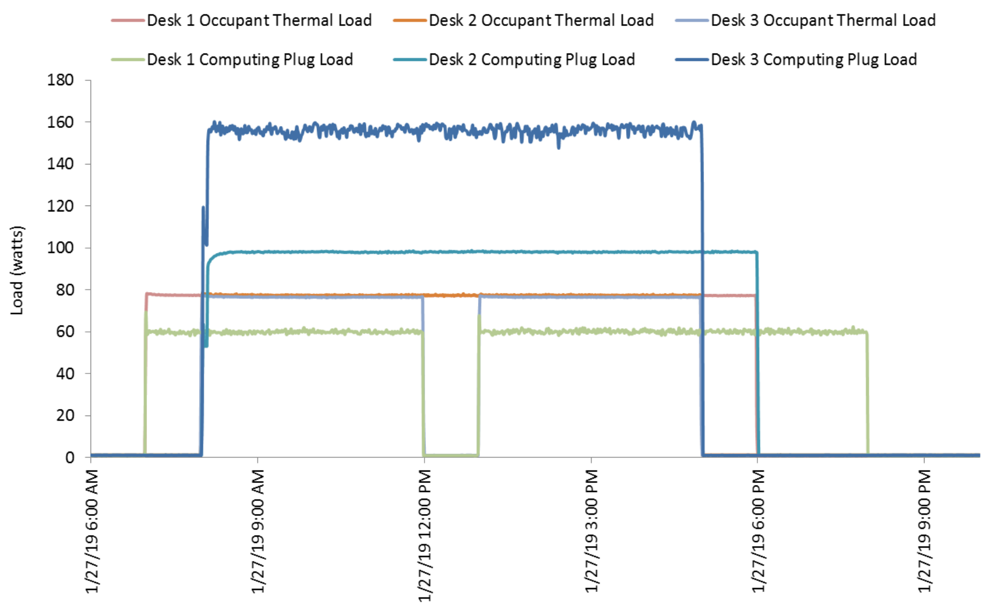


Figure 8. Example of test cell internal thermal load profile

Lighting System

For the project, the Integrated Technologies for Energy-efficient Retrofits (INTER) were comprised of the automated rollershade and blinds system from Rollease Acmeda and lighting and lighting controls from Enlighted. The lighting plan included six 2'x 4' troffer-style LED light fixtures installed in the acoustic drop ceiling at a fixture space of 8'x10'. The light fixtures installed in the test cell were LED retrofit kits with integrated sensors and controls supplied by the lighting controls vendor. The retrofit kits were 35W fixtures rated at 4,400 lumen output. Enlighted also supplied fixture controllers and luminaire-level daylight and occupancy sensors that were integrated into the LED fixtures. The light fixtures in the baseline cell were non-dimmable 3-lamp T8 fixtures, around 90W each, for the existing building base case, and dimmable 2-lamp T5 fixtures, around 62W each at full power, for the code-compliant (Title 24, 2016) base case. The baseline cell fixtures were also equipped with Enlighted fixture-level controls, which were used simply for programming scheduled on/off operation (6AM-8PM). For the Title 24 baseline case zonal daylight dimming would be required per the Test Case details above. Because the Enlighted controls and sensors were fixture – level, rather than zonal, daylight dimming was not implemented in the code-compliant baseline cell. Instead, we modeled dimming of the first and second rows of T5 fixtures (primary and secondary daylight zones) via calculations, post – data collection, based on daylight measured in the space during the test periods (modeled lighting wattage reductions due to dimming were included in HVAC load savings calculations).

Shading System

A shades and blinds installer was contracted by Rollease Acmeda to install the shading products in the retrofit test cell. The top third of the window area was covered by the blinds system with reflective louvers for directing daylight deeper into the office space, while the bottom two thirds of the window area were covered by the rollershade with a white/bronze shade material of 3% openness factor, with a white side facing out for higher solar reflectance. The system was controlled by two methods: a wireless remote configured to operate each blind and rollershade section independently with assistance from Rollease Acmeda, or a Wi-Fi gateway commissioned to operate the system through smartphone-based application. At the time of the FLEXLAB evaluation, automated solar tracking controls were in development but not yet commercially available, so automation of controls actions would be done by scheduled evens to adjust rollershade height or louver tilt angle. Additionally, because of mechanical issues with scheduled control of the blinds during the tests (detailed in the Results section), in practice the shades and blinds were adjusted in-person by wireless remote and smartphone app.

In the summer the rollershade was rolled all the way up, essentially leaving bare glass for the bottom 41” of window. In the fall the rollershade was deployed down most of the way, leaving roughly 9” of glass exposed, and in the winter the rollershade was fully deployed, with no glass exposed (see page 27 for more details). These shade positions were dictated by seasonal sun angles; in the summer sun angles are highest so direct solar penetration in the south windows was not an issue, whereas in the winter sun angles are the lowest, with direct sunlight potential (depending on cloudiness) on the south windows for most of each day.

HVAC Configuration

Zone temperature in each cell was controlled to a deadband of 68 degrees F (heating) to 72 degrees F (cooling). The HVAC system configuration for both cells was single zone Variable Air Volume, with four supply diffusers over the office spaces, served by air handler, chiller, and electric boiler. There was no chilled water reset or duct static pressure reset.

Test Measurements and Sensors

For each test scenario, the measurements made during the FLEXLAB tests are listed below. All sensors were end-to-end tested after installation to verify functionality. Tag names were developed for each individual sensor and used consistently throughout project documentation.

Energy measurements in each cell:

- Lighting kW for each row of fixtures – 1 minute interval
- Plug load kW for each plug load – 1 minute interval
- Occupancy kW for each ‘occupant’ – 1 minute interval
- Thermal load (Btu) – 5 minute interval
- Fan kWh – 1 minute interval
- Boiler plant kWh – 1 minute interval
- Chiller plant kWh – 1 minute interval

Visual environment measurements in each cell:

- Illuminance (luminous flux incident per unit area; e.g. foot-candles or lux), measured over grid of 16 points, including one measurement per desk – 1 minute interval
- Glare – 5 minute interval during occupied period

Thermal comfort measurements in each cell:

- Dry-bulb temperature – 1 minute interval

- Mean radiant temperature – 1 minute interval

For illuminance measurements, sensors were placed on each desk (2.5’ from floor, facing up) to measure work area light levels, and illuminance sensors were also placed at the same height on pedestals and rails in the halls surrounding the work area. A total of 16 sensors, shown in Figure 9, were installed in each cell. Most lighting design criteria are centered around recommendations for illuminance levels at the workplane. IES recommended practice for light levels in office work environments is around 300 lux in more recent editions of the reference (see Table 32.2 *Office Facilities Illuminance Recommendations* and in the IES Lighting Handbook). In prior guidance and standard practice however, 500 lux was a more common design criteria and is the light level chosen for this analysis.

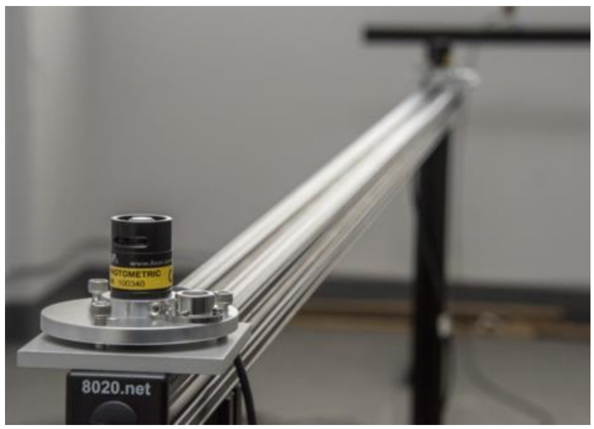


Figure 9. Licor photmetric sensor

HDR cameras with glare sensing hardware and processors were placed at two locations in each cell to monitor glare conditions to assess visual comfort (Figure 10). One HDR glare sensor package was located at 4’ height, at Desk 1 facing the direction the seated occupant would face. The other was located at the rear of the cell at 5.5’ height, approximately the standing height of a viewer in the rear of the office space, facing the window to assess glare potential from the rollershade and the daylight re-directing louvers. Glare was characterized using the daylight glare probability (DGP) index, which relies on high resolution, field-of-view high dynamic range (HDR) luminance images to assess glare. The HDR camera packages were located at select positions within the test cell to characterize surface luminances and DGP over time at viewing angles consistent with those that could be experienced by an office worker in the space.

Figure 10. Photo of HDR camera and sensor positioned for glare analysis in FLEXLAB

Hemispherical field-of-view luminance measurements were taken throughout each study day at five-minute intervals. The images are taken with commercial-grade digital cameras (Canon 60D) equipped with an equidistant fisheye lens (Sigma Ex 4.5 mm f/2.8) controlled by Mac CPUs. Bracketed low dynamic range (LDR) images are automatically taken with a fixed f-stop of 5.6 using in-house modified software (hdrgen). Four to seven images were taken per time interval depending on the brightness of the scene. The hdrgen software compiles the LDR images into a single HDR image with the camera response function determined by the software. A vertical illuminance measurement is taken by the HDR camera setup taken adjacent to each camera's lens, immediately before and after the bracketed set of images, and used in the hdrgen compositing process to convert pixel data to photometric data. HDR images are then analyzed automatically to assess discomfort glare from daylight and identify glare sources within the field of view.

The Daylight Glare Probability (DGP) index relies on these high resolution HDR images to assess glare. The index was derived through a comprehensive statistical analysis of HDR data and subjective response in a full-scale private office testbed that was retrofit with a variety of daylighting measures (Wienold and Christoffersen 2006). DGP was calculated using the *evalglare* software (Wienold 2009) and default software settings. DGP does not reflect the magnitude of glare perceived by the observer. Instead it gets around the problem of person-to-person variability in response to perceived glare by estimating the probability that a person is "disturbed" by glare (the DGP formulation defined "disturbed" based on the subject rating the daylight glare source to be "disturbing" or "intolerable"). Wienold derived a method to account for the frequency of glare over a time period, where within a defined category of comfort, 3-5% exceedance of a threshold limit is allowed. Glare ratings ranging from "imperceptible" to “intolerable” were related to DGP values in a descriptive one-way analysis of the study’s user assessment data.

In addition to light levels, cell air temperature was measured by wall-mounted temperature sensors, and mean radiant temperature sensors were placed on Desk 1 (nearest window) in each cell to monitor thermal comfort near the window wall.

Test Schedule

Three test periods of three weeks each (including setup, takedown) were targeted to cover summer, fall and winter periods to capture solstice to solstice solar impacts. Table 5 below summarizes the schedule for each test case. The test schedule was managed dynamically over the course of the test period to ensure that adequate exterior conditions (e.g. sunny periods, cloudy periods) were captured for each test permutation.

Table 5. FLEXLAB Test Schedule

Test case	Season		
	Summer	**Fall**	**Winter**
FWEB	July 18-23	Oct. 3-4,7-8	Jan. 5-10
MWEB	July 25-30	Sept. 27-Oct. 2	Jan. 11-15
FWTB	Aug. 7-13	Sept. 17-21	Jan. 25-30
MWTB	Aug. 1-6	Sept. 22-25	Jan. 17-20
LOFF	July 24	Oct. 5	Feb. 21

Results

Installation and Commissioning

Key findings from the installation and commissioning of the INTER system are described below, with the caveat that the FLEXLAB installation and commissioning process was not necessarily representative of a typical commercial installation:

- The self-powered INTER shading system (rollershades and blinds with rechargeable battery-powered motors and integrated photovoltaic chargers) functioned as intended through the test (autonomous, with no hardwired power required), though relatively few controls cycles were implemented per test period.

- The shading system Wi-Fi hub was successfully programmed to discover and control the blinds and shade motors in range using the smart-phone application. Automated changes in shade height were possible through a scheduling feature in the app.
- There were issues with deflection of the rod holding the louvers up at the top of the blinds assembly (insufficient rigidity to resist bending at center due to weight of blinds supported). This resulted in sag in the middle of the blinds, affecting reflective pattern slightly and tending to cause the pins holding the assembly up to pop out. It was necessary to tie safety loops around the axle to hold the blinds assembly up to the frame that supported the blinds and the rollershades so that it would not fall out. The ties added resistance to the rotation of the blinds axle however, reducing the freedom of the system to rotate when controls signals were sent. Automation of blind tilting via scheduled actions was not possible due to these installation constraints, as there was too much resistance and slack in the system at different blind title positions to reliably predict the tilt angle that would follow from a given controls action. Consequently the blinds tilt angle was coarsely controlled in person by remote control and then fine scale adjustments were made manually. These changes were made once per season based on the typical daily solar angles for that season (detailed below).
- At the time of deployment for FLEXLAB testing, the evaluated system (Rollease Acmeda) had no commercial control server or software that could implement advanced sequences of blinds and shades operation, such as based on a solar model for predicting solar angles through time (given the building geometry, direction that windows were facing, global positioning / latitude, etc.). Such a controls feature would allow the blinds to take best advantage of solar angle through day and season to reflect light into space, subject to glare constraints, and would allow automated rollershade operation to maximize daylighting and view access within glare constraints. Nor was there integration with any kind of radiometer or illuminance sensor as an input for sky condition that could indicate sky condition to the system (e.g. cloudiness meaning rollershades drawn even if solar model predicts glare based on sun angle).
- The ability of the reflective louvers to direct sunlight onto the ceiling deep into the test cell was confirmed visually and through photographs for different tilt angles. This feature of the system can be seen in Figures Figure 11 and Figure 12.

Figure 11. Photo looking at the blinds at +10 degree tilt (away from interior) at 2PM (Fall, 2018)

Figure 12. Photo looking at the blinds at - 20 degree tilt (into interior) at 2PM (Fall, 2018)

- Per seasonal implementation, the blind angle and rollershade height was set once at the beginning of the test period based on calculations that considered window and building geometry and solar angles at the latitude of the lab. Shade height was determined seasonally to allow daylight into space while avoiding glare; essentially eliminating direct sun through window at depth of 36” on the floor, equal to the location of the first desk. Similarly, blind angle was determined to a redirecting angle to reflect light toward ceiling but above the height that would result in direct glare for a standing occupant.

- **Summer**: blind angle at -37 degree tilt (tilted down toward test cell interior) to redirect sunlight into space. Rollershades fully up, bottom edge at 77” from floor (high sun angles meant deep penetration of direct sun was not an issue).
- **Fall**: blind angle at +10 tilt (tilted up away from test cell interior) to direct some sunlight into space while avoiding direct glare the majority of the day. Rollershade about 2/3 down, bottom edge at 45” from floor (9” of bare glass at bottom of window).
- **Winter**: blind angle at +45 tilt (tilted up away from test cell interior) to direct some sunlight into space while avoiding direct glare the majority of the day. Rollershade all the way down, bottom edge at 36” from floor (window sill height).

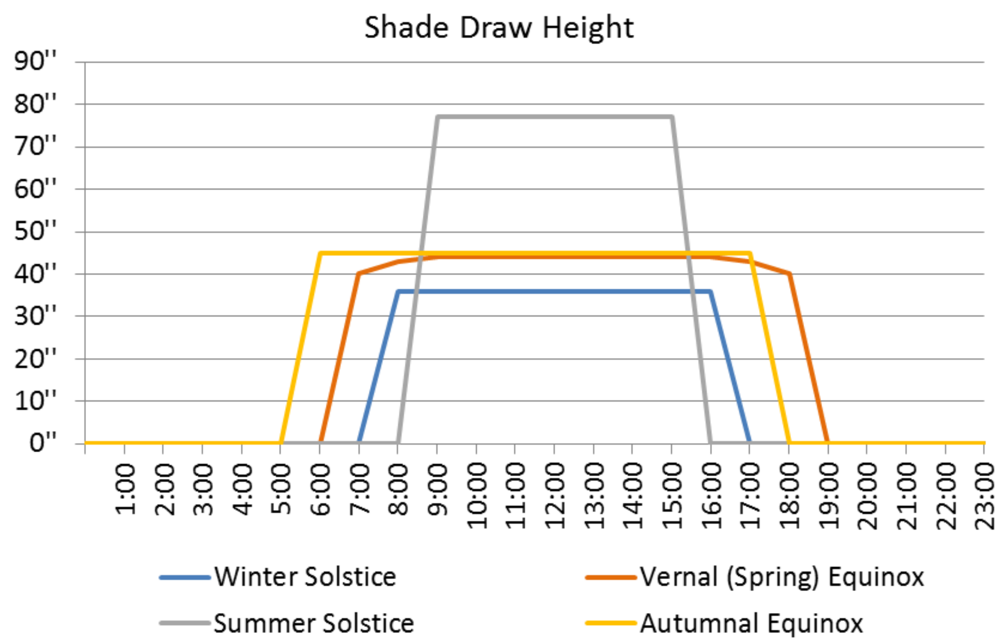


Figure 13. Plot of shade position through day calculated to prevent direct sunlight at 36” depth into cell (Y-axis=inches from floor)

Lighting Savings

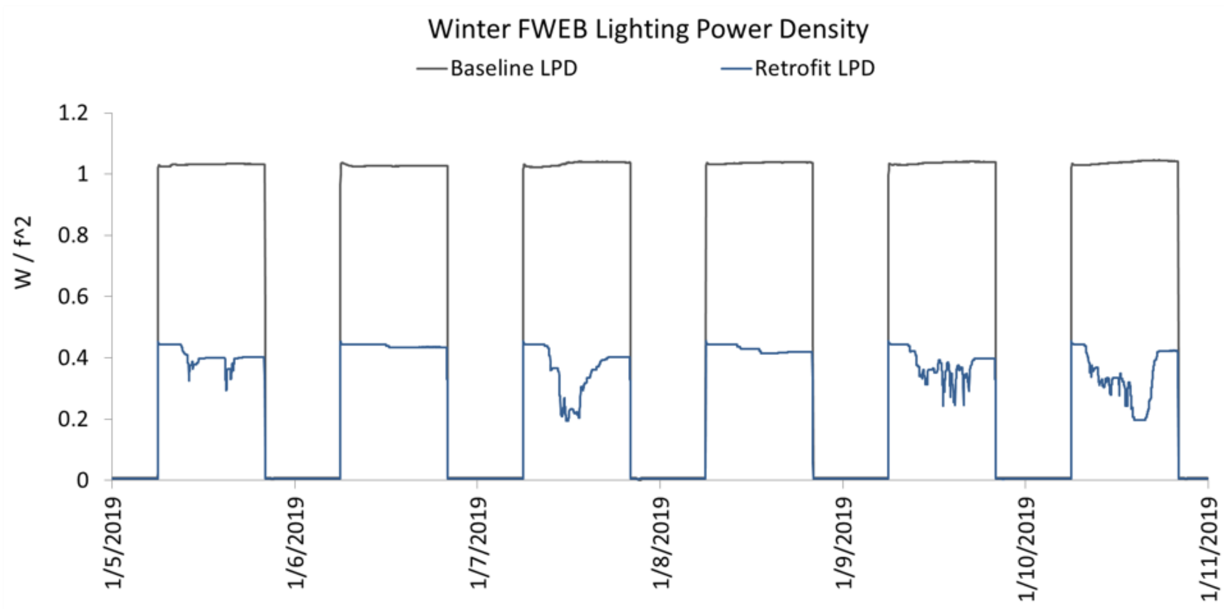
Lighting power was measured for each fixture in the baseline cell and the retrofit cell. To calculate savings, power measurements for each of the six fixtures in each cell were summed. System wattage was divided by square footage of office space to normalize results over area. Savings were calculated as the difference between average hourly lighting wattage per square foot during operating hours from baseline to retrofit. Lighting energy and energy savings, in Watt-hours/ft^2/day, can be derived simply by multiplying the average W/ft^2 by 14 operating hours per day (6AM – 8PM). Table 6 summarizes the results for each test case and season.

*Table 6. Summary lighting energy savings (Wh/ft^2/day, %)**

Test case	Summer	Fall	Winter
Full Window, Existing Building Baseline FWEB	10.8 (75.9%)	10.4 (72.6%)	9.0 (62.0%)
Mid Window, Existing Building Baseline MWEB	10.6 (75.0%)	10.1 (70.6%)	9.2 (63.2%)
Full Window, Title 24 Baseline FWTB	5.3 (62.1%)	5.0 (56.5%)	5.0 (50.3%)
Full Window, Title 24 Baseline MWTB	5.6 (60.8%)	4.9 (56.1%)	5.5 (49.2%)

**Energy data post-processed with adjustment factors for periods where middle-desk measured illuminance was lower than target (discussed later)*

Examples of the normalized lighting power as measured in the FLEXLAB cells are plotted in Figure 14. Example plots of normalized lighting power through time, for a test period with existing building baseline lighting system of T8 fluorescent fixtures with simple on/off scheduling (FWEB, winter period), and for a test period with baseline of Title 24 compliant dimmable fluorescent with zonal daylight control (FWTB, fall period).



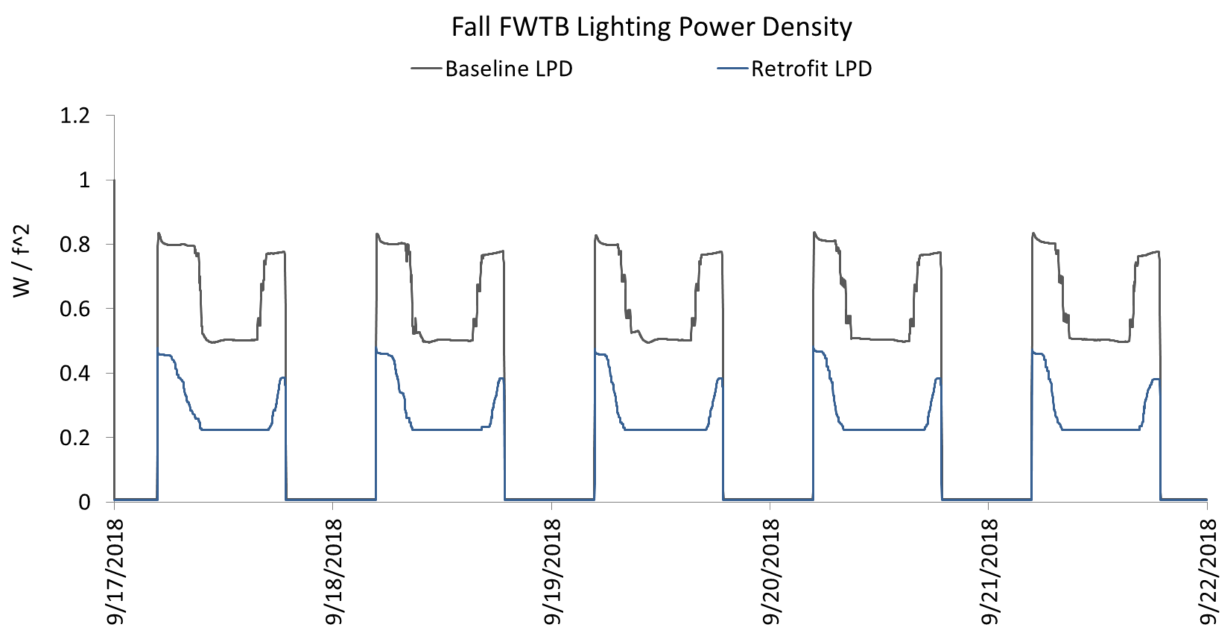
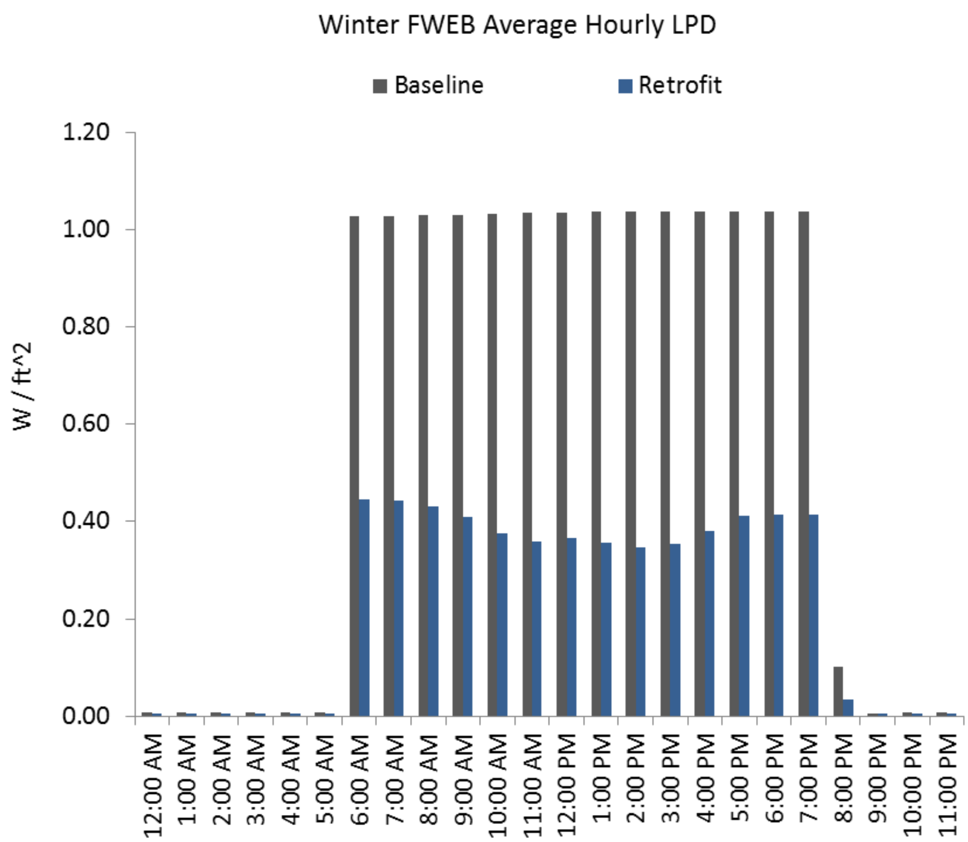


Figure 14. Example plots of normalized lighting power through time

From the daily lighting power data plotted in the time-series, average hourly lighting power (baseline and retrofit) was calculated for each test period. Hourly, daily, and test- period savings were then calculated. Graphs of hourly average lighting power for the same example test periods (FWEB, winter and FWTB, fall) are shown in Figures Figure 15 and Figure 16, along with plots of the hourly, daily, and test- period lighting power savings. Note that for summer test periods the data time stamps are not adjusted for daylight savings so the hourly results are shifted backward one hour.



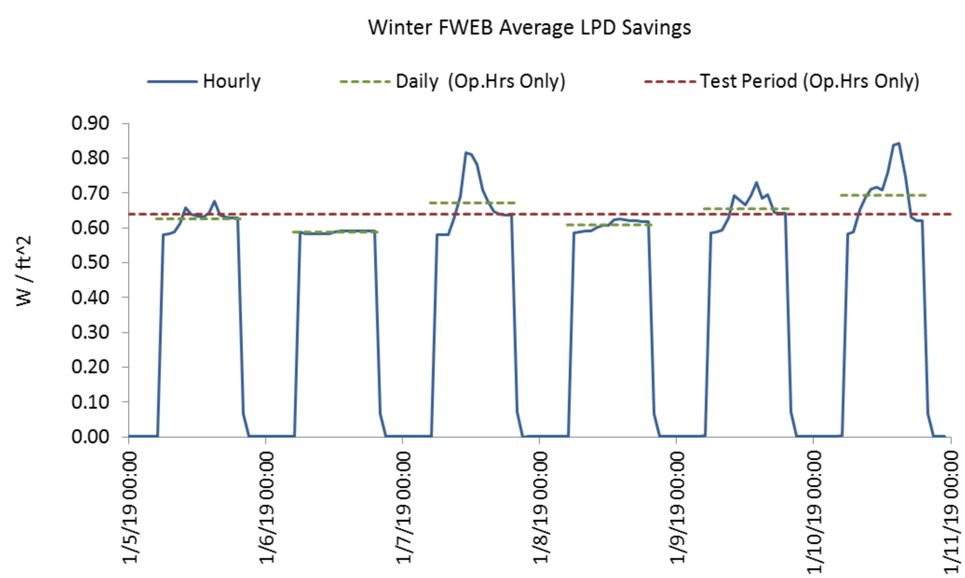


Figure 15. Example plots of hourly average lighting power (above), and lighting power savings per hour, day, and test period (below); existing building baseline

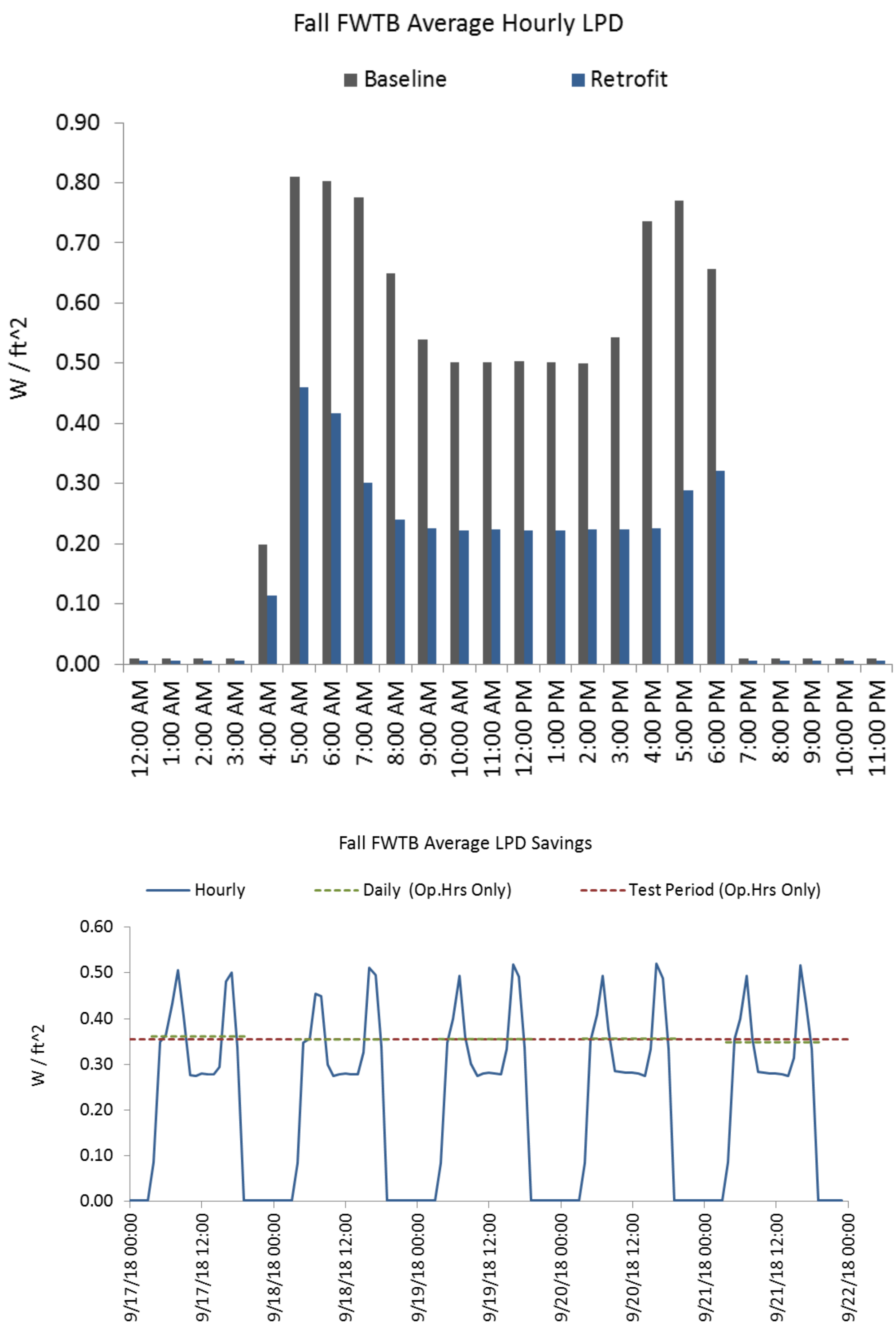


Figure 16. Example plots of hourly average lighting power (above), and lighting power savings per hour, day, and test period (below); Title 24 code-compliant building baseline

Achieving at least 500 lux at the desk was the design target for light levels when occupied. Meeting this design target was defined here as when the 1st quartile of lighting data measured during occupied hours was at least 500 lux. As discussed in more detail in the Visual Comfort section later, it was clear from test data that the retrofit LED lighting system at times did not provide quite enough light output to meet the 500 lux design criterion throughout the different test periods.[1] The middle desk is the location where light levels were analyzed for this purpose, because it is centered with respect to the whole lighting system, receiving light contributions from the nearest overhead fixture as well as adjacent fixtures to a lesser degree. This is as would be the case in most of an open office environment, and in fact in typical lighting design, edge spaces such as the window-adjacent desk in the lab setup are under-illuminated (electric light only) with respect to design targets because there are fewer adjacent light fixtures.

For the middle desk in the lab tests, in most cases median light levels were close to that design target but the 1st quartile (25th %) values were often lower. Conservatively, we did not want to calculate savings for the retrofit system at lighting energy levels that resulted in lighting performance below the design criteria. From FLEXLAB test data we empirically derived the relationship between the retrofit LED fixture power and desk light levels, so it was possible to calculate adjustment factors to increase the lighting system power for each test period to the amount that would have been necessary to meet the illuminance design criteria. The required increase in LED system wattage calculated for test period adjustments ranged from 5% to 25%. Similarly, the Title 24 baseline lighting system used during testing, consisting of 2-lamp dimmable T5 fluorescent fixtures, did not deliver quite enough light for the first quartile illuminance value measured at the middle desk to meet the design target. Lighting power adjustments from 13% to 30% were applied to the test period data for a more realistic outcome. Lighting energy usage and savings are based on test data adjusted to meet the illuminance target and are detailed in Table 7.

[1] This was not a function of commissioning or controls operation but of the LED fixtures emitting slightly less light, even at full power, than would be needed to meet the illuminance setpoint at all times. Essentially the fixtures were slightly under-specified; for an implementation more consistent with the intended setpoint, a higher – wattage LED fixture would have been required.

Table 7. Adjusted lighting system energy savings

Window Config.	Baseline Config.	Season	Average Baseline W/ft^2	Average Retrofit W/ft^2	Savings W/ft^2	Savings Wh/ft^2/ day	Savings as % of baseline
Full Window	Existing Bldg.	Summer	1.02	0.25	0.77	10.8	75.9%
		Fall	1.02	0.28	0.74	10.4	72.6%
		Winter	1.03	0.39	0.64	9.0	62.0%
Mid Window	Existing Bldg.	Summer	1.02	0.25	0.76	10.6	75.0%
		Fall	1.02	0.30	0.72	10.1	70.6%
		Winter	1.04	0.38	0.66	9.2	63.2%
Full Window	Title 24 Bldg.	Summer	0.62	0.23	0.38	5.3	62.1%
		Fall	0.63	0.27	0.36	5.0	56.5%
		Winter	0.72	0.36	0.36	5.0	50.3%
Mid Window	Title 24 Bldg.	Summer	0.66	0.26	0.40	5.6	60.8%
		Fall	0.63	0.27	0.35	4.9	56.1%
		Winter	0.79	0.40	0.39	5.5	49.2%

Plots of the hourly, daily, and test- period lighting power savings for each test period are presented in Figures Figure 17, Figure 18, Figure 19, and Figure 20.

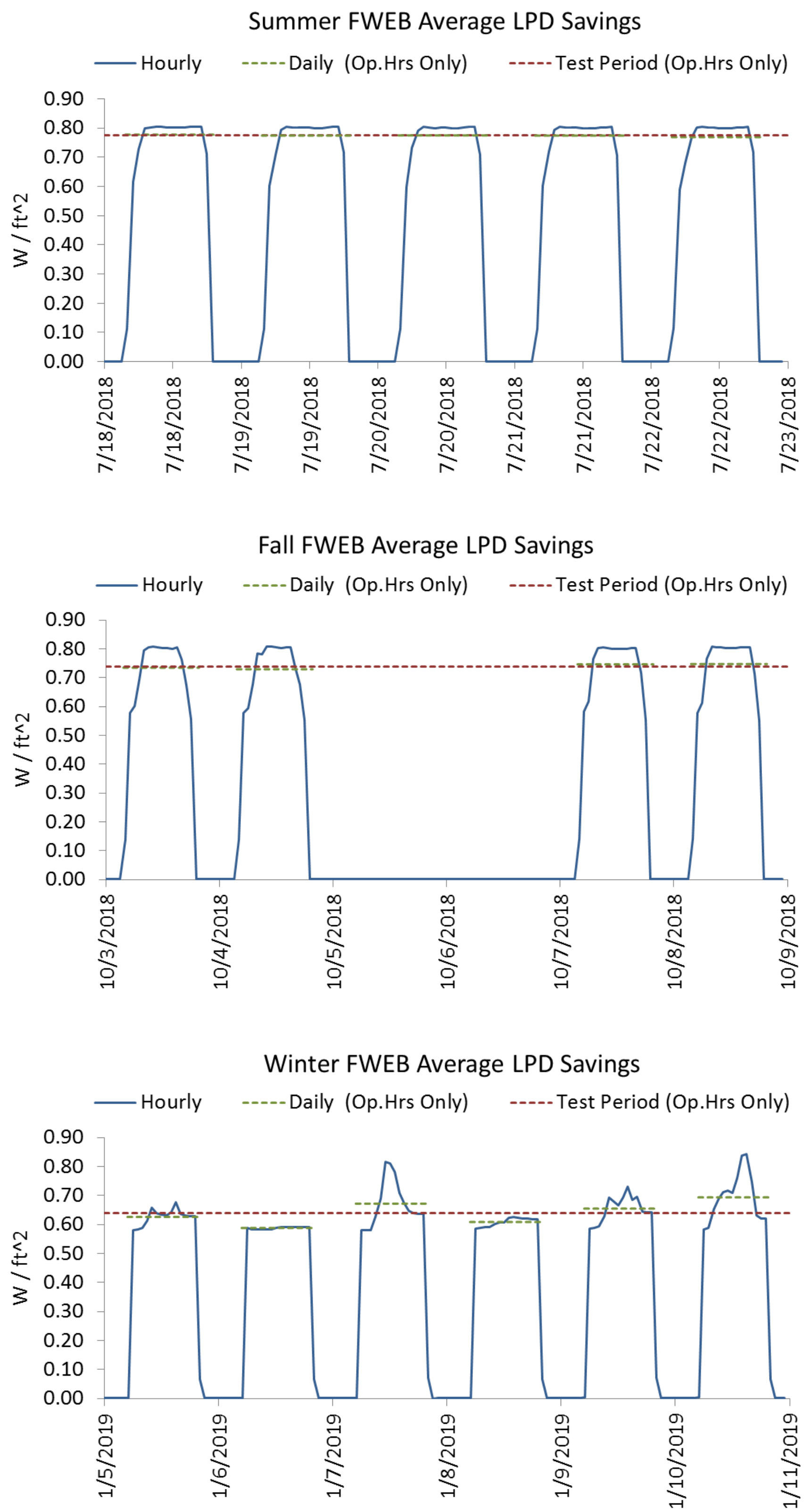


Figure 17. Full window existing building average lighting power savings

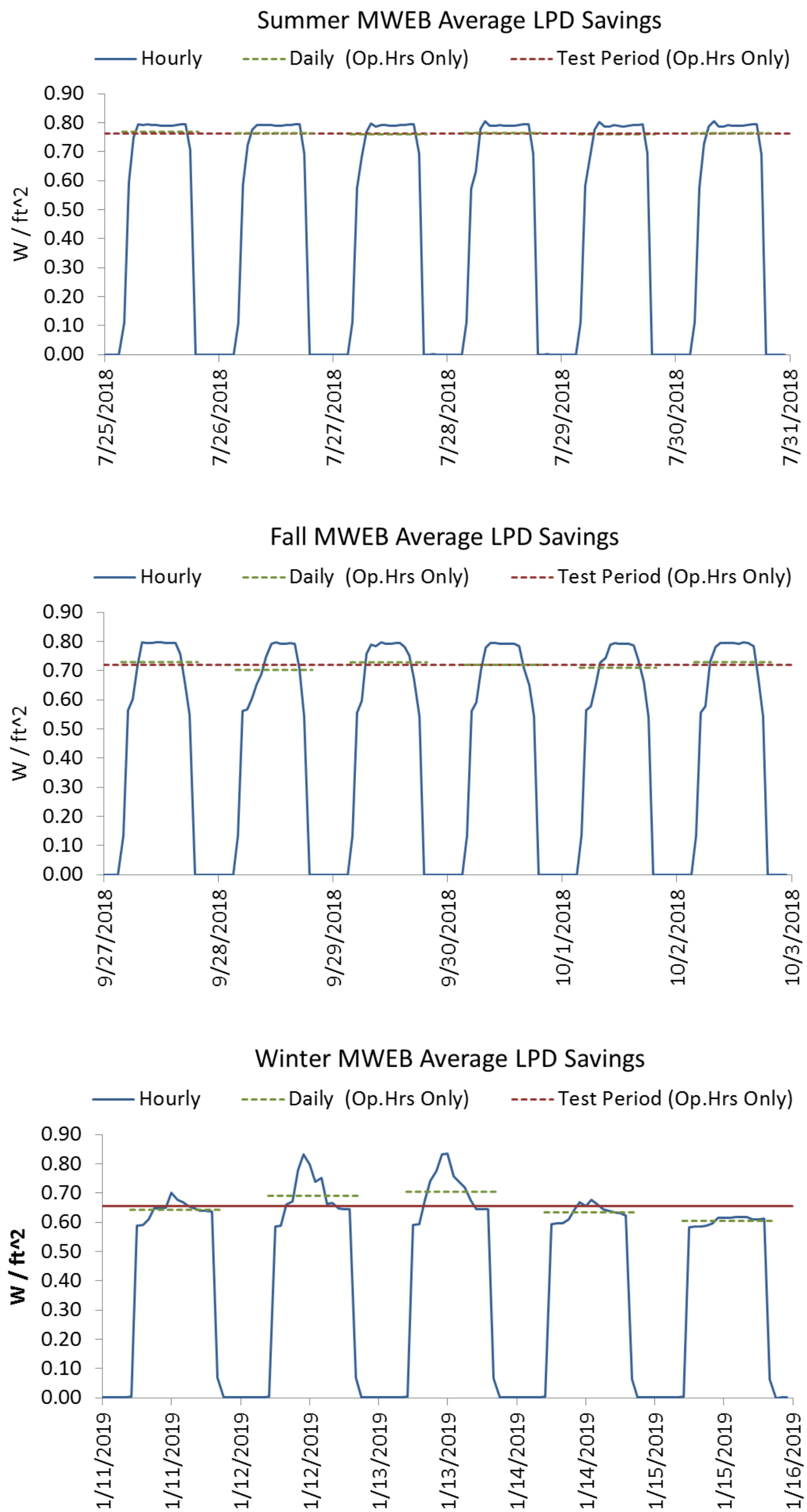


Figure 18. Mid window existing building average lighting power savings

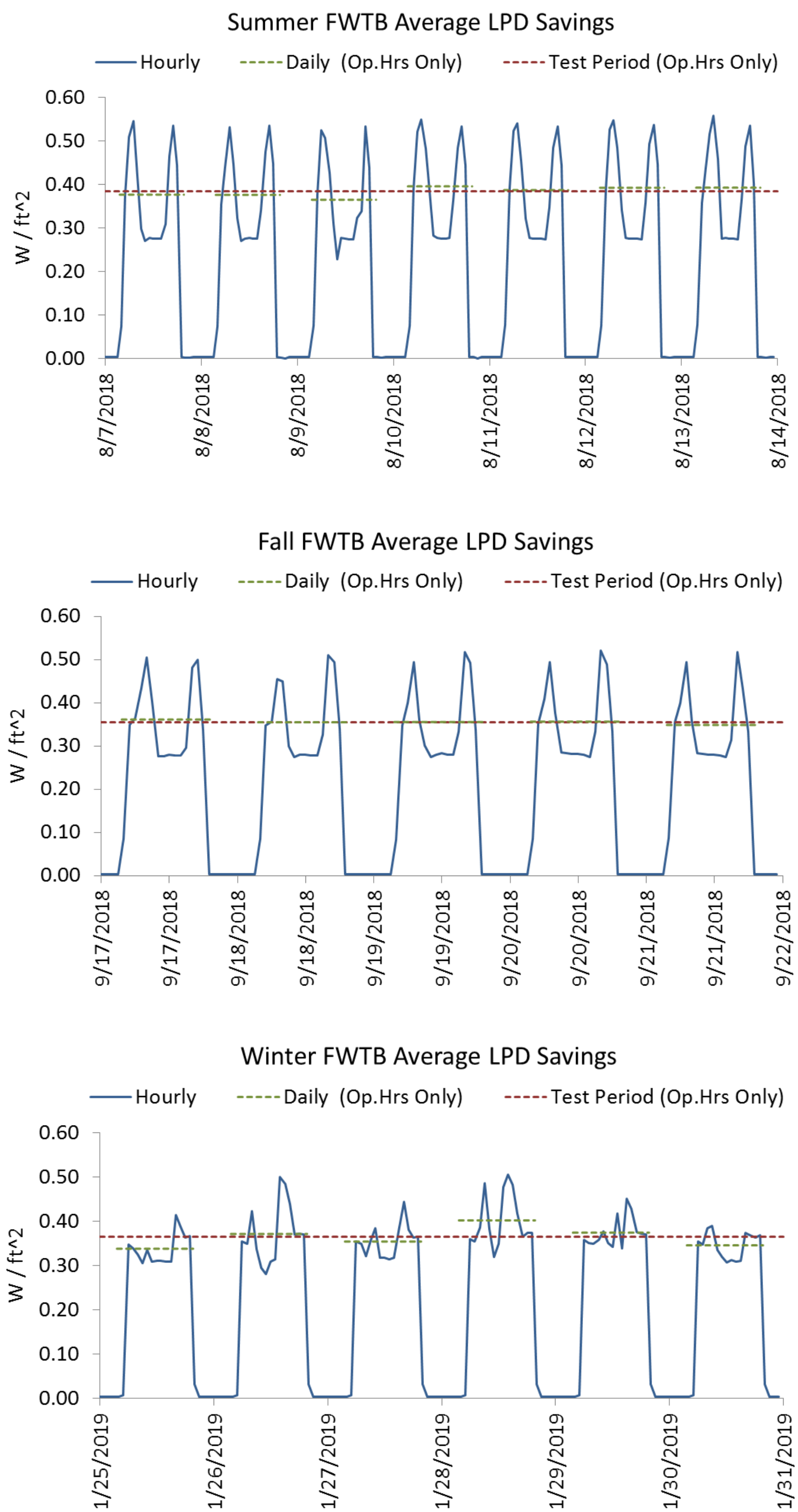


Figure 19. Full window code-compliant building average lighting power savings

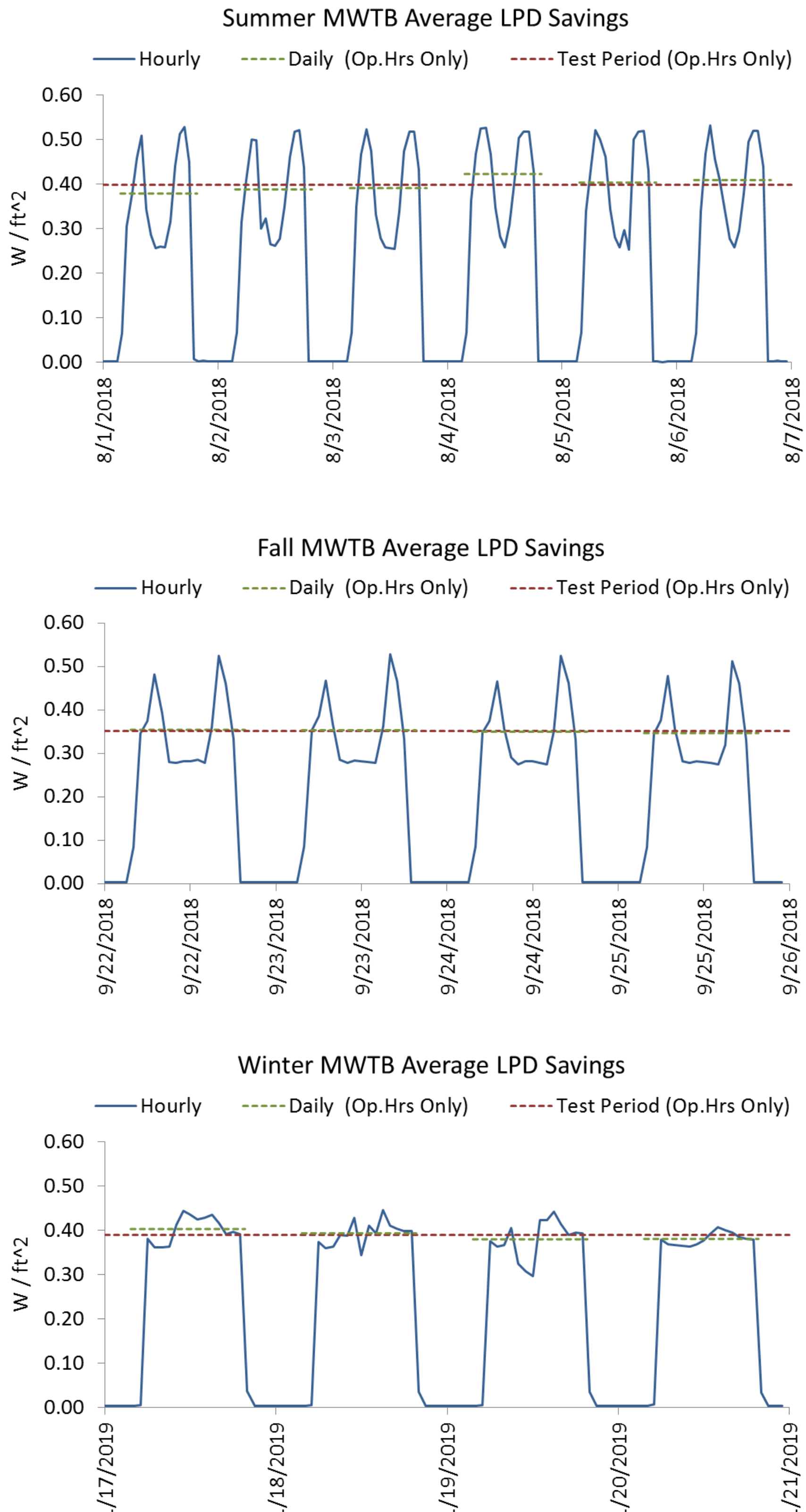


Figure 20. Mid window code-compliant building average lighting power savings

Visual Comfort

Our visual comfort analysis was comprised of two primary metrics: workplane illuminance (lux) and glare (daylight glare probability). Below we present summary tables of data analysis results and then discuss the measurement approach and results for each metric.

Illuminance

Table 8 summarizes the illuminance results in terms of median values, in lux, for each test and season for four locations: desks 1 through 3 and corridors. Achieving at least 500 lux at the desk was the design target for light levels in the space when occupied.

*Table 8. Median illuminance (lux) per test period and measurement location**

Window Config.	Baseline Config.	Season	Desk 1		Desk 2		Desk3		Corridors	
			Base.	Retro.	Base.	Retro.	Base.	Retro.	Base.	Retro.
Full Window	Existing Bldg.	Summer	1,599	2,597	773	589	541	547	821	668
		Fall	1,643	1,112	772	562	540	529	804	565
		Winter	379	316	656	545	520	517	583	499
Mid Window	Existing Bldg.	Summer	1,538	2,663	767	598	536	558	793	651
		Fall	1,204	674	739	558	526	529	732	511
		Winter	418	322	670	504	533	493	594	494
Full Window	Title 24 Bldg.	Summer	2,029	3,179	532	589	459	538	664	723
		Fall	2,240	1,187	558	574	464	536	645	573
		Winter	1,067	514	552	547	427	547	524	550
Mid Window	Title 24 Bldg.	Summer	1,410	2,323	521	604	440	559	571	610
		Fall	2,338	1,106	545	542	454	515	616	527
		Winter	373	336	520	542	415	538	434	512

**Illuminance values post-processed with adjustment factors for periods where middle-desk measured results were below illuminance target (discussed in more detail later)*

Examples of the illuminance measurements taken through time at the three desk locations are plotted in Figures Figure 21, Figure 22, and Figure 23. The time-series data was analyzed for max, min, median, 1st and 3rd quartile, and 5th and 95th percentile illuminance values to establish the basic distribution of light levels during occupied hours. The end of the "whiskers" in the plots are the 5th and 95th percentile values, while the box is bounded by the 1st and 3rd quartile values, with the median value indicated by the horizontal line inside the box. This analysis was carried out for each test configuration (FWEB, MWEB, FWTB, MWTB) and for each season (summer, fall, winter). Hourly distributions per desk as well as the illuminance distribution per desk for all test periods were calculated.

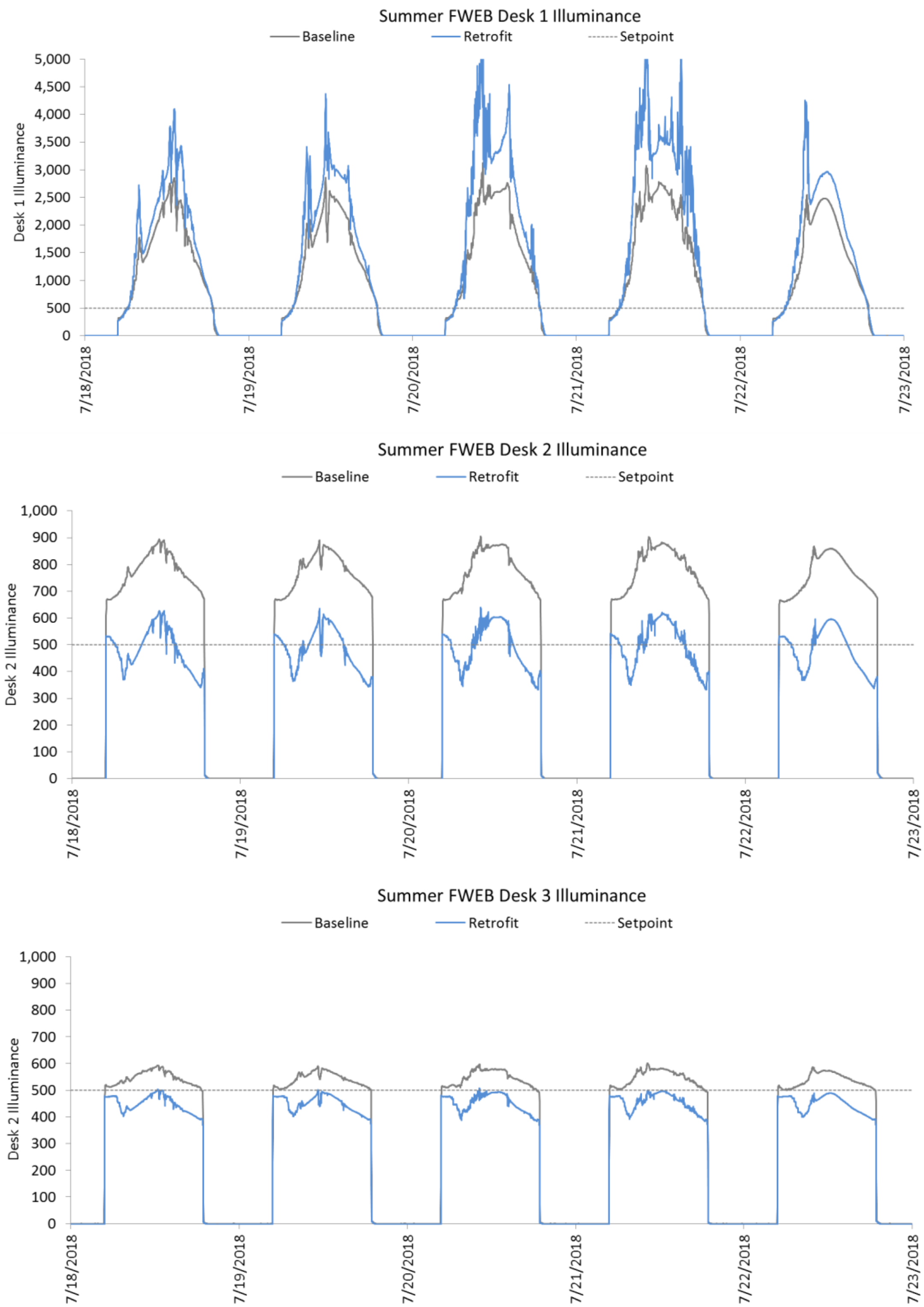


Figure 21. Examples of illuminance measurements through time for baseline and retrofit cells

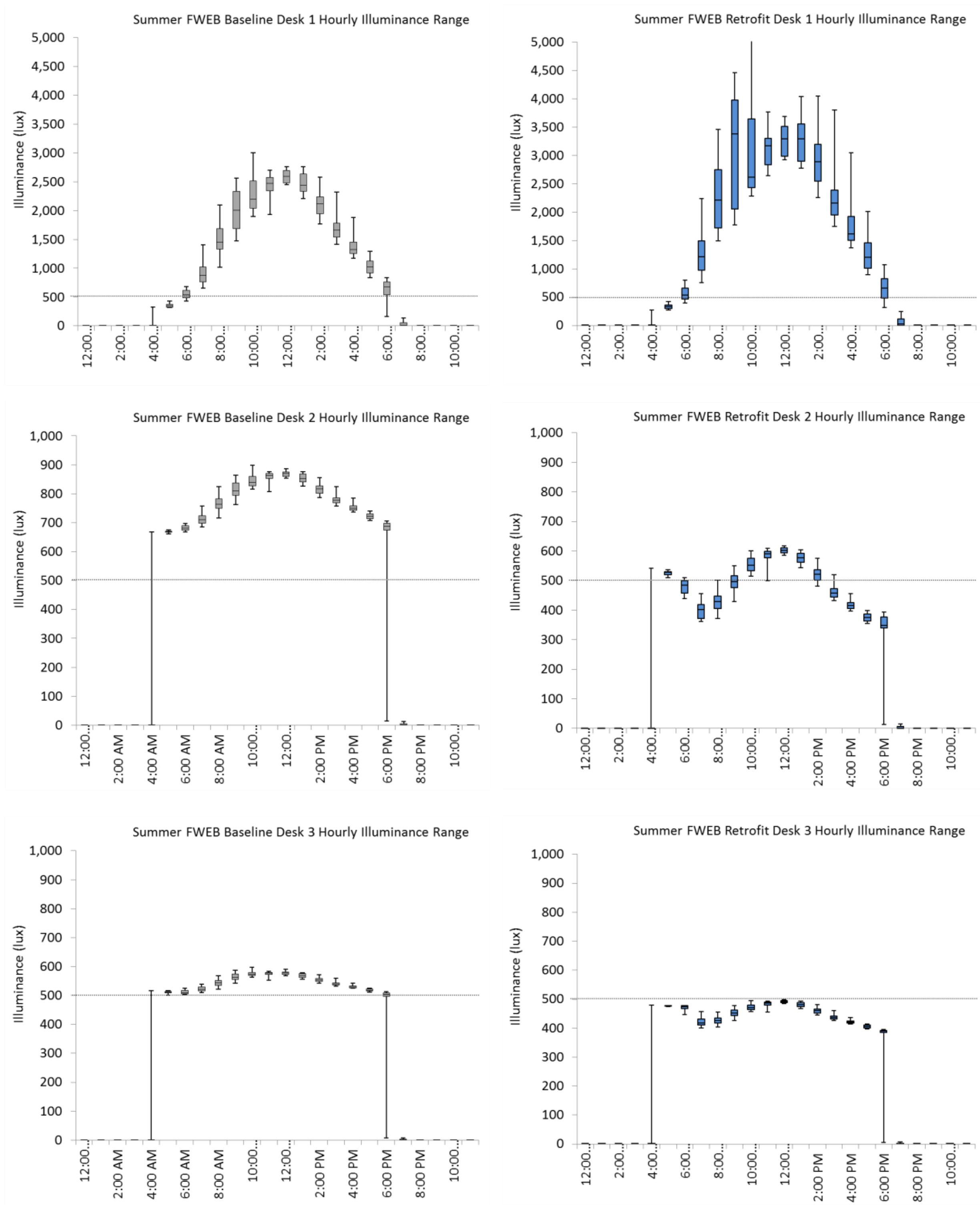


Figure 22. Example of hourly illuminance distributions as measured

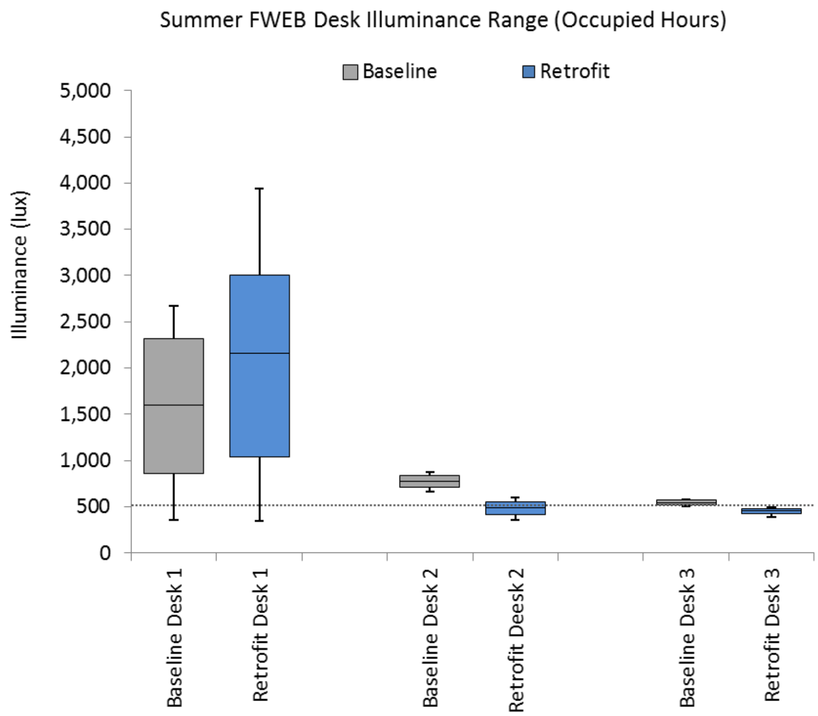


Figure 23. Example of test period illuminance distributions as measured

The "box and whisker" plots above illustrate the distributions of data from all test days in each test period. Meeting the design target was defined here as when the 1st quartile of lighting data measured during occupied hours was at least 500 lux. From the data analysis as illustrated by the time-series plots and box plots above, a few points become evident. In the case of the existing building baseline, the fluorescent lights deliver at or above the 500 lux design target throughout the workday at Desks 2 and 3, while Desk 1 receives higher light levels through most of the day due to sunlight from the nearby window. However, for the morning and evening periods at either end of the daily lighting operating schedule, when sunlight is lowest, the baseline Desk 1 light levels are actually below the 500 lux design target. This is likewise the case for the retrofit system. Given that Desk 1 is on the perimeter of the electric lighting zone however, it does not receive electric illumination in the same way as a location like Desk 2 which is in the middle of the illuminated space where all fixtures contribute to the work space light levels to some degree. Desk 1 maintained illuminance levels are a good indication of the range of daylight levels but not a good indication of typical light levels on the desks that are further into the space and surrounded by electric fixtures (also discussed in lighting energy results previously).

It is also clear in the data that at Desks 2 and 3 in the retrofit case, the light levels are sometimes below the 500 lux target. A higher-wattage LED fixture with higher light output would be necessary to ensure that the design target of 500 lux was met the majority of the time in the space. Based on those findings, which were consistent through test periods, we post-processed the lighting data to uniformly increase the LED system light levels across the test period (and increase the wattage in the lighting power data by the amount that would be required to achieve the light level increase), by an adjustment factor such that for Desk 2 the 1st quartile value met the 500 lux target. Due to differences in daylight availability from test to test, and given that the system was daylight-responsive, a different adjustment factor was applied to each test period. These factors were derived from the difference between measured 1st quartile light level and the 500 lux design target (Figures Figure 24, Figure 25). The required increase in LED system light output for test period adjustments ranged from 5% to 25%. Similarly, the Title 24 baseline lighting system used during testing in some cases did not deliver enough light for the first quartile illuminance value at Desk 2 to meet the design target. Lighting system output adjustments from 15% to 30% were applied to the Title 24 baseline test period data for a more realistic outcome that met the intended design criterion. Related adjustment factors for LED and T5 fixture wattage were also calculated, based on the empirical relationship between desk light level and fixture wattage (in the absence of daylight) established by measurements in the test space, and were applied to lighting power data for a more reasonable comparison (we did not want to calculate energy savings for a system that was not meeting the design parameters).

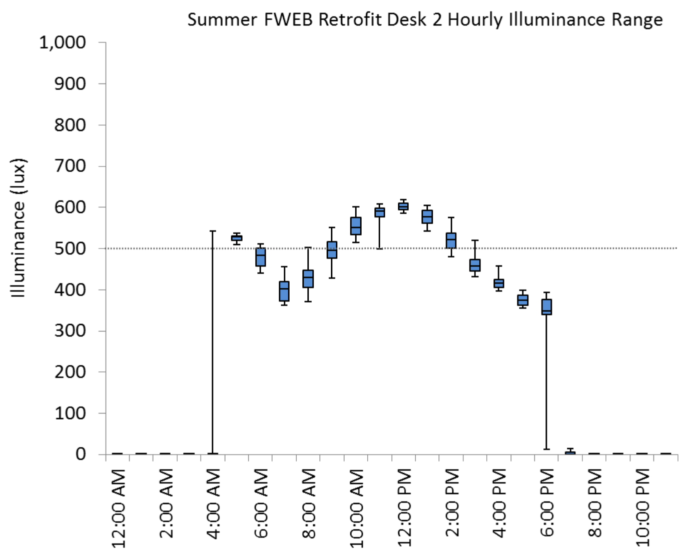


Figure 24. Measured illuminance values: FWEB summer test period

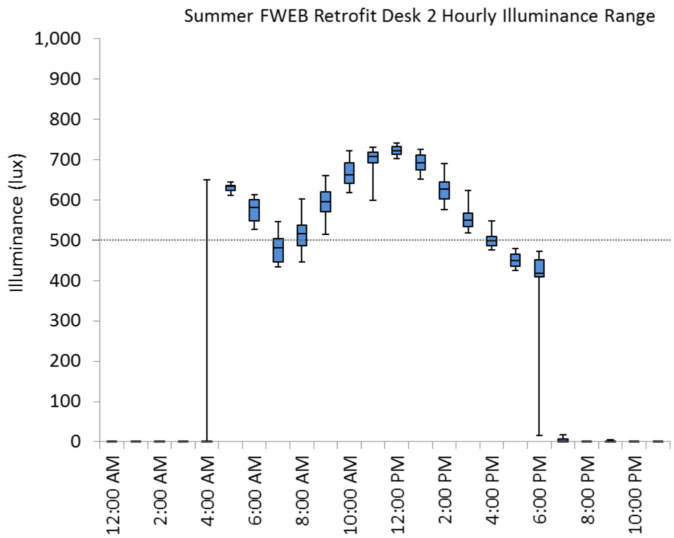


Figure 25. Adjusted illuminance values: FWEB summer test period

Figure Figure 26, Figure 27, Figure 28, and Figure 29 illustrate the baseline and retrofit light level ranges during occupied hours (when the lighting systems were operational) for the three desk locations in each test configuration through the three seasons of testing. Side by side box plots portray the light level ranges as measured and after the adjustment factors were applied.

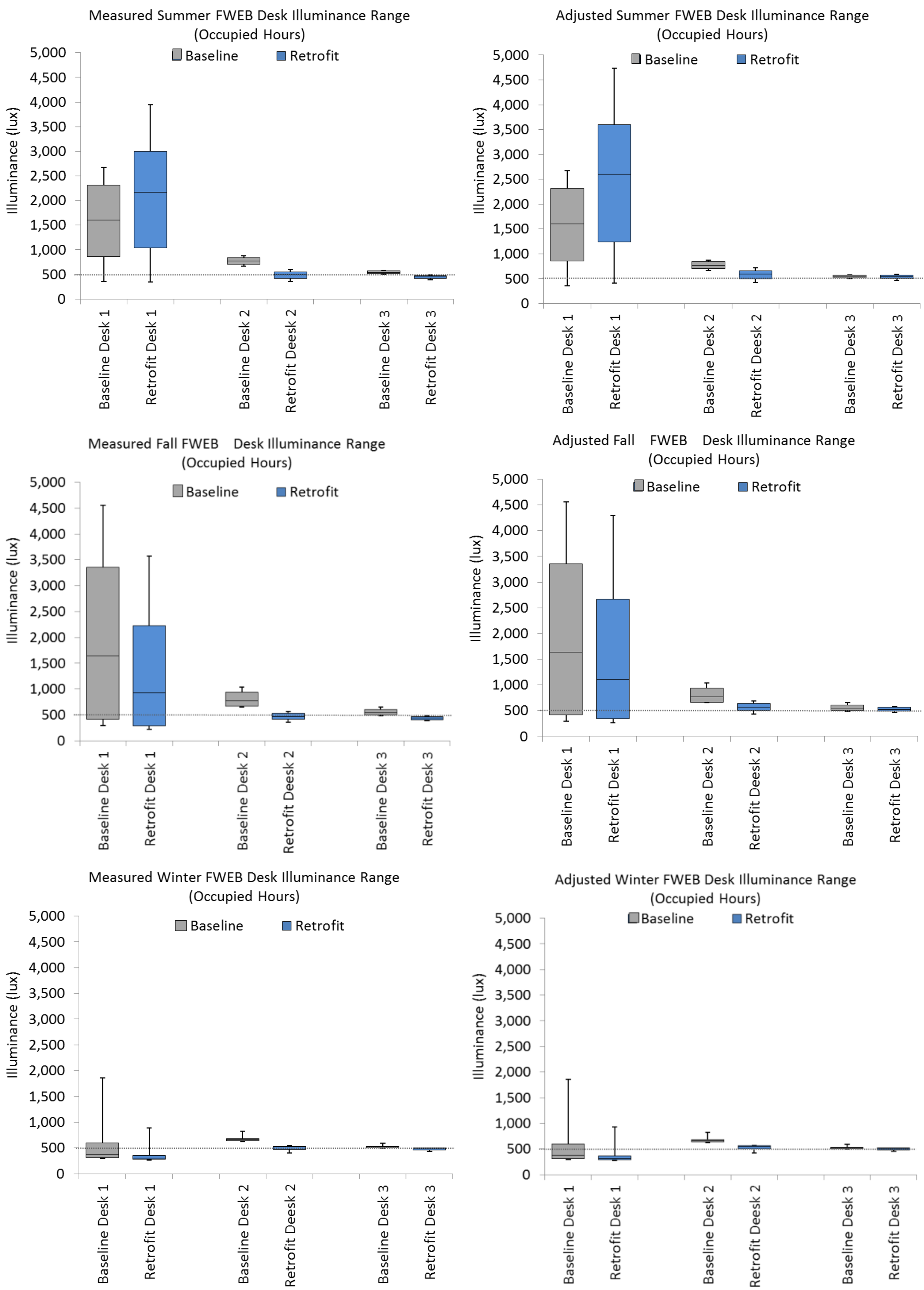


Figure 26. Full window existing building illuminance ranges: measured (left) and adjusted (right)

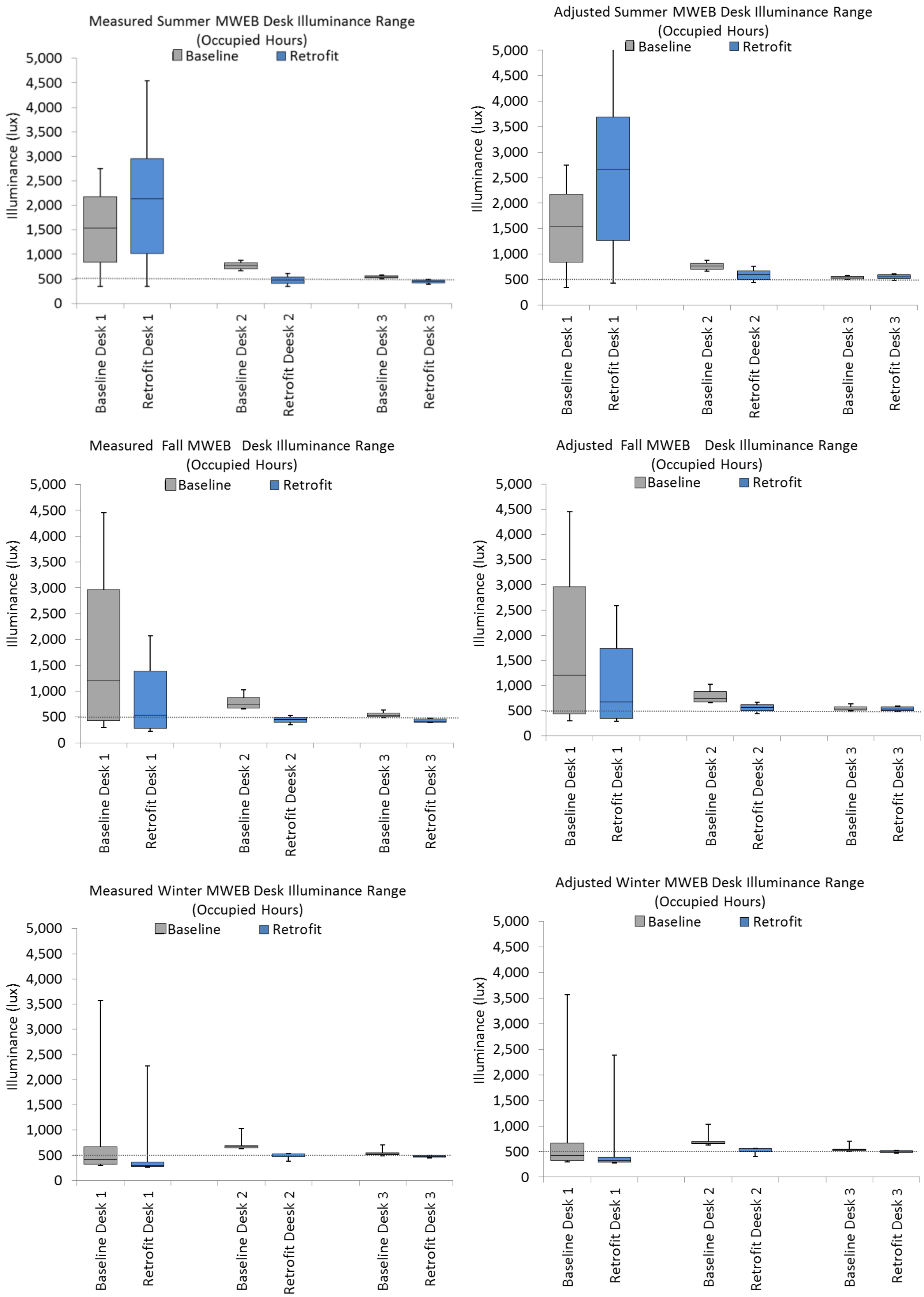


Figure 27. Mid window existing building illuminance ranges: measured (left) and adjusted (right)

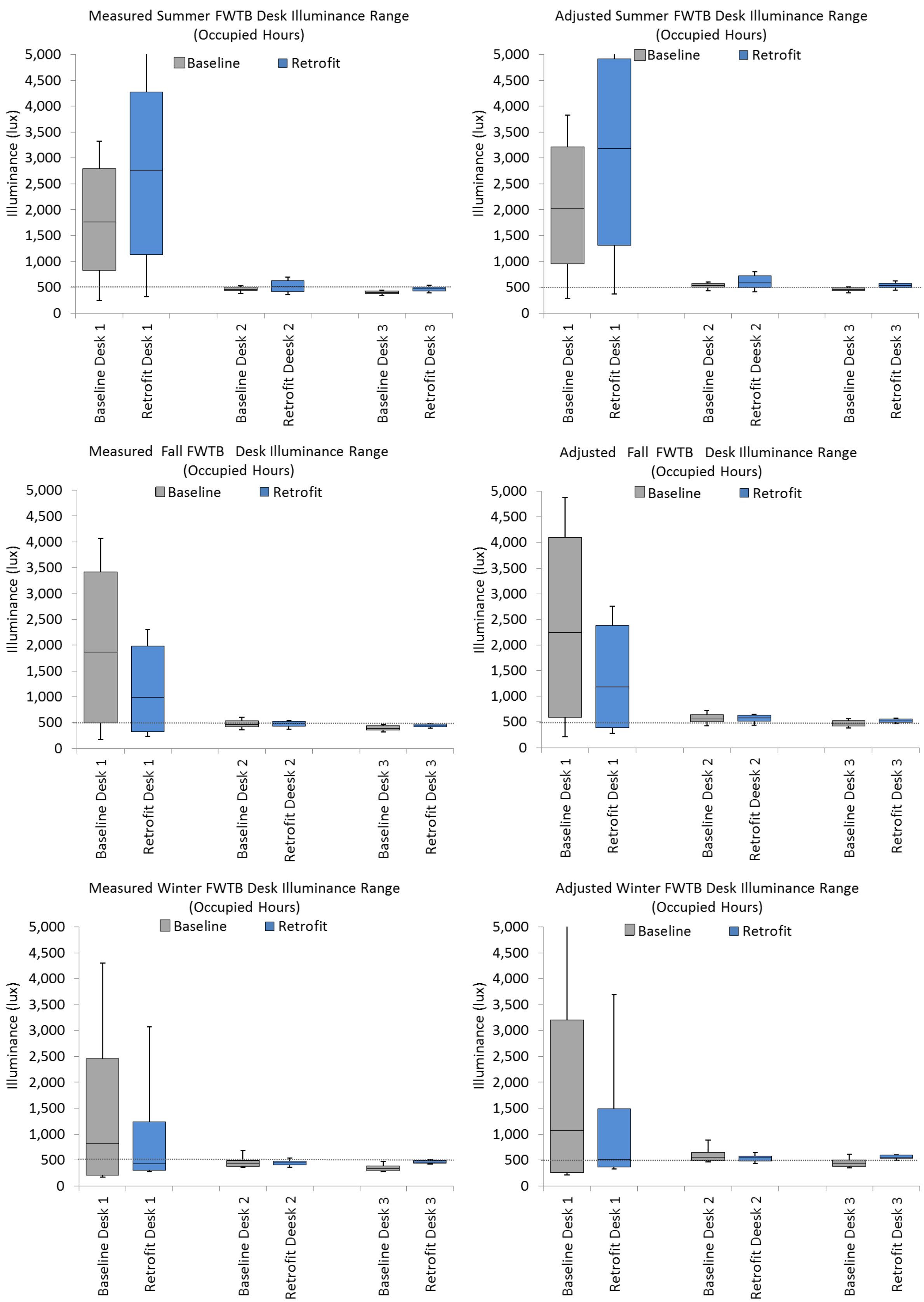


Figure 28. Full window code-compliant building illuminance ranges: measured (left) and adjusted (right)

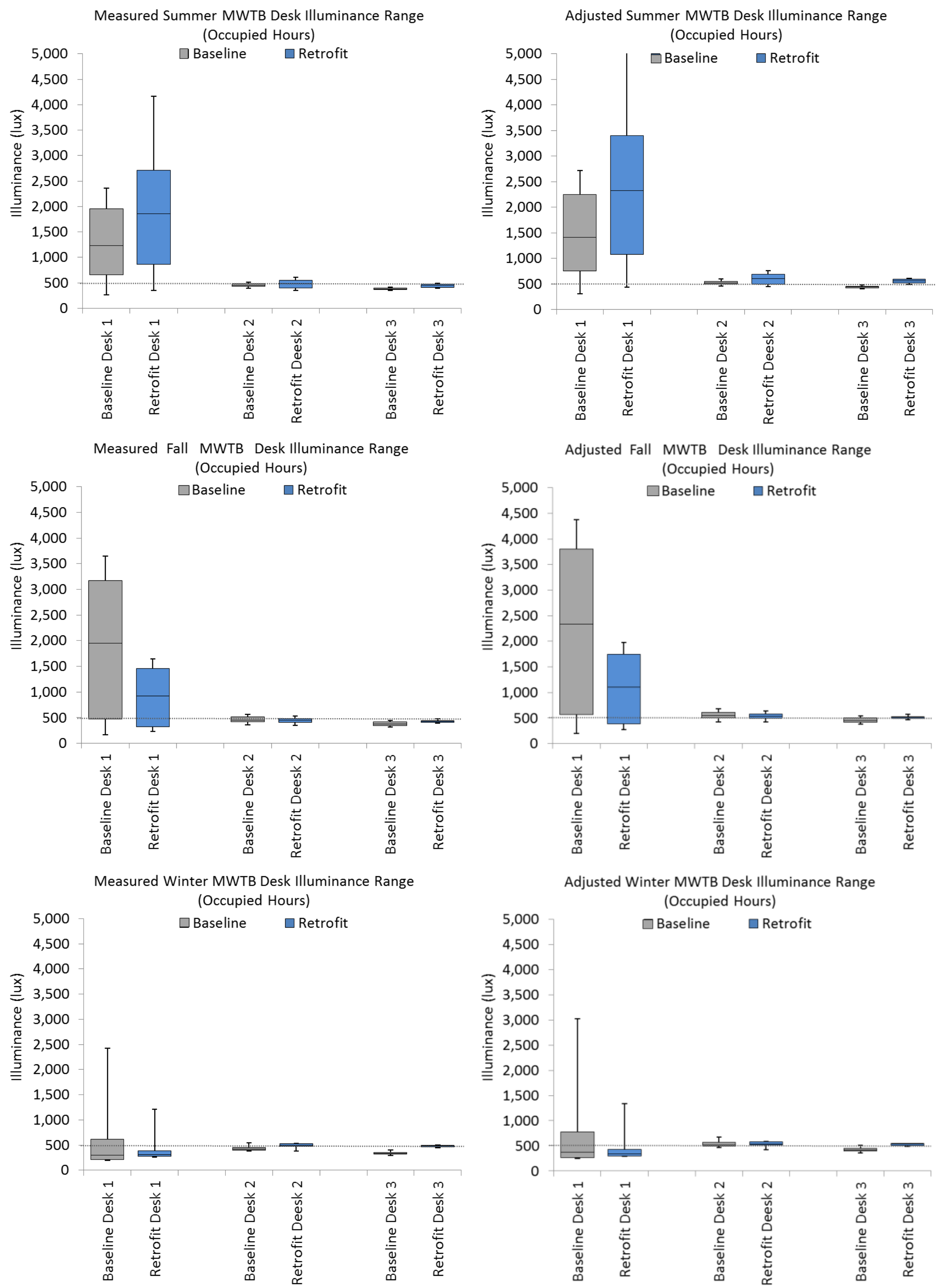


Figure 29. Mid window code-compliant building illuminance ranges: measured (left) and adjusted (right)

Glare

Table 9 summarizes the various levels of daylight glare probability (DGP) for each test case and season, for two locations in the baseline and retrofit test cells. The classes of glare as defined by DGP are imperceptible (<0.35; glare not noticed), perceptible (0.35 – 0.39, minor glare that does not impact ability to work), disturbing (0.40 – 0.45, would prefer to lower shade or move, productivity is reduced), and intolerable (>0.45, glare bad enough to preclude working).

*Table 9. Summary glare analysis results (average daily % time in each category)**

Test Period		Test Cell	Front HDR Camera				Back HDR Camera			
			Imperceptible	Perceptible	Disturbing	Intolerable	Imperceptible	Perceptible	Disturbing	Intolerable
FWEB	Summer	Baseline	96%	0%	0%	0%	100%	0%	0%	0%
		Retrofit	99%	1%	0%	0%	98%	0%	0%	0%
	Fall	Baseline	95%	3%	1%	0%	99%	0%	0%	0%
		Retrofit	98%	0%	0%	0%	98%	0%	0%	0%
	Winter	Baseline	96%	0%	0%	0%	99%	0%	0%	0%
		Retrofit	71%	0%	0%	0%	97%	0%	0%	0%
MWEB	Summer	Baseline	99%	0%	0%	0%	98%	0%	0%	0%
		Retrofit	99%	0%	0%	0%	96%	2%	0%	0%
	Fall	Baseline	97%	2%	0%	0%	98%	0%	0%	0%
		Retrofit	97%	0%	0%	0%	98%	0%	0%	0%
	Winter	Baseline	99%	0%	0%	0%	99%	0%	0%	0%
		Retrofit	96%	0%	0%	0%	98%	0%	0%	0%
FWTB	Summer	Baseline	99%	0%	0%	0%	99%	0%	0%	0%
		Retrofit	84%	15%	0%	0%	84%	15%	0%	0%
	Fall	Baseline	94%	5%	0%	0%	98%	0%	0%	0%
		Retrofit	98%	0%	0%	0%	98%	0%	0%	0%
	Winter	Baseline	91%	5%	0%	0%	98%	0%	0%	0%
		Retrofit	97%	1%	0%	0%	97%	0%	0%	0%
MWTB	Summer	Baseline	99%	0%	0%	0%	100%	0%	0%	0%
		Retrofit	100%	0%	0%	0%	94%	4%	0%	0%
	Fall	Baseline	98%	0%	0%	0%	99%	0%	0%	0%
		Retrofit	99%	0%	0%	0%	97%	0%	0%	0%
	Winter	Baseline	98%	0%	0%	0%	98%	0%	0%	0%
		Retrofit	96%	0%	0%	0%	98%	0%	0%	0%

**Days with more than 10% data "unknown" excluded. Do not always add to 100% due to some missing data.*

Glare was characterized using the daylight glare probability (DGP) index, which relies on high resolution, wide field-of-view high dynamic range (HDR) luminance images to assess glare. The HDR camera packages were located at select positions within the test cell to characterize surface luminances and

DGP through time at viewing angles consistent with those that could be experienced by an office worker in the space. The imagery was then analyzed automatically by software to assess discomfort glare from sources within the field of view. Examples of the imagery and luminance maps that are generated from them as well as the daily DGP results are shown in Figure 30 below. For both the baseline (venetian blind set to blocking angle) and the retrofit case, glare was well mitigated in the test cells. Very little time was logged in ranges other than imperceptible.

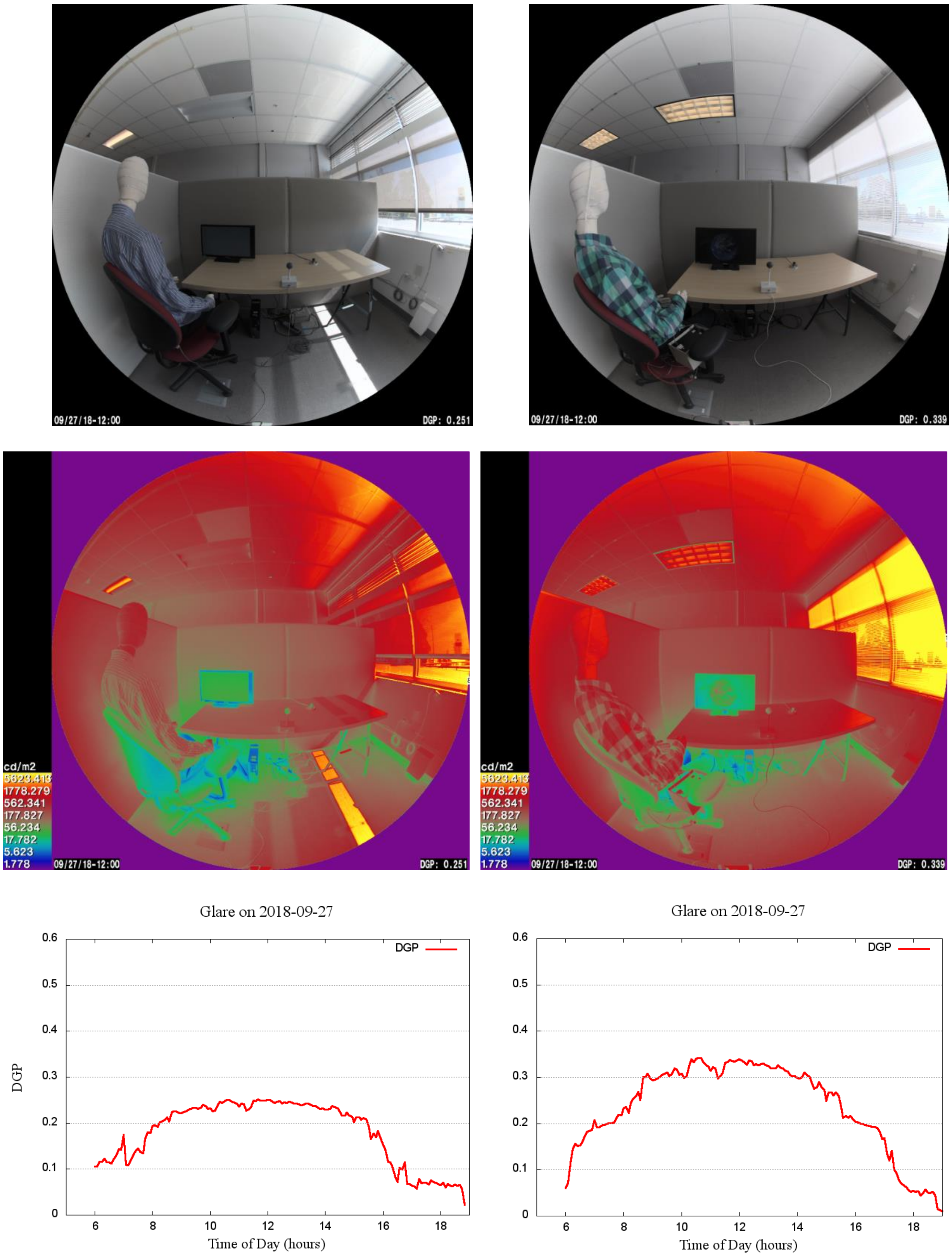


Figure 30. Example glare analysis imagery and plots for front desk: baseline (right) and retrofit (left)

The ranges of glare as measured by the HDR instruments for occupied period of each day, at both locations in the baseline and retrofit cell, are illustrated in Figures Figure 31, Figure 32, Figure 33, and Figure 34. The bar graphs depict the fraction of each day that glare was within standard bins, from imperceptible to intolerable. The line plots show the glare measurements through time. Missing data is shown as “unknown (grey)” in the following figures and is due to occasional outages from the HDR camera equipment

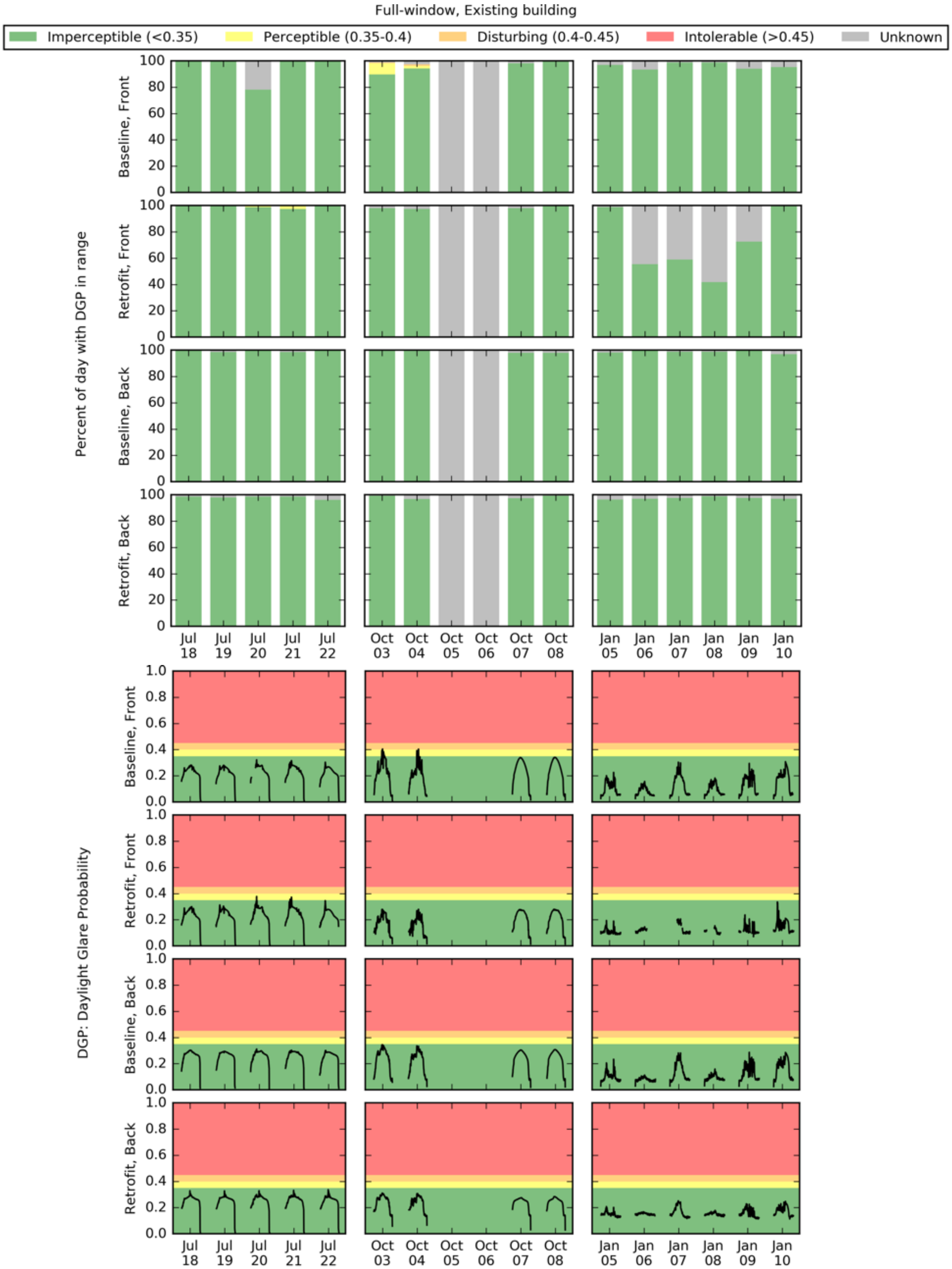


Figure 31. Full window existing building baseline Daylight Glare Probability results

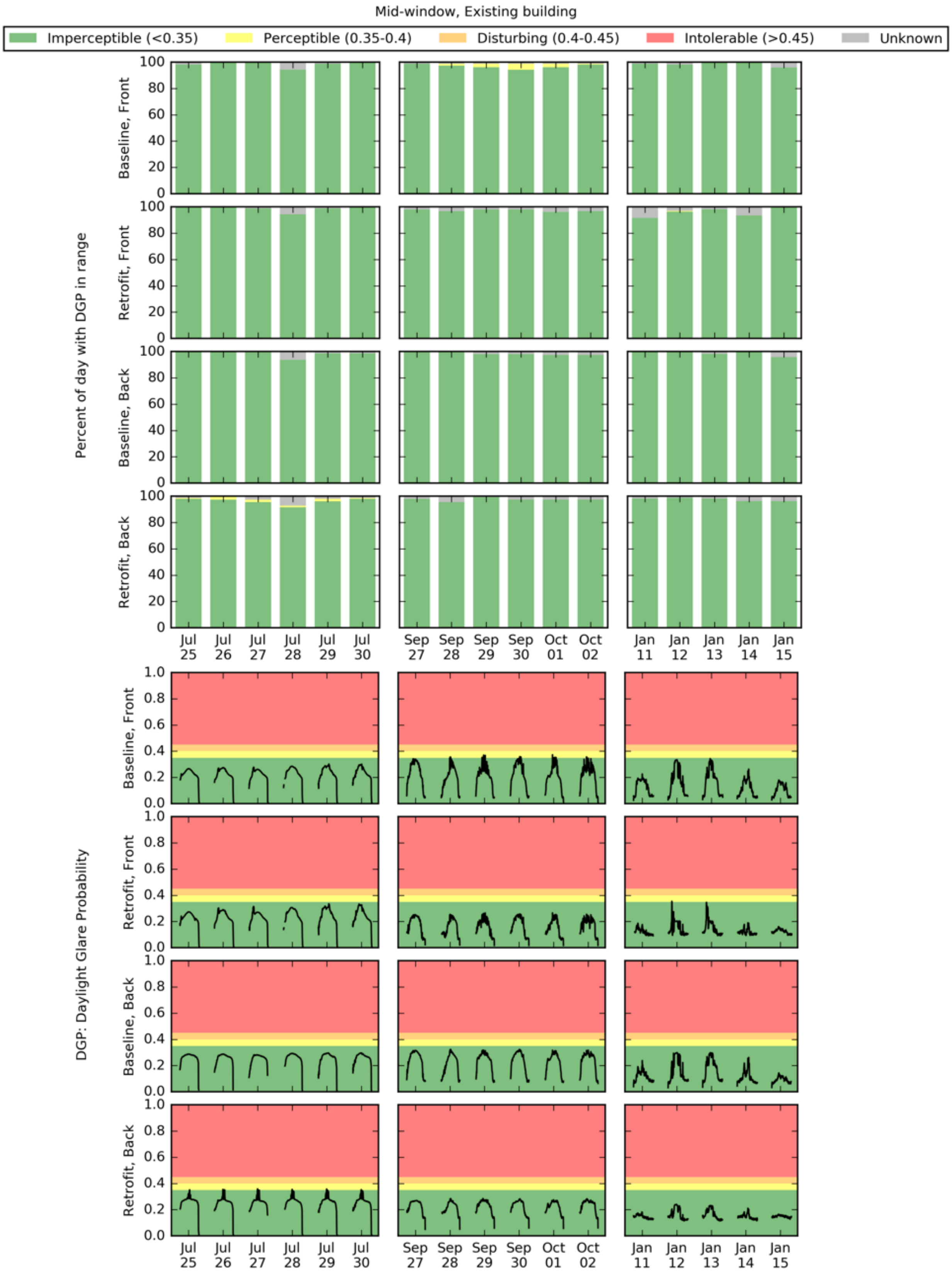


Figure 32. Mid window existing building baseline Daylight Glare Probability results

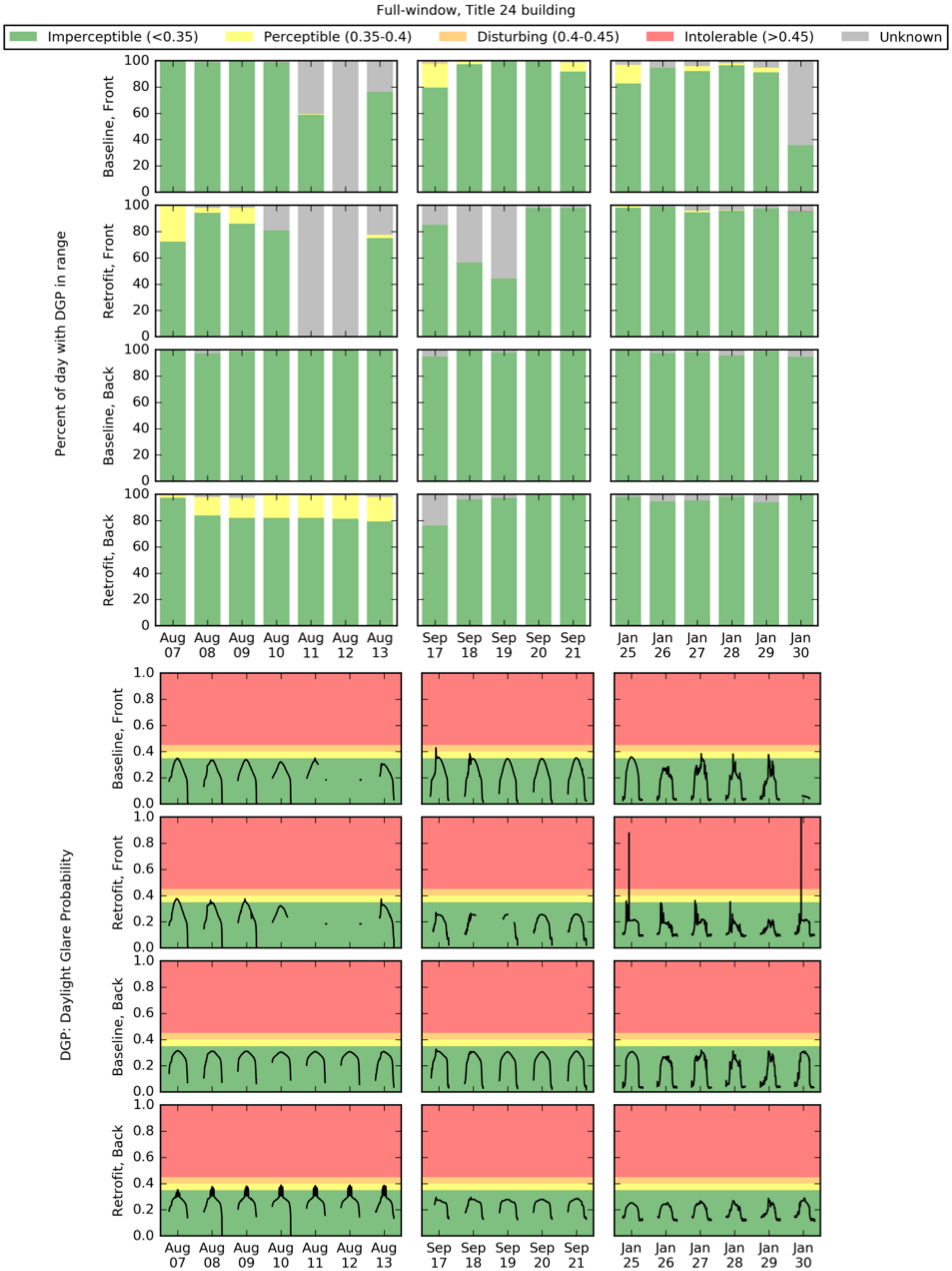


Figure 33. Full window code-compliant building baseline Daylight Glare Probability results

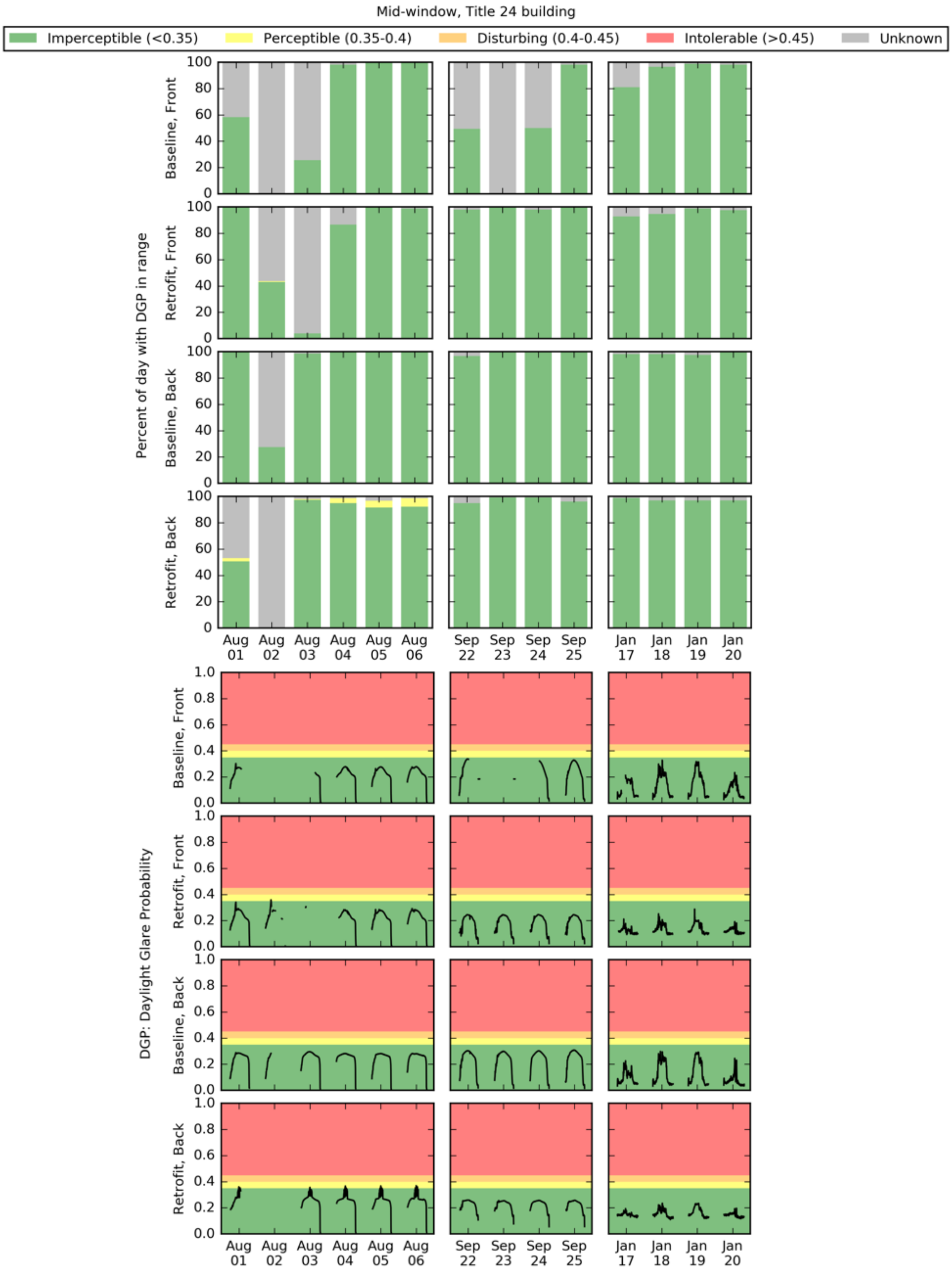


Figure 34. Mid window code-compliant building baseline Daylight Glare Probability results

HVAC Load Savings

The combination of the dimmable LED fixtures and automated rollershades and daylight redirecting louvers in the retrofit cell generally led to significant cooling load savings, ranging from 11 to 14 Wh/ft^2/day (28% to 43%) savings relative to the existing building baseline condition (higher wattage fluorescent fixtures with no dimming, venetian blinds), and some heating load penalty, from -1.3 to -2.7 (-17% to -53%). For the code-compliant baseline case, with the lower-wattage lighting system, cooling savings due to the retrofit system are less but are still significant, in the 4.3 to 8.8 Wh/ft^2/day (15% to 76%) range (Table 10). Importantly these savings are not whole building HVAC load savings, but rather load savings for the 30' deep zone (from south perimeter wall) in which the HVAC load was measured.

Table 10. Summary HVAC load savings (Wh/ft^2/day, %)

Test case		Summer	Fall	Winter
FWEB	Cooling	11 (36%)	11 (28%)	(no cooling)
	Heating	-1.9 (%n/a)	-1.2 (%n/a)	-2.3 (-17%)
	Days tested	2	4	2
MWEB	Cooling	11 (38%)	14 (43%)	1.1 (100%)
	Heating	-1.3 (-44%)	-1.6 (-53%)	-2.7 (-27%)
	Days tested	6	6	1
FWTB	Cooling	6 (19%)	6.5 (15%)	5.9 (26%)
	Heating	-0.59 (-18%)	-0.2 (-8%)	-0.3 (-5%)
	Days tested	7	2	6
MWTB	Cooling	6.7 (25%)	8.8 (24%)	4.3 (76%)
	Heating	-0.84 (-24%)	-0.22 (-6%)	-1.4 (-16%)
	Days tested	5	3	4

Figures Figure 35, Figure 36, Figure 37, and Figure 38 show the daily pattern of cooling and heating load in the baseline and retrofit cells for each test period. For most test conditions, soon after occupant thermal loads are present in the morning, along with computers and monitors turning on and also adding heat, heat builds up in the test space and the cells go into cooling mode. Lighting wattage in the conditioned space results in additional heat that must be rejected by cooling, so the effect of reducing lighting wattage with the LEDs and daylighting control is a reduction in cooling demand as well. On the other hand if the space is in heating mode, i.e. heating is required to maintain setpoint, reductions in lighting wattage lead to an increase in heating required, resulting in negative load savings.

It is notable that the cooling load savings tend to be very close to, but slightly more than, the energy savings from the lighting system during the same period. This indicates some additional HVAC savings from the system beyond just what is attributable to reductions in lighting wattage, and presumably due to less solar heat transmission from the exterior through the rollershade and blinds.

The test cells spent little time in heating mode during daytime operating hours, in large part due to the relatively mild climate of the Bay Area (small temperature differential between outside air and indoor setpoint). The setpoint for inside air temperature for the baseline and test cells was 68 degrees F (heating) and 72 degrees F (cooling). It should also be noted that for heating load differences, because the spaces spent little time in heating mode during operating hours, and experienced very little overall heating load, the relative (%) differences are less important and can be misleading; very small absolute differences had at times very large relative impacts. The absolute figures are therefore more useful.

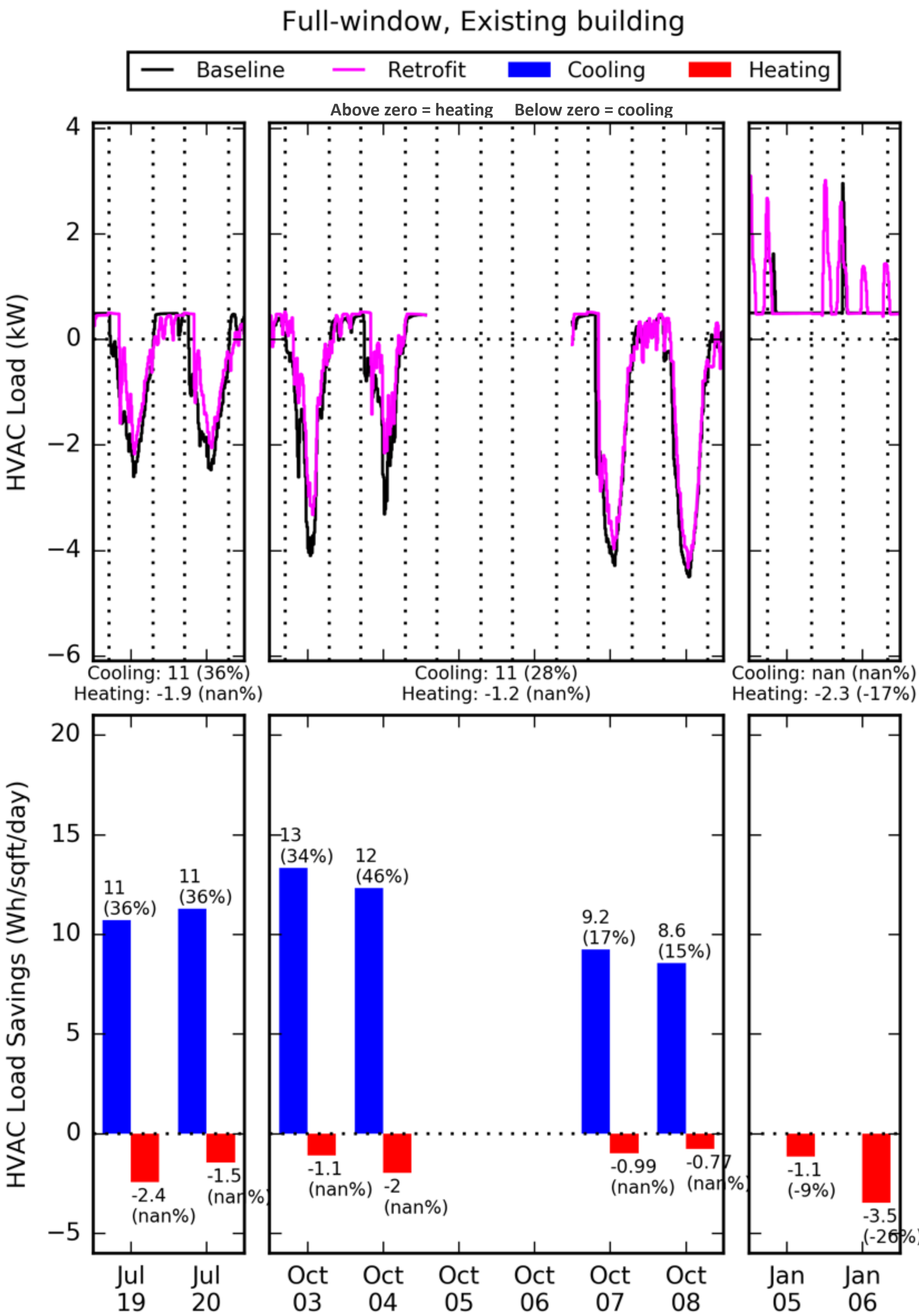


Figure 35. Full window existing building baseline HVAC load and load savings

(NaN: "not a number." Insufficient data and not applicable for the analysis)

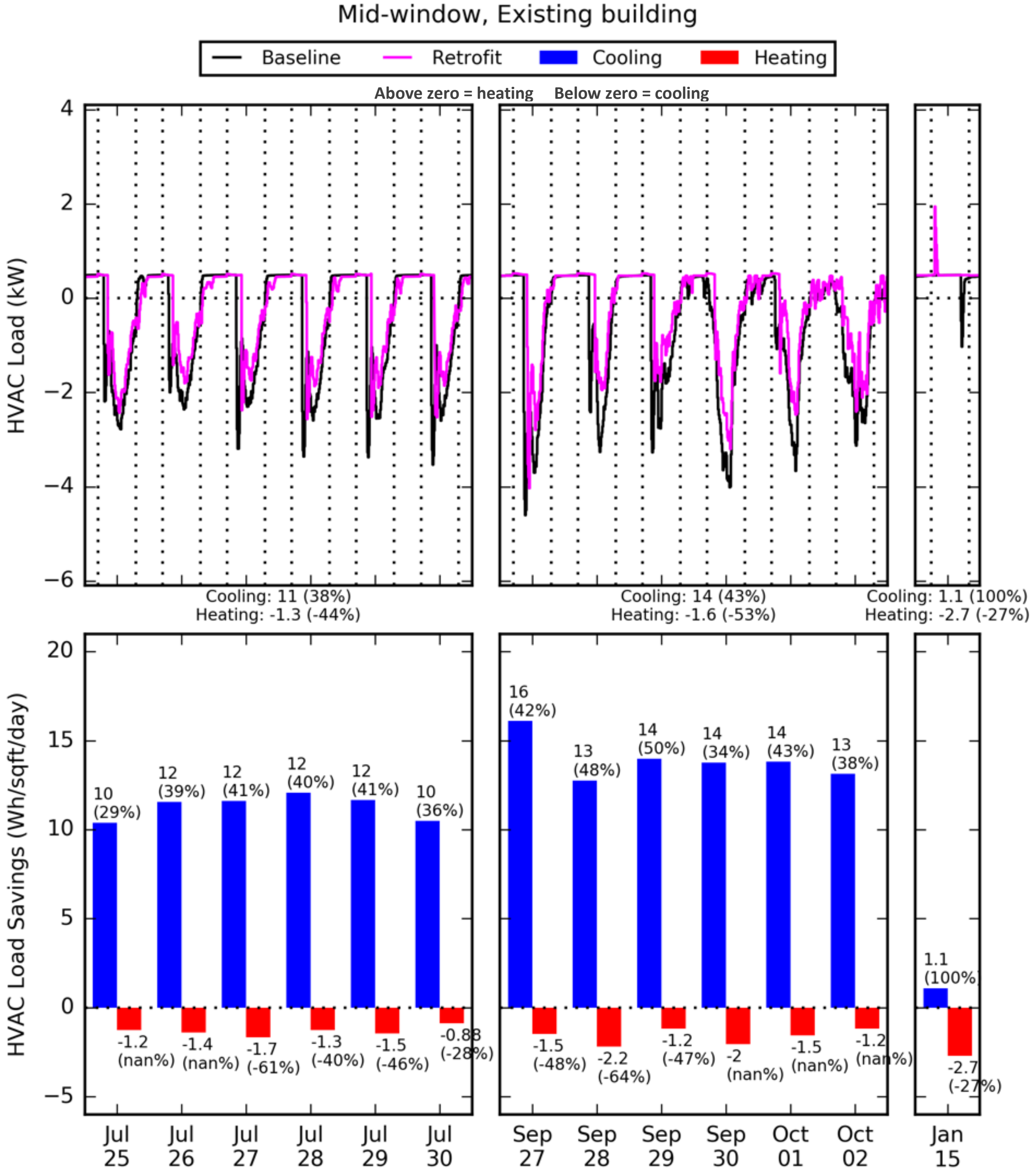


Figure 36. Mid window existing building baseline HVAC load and load savings (NaN: "not a number." Insufficient data and not applicable for the analysis)

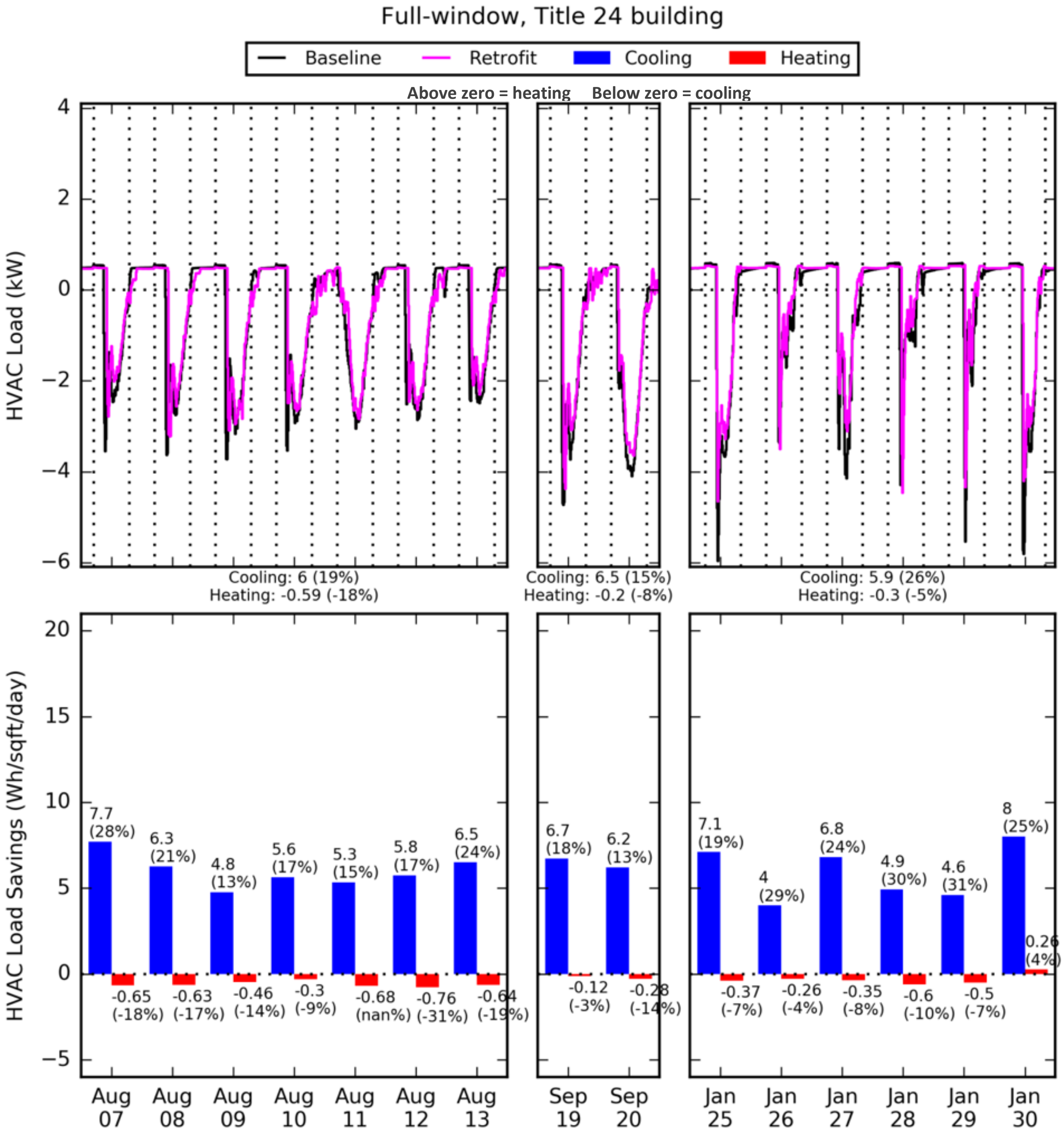


Figure 37. Full window code-compliant building baseline HVAC load and load savings (NaN: "not a number." Insufficient data and not applicable for the analysis)

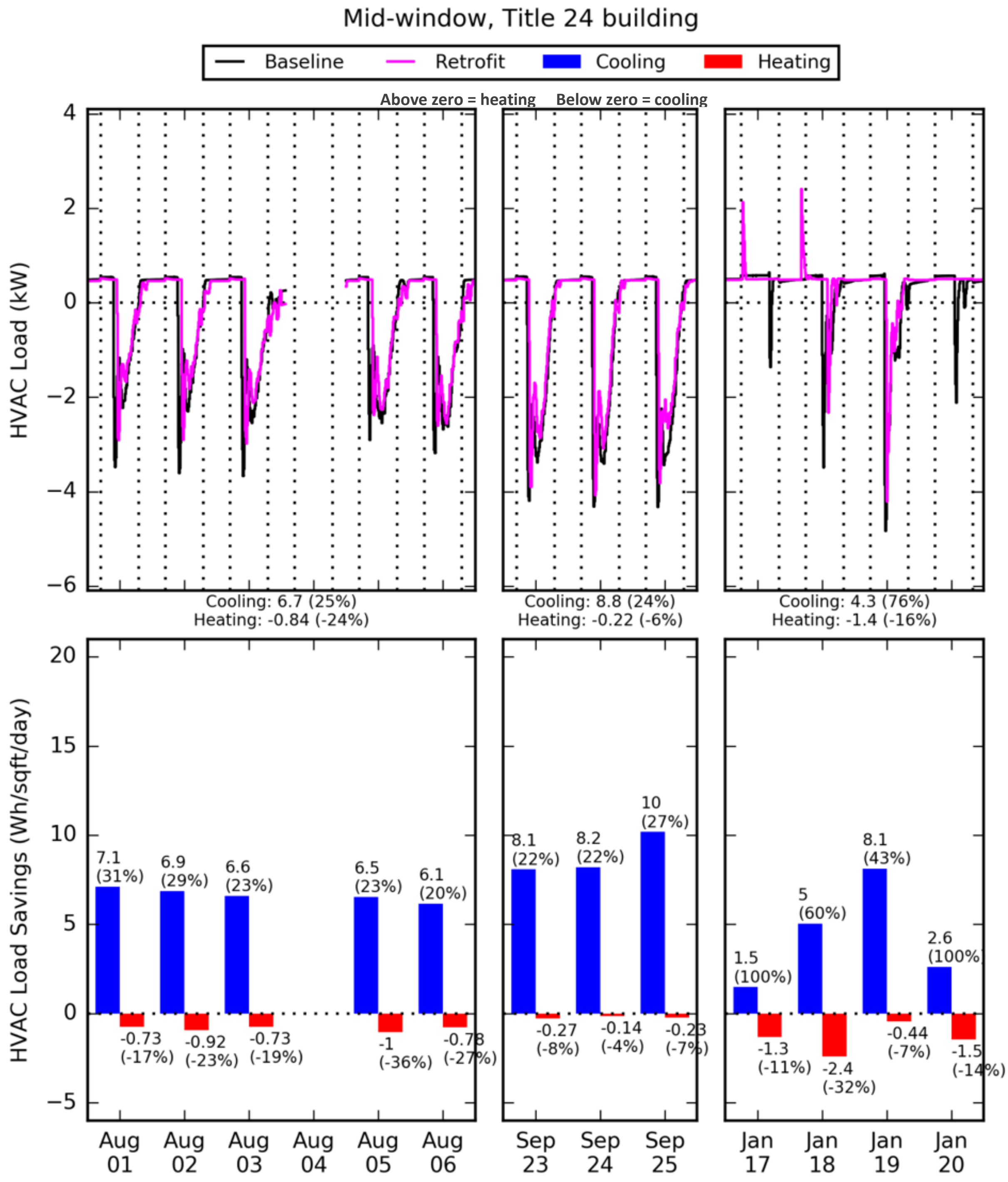


Figure 38. Mid window code-compliant building baseline HVAC load and load savings

Thermal Comfort

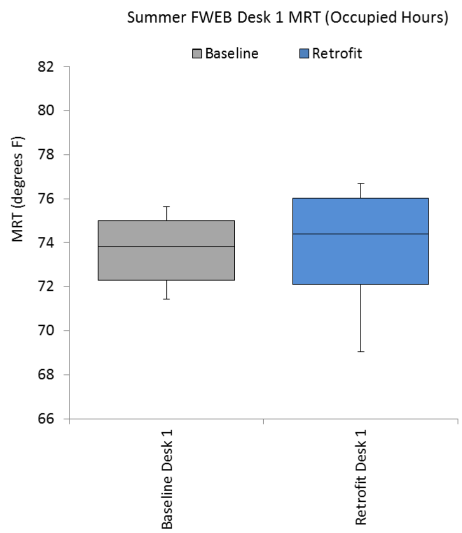
Table 11 summarizes the mean radiant temperature measurements during occupied periods, for each test case and season.

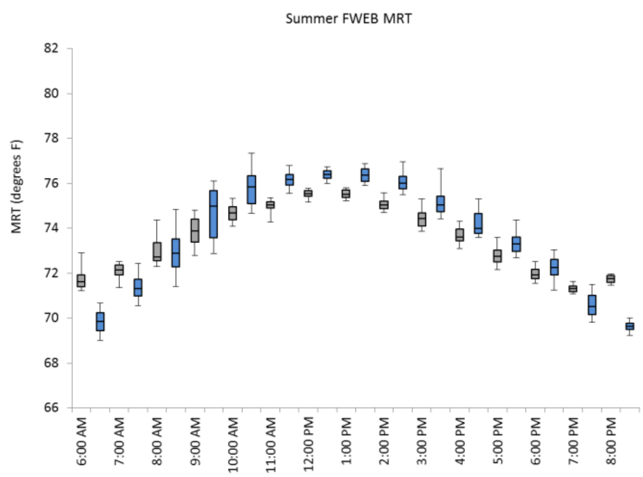
Table 11. Summary mean radiant temperature (°F) results
(median value from occupied hours of test period)

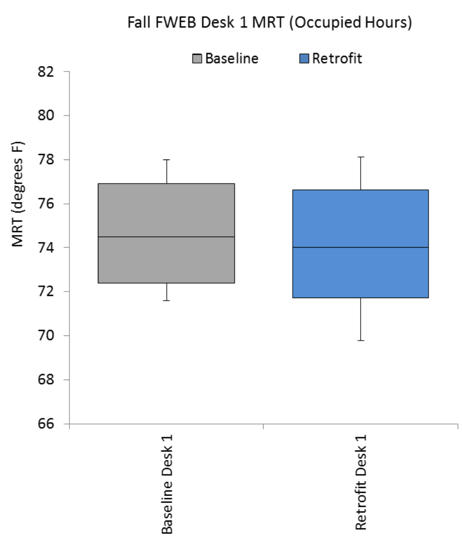
Test case	Summer.		Fall		Winter	
	Base.	Retro.	Base.	Retro.	Base.	Retro.
FWEB	73.8	74.4	74.5	74.0	70.1	68.1
MWEB	73.7	74.1	73.6	73.2	72.0	68.9
FWTB	74.7	75.3	75.5	74.3	73.9	72.8
MWTB	74.0	74.3	75.8	74.4	72.5	70.6

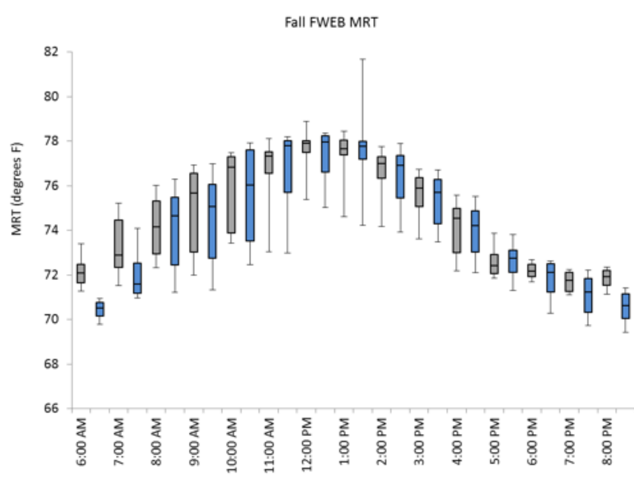
A mean radiant temperature sensor was placed on the desk closest to the window wall (Desk 1) in the baseline and test (retrofit) cell. The sensor readings could be compared to evaluate thermal comfort and differences between cells due to different shading systems covering the windows. The baseline cell had standard venetian blinds pulled down across the windows, with louvers open to an angle set to block direct glare. This was done via a seasonal adjustment, from flat (zero degree angle) in the summer to +30 degrees in the fall (interior edge up) and +45 degrees in the winter. The retrofit cell had the redirecting blinds in the top third of the window bay, and a rollershade serving the bottom two thirds of the glass (around 41" total glass). In the summer the rollershade was rolled all the way up, essentially leaving bare glass for the bottom 41" of window. In the fall the rollershade was deployed down most of the way, leaving roughly 9" of glass exposed, and in the winter the rollershade was fully deployed, with no glass exposed. These shade positions were dictated by seasonal sun angles; in the summer sun angles are highest so direct solar penetration in the south windows was not an issue, whereas in the winter sun angles are the lowest, with direct sunlight potential (depending on cloudiness) on the south windows for most of each day.

Mean radiant temperatures were for the most part very similar in the baseline and retrofit cells (Figures 39-42). In the summer, the desk near the window was slightly warmer in the retrofit cell, though typically by less than 1 degree F. In the fall, the retrofit location was just slightly cooler than the baseline location, though by less than 0.5 degree F to slightly over 1 degree F depending on the test case. There was a median difference of between around 1 to 2 degree F for the cell configurations in the winter season, with the retrofit location being cooler, potentially indicating higher radiative transmission through the rollershade (all the way down) than through the venetian blinds (down with +45 degree upward louvre tilt).









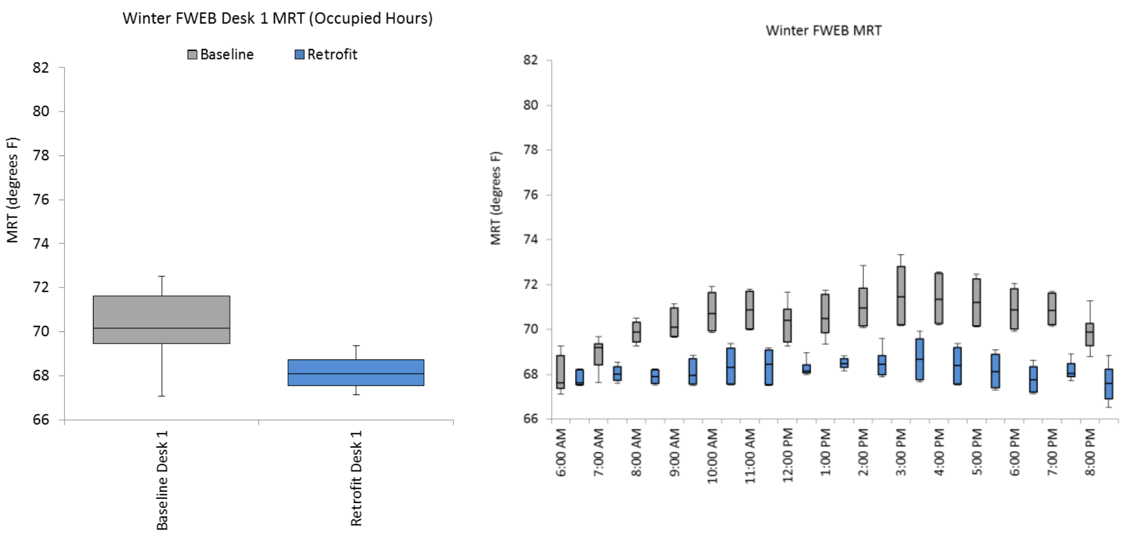
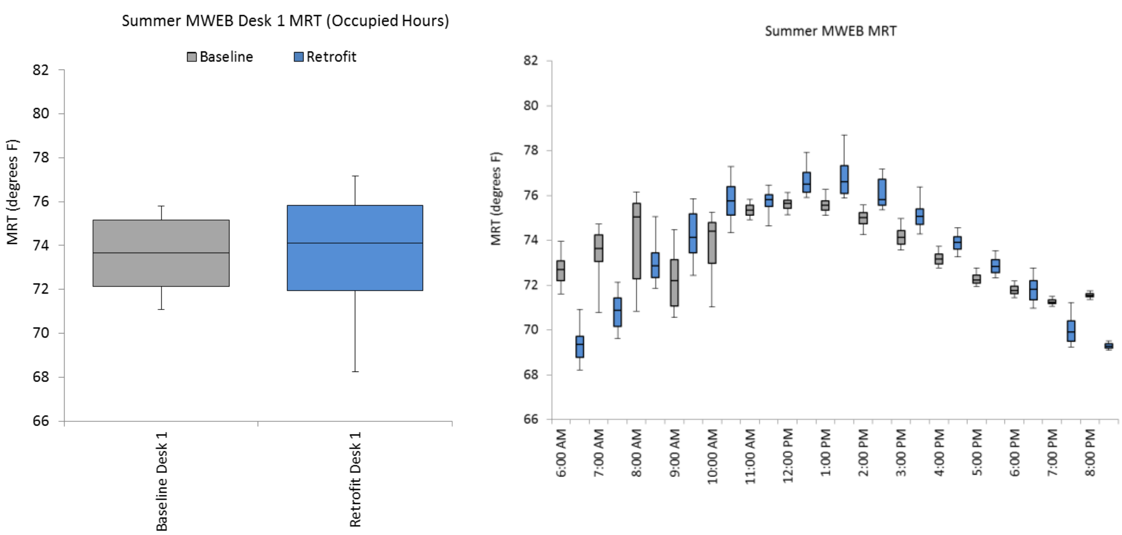


Figure 39. Full window existing building baseline mean radiant temperature ranges (test period and hourly)



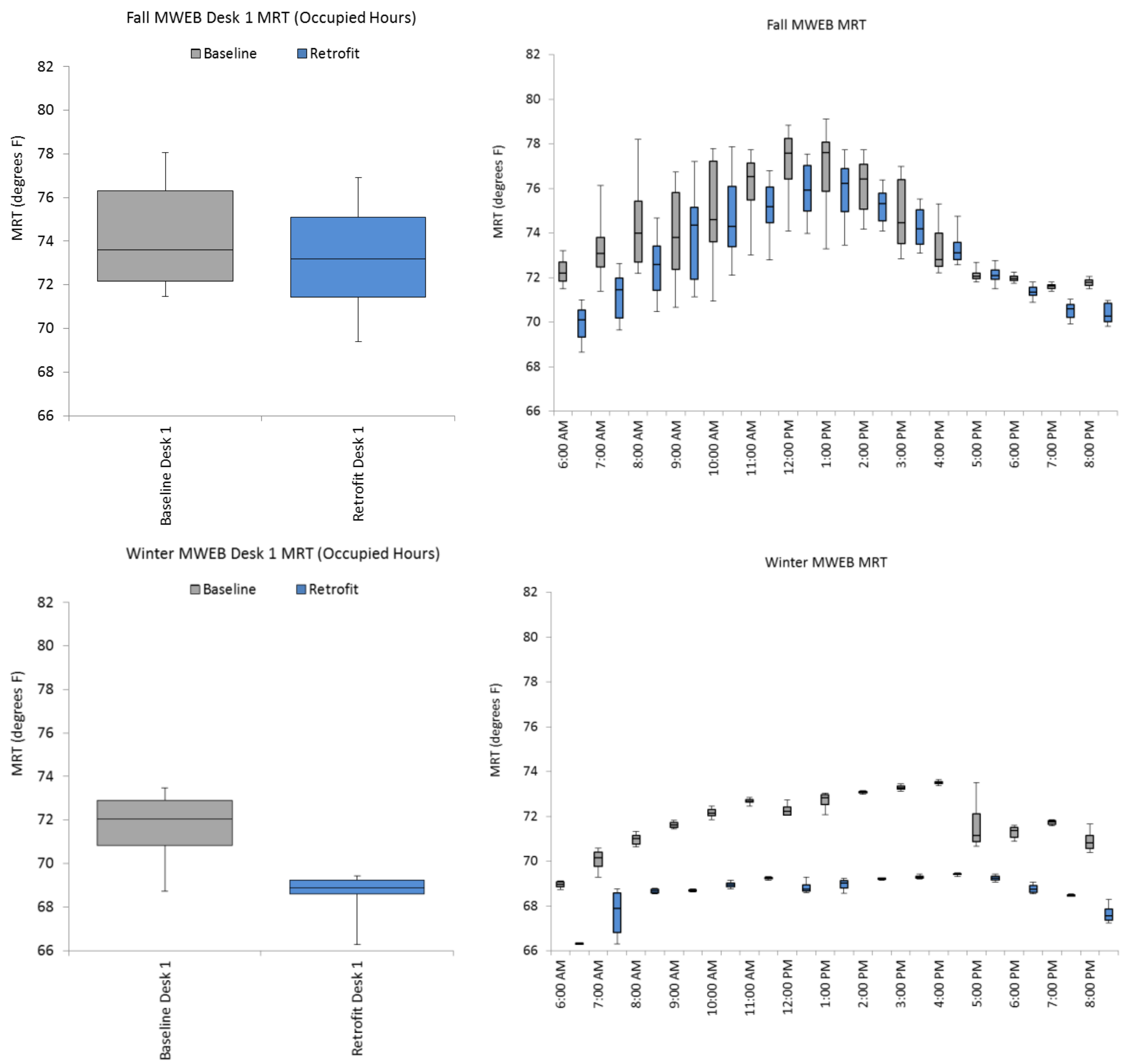
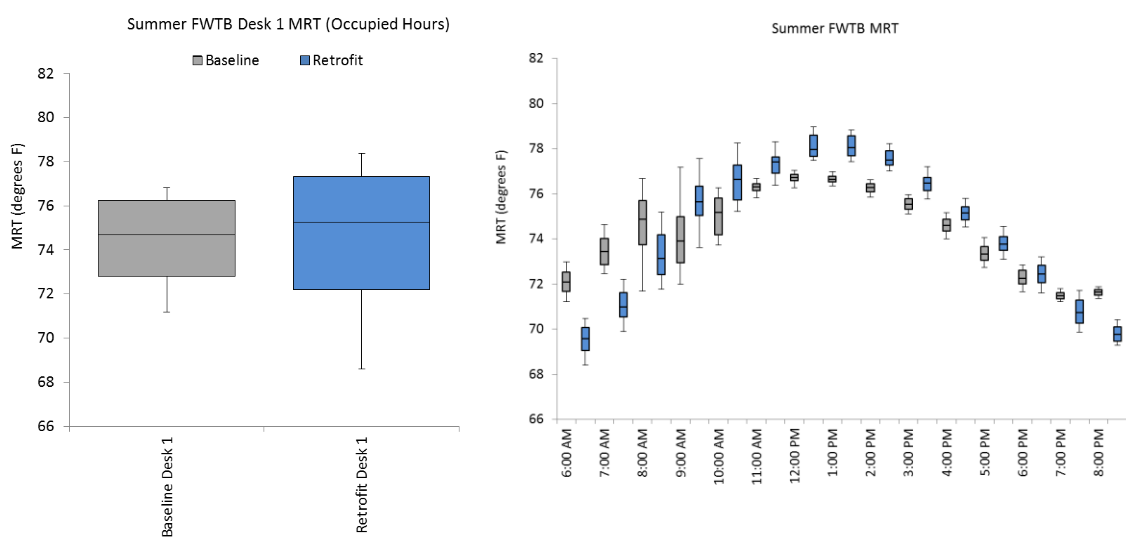


Figure 40. Mid window existing building baseline mean radiant temperature ranges (test period and hourly)



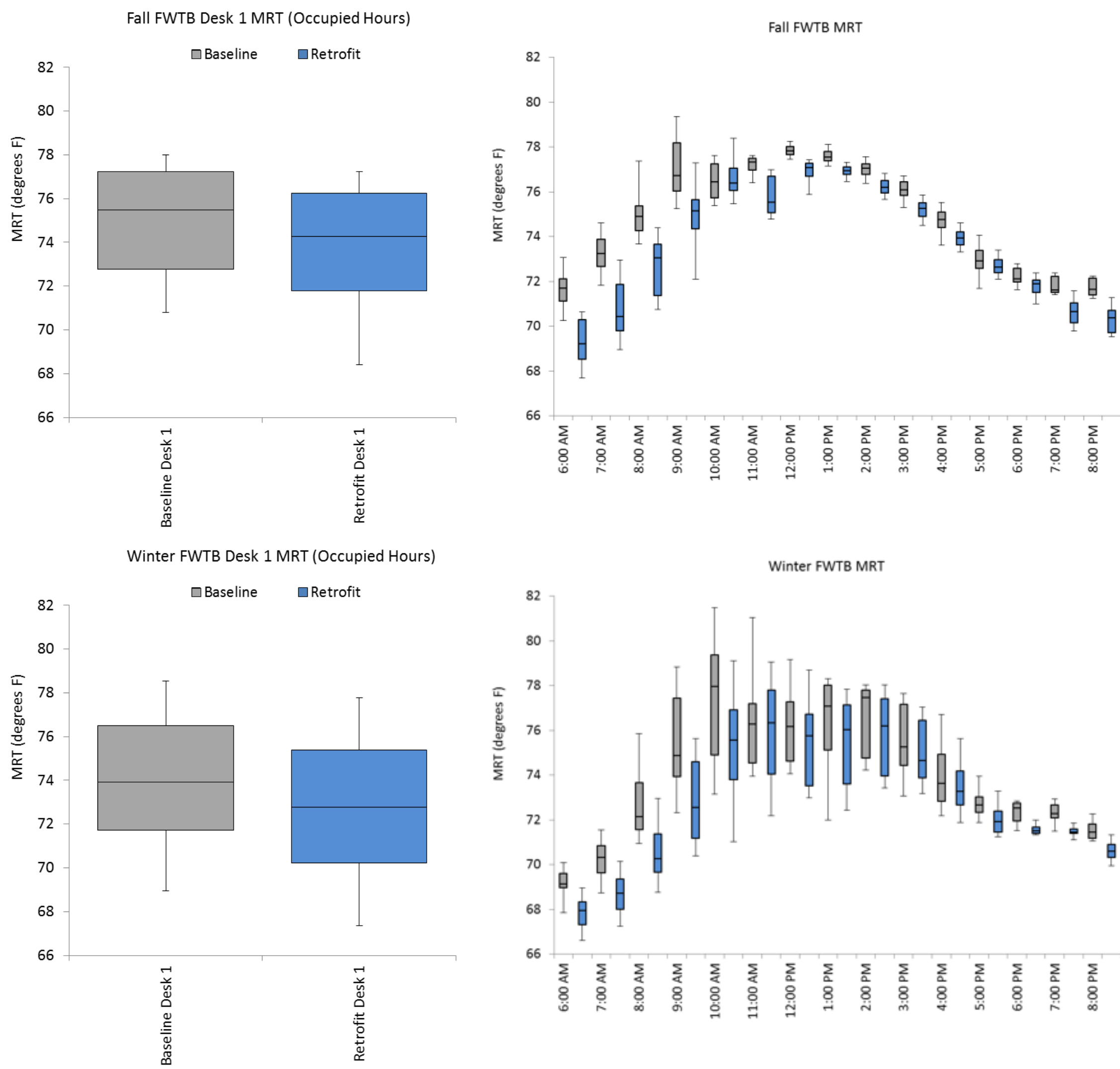
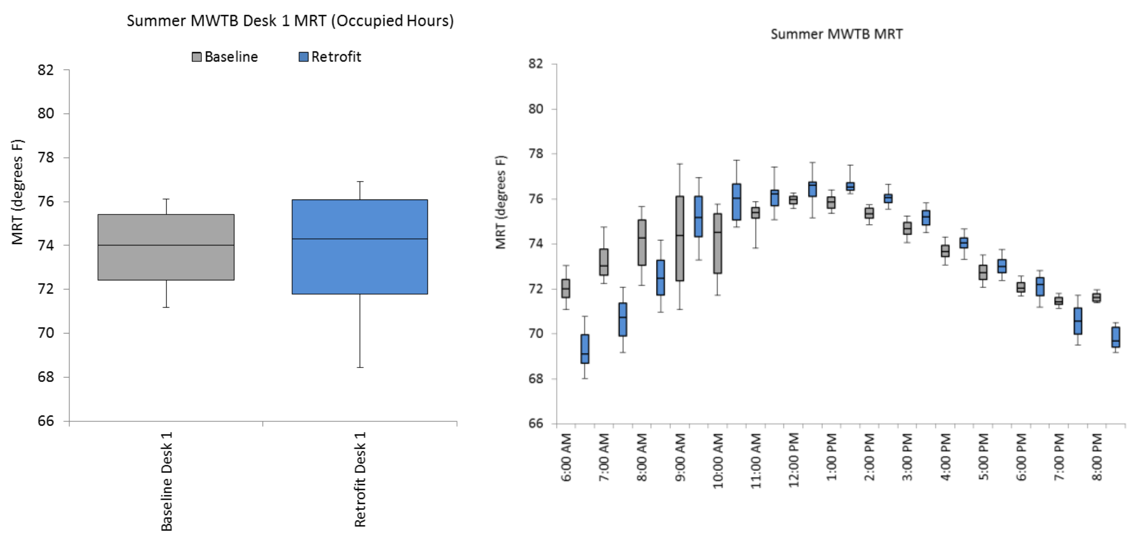


Figure 41. Full window code-compliant building baseline mean radiant temperature ranges (test period and hourly)



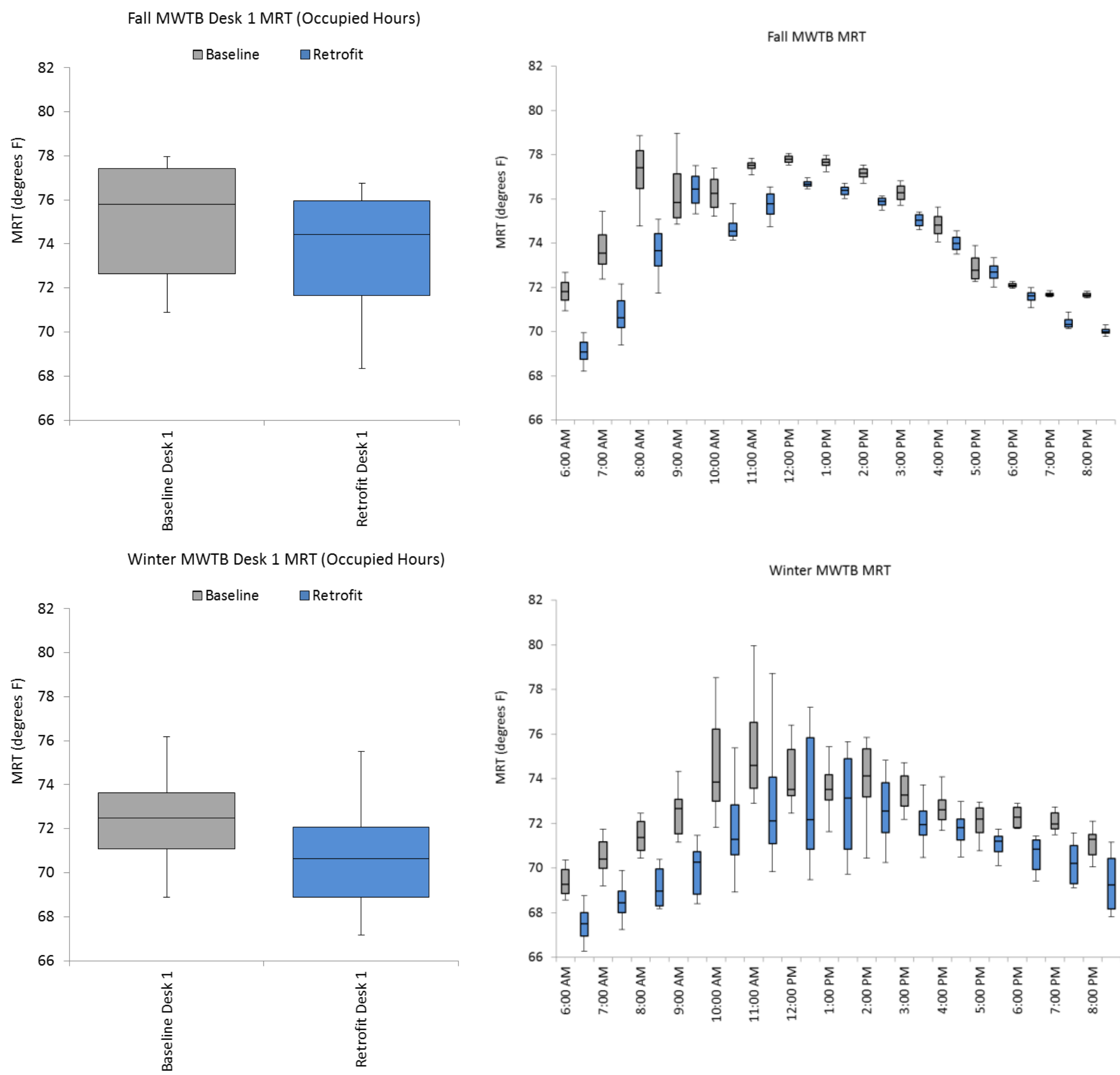


Figure 42. Mid window code-compliant building baseline mean radiant temperature ranges (test period and hourly)

Conclusions and Recommendations

LBNL's FLEXLAB test facility was used to test the INTER system of automated shading products and LED dimmable lighting with daylight controls, comparing it to two baselines: an existing building baseline of non-dimmable fluorescent fixtures on scheduled operation, and a Title 24 baseline of dimmable fluorescents with stepped zonal daylight dimming for the primary and secondary fixtures. The test periods were approximately three weeks each in summer, fall, and winter.

The lighting savings for the existing baseline case ranged from 62% in winter (less daylight dimming possible) to 76% in summer (more daylight dimming). For the Title 24 baseline, the lighting energy savings ranged from 49% in winter to 62% in summer. HVAC load savings were found for all configurations when in cooling mode, with HVAC cooling load savings being very close to lighting energy savings, indicating that the majority of HVAC load difference is due to the lower-wattage electric lighting in the retrofit case. Some HVAC load penalty (negative savings) was found in heating mode, as expected, though based on internal loads and climate conditions at the test location, little time was spent in heating. For thermal comfort near the window wall, no meaningful difference was found between the mean radiant temperature in the baseline and retrofit cases.

The illuminance design criterion was met in the baseline and retrofit condition, albeit with some minor adjustments to increase lighting power and light levels to ensure maintained illuminance was at or above the design criterion. The daylight glare probability analysis from test data showed that glare was adequately controlled for all test periods in the baseline cases and the retrofit case.

The installation and commissioning of the INTER system revealed minor mechanical issues with the shading system, which were addressed without much difficulty. At the time of FLEXLAB testing, there was no commercial control server or software for automated shade operation based on solar conditions, so this capability was not tested. All other aspects of the INTER system operated as expected.

Finally, it should be noted that FLEXLAB testing does not address any occupant interactions. These aspects will be tested through field demonstration studies.

References

Title 24. Building Energy Efficiency Standards - Title 24. California Energy Commission. https://www.energy.ca.gov/programs-and-topics/programs/building-energy-efficiency-standards. Accessed July 2019.

Wienold, J. and Christoffersen, J. 2006. Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. Energy and Building. 38 (2006) 743-757.

Wienold, J. 2009. Dynamic Daylight Glare Evaluation. Eleventh International IBPSA Conference. Glasgow, Scotland. 2009.

IES 2011. The Lighting Handbook, 10^{th} Edition. Illuminating Engineering Society. 2011.

Appendix I. Test Reconfiguration Details

For each test case, the tables below list the testbed components and equipment configurations.

Table 12. Tests FWEB, MWEB (existing building baseline cases) configuration details

Component	**B – Test Case**	**A – Baseline**
Opaque Envelope	Metal stud wall construction w/ R-19 batt cavity insulation	Metal stud wall construction w/ R-19 batt cavity insulation
Glazing	● Single-pane window w/ aluminum frame, single thermal break ● WWR ~0.50	● Single-pane window w/ aluminum frame, single thermal break ● WWR ~0.50
Glazing lintel height	● Full height FW tests ● 12” below ceiling for MW tests. For this case, the existing shading configuration will remain in place, with the upper 12” of the window blocked off so that it does not contribute lighting into the space	● Full height for FW tests ● 12” below ceiling for MW tests. For this case, the existing shading configuration will remain in place, with the upper 12” of the window blocked off so that it does not contribute lighting into the space
Exterior Shades	None	None
Interior Shades	Rollease automated shades with integrated PV and battery for power, set for each season as follows: Summer: Shades fully retracted. Fall: Shades deployed to 45” above floor. Winter: Shades fully deployed	Manual venetian blinds, all the way down. Summer: blinds in horizontal position Fall: +30 degree tilt (interior edge up) Winter: +45 degree tilt (interior edge up)
Interior Automated Light Redirecting Louver	Rollease blinds with integrated PV and battery for power, set for each season as follows: Summer: Blind angle = -30degrees Fall: Blind angle = +10 degrees Winter: +45 degrees	N/A
Interior Partitions	5ft high	5ft high

<table>
<tr><th>Component</th><th>B – Test Case</th><th>A – Baseline</th></tr>
<tr><td>HVAC</td><td>VAV single zone, unocc. setbacks/shutoff. Occupied hours 6am-8pm. Controlled to setpoint of 21C. No economizer control or ventilation.</td><td>VAV single zone, unocc. setbacks/shutoff. Occupied hours 6am-8pm. Controlled to setpoint of 21C. No economizer control or ventilation.</td></tr>
<tr><td>Lighting</td><td>0.40 W/ft^2, LED 2x4 troffer tuned to 500lux at workplane (or full output), occ. sensing, daylight dimming (Enlighted), scheduled on/off operation (assuming occupancy throughout workday), daylight harvesting at perimeter. Dimming operation:
● All six fixtures dim independently based on fixture-level daylight sensor, from full output to off at full dim if/when sufficient daylight is present.
● Scheduled on/off operation: 6am-8pm</td><td><u>Existing Building Baseline:</u>
1.0 W/ft^2, 3-lamp T8 2x4 troffer, no automated controls.
● Scheduled on/off operation: 6am-8pm</td></tr>
<tr><td>Plug Loads</td><td>Plug loads: 0.5 W/ft^2 , simulated occupancy profile via timeclock</td><td>Plug loads: 0.5 W/ft^2, simulated occupancy profile via timeclock</td></tr>
<tr><td>Plug Load Controls</td><td>Per discussion with project team, we did not test plug load controls.</td><td>N/A</td></tr>
<tr><td>Equipment from
‘Loaner Pool’</td><td colspan="2">● Lighting measurement: 16 LiCor 210 photometers per cell. Placed at desk height without nearby obstructions above plane of measurement.
● Glare measurement: 2 HDR fisheye camera lens packages per cell, one mounted parallel to window (facing computer monitor, as occupant would) 4ft from façade and at 4ft height; the other mounted at 5.5ft standing height, perpendicular to window (viewing towards the window).
● Thermal comfort measurement: one mean radiant temperature sensor located on first desk, 6ft from window.</td></tr>
<tr><td>Occupant Thermal Generators</td><td colspan="2">3 total in each cell, one per cubicle. 77W sensible load each per ASHRAE 90.1 User Guide. Programmable timers.</td></tr>
<tr><td>Additional Sensors</td><td colspan="2">N/A</td></tr>
<tr><td>Additional Measurement Equipment/ Instrumentation</td><td colspan="2">N/A</td></tr>
</table>

Table 13. Tests FWTB, MWTB (Title 24 baseline cases) configuration details

Component	**B – Test Case**	**A – Baseline**
Opaque Envelope	Metal stud wall construction w/ R-19 batt cavity insulation	Metal stud wall construction w/ R-19 batt cavity insulation
Glazing	● Single-pane window w/ aluminum frame, single thermal break ● WWR 0.50	● Single-pane window w/ aluminum frame, single thermal break ● WWR 0.50
Glazing upper lintel height	● Full height for FW tests ● To 12” below ceiling for MW tests. For this case, the existing shading configuration will remain in place, with the upper 12” of the window blocked off so that it does not contribute lighting into the space	● Full height for FW tests ● To 12” below ceiling for MW tests. For this case, the existing shading configuration will remain in place, with the upper 12” of the window blocked off so that it does not contribute lighting into the space
Exterior Shades	None	None
Interior Shades	Rollease automated shades with integrated PV and battery for power, set for each season as follows: Summer: Shades fully retracted. Fall: Shades deployed to 45” above floor (window sill at 36”). Winter: Shades fully deployed	Manual venetian blinds, all the way down. Summer: blinds in horizontal position Fall: +30 degree tilt (interior edge up) Winter: +45 degree tilt (interior edge up)
Interior Automated Light Redirecting Louver	Rollease blinds with integrated PV and battery for power, set for each season as follows: Summer: Blind angle = -30degrees; Fall: Blind angle = +10 degrees. Winter: +45 degrees	N/A
Interior Partitions	● 5ft high	● 5ft high
HVAC	VAV single zone, unocc. setbacks/shutoff.	VAV single zone, unocc. setbacks/shutoff.

Component	B – Test Case	A – Baseline
	Occupied hours 6am-8pm. Controlled to setpoint of 21C. No economizer control or ventilation.	Occupied hours 6am-8pm. Controlled to setpoint of 21C. No economizer control or ventilation.
Lighting	0.40 W/ft^2, LED 2x4 troffer tuned to 500lux at workplane (or full output), occ. sensing, daylight dimming (Enlighted), scheduled on/off operation (assuming occupancy throughout workday), daylight harvesting at perimeter. Dimming operation: ● All six fixtures dim independently based on fixture-level daylight sensor, from full output to off at full dim if/when sufficient daylight is present. ● Scheduled on/off operation: 6am-8pm	Title 24 Baseline: 0.75 W/ft^2 (per 2016 CA T24, Table 140.6-C, area category method for offices >250sf), 2-lamp T5 2x4 troffer, scheduled on/off operation (assuming occupancy throughout workday), daylight harvesting at perimeter (primary and secondary zone). Dimming operation: ● Stepped dimming, per the steps in the min. condition table (2016 CA T24, Table 130.1-A). Daylight responsive in the 2x head height distance from the window (i.e. first 2 rows only; primary and secondary). Calibrated dimming at 150% of target illuminance minimum approach in the primary and secondary sidelit daylit zones. ● Scheduled on/off operation: 6am-8pm
Plug Loads	Plug loads: 0. 5 W/ft^2 , simulated occupancy profile via timeclock	Plug loads: 0. 5 W/ft^2, simulated occupancy profile via timeclock
Plug Load Controls	Per discussion with project team, we did not test plug load controls.	N/A
Equipment from ‘Loaner Pool’	● Lighting measurement: 16 LiCor 210 photometers per cell. Placed at desk height without nearby obstructions above plane of measurement. ● Glare measurement: 2 HDR fisheye camera lens packages per cell, one mounted parallel to window (facing computer monitor, as occupant would) 4ft from façade and at 4ft height; the other mounted at 5.5ft standing height, perpendicular to window (viewing towards the window). ● Thermal comfort measurement: one mean radiant temperature sensor located on first desk, 6ft from window.	

Component	B – Test Case	A – Baseline
Occupant Thermal Generators	3 total in each cell, one per cubicle. 77W sensible load each per ASHRAE 90.1 User Guide. Programmable timers .	

Appendix II. Lab Measurement Specifications

Table 14. Measurement Specifications

	Measurements	Sensors	Quantity	Uncertainty
Weather	Global and diffuse horizontal irradiance	Delta-T Devices SPN1-A990	1	+/- 5% | +/- 10W/m²
	Outside air dry bulb temperature	BAPI BA/10K-2(XP)-O-BB	1	+/- 0.1°C
HVAC **(per cell)**	Ducted air temperature (return, mixed and supply)	BAPI BA/10K-2-(XP)-SP	3	Calibrated at +/- 0.05°C
	Ducted air flowrate (supply and return)	Ebtron Gold BTM116-PC	2	+/- 3% (< 5000 fpm)
	Ducted air pressure (supply and return)	TEC DG-700	2	+/- 1% | +/- 5 iwg
	Chilled water temperature (supply and return)	BAPI BA/T1K-DIN-[0 TO 100F]-I-2"-BB	2	+/- 0.055°F
	Chilled water flowrate	Siemens Sitrans FM MAG 1100	1	+/- 0.2% (> 0.3 fps)
	Hot water temperature (supply and return)	BAPI BA/T1K-DIN-[32 TO 212F]-I-2"-BB	2	+/- 0.055°F
	Hot water flowrate	Siemens Sitrans FM MAG 1100	1	+/- 0.25% (> 0.3 fps)
	Fan Power	Circuit breaker measurements	1	+/- 2% (typically +/- 1%)

	Measurements	Sensors	Quantity	Uncertainty
Loads (per cell)	Cell lights, occupants, plug loads power	Circuit breaker measurements	6	+/- 2% (typically +/- 1%)
Illuminance	Photosensor	LiCor LI-210R + UTA amplifier (UTA/BNC type)	16 per cell	~10 lx
Glare	Fisheye lens camera packages for daylight glare probability	LBNL custom-built, Canon camera	4 (2 per test cell)	
Thermal Comfort	Mean radiant temp	Globe Temp Sensor	1 per cell	

Appendix III. Measured Lighting System Energy Savings

Table 15. Measured lighting energy savings (prior to post-processing wattage to ensure that lighting systems met design target of 500 lux at Desk 2)

Window Config.	Baseline Config.	Season	Average Baseline W/ft^2	Average Retrofit W/ft^2	Savings W/ft^2	Savings Wh/ft^2/ day	Savings as % of baseline
Full Window	Existing Bldg.	Summer	1.02	0.20	0.81	11.3	79.9%
		Fall	1.02	0.23	0.79	11.1	77.2%
		Winter	1.03	0.37	0.66	9.2	63.8%
Mid Window	Existing Bldg.	Summer	1.02	0.20	0.81	11.3	80.0%
		Fall	1.02	0.24	0.78	10.9	76.5%
		Winter	1.04	0.36	0.67	9.4	64.9%
Full Window	Title 24 Bldg.	Summer	0.55	0.20	0.34	4.8	62.7%
		Fall	0.54	0.23	0.31	4.3	57.6%
		Winter	0.57	0.30	0.27	3.8	47.8%
Mid Window	Title 24 Bldg.	Summer	0.58	0.21	0.37	5.2	64.5%
		Fall	0.53	0.23	0.31	4.3	57.2%
		Winter	0.65	0.36	0.29	4.1	44.1%

Appendix IV. Mean Radiant Temperature vs. Irradiance

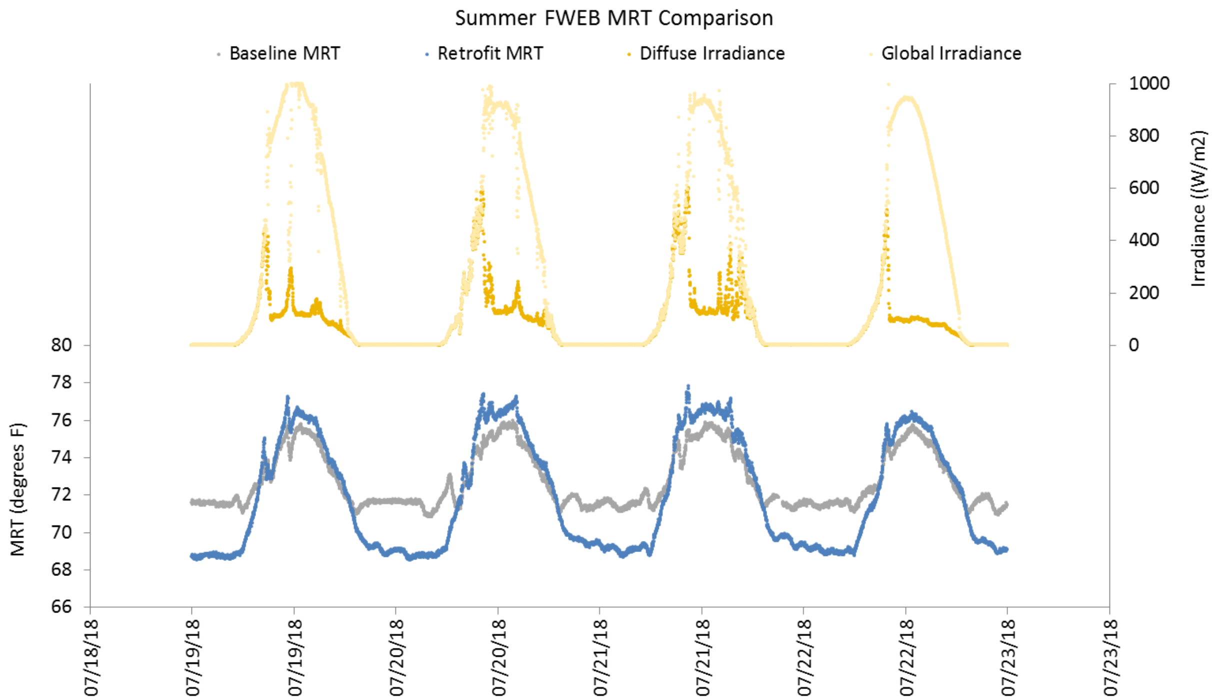


Figure 43. Summer full window existing building baseline mean radiant temperature and solar irradiance

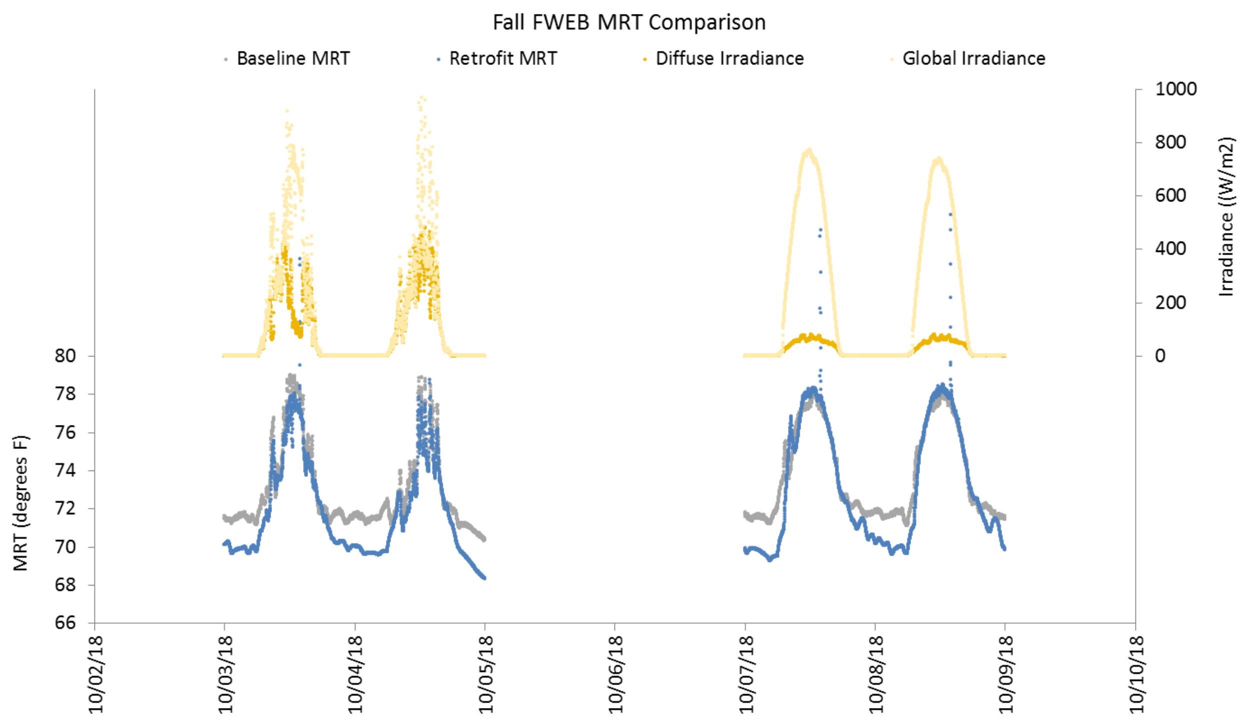


Figure 44. Fall full window existing building baseline mean radiant temperature and solar irradiance

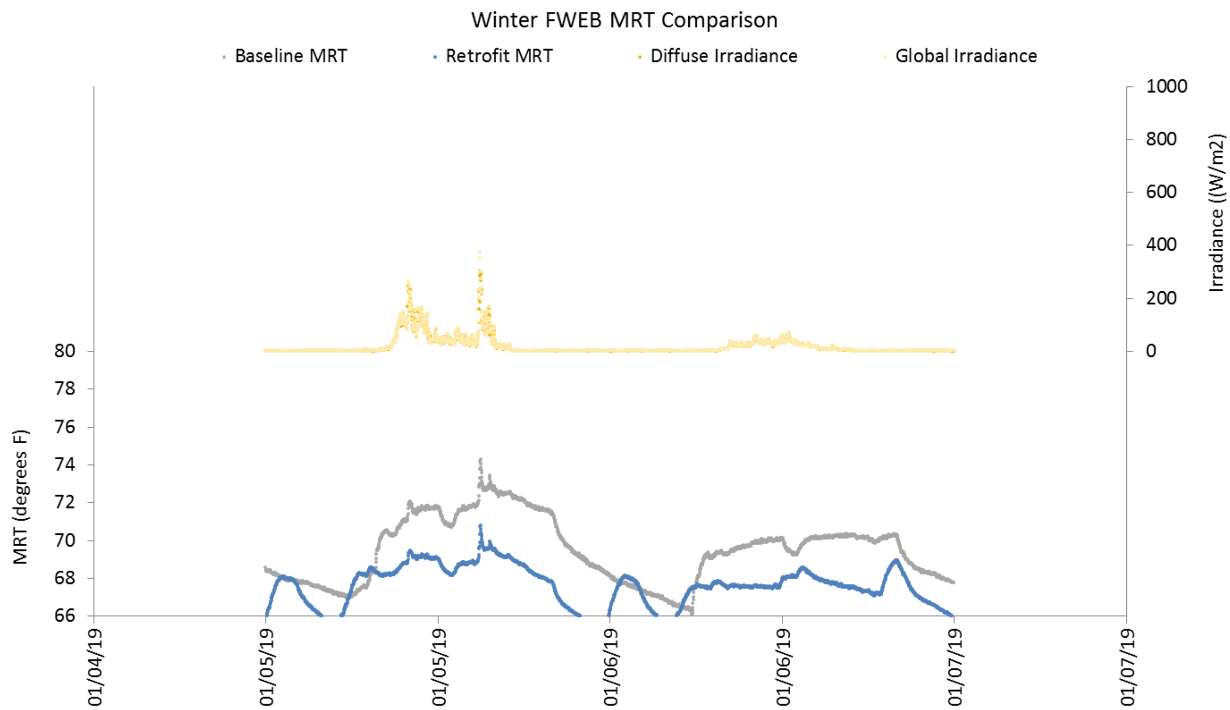


Figure 45. Winter full window existing building baseline mean radiant temperature and solar irradiance

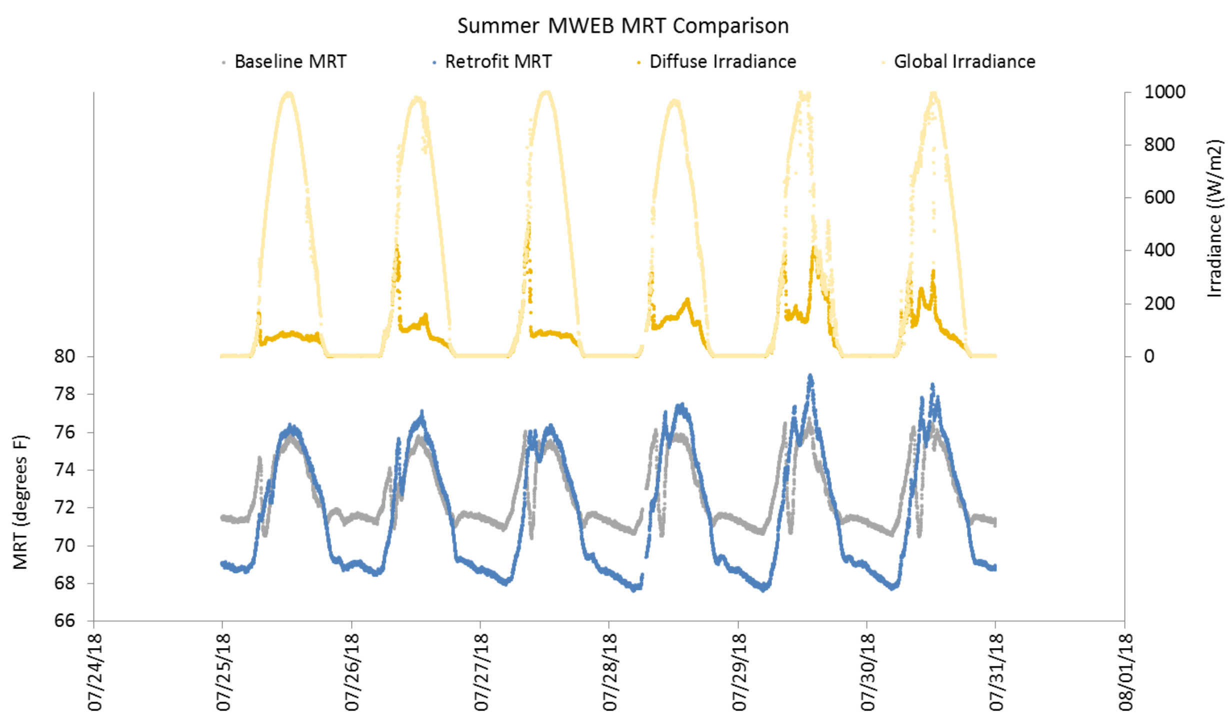


Figure 46. Summer mid window existing building baseline mean radiant temperature and solar irradiance

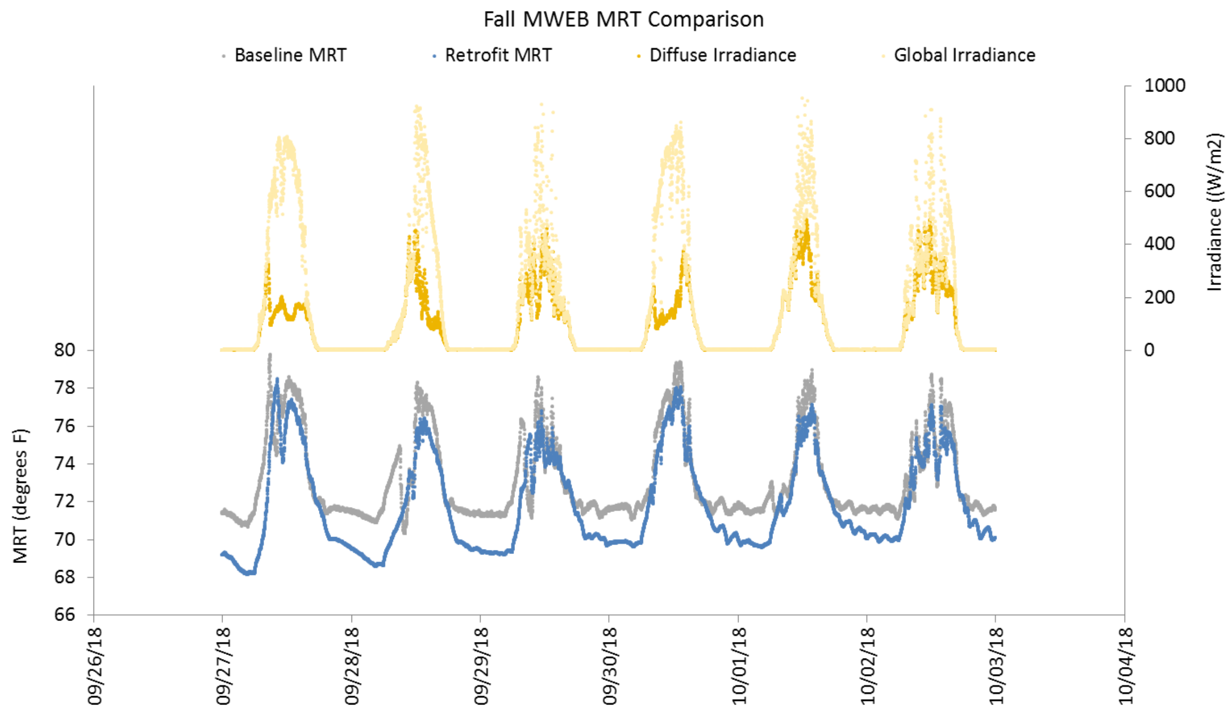


Figure 47. Fall mid window existing building baseline mean radiant temperature and solar irradiance

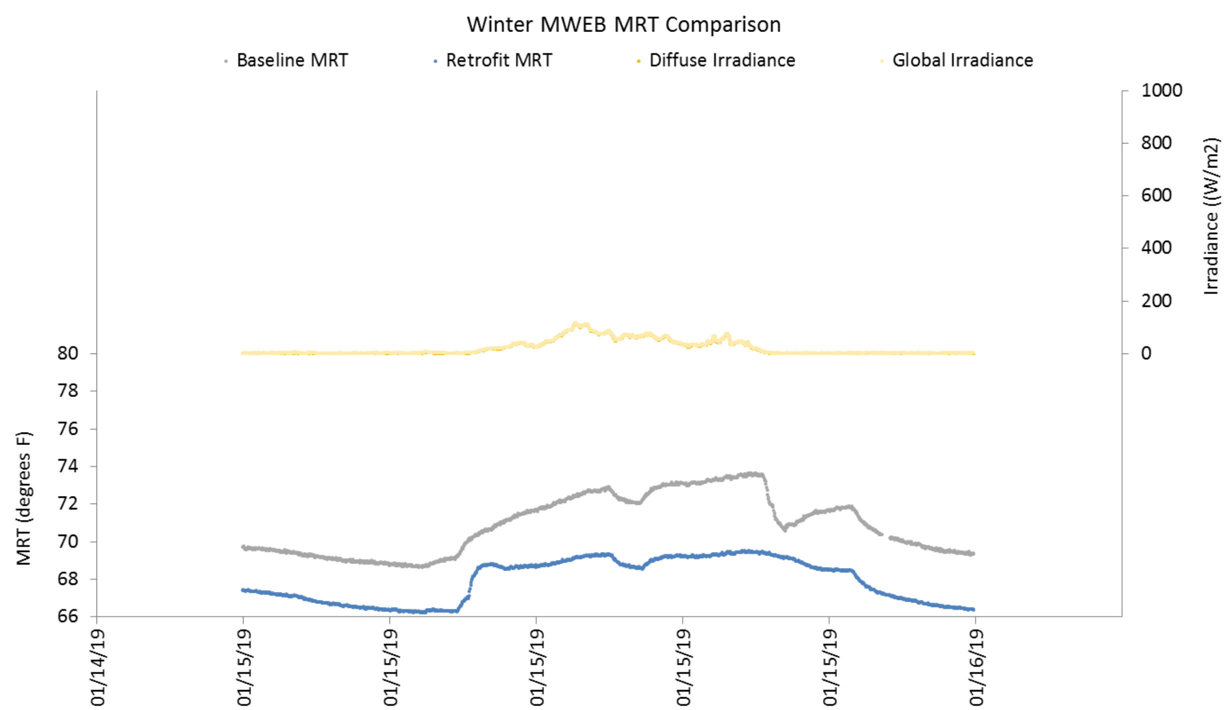


Figure 48. Winter mid window existing building baseline mean radiant temperature and solar irradiance

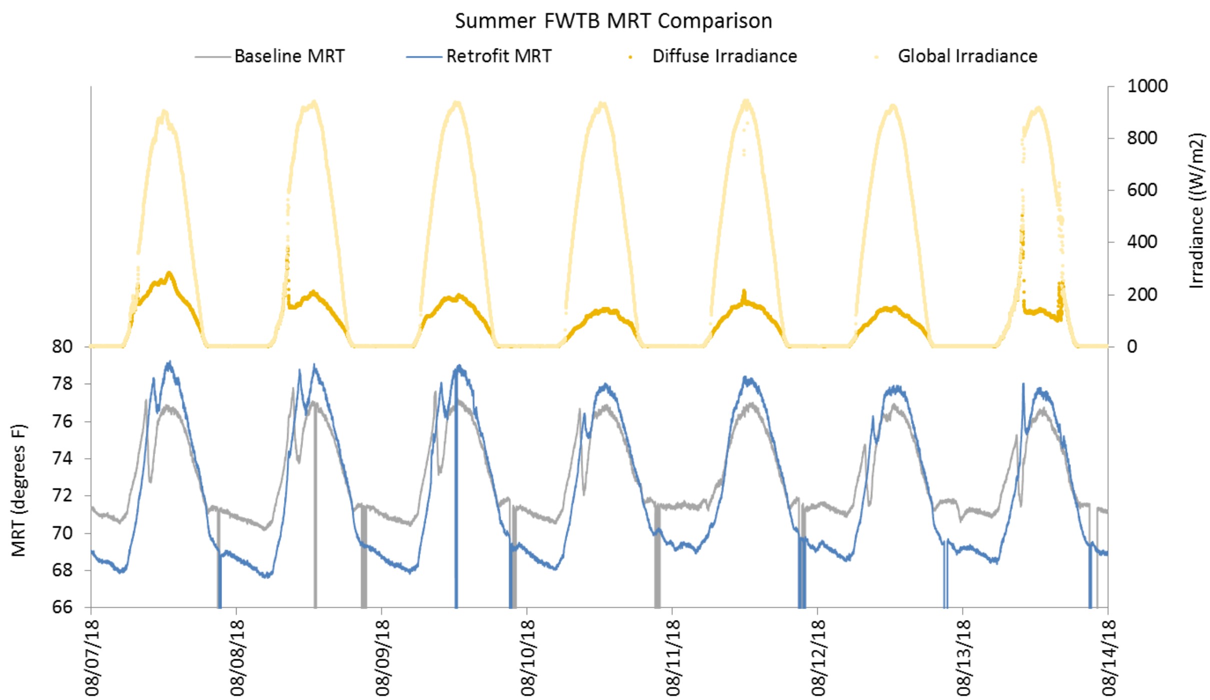


Figure 49. Summer full window code-compliant building baseline mean radiant temperature and solar irradiance

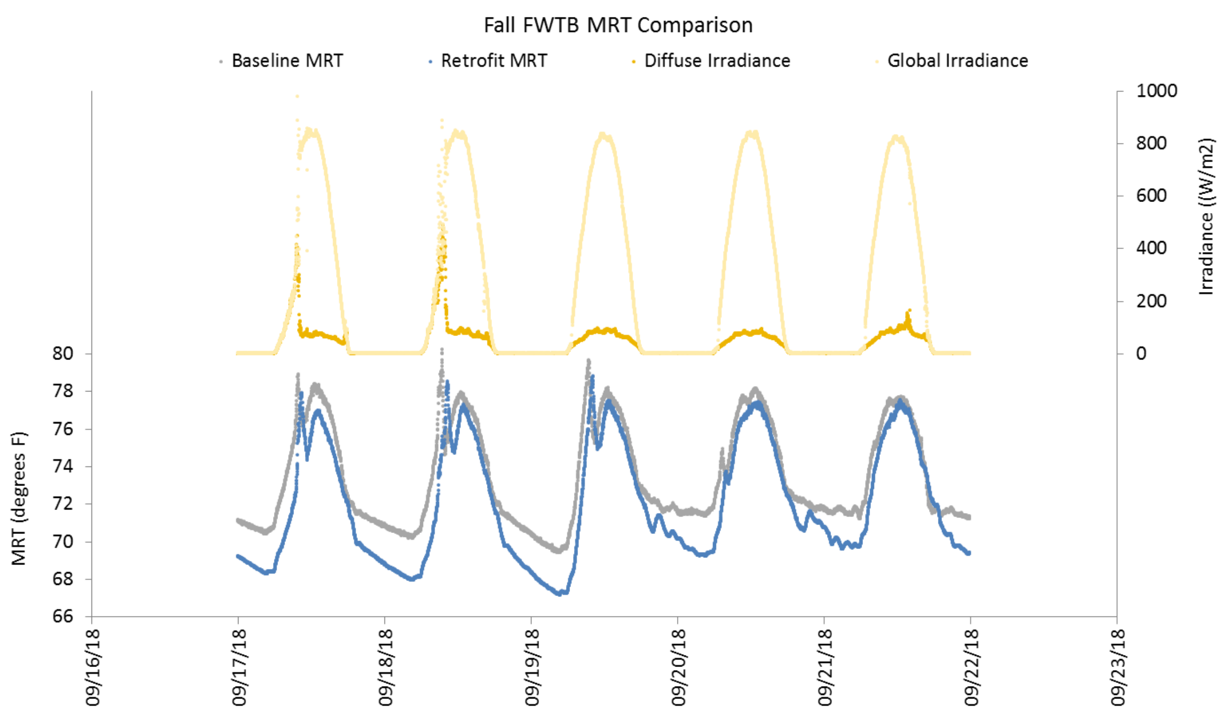


Figure 50. Fall full window code-compliant building baseline mean radiant temperature and solar irradiance

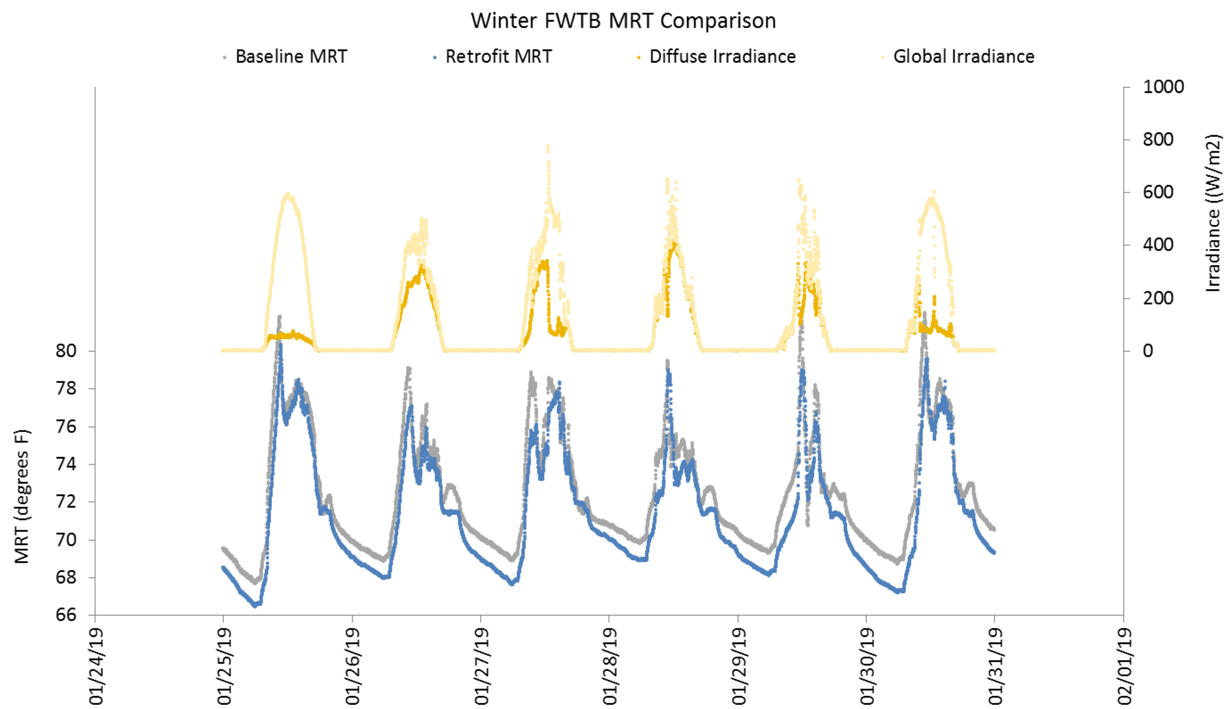


Figure 51. Winter full window code-compliant building baseline mean radiant temperature and solar irradiance

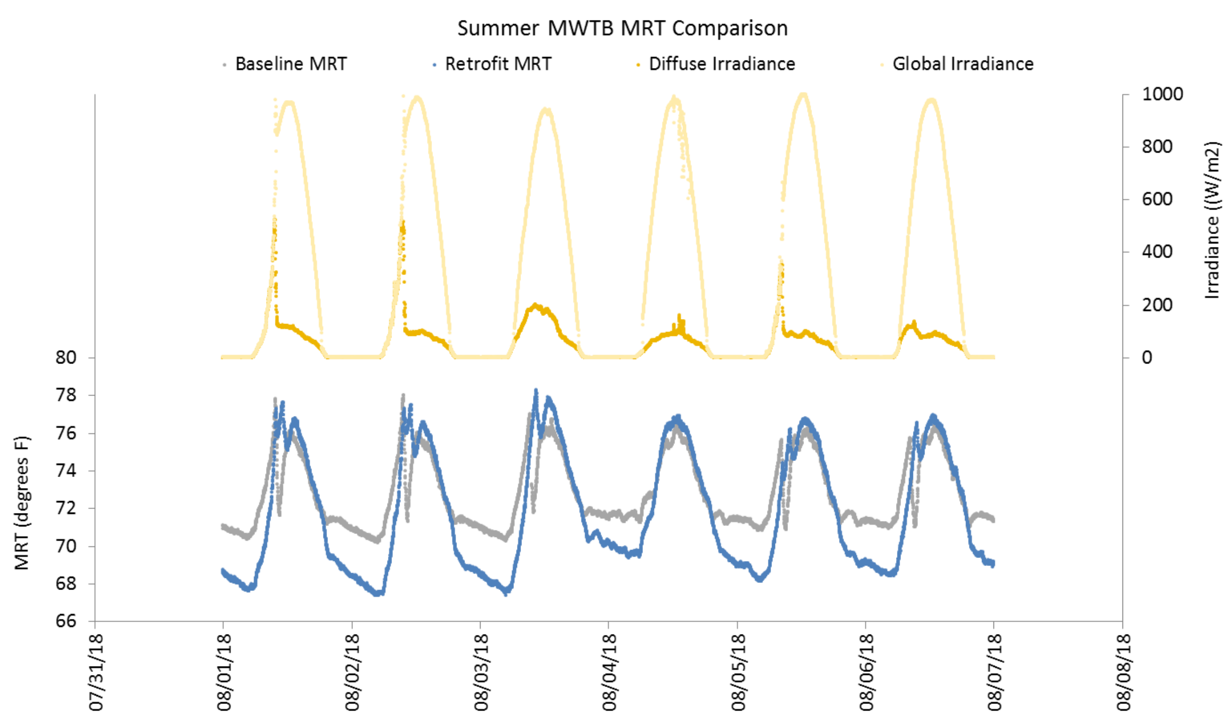


Figure 52. Summer mid window code-compliant building baseline mean radiant temperature and solar irradiance

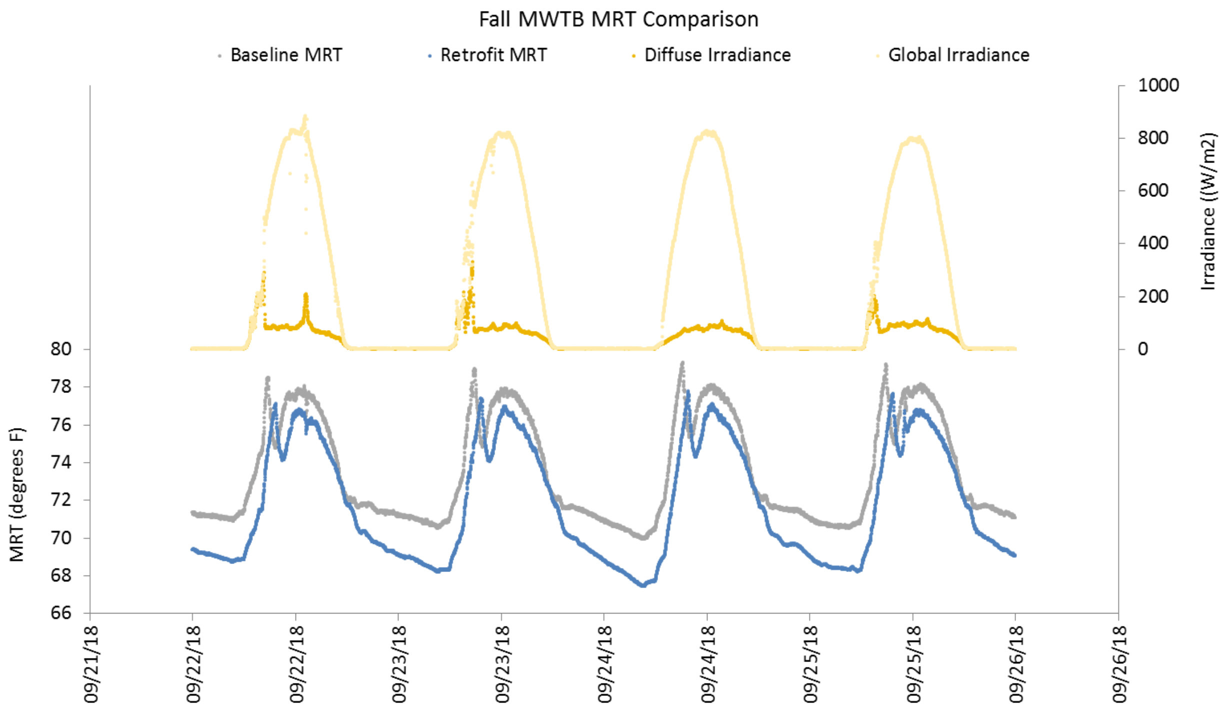


Figure 53. Fall mid window code-compliant building baseline mean radiant temperature and solar irradiance

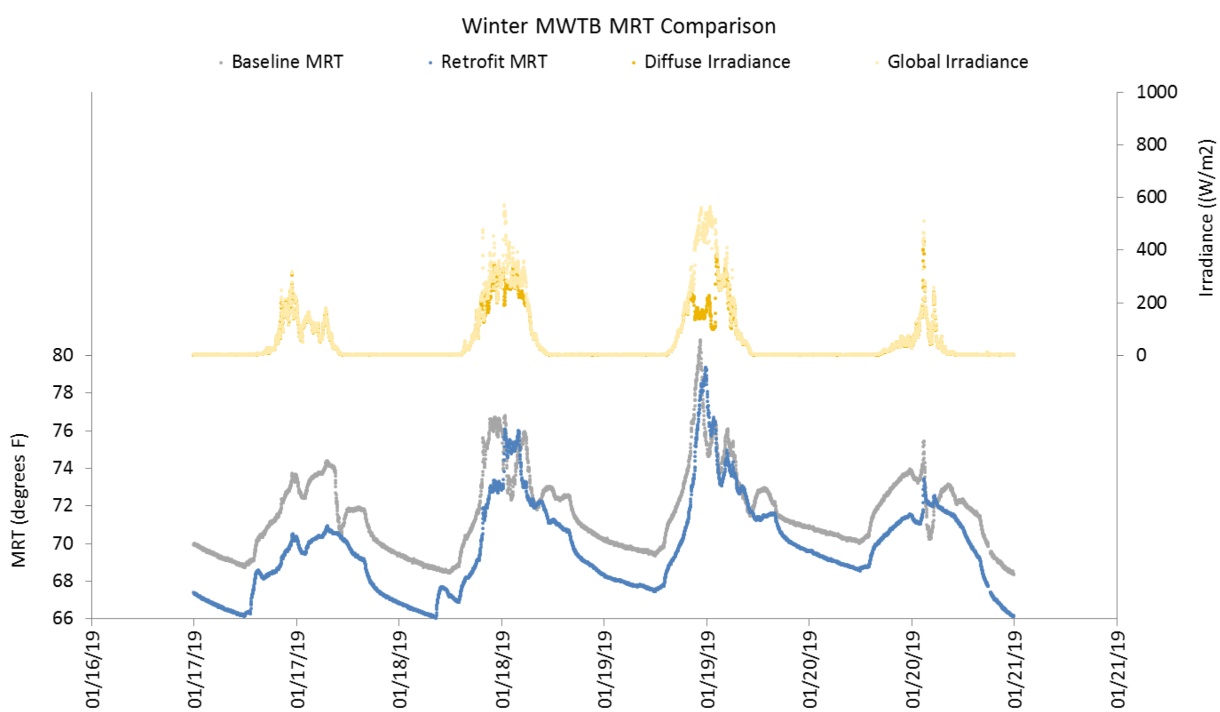


Figure 54. Winter mid window code-compliant building baseline mean radiant temperature and solar irradiance