Title

Zero Net Energy Retrofits for Small Commercial Offices: Zero Net Energy Package and Tubular Daylighting Device FLEXLAB Test Results Report

Authors

Fernandes, Luis

Regnier, Cynthia

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Building Technology & Urban Systems Division
Energy Technologies Area
Lawrence Berkeley National Laboratory

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Luis Fernandes, Cindy Regnier

Energy Technologies Area
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Abstract
This report is a part of the California Energy Commission Electric Program Investment Charge program study "Zero Net Energy Retrofits for Small Commercial Offices". The four-year research study launched in January 2017 and it involves lab testing, field demonstration, performance measurement and verification, and occupant engagement efforts to move an integrated set of emerging commercial retrofit technologies into wider adoption in order for small commercial offices to achieve zero net energy (ZNE) performance. This document provides the results of the FLEXLAB testing of a ZNE retrofit package applicable to both Southern and Northern California climates. The retrofit package consisted of modulating supply diffusers, LED lighting and daylight dimming, reduced plug load power and tubular daylighting devices (TDDs) for providing daylighting into core spaces. This document also provides the daylighting availability and lighting energy reduction potential specifically for the TDDs. Tests were conducted at LBNL's FLEXLAB® facility, a customizable and configurable whole building integrated systems test facility. Results show that packages of ZNE measures resulting in substantial energy savings relative to standard practice. During cooling-dominated periods, total energy savings were 65% for south orientation and 68% for west orientation; during heating-dominated periods total energy savings were 22% for south orientation and 25% for west orientation. The introduction of the ZNE measures did not cause any measurable changes in visual comfort. Thermal comfort measurements results showed variations in thermal comfort between the two configurations, but within an acceptable range. TDD-specific tests showed potential annual lighting energy savings of 27% to 69% (annualized EUI of 0.61 to 1.42 kWh/ft^2, assuming an installed LPD of 0.75 W/ft^2) for 22" TDDs and 22% to 32% (annualized EUI of 1.52 to 1.53 kWh/ft^2, assuming an installed LPD of 0.75 W/ft^2) for 14" TDDs, with no negative impacts on visual comfort.

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1 Introduction

This report is a part of the California Energy Commission Electric Program Investment Charge program study “Zero Net Energy Retrofits for Small Commercial Offices”. The four-year research study launched in January 2017 and it involves lab testing, field demonstration, performance measurement and verification, and occupant engagement efforts to move an integrated set of emerging commercial retrofit technologies into wider adoption in order for small commercial offices to achieve zero net energy (ZNE) performance. Integral Group (2018) documents the set of technologies, referred to in this report as ZNE retrofit packages.

This document provides the results of the FLEXLAB testing of one ZNE retrofit package applicable to both Southern and Northern California climates. The retrofit package consisted of modulating supply diffusers (Accutherm Therma-Fuser) with variable air volume (VAV) control and ventilation only air, LED lighting and daylight dimming, reduced plug load power and tubular daylighting devices (TDDs) for providing daylighting into core spaces. This document also provides the daylighting availability and lighting energy reduction potential specifically for the TDDs. The report describes the test objectives and features, test cases, schedule, and measurements of the energy savings, and visual and thermal comfort performance of the ZNE package. The performance of the TDDs is examined as part of the ZNE package and as a standalone system.

2 Test methodology

This section introduces the facility, test configurations, calendar, and instrumentation used in the experiment.

2.1 Facility

Tests were conducted at LBNL’s FLEXLAB® facility[1] located in Berkeley, California (Figure 1). FLEXLAB is a completely customizable and configurable whole building integrated systems test facility that was designed to study, develop and validate systems level solutions, tools and processes for the commercial building market. Launched in 2014, FLEXLAB has four testbeds each consisting of two identical test cells calibrated to a high level of accuracy between test cells, enabling detailed evaluations under controlled conditions. FLEXLAB provides energy monitoring at the device level, as well as high-accuracy instrumentation and sensors to capture numerous other performance conditions. FLEXLAB provides reconfiguration capabilities to enable streamlined study of multiple permutations of zone-level technologies, and space configurations, such as perimeter and core conditions. FLEXLAB’s detailed testbed calibration included stringent thermal performance criteria and a robust high-accuracy data set that can be used for validation against other

[1] https://flexlab.lbl.gov

measurement systems. FLEXLAB can replicate the thermal loads of almost all U.S. climate zones and provides feedback on energy performance, thermal and visual comfort, and other indoor environmental performance metrics.

Figure 1. FLEXLAB at LBNL.

For the tests detailed in this report, FLEXLAB's rotating testbed was used. It is comprised of two identical cells, approximately 20 x 30 feet each, and the whole building can be rotated in order to vary the orientation of the façade.

2.2 Measurement accuracy and test cell calibration

High accuracy thermal and power measurements were used throughout the test period. A full range of sensor specifications and accuracies is detailed in Appendix A.

A calibration run was conducted with both test cells in the same configuration. Lights, plug loads and occupant thermal generators were turned off in each cell and identical HVAC systems and sequences of operation were put in place. Test cell calibration was conducted from August 11 (00:00) to August 13 (00:00), 2018. Appendix B documents the test conditions under which this calibration run occurred. Table 1 provides the cumulative daily and average hourly thermal load difference between the two cells for each test day. In general, the test cells performed nearly identically. The magnitude of the thermal load differences is within the error band of the accuracy of the thermal load sensing devices for the loads measured (see Appendix A).

Table 1. Calibration results: daily and average hourly thermal load differences

Test day	Difference between FLEXLAB test cells	
	Cumulative daily thermal load difference between cells (kWh)	Hourly average thermal load difference (W)

Aug 11, 2018	0.077	3.20
Aug 12, 2018	0.483	20.12

2.3 Test configurations

Two main different configurations were tested:

1. **ZNE package:** evaluation of the overall performance of a package of energy-efficiency measures, including HVAC, lighting, TDDs, and plug loads.
2. **TDD:** evaluation of the daylight delivery and glare performance of TDDs, as well as of the reduction in potential lighting energy use.

Additionally, variations on each main configuration were tested, resulting in 12 tested configurations in total (two variations of the ZNE package configuration and 10 variations of the TDD configuration). Tables 2 details the ZNE package configuration, which was tested for south and west façade orientations. Table TDD shows the 10 variations of the TDD configuration. In the TDD configuration, the test cell's windows were blocked to simulate an interior space, and interior partitions were set up to create a 16 x 14 ft enclosure. The FLEXLAB cell used for the TDD-only tests was the same used as reference cell for the ZNE package tests.

Table 2. ZNE package test configuration.

	Cell	
	Reference	**ZNE package**
HVAC	Packaged variable air volume with hydronic coils, gas furnace, static supply diffusers	Variable refrigerant flow, dedicated outdoor air system, wide deadband, setbacks/shutoff when space unoccupied, modulating supply diffusers
Façade	25% window to wall ratio; single-pane window, thermally broken (single break) aluminum frame; metal stud wall, R-19 batt cavity insulation	
Lighting	1.19 W/ft2, T8 fluorescent, no automated controls	0.4 W/ft2, LED, occupancy sensing, daylight harvesting, tubular daylight device
Plug Loads	0.77 W/ft2 connected load, 90% diversity, 0.70 W/ft2 max. operating load	0.539 W/ft2 connected load, 90% diversity, 0.485 W/ft2 max. operating load

Table TDD. TDD configuration variations.

Configuration	Diameter (in)	Manufacturer	Dome	Diffuser
TDD-SPP	22	Solatube	Prismatic	Prismatic

TDD-SPF	22	Solatube	Prismatic	Fresnel
TDD-SCP	22	Solatube	Clear	Prismatic
TDD-SCF	22	Solatube	Clear	Fresnel
TDD-VPP	22	Velux	Prismatic	Prismatic
TDD-VPF	22	Velux	Prismatic	Fresnel
TDD-VCP	22	Velux	Clear	Prismatic
TDD-VCF	22	Velux	Clear	Fresnel
TDD-14A	14	Solatube	Prismatic	Fresnel
TDD-14B	14	Solatuve	Prismatic	Frosted

2.4 Test calendar

Each test configuration was tested up to four times. Tests were conducted between January 2018 and January 2019, in order to cover a representative range of weather conditions and solar angles. Table 3 shows the test dates for each configuration. In the first batch of tests, all TDD-only configurations were tested, in order to understand whether there were substantial differences in performance between them. The number of configurations was progressively reduced in subsequent tests. The duration of the TDD-only tests was variable, in order to obtain sufficient data under clear sky.

Table 3. Dates each configuration was tested.

Configuration	**Test 1**	**Test 2**	**Test 3**	**Test 4**
ZNE package, south-facing	May 3 - May 10	Jun 13 - Jun 19	Aug 18 - Aug 24	Dec 5 - Dec 11
ZNE package, west-facing	May 11 - May 17	Jun 20 - Jun 26	Aug 25 - Aug 31	Dec 13 - Dec 20
TDD-SPP	Feb 9 - Feb 14	May 19 - May 21		
TDD-SPF	Feb 15 - Feb 16	May 22 - May 23	May 31 - Jun 3	Jan 4 - Jan 9
TDD-SCP	Feb 17 - Feb 20			
TDD-SCF	Feb 21 - Feb 22	May 25 - May 29		
TDD-VPP	Feb 24 - Feb 26			
TDD-VPF	Feb 27 - Feb 28			
TDD-VCP	Mar 7 - Mar 9			
TDD-VCF	Mar 10 - Mar 11	May 9 - May 10		
TDD-14A	May 5	Sep 11 - Sep 12	Jan 11 - Jan 23	
TDD-14B	May 7	Sep 14 - Sep 15	Jan 25 - Jan 30	

2.5 Experimental layout

Figures 3 and 4 show the experimental layout for the ZNE package tests. Figure 5 shows the experimental layout for the TDD tests.

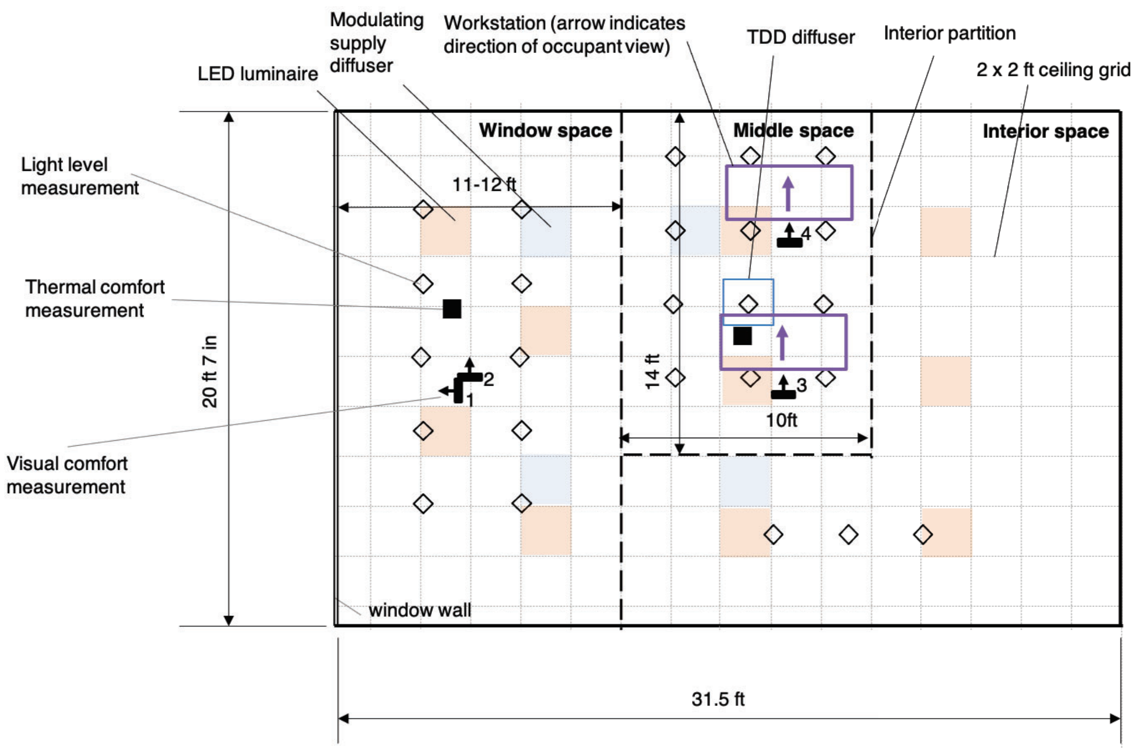

Figure 3. Layout for ZNE package tests in the test cell.

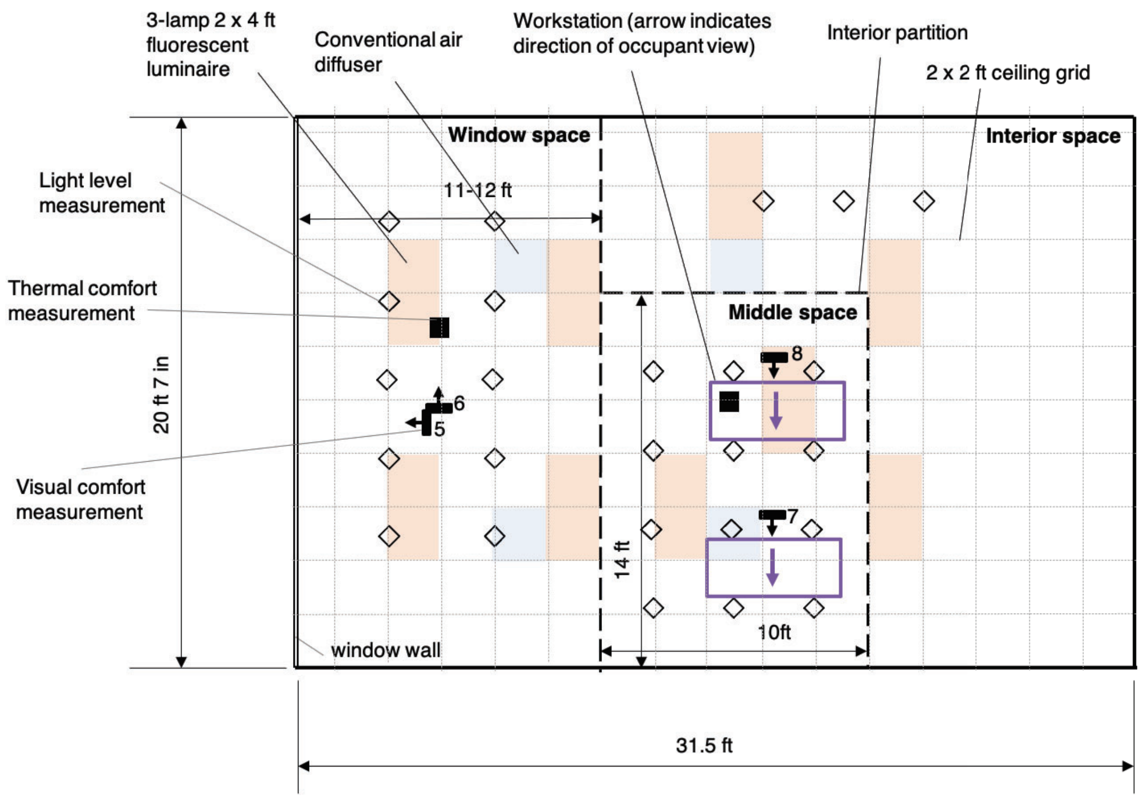

Figure 4. Layout for ZNE package tests in the baseline cell.

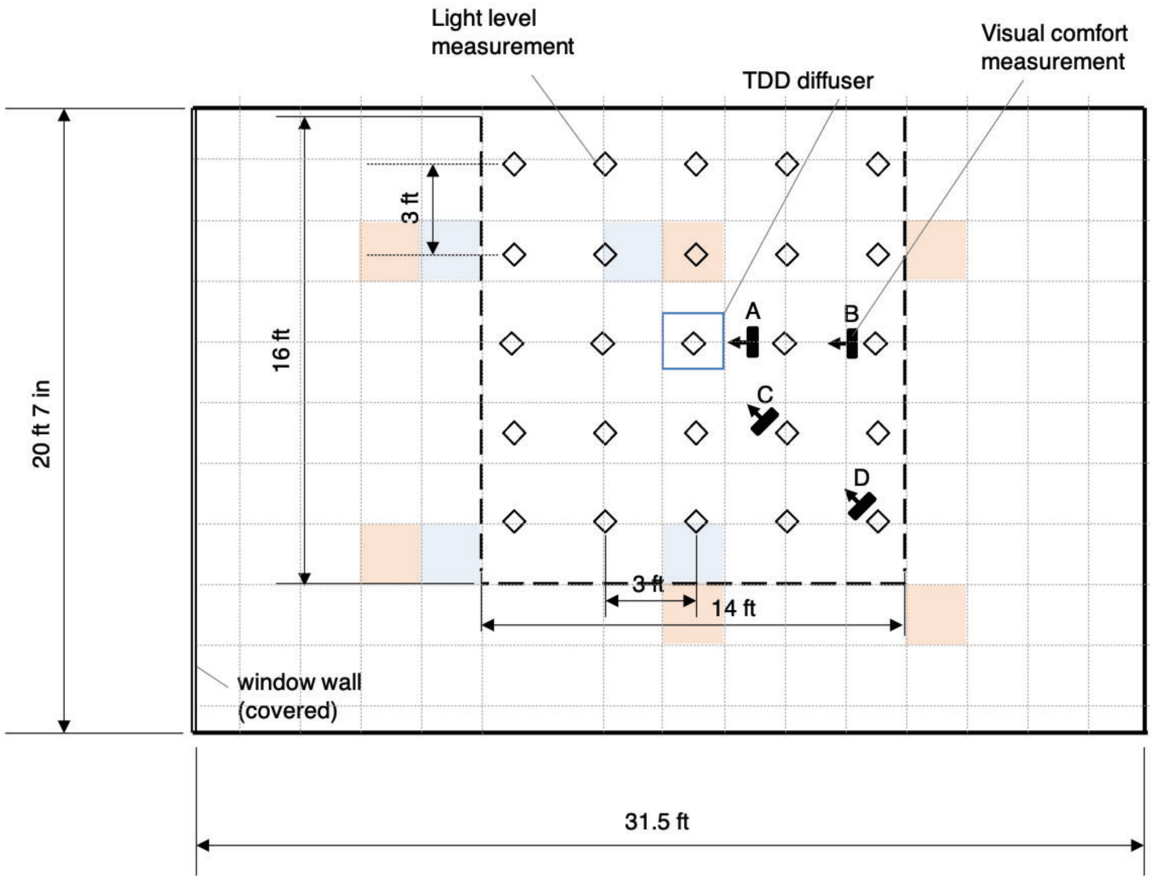

Figure 5. Layout for TDD tests.

2.6 Measurements

Multiple types of measurement were performed during this experiment, both inside and outside the test cells. They are described in more detail in this subsection.

2.6.1 Sky cover

In order to evaluate sky cover, exterior global and diffuse horizontal irradiance were measured using a Hukseflux SR12 weather station, for the purposes of evaluating sky cover. These instruments were mounted on another test facility situated approximately one thousand feet from the test cells. Cursory tests indicated an inconsequential difference between these data and data gathered at the FLEXLAB location.

2.6.2 Workplane illuminance

Inside each cell, horizontal illuminance was measured using Licor LI-210 photometers, which were mounted 30 inches above the floor and leveled. Figure 6 shows one of these photometers mounted on a stand inside one of the test cells. Horizontal illuminance data was used for assessing light levels within the space.

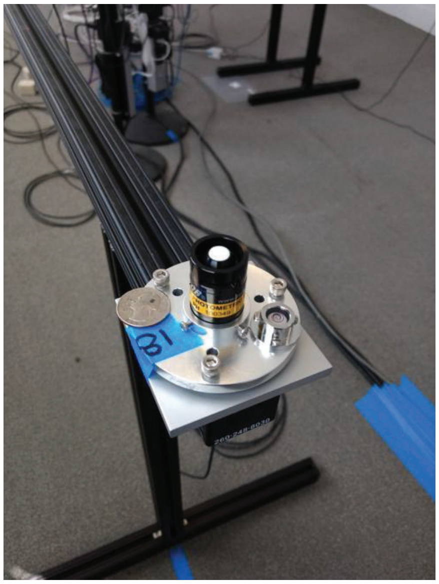

Figure 6. Photometer on stand inside test cell.

2.6.3 Visual comfort

Visual comfort was measured using high-dynamic-range (HDR) luminance mapping techniques and the daylight glare probability (DGP) metric [Wienold, 2006]. Every 5 minutes, HDR images were captured using digital single-lens reflex cameras fitted with fisheye lenses, auxiliary sensors and computing equipment (Figure 7). Each HDR image was processed in order to obtain a luminance map of the image, i.e., calculate the luminance of each pixel. A luminance map taken in FLEXLAB is shown in Figure 8. Each luminance map is then converted into a DGP value.

Figure 7. High-dynamic-range luminance mapping apparatus.

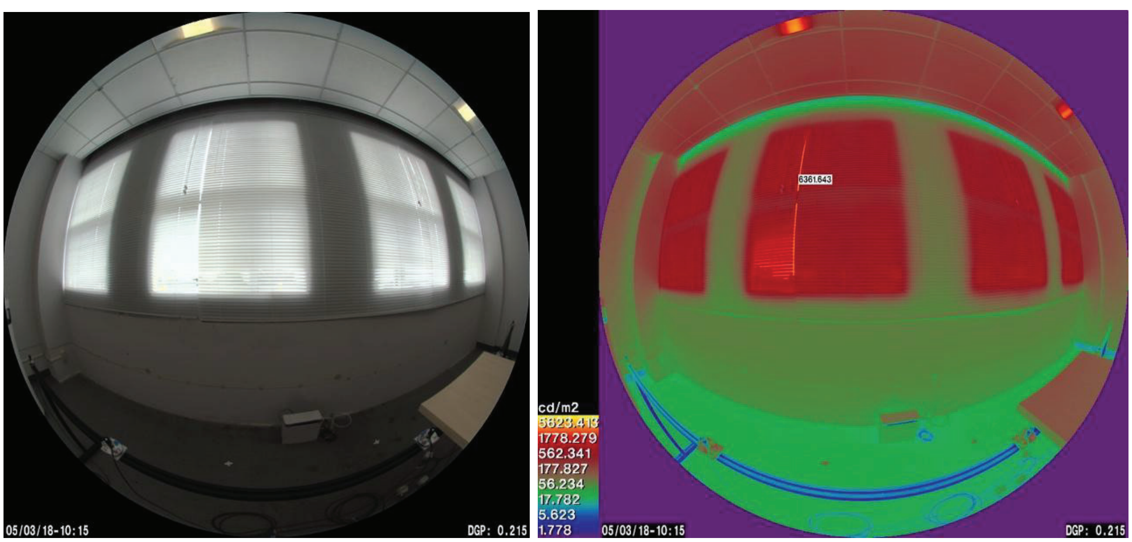

Figure 8. HDR image (*left*) and corresponding luminance map (*right*) of scene in FLEXLAB.

The DGP metric represents the probability, between 0 and 1, that occupants in the space will experience glare when their eyes are at the position of the camera lens at the time that the HDR image was captured. Subjective ratings corresponding to DGP values are as follows: 0.30, 0.35, 0.40 and 0.45 are the thresholds for “just-imperceptible glare,” “just-perceptible glare,” “just-disturbing glare,” and “just-intolerable” glare. In general, it is desirable that DGP remains below 0.35 (“just-perceptible glare”), and that breaches above 0.35 are of short duration and do not exceed 0.40 (“just-disturbing glare”).

2.6.4 Thermal comfort

Thermal comfort was evaluated using the predicted mean vote/predicted percentage of dissatisfied (PMV/PPD) metric [ANSI/ASHRAE, 2013]. PMV is a value between -3 and 3 that indicates how occupants are likely to perceive the space: values of -3, -2, -1, 0, 1, 2, 3 correspond to perceptions of the space as “cold,” “cool,” “slightly cool,” “neutral,” “slightly warm,” “warm,” and “hot,” respectively. PPD represents the percentage of people who would not be satisfied with the measured thermal environment. In order to achieve comfortable conditions, it is recommended that PPD be maintained under 20% and PMV between -0.5 and 0.5.

PMV and PPD are calculated from indoor measurements of the dry-bulb air temperature, mean radiant temperature and air velocity. Relative humidity was assumed to be 50%. These quantities were measured using several apparatuses such as the one shown in Figure 9.

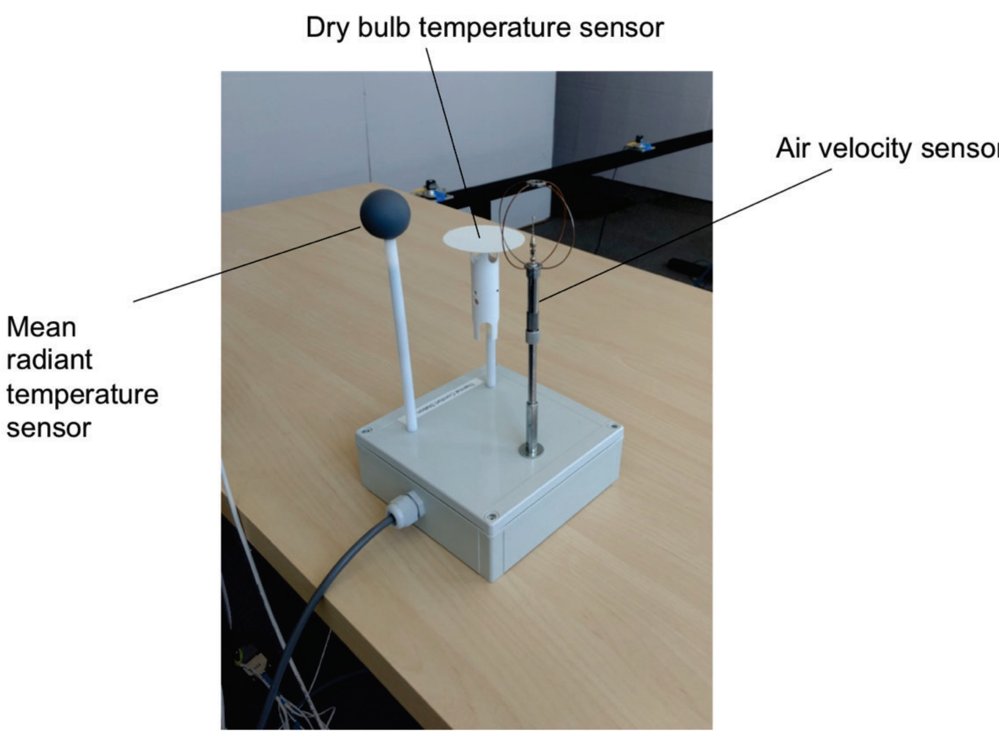

Figure 9. Thermal comfort measuring station.

2.6.5 HVAC energy use

Heating and cooling thermal energy use were measured independently for each test cell by determining the heat transfer in each cell’s hot and chilled water loops based on water loop flow rate and temperature drop. These heating and cooling loads were converted into actual energy use for reference and ZNE configurations using EnergyPlus [DOE, 2021] mathematical models for each of the two configurations that included efficiency curve data for each configuration's packaged HVAC equipment. Electric energy use of fans and pumps was also measured.

2.6.6 Lighting energy use

Lighting energy use was measured by power meters installed at the circuit breakers that monitored individual luminaire circuits. For each cell, total lighting energy consumption was computed by summing the energy consumption of each luminaire.

2.7 Systems

This subsection describes the physical characteristics of the energy-consuming systems used in this experiment.

2.7.1 HVAC

The HVAC system evaluated in testing consisted of a rooftop, 100% outside air high efficiency heat pump, with energy recovery on the relief air. The air handling unit (AHU), which had a variable frequency drive (VFD) fan, supplies to modulating supply diffusers (MSDs) located throughout the conditioned zone. The controls strategy specified space conditioning through the use of the outside air only unit, while allowing for a larger deadband for heating and cooling setpoints. The base case for comparison was a standard minimally compliant Title 24 gas furnace (80% efficiency).

2.7.1.1 Modulating supply diffusers

MSDs are ceiling supply diffusers that are mounted in a ceiling grid that enable aariable air volume (VAV) control right at the diffuser. In general, MSDs have an internal damper that is modulated closed or open depending on the mode of operation of the air handling system (heating or cooling), and the thermostatic setpoints set manually at the diffuser. Several MSD models are available; the ones used in this experiment have thermally actuated dampers, where a wax product expands or contracts to modulate the damper open or closed depending on the desired setpoints. Other models provide electric actuation, with wall mounted thermostats, and BACnet controls communication to the central AHU. The advantage of these diffusers is that they may provide more granular temperature controls for workspaces over traditional whole-zone control strategies. In addition, by design MSDs require a lower pressure drop duct design, which improves fan energy performance throughout all modes of operation.

In the ZNE package test cell, the enclosed office spaces one 2'x2' Thermafuser model TF-HC MSD, and the perimeter space had two MSDs of the same model and size. Each MSD tested was thermally actuated, with no connection to the centralized HVAC controls. The wax cylinder thermostats on each MSD were set to 20.0°C and 25.6°C setpoints for heating and cooling mode, respectively. Figure 3 shows the locations of the MSDs in the test cell. The ductwork was generally sized for a pressure drop of 0.08” w.g./100LF of straight duct.

The base case condition consisted of regular (non-modulating) ceiling supply diffusers, with ductwork generally sized for a pressure drop of 0.10” w.g. /100LF of straight ductwork. Figure 4 shows the locations of the supply diffusers in the reference test cell.

2.7.1.2 Air handling units

In the case of both the ZNE package and reference cells, the AHUs were programmed for an occupied schedule of 7 AM to midnight during workdays (Monday to Friday), 7 AM to 7 PM on Saturdays, and 7 AM to 6 PM on Sundays.

The reference cell AHU was selected to emulate a gas packaged direct expansion AHU, with no economizer, no demand based ventilation and no energy recovery on the relief air. Minimum airflow was set to 30% of maximum airflow. The AHU was scheduled for a 23.9°C cooling setpoint, and a 21.1°C heating setpoint. The cooling and heating supply air temperature setpoints were 12.8°C and 35.0°C, respectively.

The ZNE package cell AHU was set for 100% outside air operation only, with no recirculation. Supply fan speed is controlled to maintain duct static pressure at setpoint when the fan was proven on. The MSDs were set for individual zone setpoints as noted above, and per the following setpoints:

1) Zone Cooling temperature setpoint shall be 25.6°C (all hours, year-round).
2) Zone Heating temperature setpoint shall be 21.1°C (all hours, year-round).

The ZNE package cell AHU supply air temperature control loops were enabled when the supply fan was proven on, and disabled with output set to zero (i.e., no heating, no cooling, and no heat recovery) otherwise. The supply air temperature setpoints were as follows:

- Minimum cooling supply air temperature: 12.8°C
- Maximum cooling supply air temperature: 20.0°C
- Minimum heating supply air temperature: 24.4°C
- Maximum heating supply air temperature: 35°C

Both the reference and ZNE package cell AHUs were monitored for supply air flow, supply and return air temperatures, and each AHU was served by individual hot and chilled water coils where water flow, supply temperature, and return temperature were metered. In this way, thermal energy provided to each test cell in heating and cooling modes was monitored.

2.7.2 Electric lighting

In the ZNE package cell, electric lighting was provided by ten 2’x2’ Philips SpaceWise LED luminaires, each rated at 26 W (Figure 10, left). Each of these luminaires has a passive infrared occupancy sensor as well as a photosensor, and they can autonomously dim or turn off based on available daylight and/or detected occupancy. Moreover, luminaires can be grouped so their response to occupancy and/or available daylight is the same within the group. For this experiment, luminaires were set to dim individually according to available daylight, but to respond as a group when occupancy was detected. A device was constructed — using a heat source, a table fan and a timer — that would trigger one of the occupancy sensors in order to approximate a desired occupancy schedule (Table 4).

Nine 2’x4’ three-lamp fluorescent troffers provided electric lighting to the reference cell. These luminaires were fitted with 32 W fluorescent lamps that had been seasoned for at least 100 hours. In order to better match the desired lighting power density of 1.19 W/ft^2, a non-lighting 70 W load was added to the lighting circuits. Reference cell lights were on from 7 AM to midnight on weekdays and 7 AM to 7 PM on weekends.

Lighting power consumption was monitored separately for each of the three intra-cell spaces shown in Figures 3 and 4.

Figure 10. Luminaires used in the tests: LED luminaire (*left*) and fluorescent troffer (*right*).

Table 4. Occupancy schedule.

Hour	Occupancy		
	Weekday	Saturday	Sunday
0	0%	0%	0%
1	0%	0%	0%
2	0%	0%	0%
3	0%	0%	0%
4	0%	0%	0%
5	0%	0%	0%
6	10%	10%	5%
7	20%	10%	5%
8	95%	30%	5%
9	95%	30%	5%
10	95%	30%	5%
11	95%	30%	5%
12	50%	10%	5%
13	95%	10%	5%
14	95%	10%	5%
15	95%	10%	5%
16	95%	10%	5%
17	30%	5%	5%
18	10%	5%	5%
19	10%	0%	0%
20	10%	0%	0%
21	10%	0%	0%
22	5%	0%	0%
23	5%	0%	0%

2.7.3 Tubular daylighting devices

The tubular daylight devices (TDDs) tested were manufactured by two different companies: Solatube and Velux. Each 22” diameter TDD was tested a clear dome and a prismatic dome (Figure 11) as well as two different diffusers at the bottom: a prismatic diffuser and a Fresnel diffuser (Figure 12), both 2’x2’. A smaller, Solatube 14” diameter TDD was also tested with a prismatic dome. Two bottom diffusers were tested on this smaller TDD: a 2’x2’ Fresnel diffuser similar to its 22” equivalent, and a frosted 14” round diffuser (Figure 13).

Figure 11. The two types of dome tested: clear (*left*) and prismatic (*right*).

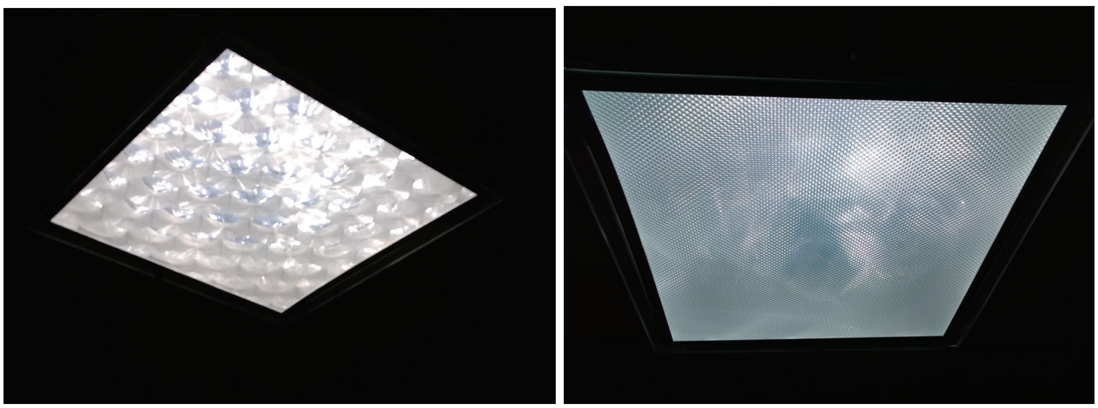

Figure 12. The two types of diffuser tested: prismatic (*left*) and Fresnel (*right*). Note that images are underexposed in order to show diffuser detail and aren't a good indicator of actual brightness.

Figure 13. Frosted 14" round diffuser.

2.7.4 Plug loads

Plug loads were provided by desktop personal computers running custom software that sets power consumption to a desired level according to a schedule. The schedule was set to provide the best approximation to the schedule recommended by ASHRAE 90.1 [ASHRAE, 2007] (Table 5), with a maximum target value of 497 W for the reference cell and 348 W for the ZNE package cell.

Table 5.

Hour	Power level		
	Weekda y	Saturda y	Sunda y
0	5%	5%	5%
1	5%	5%	5%
2	5%	5%	5%
3	5%	5%	5%
4	5%	5%	5%
5	10%	5%	5%
6	10%	10%	5%
7	30%	10%	5%
8	90%	30%	5%
9	90%	30%	5%
10	90%	30%	5%
11	90%	30%	5%
12	80%	15%	5%
13	90%	15%	5%
14	90%	15%	5%
15	90%	15%	5%
16	90%	15%	5%
17	50%	5%	5%
18	30%	5%	5%
19	30%	5%	5%
20	20%	5%	5%
21	20%	5%	5%
22	10%	5%	5%
23	5%	5%	5%

3 Results

Overall, the ZNE package resulted in substantial energy savings relative to the reference configuration, with the exception of HVAC energy use during heating-dominated periods. During cooling-dominated periods, measured HVAC thermal energy savings were 79% for south orientation and 81% for west orientation. Conversely, HVAC thermal energy consumption during heating-dominated periods increased by 25% and 49%, for south and west orientations, respectively. In terms of calculated actual HVAC energy use, for cooling-dominated periods savings relative to the reference configuration were 49% for south orientation and 63% for west orientation. During heating-dominated periods, consumption increased 41% and 77%, for south and west orientations, respectively. For plug loads, the ZNE package obtained 31%

energy savings relative to the reference condition, regardless of orientation. Importantly, there were no measured differences in visual comfort between the ZNE package and the reference configuration. Regarding thermal comfort, the ZNE package was somewhat warmer than the reference condition during cooling-prevalent periods, and cooler for heating-prevalent periods. These differences appear to be within an acceptable, and easily mitigatable, range.

The TDD-only tests showed overall potential lighting energy savings of 23% to 69%, depending on the diameter of the TDD and sky cover. Moreover, no negative visual comfort impacts were measured during TDD testing. For a given TDD tube diameter, there were no substantial differences in daylight delivery and visual comfort between TDD dome and diffuser types.

3.1 ZNE package tests

3.1.1 HVAC

3.1.1.1 Measured thermal energy use

During the May, June and August 2018 test periods, outside air temperature was generally within a band between 10˚C and 25˚C (see Figure 14 through Figure 16). However, there were three days in the June 2018 period during which maximum temperatures were in the 28-34˚C range (Figures 14 and 15) and one day in the August 2018 test period with a maximum temperature of 27˚C (Figure 16. In December 2018, outside air temperature ranged from 5 ˚C to 25 ˚C (Figure 17).

The reference cell was in cooling mode most of the days during the May, June and August 2018 test periods, whereas the ZNE package cell showed moderate levels of both heating and cooling these periods (Figure 16 to Figure 20). For these periods, overall HVAC thermal energy use was substantially lower in the ZNE package cell than in the reference cell. For the south orientation, the total HVAC thermal energy use was 290 and 62 kWh for the reference and ZNE package cells, respectively, representing a savings of 79% relative to the reference cell. For the west orientation, the corresponding values were 353 and 66 kWh, representing a 81% savings relative to the reference cell.

The December test showed vastly different energy use patterns, with the reference cell operating in both heating and cooling mode and the ZNE package cell operating in heating mode only (Figure 21). During this period, total HVAC energy use for the south-facing orientation was 84 kWh in the reference cell and 106 kWh in the ZNE package cell, representing a 25% increase in energy consumption relative to the reference test cell. The corresponding energy use values for west orientation are 56 kWh and 84 kWh for the reference and ZNE package cells, respectively, resulting in a 49% increase in energy consumption relative to the reference test cell.

Results from each test period are presented in Table 6 for total thermal energy use and Table 7 for average daily thermal energy use.

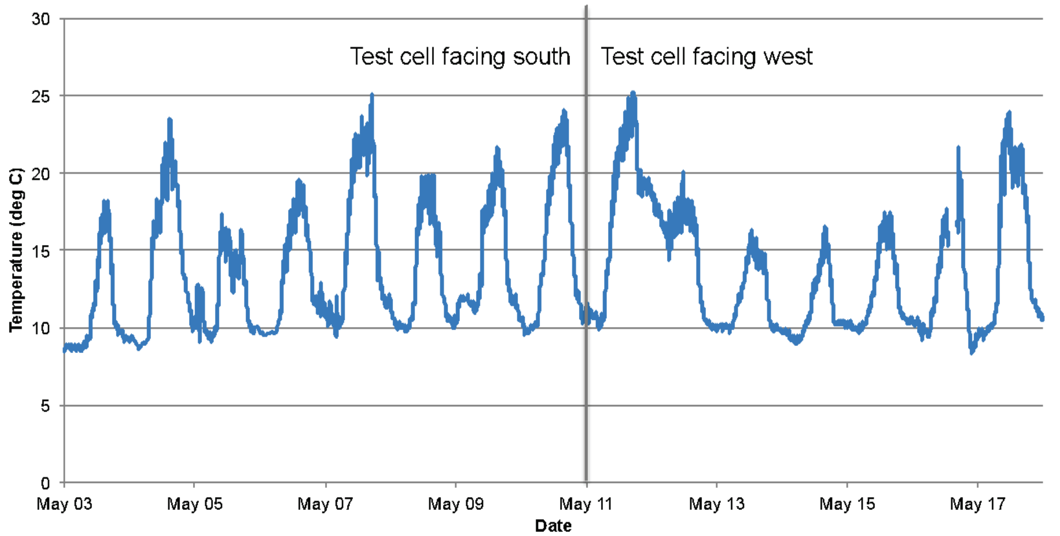

Figure 14. Outside air temperature during May 2018 test period.

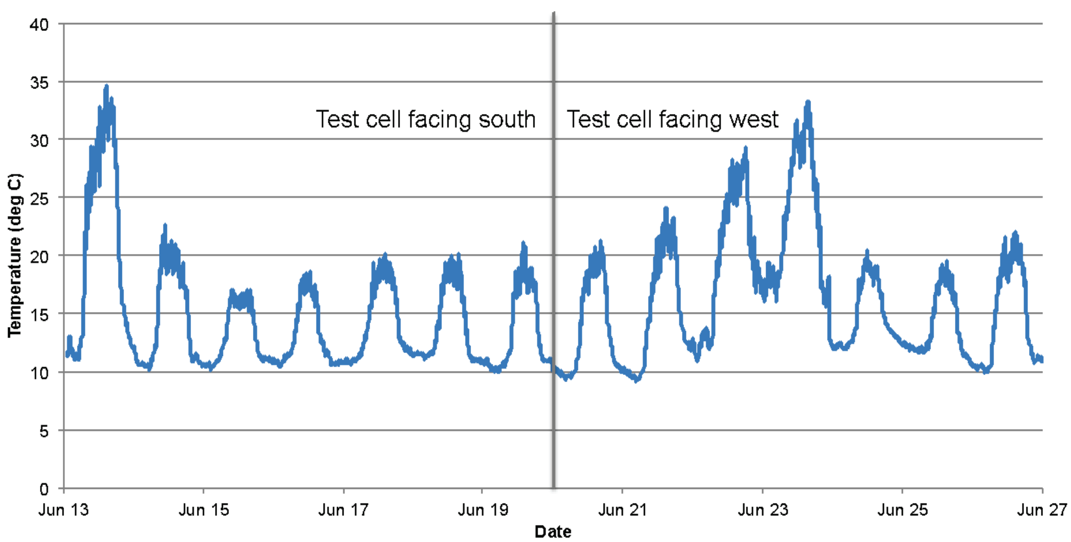

Figure 15. Outside air temperature during June 2018 test period.

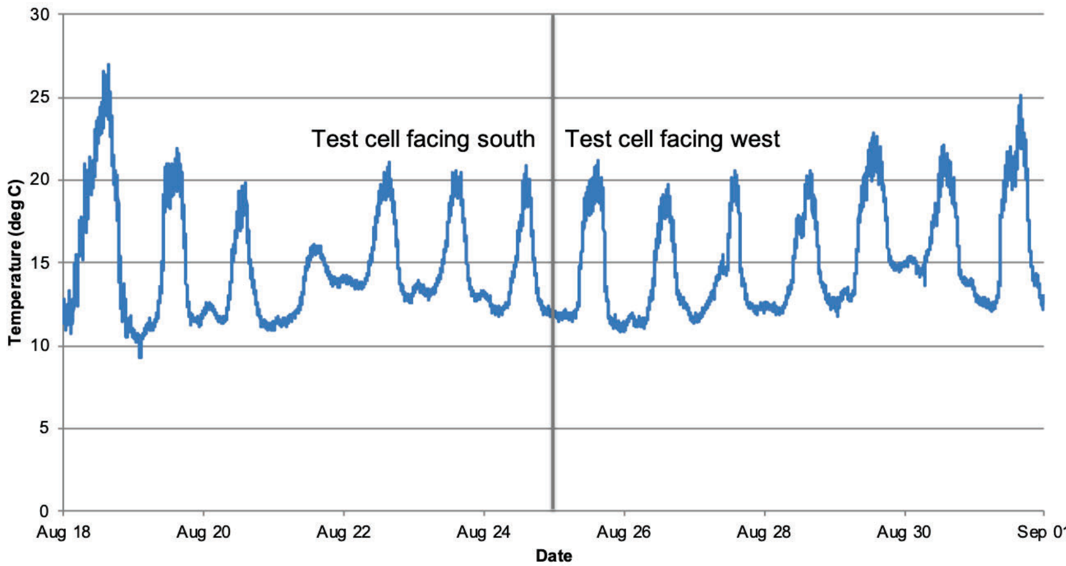

Figure 16. Outside air temperature during August 2018 test period.

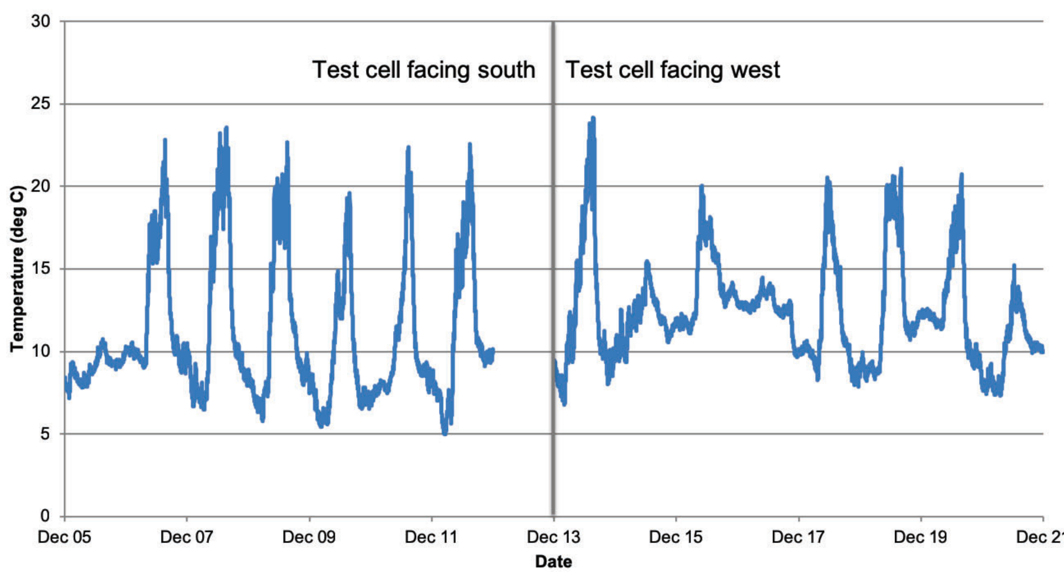

Figure 17. Outside air temperature during December 2018 test period.

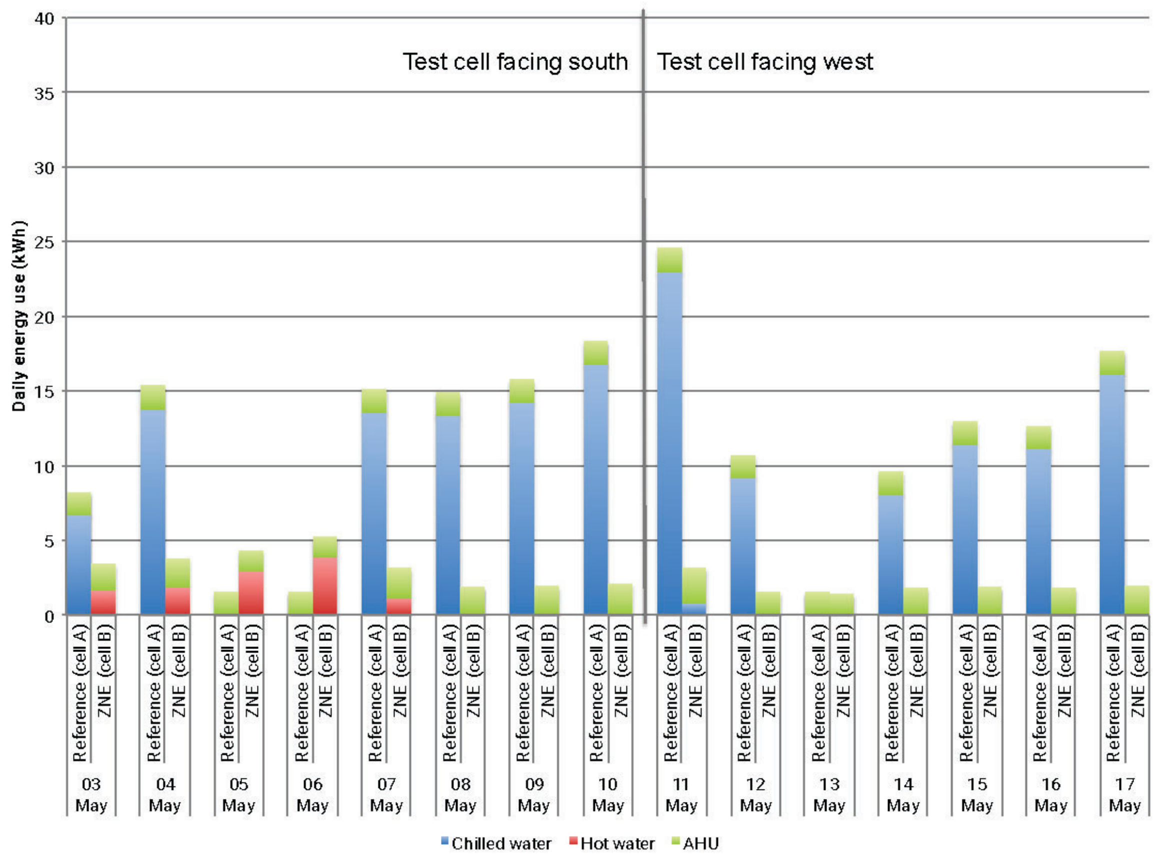

Figure 18. Daily HVAC thermal energy consumption during May 2018 test period.

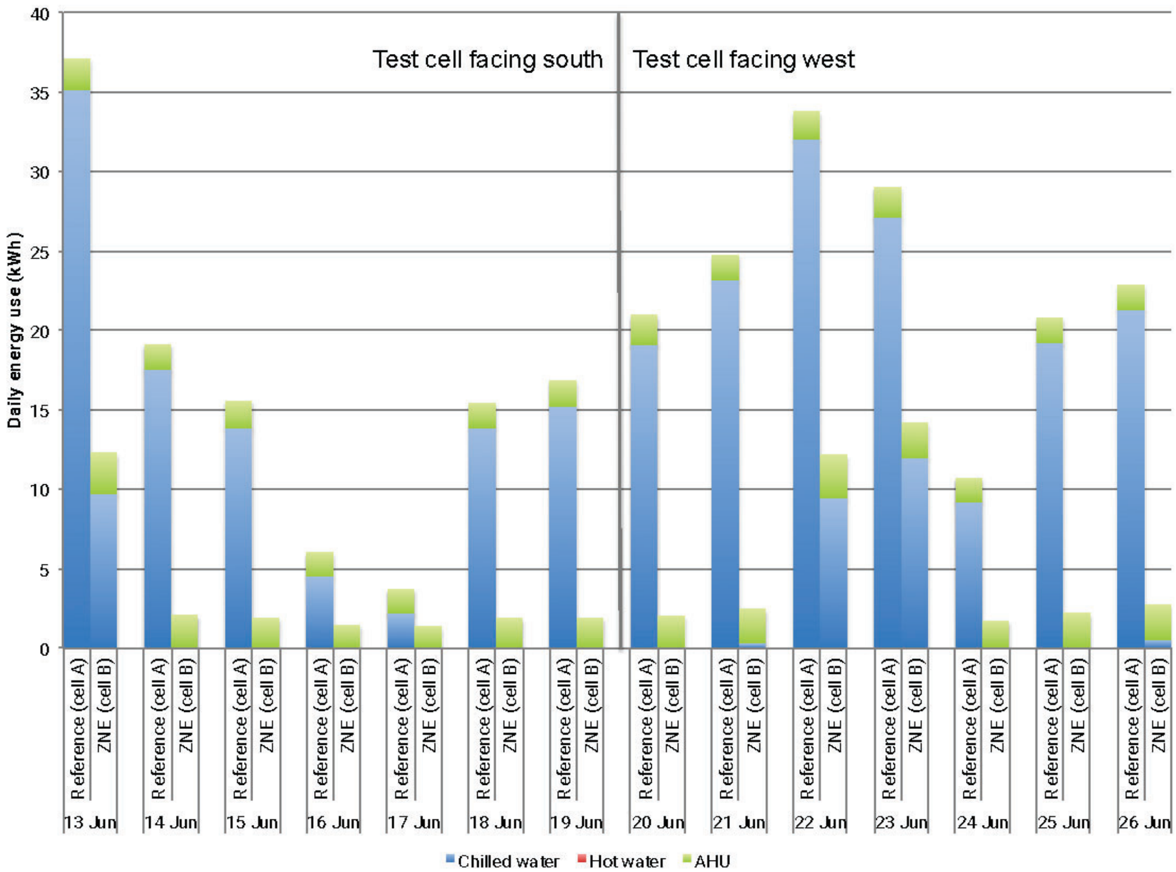

Figure 19. Daily HVAC thermal energy consumption during June 2018 test period.

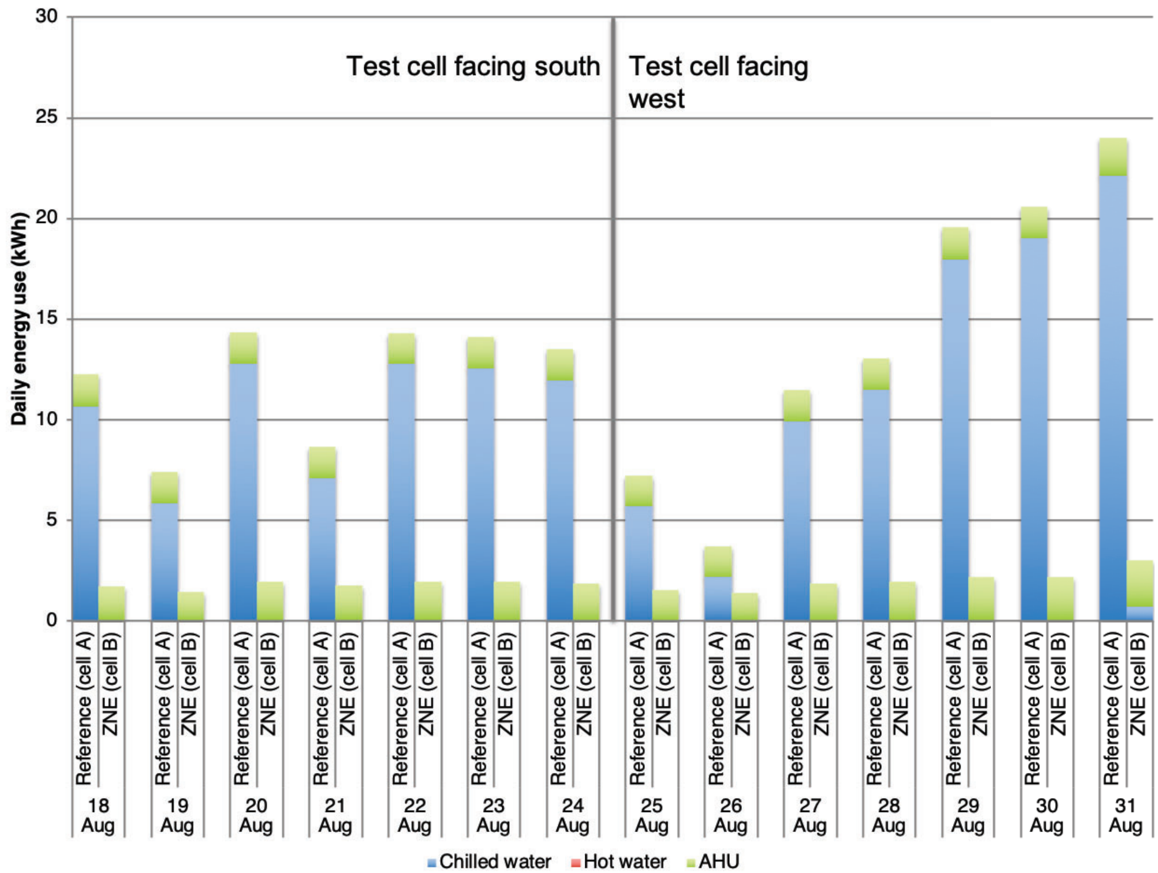

Figure 20. Daily HVAC thermal energy consumption during August 2018 test period.

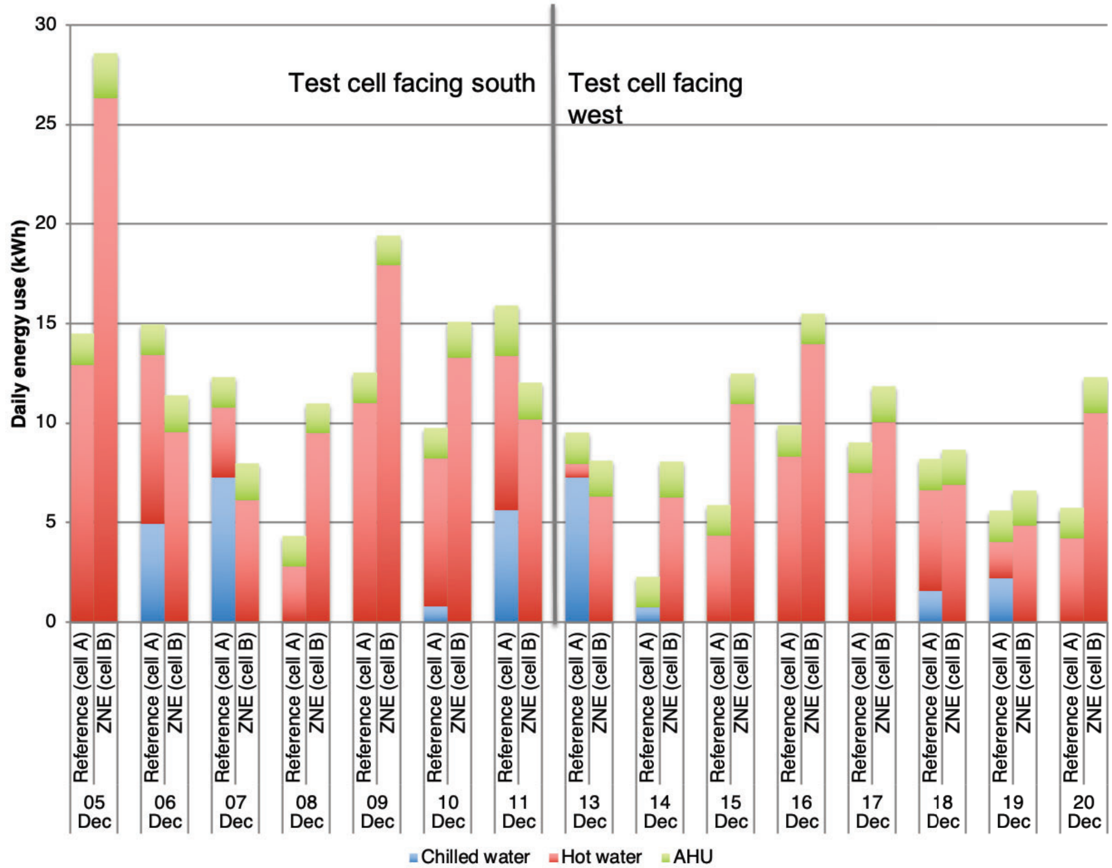

Figure 21. Daily HVAC thermal energy consumption during December 2018 test period.

Table 6. Total HVAC thermal energy.

Month	Orientation	Testing days	Total energy (kWh)								ZNE package savings
			Reference				ZNE package				
			Chilled water	Hot water	AHU	Total	Chilled water	Hot water	AHU	Total	
May	South	8	78.2	0.0	12.8	91.0	0.0	11.4	14.6	26.0	71%
	West	7	78.7	0.0	11.1	89.8	0.8	0.0	12.9	13.7	85%
Jun	South	7	102.2	0.0	11.8	113.9	9.7	0.0	13.3	23.0	80%
	West	7	151.0	0.0	12.1	163.1	22.2	0.0	15.5	37.7	77%
Aug	South	7	73.6	0.0	10.9	84.6	0.0	0.0	12.7	12.7	85%
	West	7	88.4	0.0	11.3	99.7	0.7	0.0	13.5	14.2	86%
Dec	South	7	18.6	53.8	11.9	84.3	0.0	92.8	12.7	105.5	-25%
	West	8	11.8	31.9	12.5	56.2	0.0	69.6	14.0	83.6	-49%

Table 7. Average daily HVAC thermal energy.

Month	Orientation	Testing days	Average daily energy (kWh)								ZNE package savings
			Reference				ZNE package				
			Chilled water	Hot water	AHU	Total	Chilled water	Hot water	AHU	Total	
May	South	8	9.8	0.0	1.6	11.4	0.0	1.4	1.8	3.2	71%
	West	7	11.2	0.0	1.6	12.8	0.1	0.0	1.8	2.0	85%
Jun	South	7	14.6	0.0	1.7	16.3	1.4	0.0	1.9	3.3	80%
	West	7	21.6	0.0	1.7	23.3	3.2	0.0	2.2	5.4	77%
Aug	South	7	10.5	0.0	1.6	12.1	0.0	0.0	1.8	1.8	85%
	West	7	12.6	0.0	1.6	14.2	0.1	0.0	1.9	2.0	86%
Dec	South	7	2.7	7.7	1.7	12.0	0.0	13.3	1.8	15.1	-25%
	West	8	1.5	4.0	1.6	7.0	0.0	8.7	1.7	10.5	-49%

3.1.1.2 Calculated gas and electric energy use

This subsection shows results from the calculations of actual energy consumption needed in order to provide the measured levels of thermal energy (heating or coolling) detailed in the previous subsection. I.e., once HVAC equipment efficiency is taken into account, the amount of energy in the form of electricity or gas that is required for heating or cooling is different (greater or smaller) than the heat removed (in the case of cooling) or provided (in the case of heating) to the space.

Figure 22 through Figure 25 show daily HVAC energy consumption for each of the four testing periods; Table 8 through Table 11 show the total and daily average energy use and energy use intensities (EUIs). For measured thermal energy, the reference cell was in cooling mode for the May, June and August 2018 test periods, whereas the ZNE package cell showed a mix of cooling and heating mode. In December, the reference cell had some cooling as well as heating, whereas the ZNE cell showed only heating. The main difference between these calculated energy use values and the measured thermal energy values is that, once HVAC equipment efficiency is taken into account, the amount of energy required for heating increases substantially in comparison to cooling energy needs. For May, June and August 2018 combined, calculated HVAC energy use for the south orientation was 115 kWh and 59 kWh in the reference and ZNE package cells respectively, resulting in 49% energy savings relative to the reference cell. The corresponding values for the west orientation are 133 kWh and 50 kWh in the reference and test cells, respectively, resulting in 63% energy savings. During the December 2018 test, HVAC energy use for the south orientation was 85 kWh and 120 kWh for the reference and ZNE package cells, respectively, resulting in a 41% increase in energy consumption relative to the reference test cell. The corresponding values for the west orientation are 56 kWh and 99 kWh for the reference and ZNE package cells, respectively, resulting in a 77% in energy consumption.

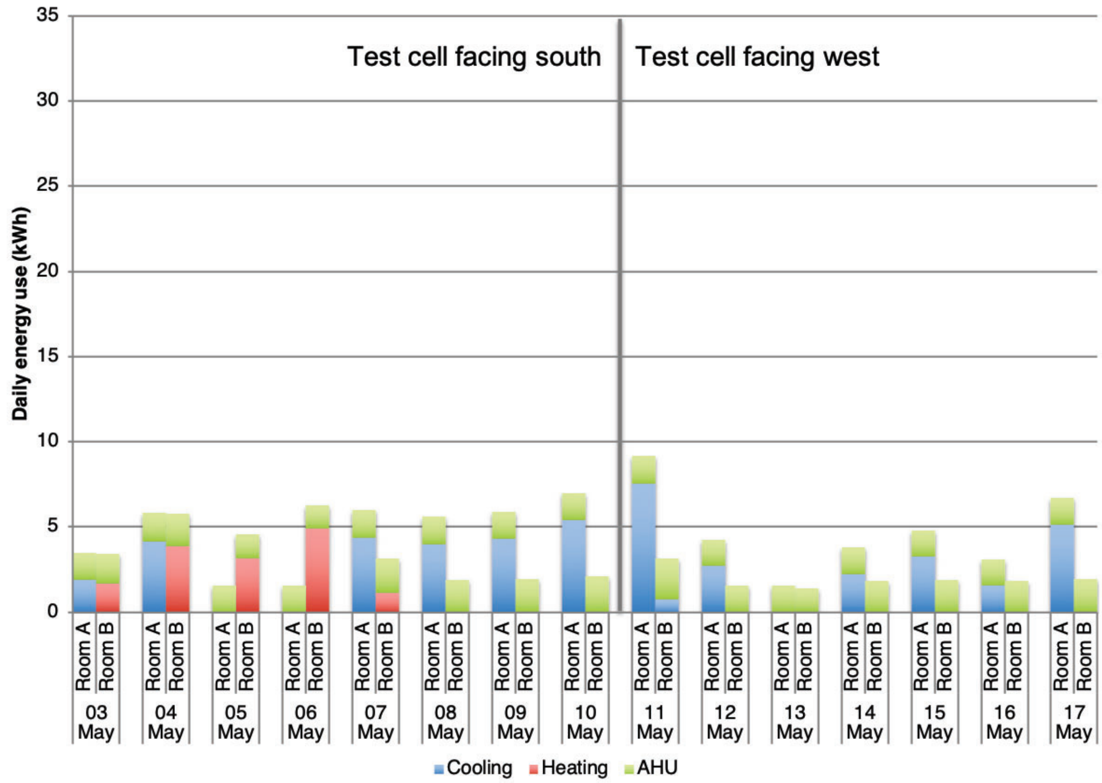

Figure 22. Daily HVAC energy consumption during May test period.

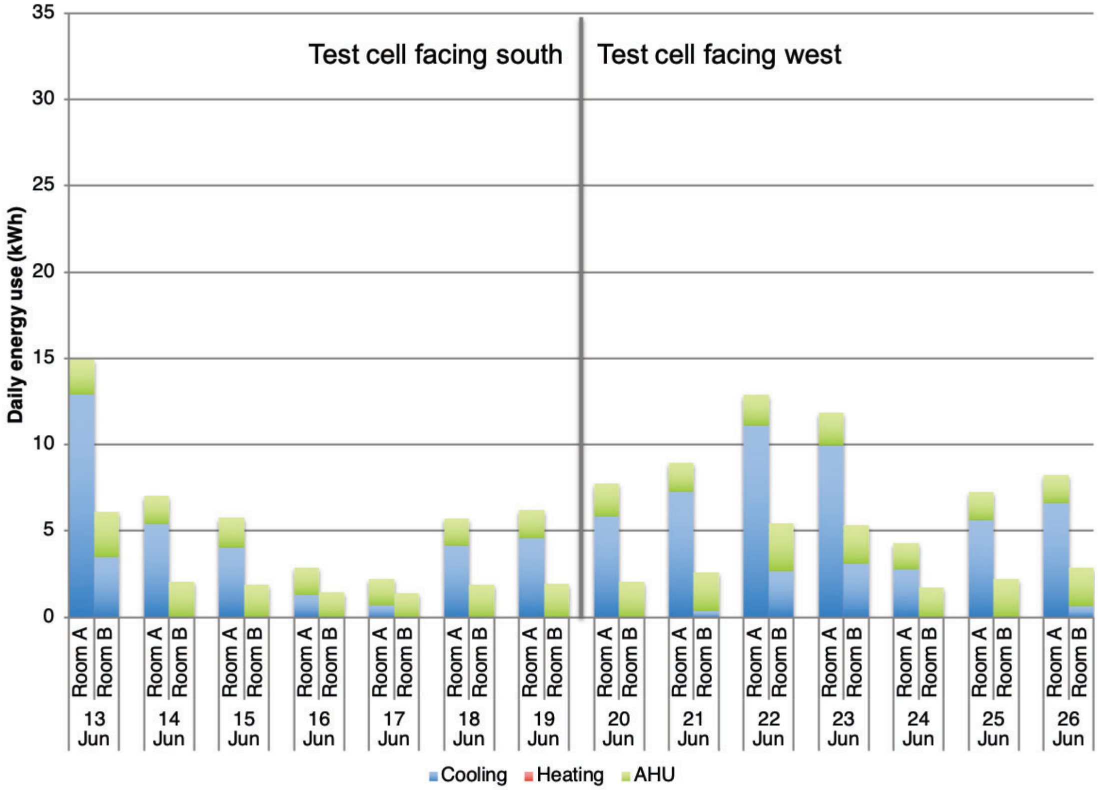

Figure 23. Daily HVAC energy consumption during June test period.

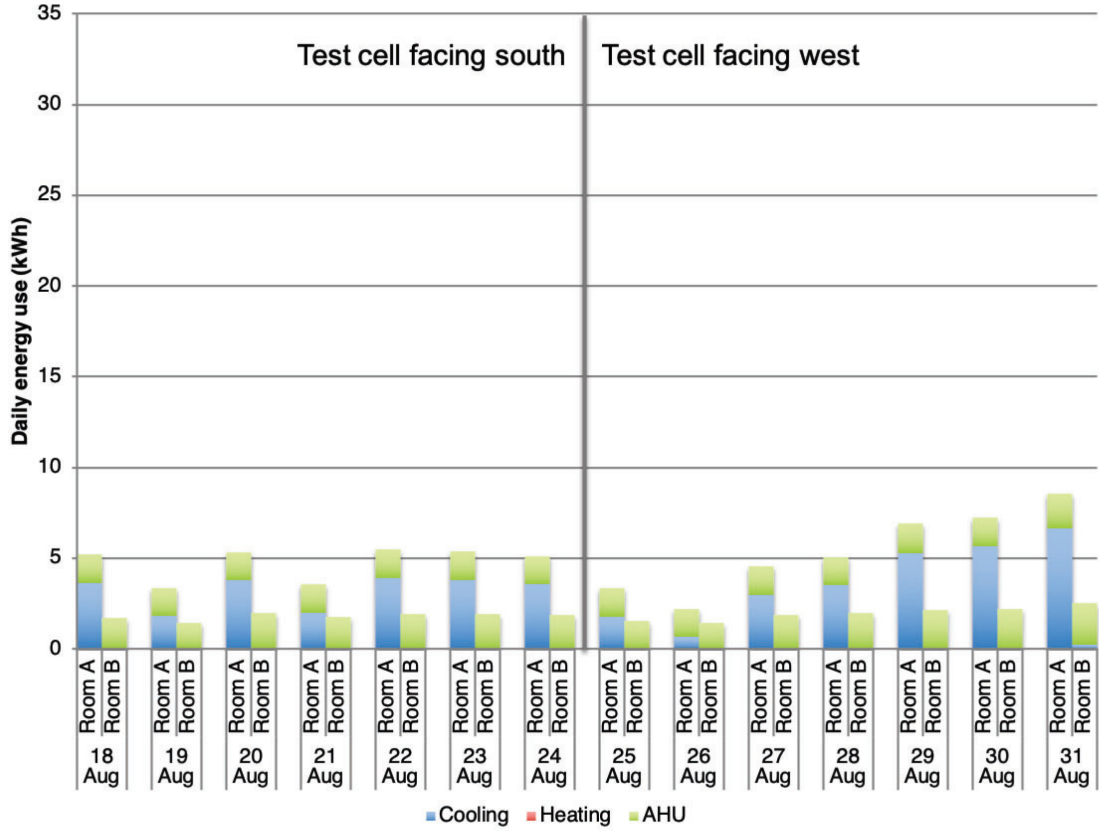

Figure 24. Daily HVAC energy consumption during August test period.

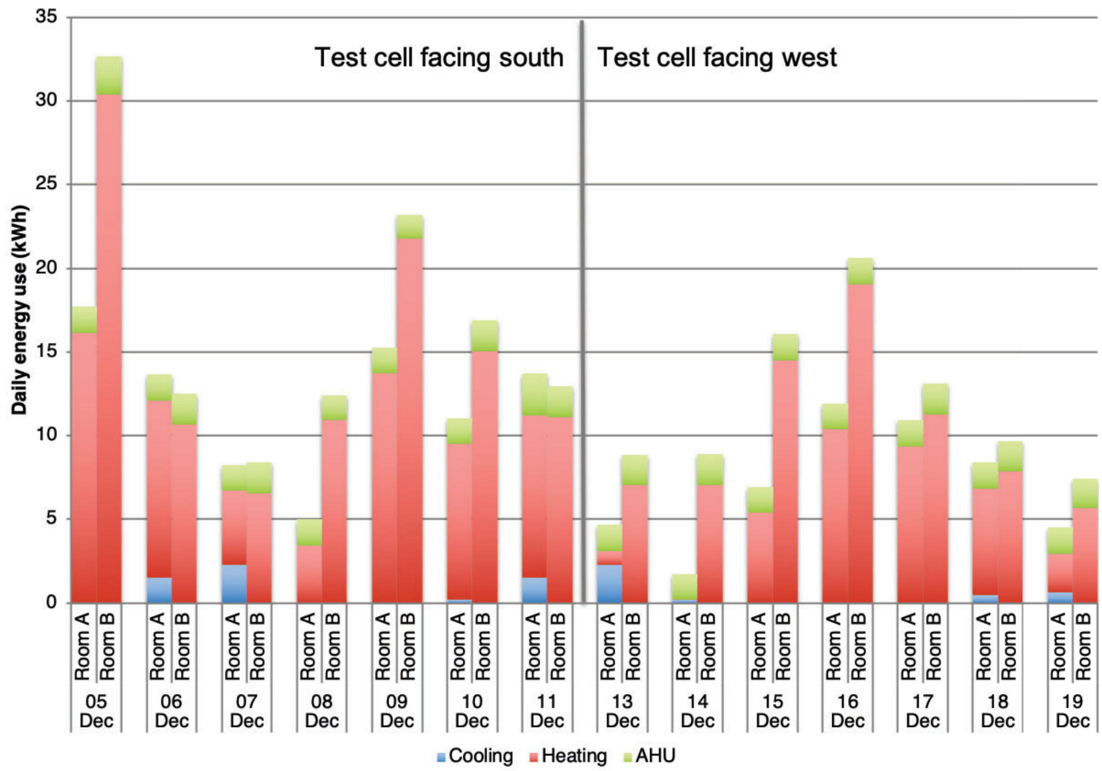

Figure 25. Daily HVAC energy consumption during December test period.

Table 8. Total HVAC energy use.

Month	Orientation	Testing days	Total energy (kWh)								ZNE package savings
			Reference				ZNE package				
			Cooling	Heating	AHU	Total	Cooling	Heating	AHU	Total	
May	South	8	24.1	0.0	12.8	36.9	0.0	14.7	14.6	29.3	21%
	West	7	22.4	0.0	11.1	33.4	0.7	0.0	12.9	13.6	59%
Jun	South	7	33.1	0.0	11.8	44.9	3.5	0.0	13.3	16.8	63%
	West	7	49.2	0.0	12.1	61.3	6.8	0.0	15.5	22.3	64%
Aug	South	7	22.5	0.0	10.9	33.4	0.0	0.0	12.7	12.7	62%
	West	7	26.5	0.0	11.3	37.8	0.2	0.0	13.5	13.7	64%
Dec	South	7	5.6	67.2	11.9	84.7	0.0	106.5	12.7	119.2	-41%
	West	8	3.6	39.9	12.5	56.0	0.0	84.9	14.0	98.9	-77%

Table 9. Average daily HVAC energy use.

Month	Orientation	Testing days	Average daily energy (kWh)								ZNE package savings
			Reference				ZNE package				
			Cooling	Heating	AHU	Total	Cooling	Heating	AHU	Total	
May	South	8	3.0	0.0	1.6	4.6	0.0	1.8	1.8	3.7	21%
	West	7	3.2	0.0	1.6	4.8	0.1	0.0	1.8	1.9	59%
Jun	South	7	4.7	0.0	1.7	6.4	0.5	0.0	1.9	2.4	63%
	West	7	7.0	0.0	1.7	8.8	1.0	0.0	2.2	3.2	64%
Aug	South	7	3.2	0.0	1.6	4.8	0.0	0.0	1.8	1.8	62%
	West	7	3.8	0.0	1.6	5.4	0.0	0.0	1.9	2.0	64%
Dec	South	7	0.8	9.6	1.7	12.1	0.0	15.2	1.8	17.0	-41%
	West	8	0.4	5.0	1.6	7.0	0.0	10.6	1.7	12.4	-77%

Table 10. HVAC EUI.

Month	Orientation	Testing days	EUI (Wh/ft^2)								ZNE package savings
			Reference				ZNE package				
			Cooling	Heating	AHU	Total	Cooling	Heating	AHU	Total	
May	South	8	37.4	0.0	19.8	57.3	0.0	22.8	22.6	45.38	21%
	West	7	34.7	0.0	17.1	51.8	1.1	0.0	20.0	21.10	59%
Jun	South	7	51.3	0.0	18.2	69.6	5.4	0.0	20.7	26.03	63%
	West	7	76.3	0.0	18.8	95.0	10.5	0.0	24.0	34.56	64%
Aug	South	7	34.9	0.0	17.0	51.8	0.0	0.0	19.7	19.67	62%
	West	7	41.1	0.0	17.6	58.7	0.3	0.0	20.9	21.18	64%
Dec	South	7	8.6	104.2	18.5	131.3	0.0	165.1	19.6	184.74	-41%
	West	8	5.6	61.9	19.3	86.8	0.0	131.6	21.7	153.33	-77%

Table 11. Average daily HVAC EUI.

Month	Orientation	Testing days	Average daily EUI (Wh/ft^2)								ZNE package savings
			Reference				ZNE package				
			Cooling	Heating	AHU	Total	Cooling	Heating	AHU	Total	
May	South	8	4.7	0.0	2.5	7.2	0.0	2.9	2.8	5.7	21%
	West	7	5.0	0.0	2.4	7.4	0.2	0.0	2.9	3.0	59%
Jun	South	7	7.3	0.0	2.6	9.9	0.8	0.0	3.0	3.7	63%
	West	7	10.9	0.0	2.7	13.6	1.5	0.0	3.4	4.9	64%
Aug	South	7	5.0	0.0	2.4	7.4	0.0	0.0	2.8	2.8	62%
	West	7	5.9	0.0	2.5	8.4	0.0	0.0	3.0	3.0	64%
Dec	South	7	1.2	14.9	2.6	18.8	0.0	23.6	2.8	26.4	-41%
	West	8	0.7	7.7	2.4	10.8	0.0	16.5	2.7	19.2	-77%

Hourly, daily and per-orientation variation in lighting energy savings is shown in Figure 26 through Figure 29 for the May, June, August, and December 2018 test periods, respectively.

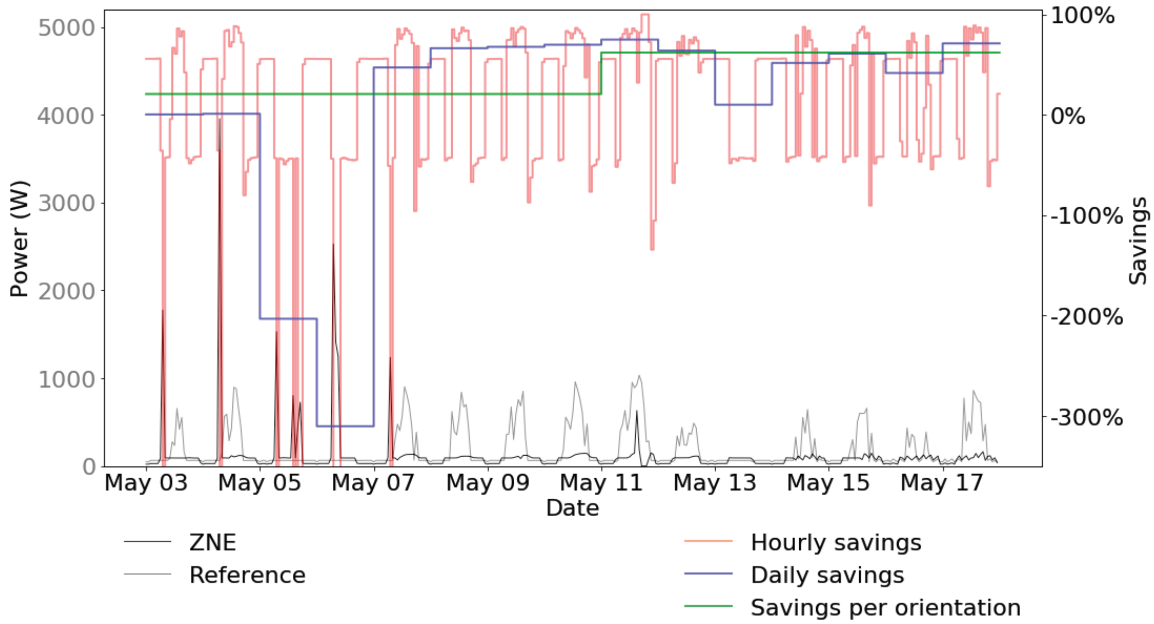

Figure 26. Hourly, daily and per-orientation HVAC energy savings for May testing period.

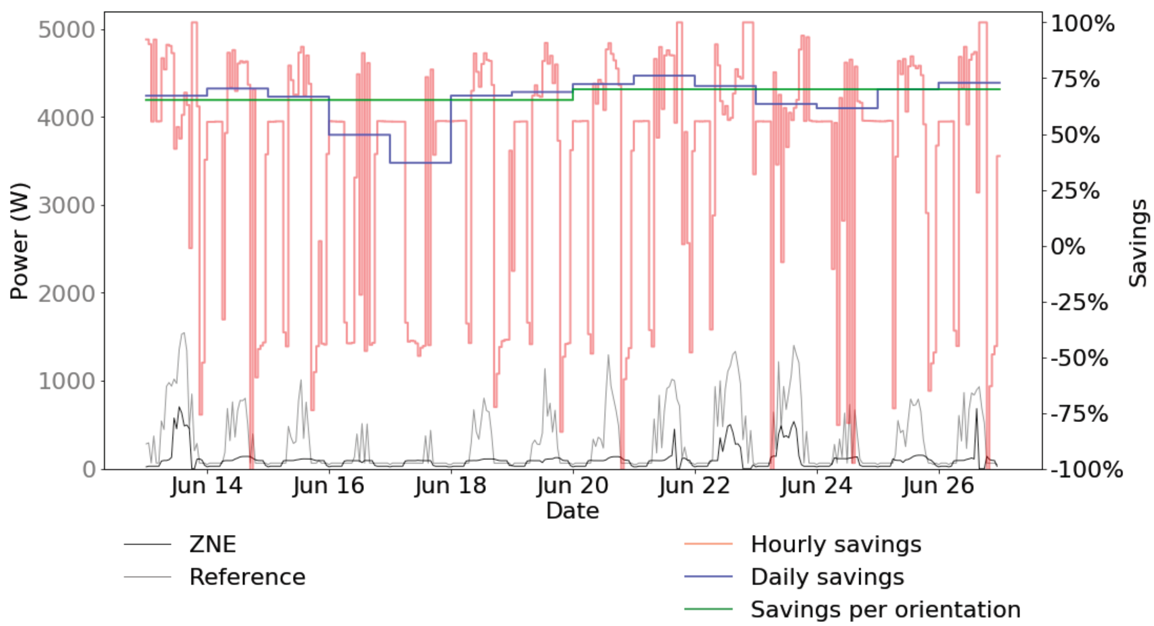

Figure 27. Hourly, daily and per-orientation HVAC energy savings for June testing period.

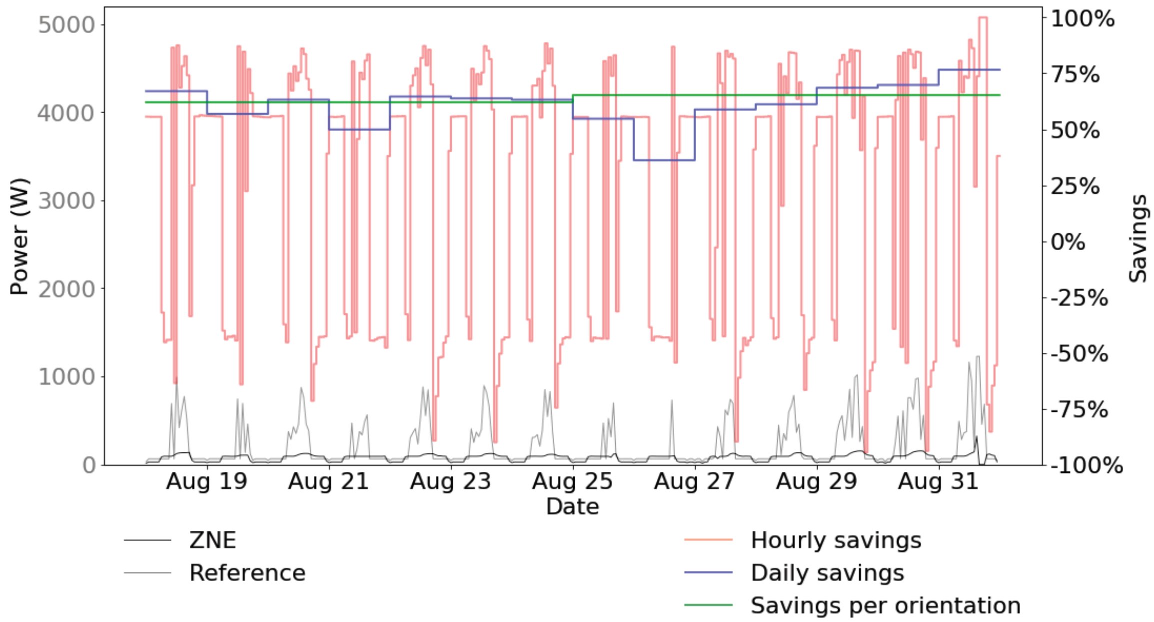

Figure 28. Hourly, daily and per-orientation HVAC energy savings for August testing period.

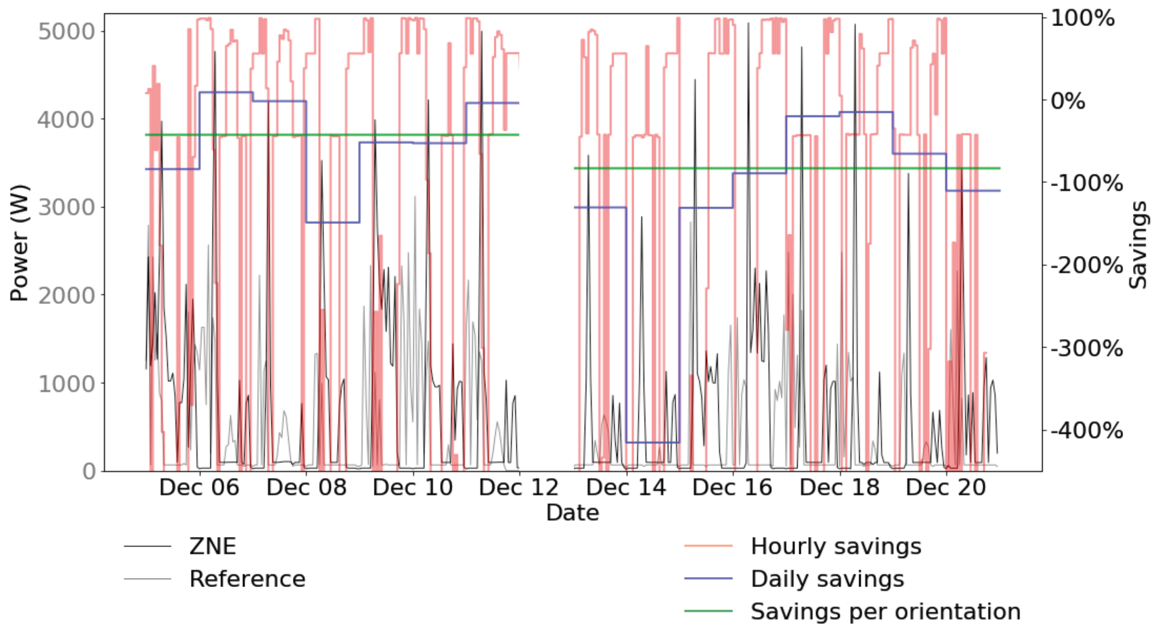

Figure 29. Hourly, daily and per-orientation HVAC energy savings for December testing period.

3.1.2 Thermal comfort

PMV and PPD distributions for the middle and window spaces of the reference and ZNE package cells are shown in Figure 30 and Figure 31, respectively, for one-minute averages during the times of greater occupancy (8 AM and 6 PM). Note that, for simplicity of analysis, south and west orientations were here combined for each test period. The values measured by the air velocity sensors were found to not be reliable due to equipment failure; the air velocity was determined from the manufacturers' specifications for the conventional and modulating supply diffusers for the reference and ZNE package cells, specifically. Air velocity determined using this method was 0.28 and 0.34 m/s for the middle and window spaces of the reference cell and 0.10 and 0.05 m/s for the middle and window spaces of the ZNE package cell, respectively.

During the cooling season (May, June, and August), the ZNE package cell appears warmer (i.e., higher average PMV) than the reference cell, with perhaps some overcooling in the window space of the reference cell (PMV around -0.5 to -1, or "slightly cool"). As a consequence, there is a substantial occurrence of PPD values in that space that are above the 20% limit, unlike in the other three spaces. During the heating season (December), the ZNE package cell appears cooler than the reference cell, with the window space frequently in the -0.5 to -1 ("slightly cool") PMV range. Again, this is also reflected in frequent PPD values above 20% for that space. It is possible that the single-pane windows play a part in making the window space in both cells less comfortable than it would be with a better insulating window, such as a low-emissivity double-pane window.

When taken together, the results indicate that the ZNE package maintained acceptable levels of thermal comfort for a substantial amount of time, with the possible exception of areas near single pane windows during the heating season. This exception might be mitigated by retrofitting windows to be more insulating, or by using any shading devices that reduce the convective movement of air close to the window, e.g., cellular shades.

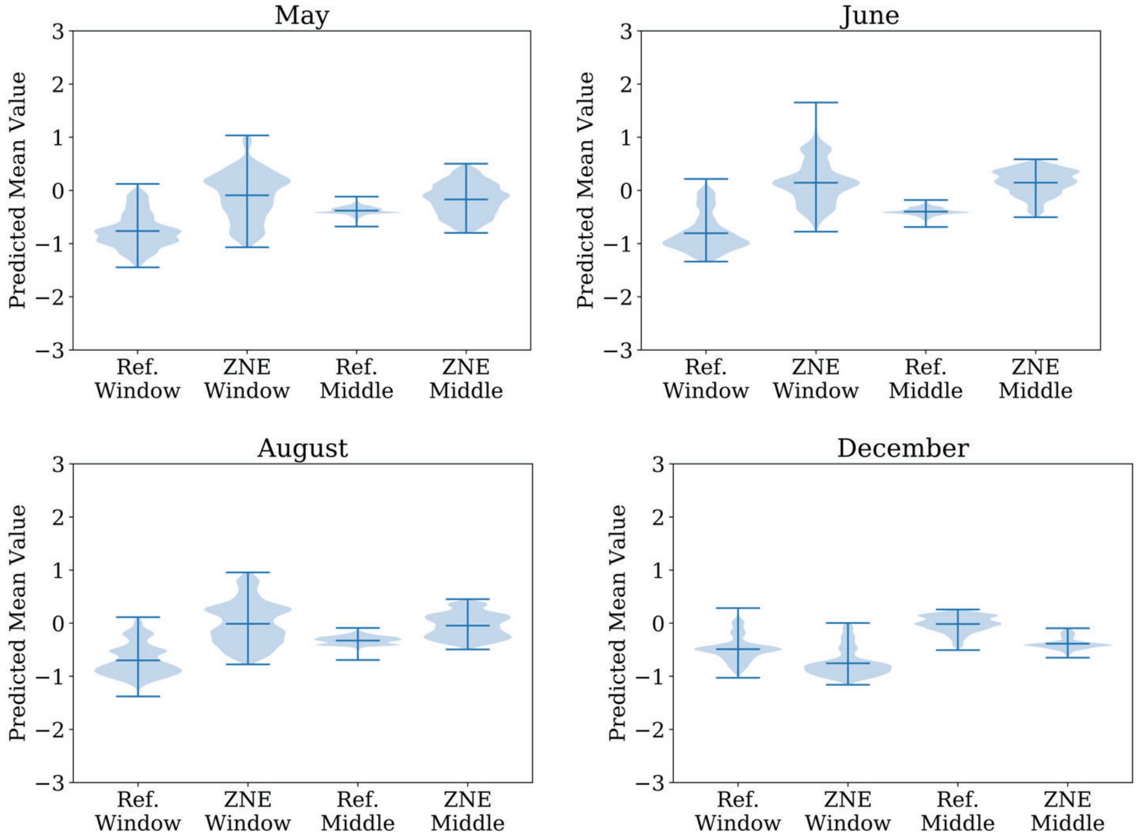

Figure 30. Kernel-density estimator distribution plots of Predicted Mean Value for each of the four 2018 ZNE package test periods. In each distribution, the horizontal lines indicate the minimum, median, and maximum values.

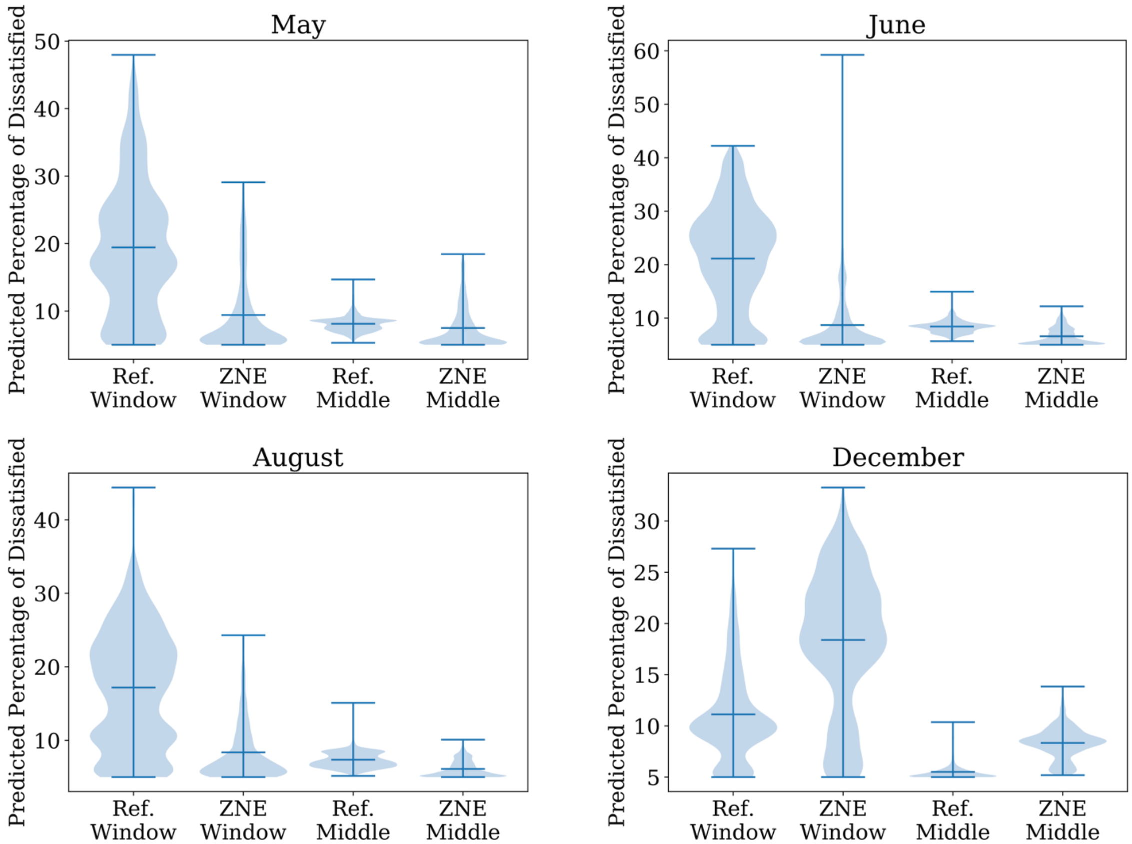

Figure 31. Kernel-density estimator distribution plots of Predicted Percentage of Dissatisfied for each of the four 2018 ZNE package test periods. In each distribution, the horizontal lines indicate the minimum, median, and maximum values.

3.1.3 Lighting energy

Lighting energy consumption throughout the four 2018 testing periods was substantially lower in the ZNE package cell than in the reference cell (Figure 32 to Figure 35). For the south orientation, total lighting energy use was 85% lower in the ZNE cell when compared to the reference cell (48 kWh versus 328 kWh, respectively, across the four tests). For the west orientation the lighting energy use reduction was also 85% (49 kWh versus 327 kWh). When analyzing lighting energy use by each of the three spaces into which each cell was divided, lighting energy use reduction was 90%, 89% and 76% for the window, middle and interior spaces, respectively, for the south orientation. For the west orientation the corresponding values are very similar: 90% reduction for window, 89% reduction for middle, and 77% reduction for interior. More detail is shown in Table 8. These results are presented in terms of average daily energy use in Table 9 and EUI in Table 10 and Table 11. Hourly, daily and per-orientation variation in lighting energy savings is shown in Figures 36 through Figure 39.

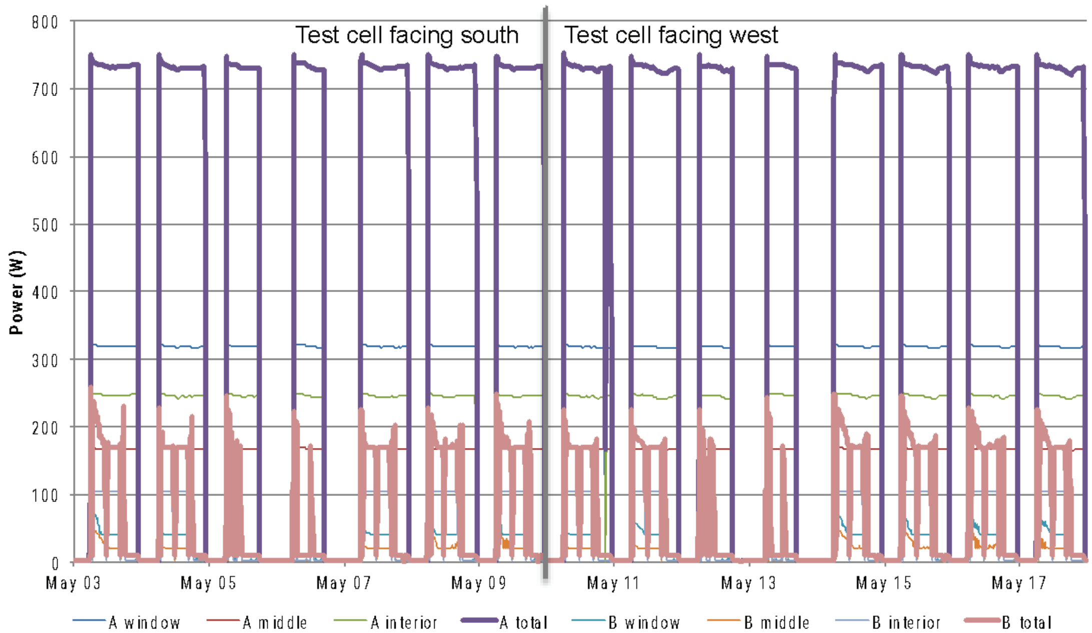

Figure 32. Lighting power consumption during May 2018 test period.

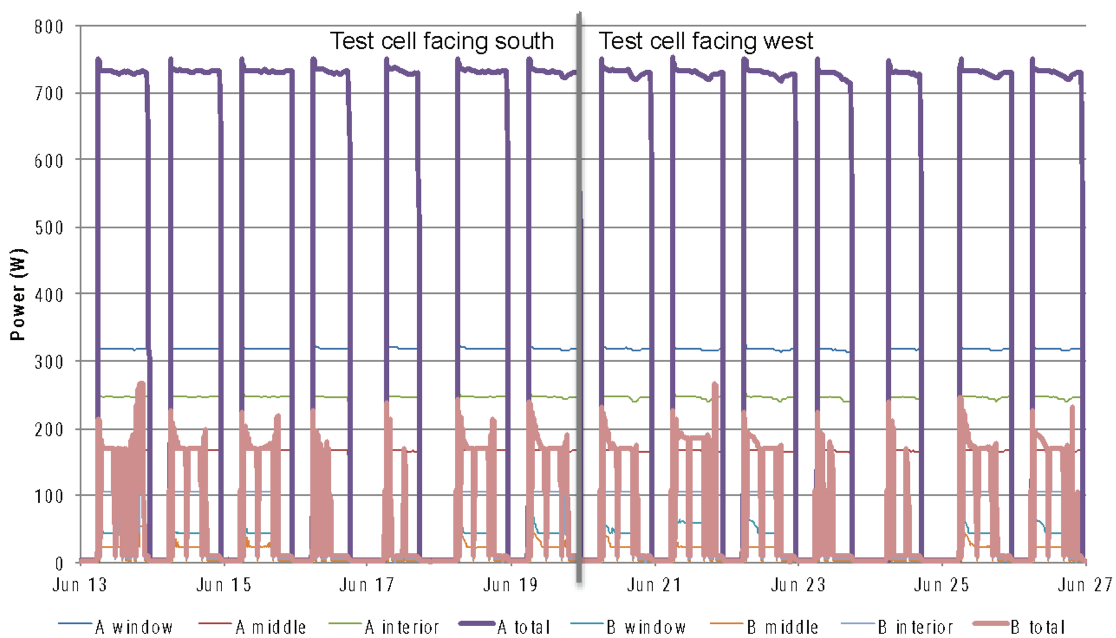

Figure 33. Lighting power consumption during June 2018 test period.

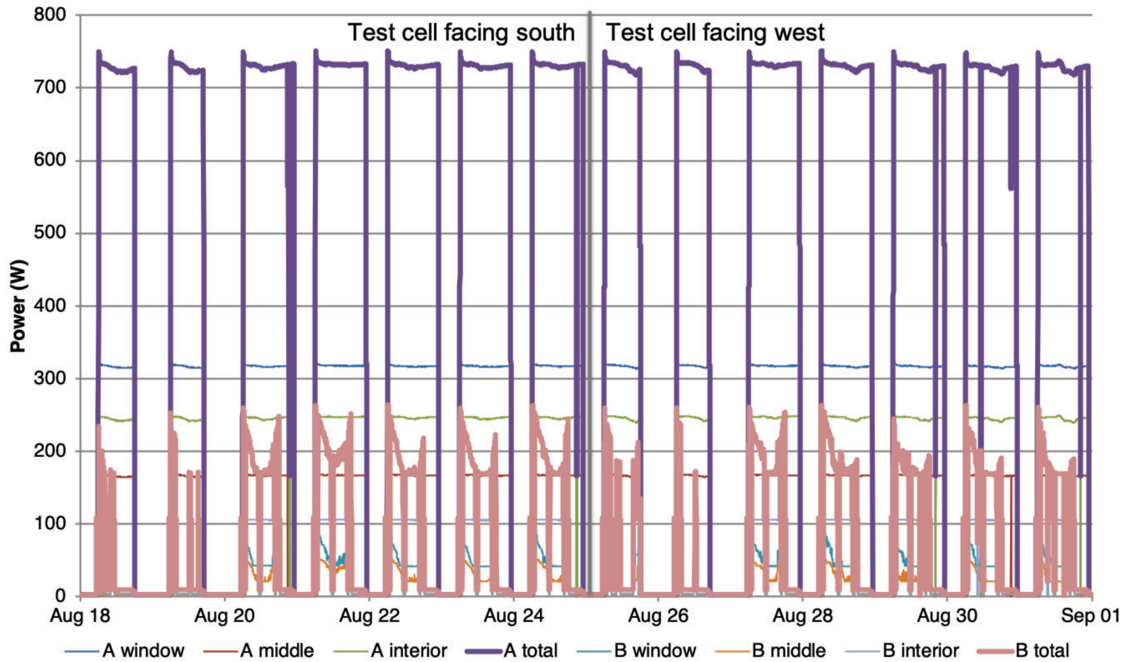

Figure 34. Lighting power consumption during August 2018 test period.

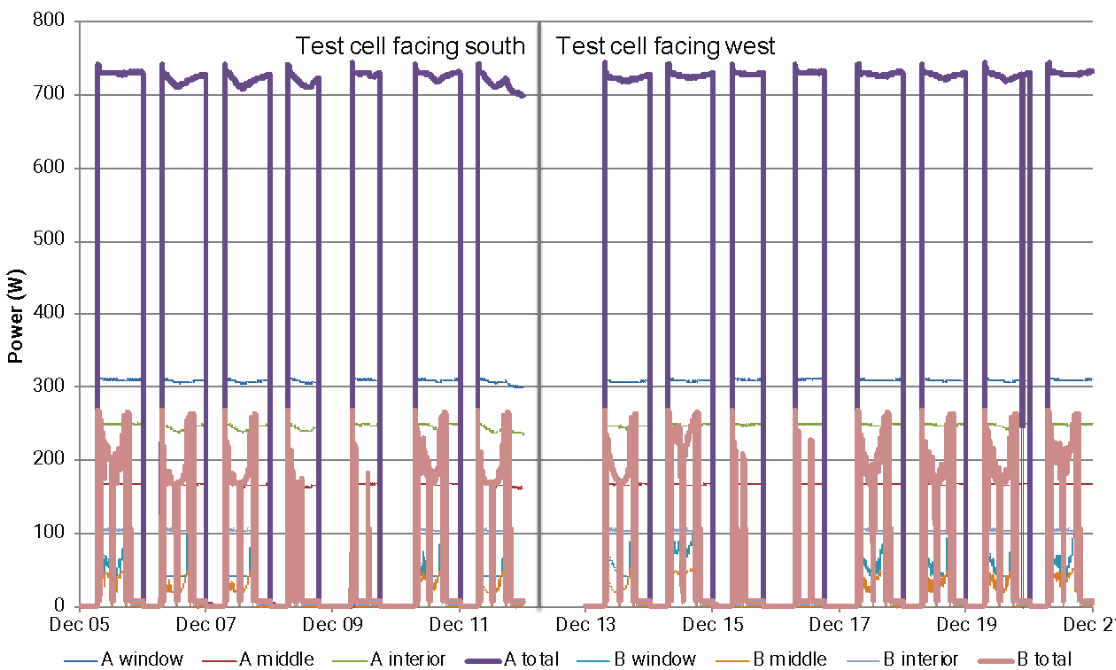

Figure 35. Lighting power consumption during December 2018 test period.

Table 12. Total lighting energy consumption.

Mo.	Orient.	Testing days	Total energy (kWh)								ZNE package savings			
			Reference				ZNE package							
			W	M	I	Total	W	M	I	Total	W	M	I	Overall
May	South	8	39.8	21.0	30.8	91.6	3.52	2.02	7.34	12.9	91%	90%	76%	86%
	West	7	34.4	18.1	26.7	79.2	3.13	1.75	6.23	11.1	91%	90%	77%	86%
Jun	South	7	34.4	18.1	26.7	79.2	3.19	1.81	6.37	11.4	91%	90%	76%	86%
	West	7	34.3	18.0	26.6	78.9	3.30	1.65	6.32	11.3	90%	91%	76%	86%
Aug	South	7	34.1	18.0	26.4	78.5	3.5	2.2	6.3	12.1	90%	88%	76%	85%
	West	7	33.9	17.9	26.3	78.2	3.5	2.1	6.4	12.0	90%	88%	76%	85%
Dec	South	7	33.4	18.1	26.7	78.2	3.7	2.3	6.1	12.0	89%	87%	77%	85%
	West	8	38.8	21.1	31.2	91.0	4.7	2.8	7.0	14.5	88%	87%	78%	84%

W - window; M - middle; I - interior

Table 13. Average daily lighting energy consumption.

Mo.	Orient.	Testing days	Average daily energy (kWh)								ZNE package savings			
			Reference				ZNE package							
			W	M	I	Total	W	M	I	Total	W	M	I	Overall
May	South	8	4.97	2.63	3.85	11.5	0.44	0.25	0.92	1.61	91%	90%	76%	86%
	West	7	4.92	2.59	3.81	11.3	0.45	0.25	0.89	1.59	91%	90%	77%	86%
Jun	South	7	4.91	2.58	3.81	11.3	0.46	0.26	0.91	1.62	91%	90%	76%	86%
	West	7	4.90	2.58	3.79	11.3	0.47	0.24	0.90	1.61	90%	91%	76%	86%
Aug	South	7	4.87	2.57	3.78	11.2	0.50	0.32	0.90	1.72	90%	88%	76%	85%
	West	7	4.84	2.56	3.76	11.2	0.50	0.30	0.91	1.71	90%	88%	76%	85%
Dec	South	7	4.78	2.59	3.81	11.2	0.52	0.32	0.87	1.72	89%	87%	77%	85%
	West	8	4.84	2.64	3.90	11.4	0.59	0.35	0.87	1.81	88%	87%	78%	84%

W - window; M - middle; I - interior

Table 14. Lighting EUI.

Mo.	Orient.	Testing days	EUI (Wh/ft^2)								ZNE package savings			
			Reference				ZNE package							
			W	M	I	Avg.	W	M	I	Avg	W	M	I	Overall
May	South	8	169	150	114	142	14.9	14.4	27.3	20.0	91%	90%	76%	86%
	West	7	146	129	99	123	13.3	12.5	23.1	17.2	91%	90%	77%	86%

Jun	South	7	146	129	99	123	13.5	12.9	23.7	17.6	91%	90%	76%	86%
	West	7	145	129	99	122	14.0	11.8	23.5	17.5	90%	91%	76%	86%
Aug	South	7	145	128	98	122	14.9	15.9	23.5	18.7	90%	88%	76%	85%
	West	7	144	128	98	121	15.0	15.0	23.7	18.6	90%	88%	76%	85%
Dec	South	7	142	130	99	121	15.5	16.2	22.6	18.7	89%	87%	77%	85%
	West	8	164	151	116	141	20.1	19.9	26.0	22.5	88%	87%	78%	84%

W - window; M - middle; I - interior

Table 15. Average daily lighting EUI.

Mo.	Orient.	Testing days	Average daily EUI (Wh/ft^2)								ZNE package savings			
			Reference				ZNE package							
			W	M	I	Avg.	W	M	I	Avg.	W	M	I	Overall
May	South	8	21.10	18.76	14.30	17.75	1.87	1.80	3.41	2.50	91%	90%	76%	86%
	West	7	20.85	18.50	14.14	17.54	1.90	1.79	3.31	2.46	91%	90%	77%	86%
Jun	South	7	20.83	18.46	14.16	17.53	1.93	1.85	3.38	2.52	91%	90%	76%	86%
	West	7	20.78	18.39	14.09	17.47	2.00	1.68	3.35	2.50	90%	91%	76%	86%
Aug	South	7	20.65	18.35	14.03	17.39	2.12	2.27	3.35	2.67	90%	88%	76%	85%
	West	7	20.55	18.30	13.96	17.31	2.14	2.14	3.38	2.66	90%	88%	76%	85%
Dec	South	7	20.27	18.50	14.15	17.33	2.22	2.31	3.23	2.66	89%	87%	77%	85%
	West	8	20.55	18.83	14.48	17.64	2.51	2.48	3.25	2.81	88%	87%	78%	84%

W - window; M - middle; I - interior

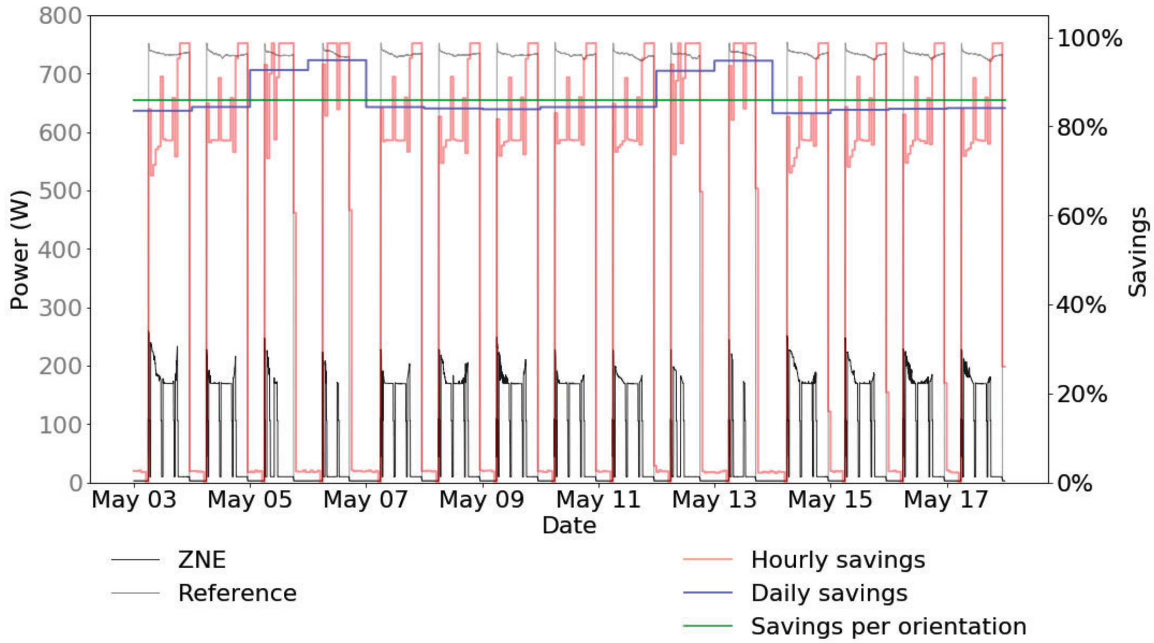

Figure 36. Hourly, daily and per-orientation lighting energy savings for May testing period.

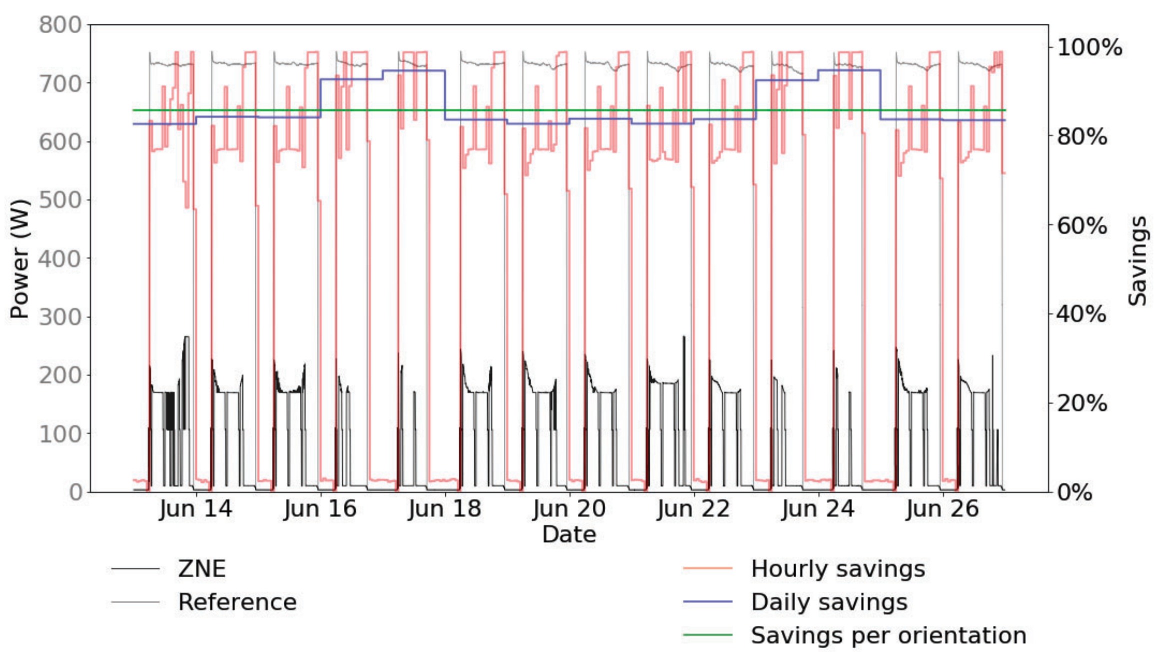

Figure 37. Hourly, daily and per-orientation lighting energy savings for June testing period.

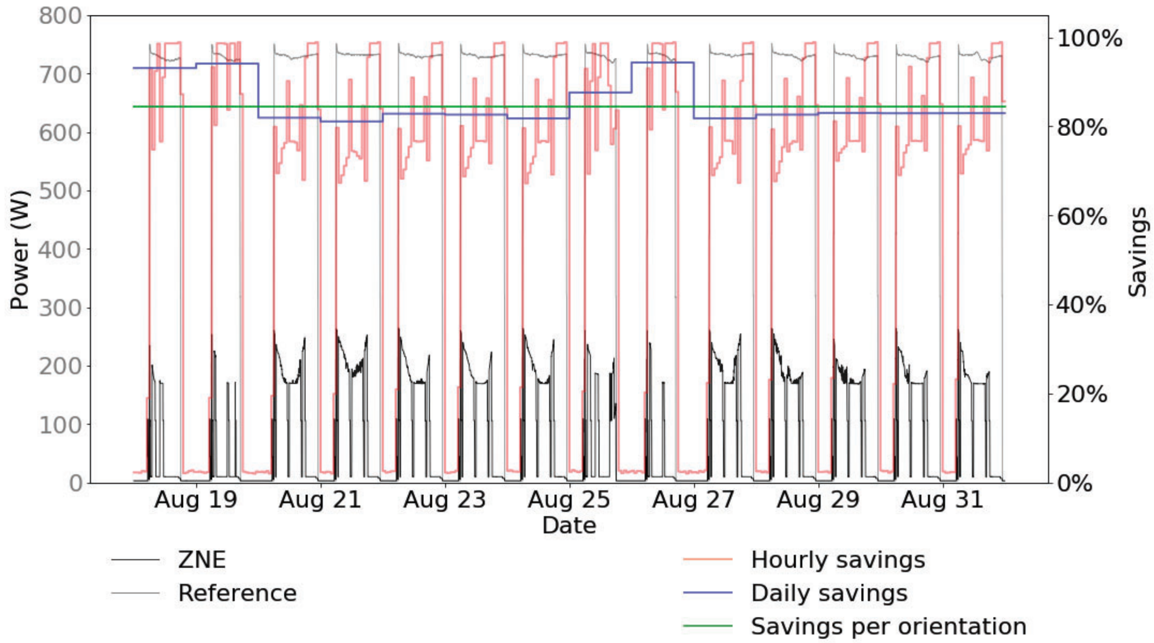

Figure 38. Hourly, daily and per-orientation lighting energy savings for August testing period.

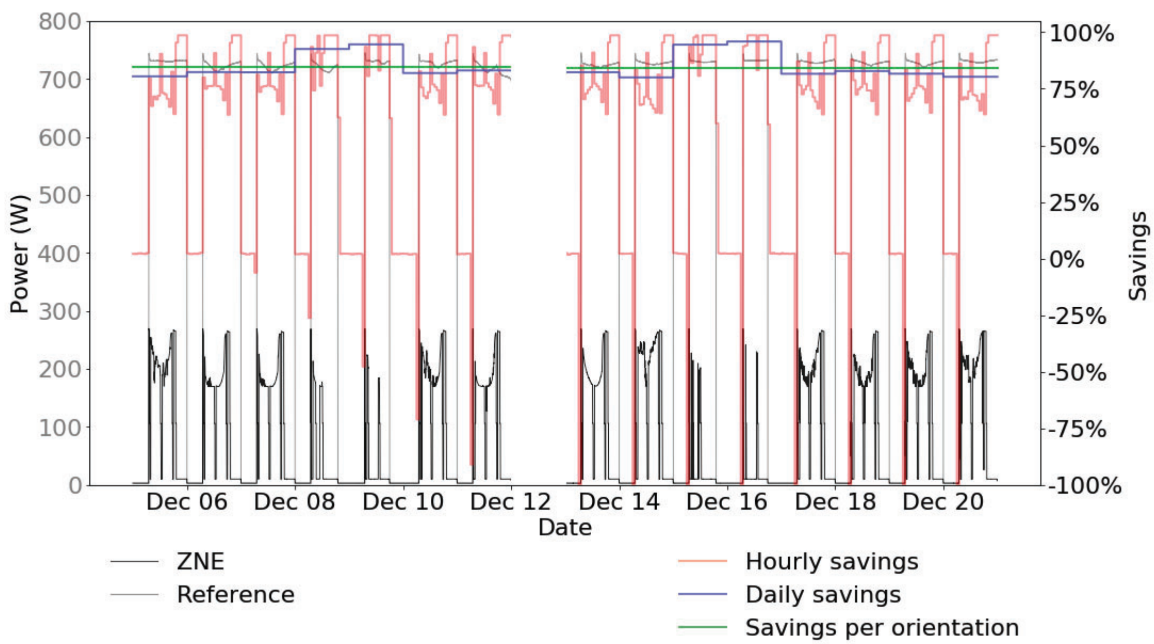

Figure 39. Hourly, daily and per-orientation lighting energy savings for December testing period.

3.1.4 Plug loads

Plug load energy use was 31% lower in the ZNE package cell than in the reference cell (88 kWh versus 127 kWh for the four tests combined; these values were identical for both orientations). Figure 40 through Figure 43 show plug load power consumption during the four 2018 test periods. Energy use is shown in Table 12 and Table 13. Hourly, daily and per-orientation variation in plug load energy savings is shown in Figure 44 through Figure 47.

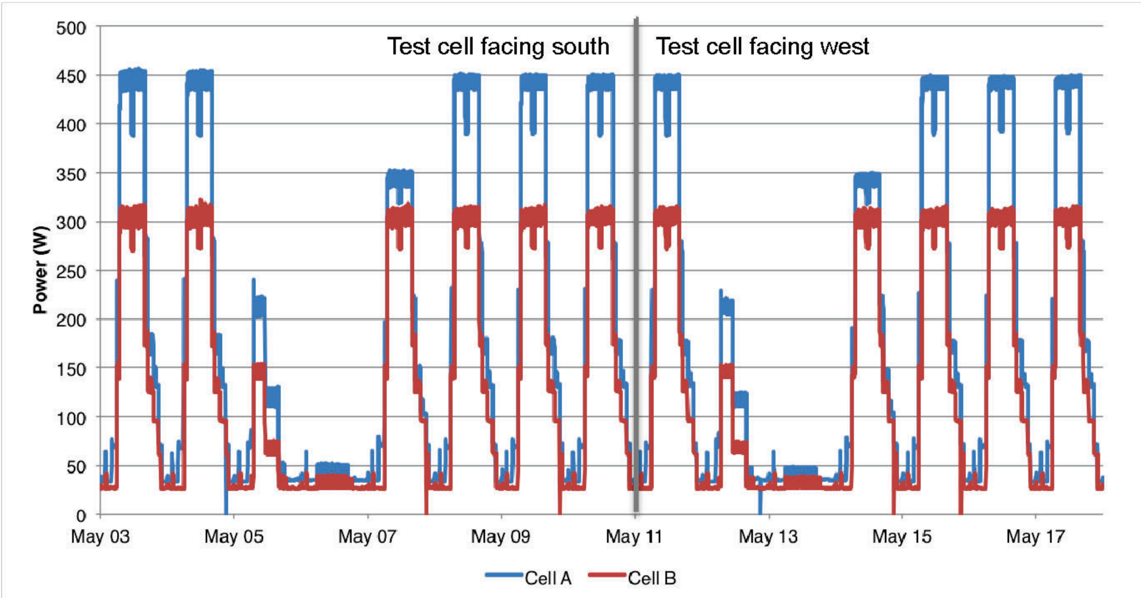

Figure 40. Plug load power consumption during May 2018 test period.

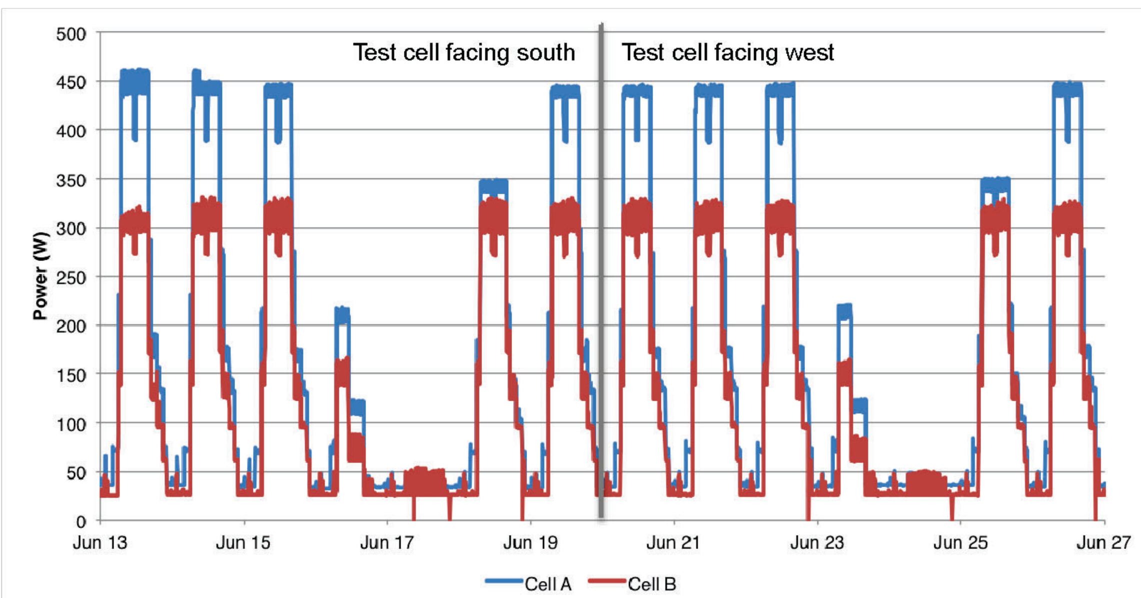

Figure 41. Plug load power consumption during June 2018 test period.

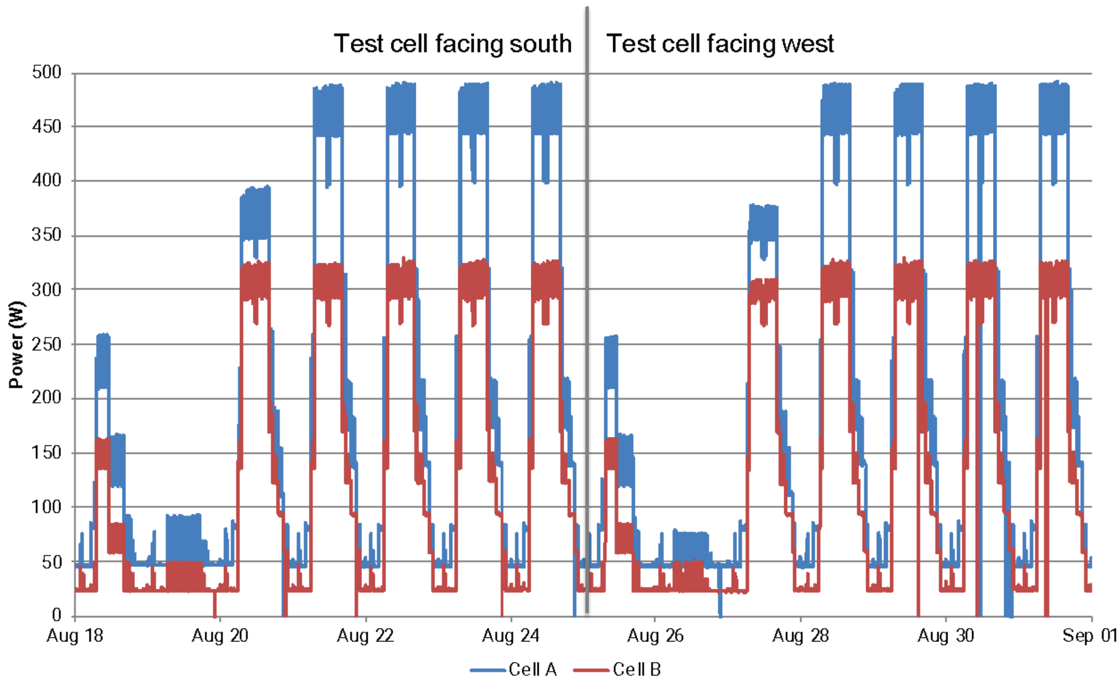

Figure 42. Plug load power consumption during August 2018 test period.

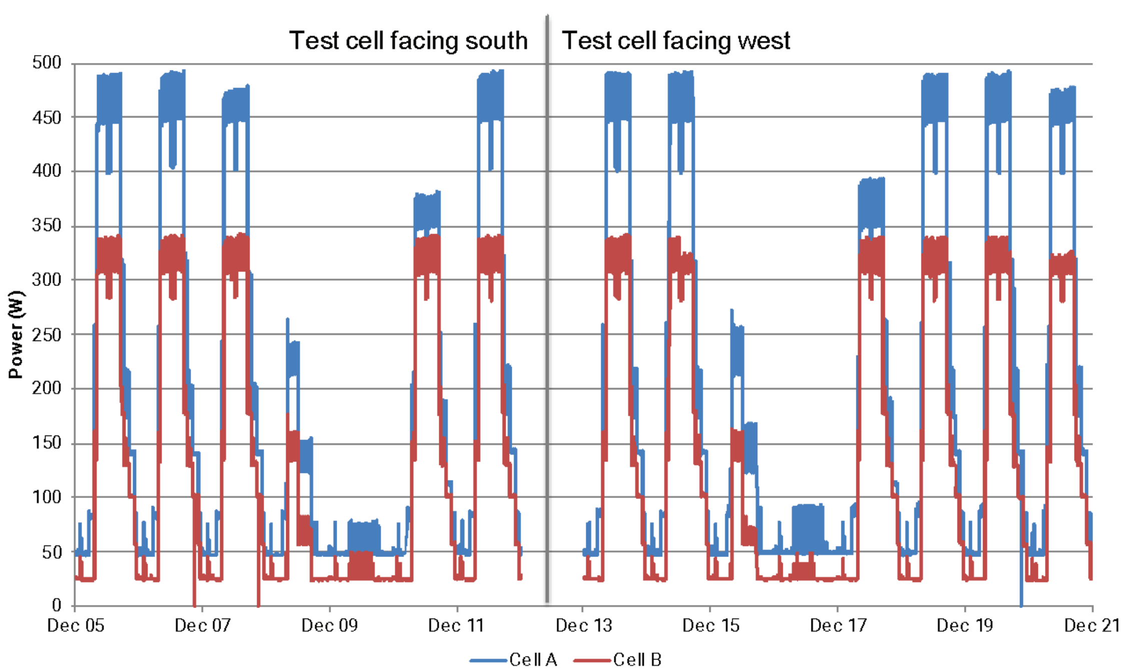

Figure 43. Plug load power consumption during December 2018 test period.

Table 16. Plug load energy use.

Month	Orientation	Testing days	Total energy (kWh)	Average daily energy (kWh)	ZNE package savings

			Ref.	ZNE	Ref.	ZNE	
May	South	8	34.53	24.68	4.32	3.09	29%
	West	7	29.12	20.92	4.16	2.99	28%
Jun	South	7	28.90	20.99	4.13	3.00	27%
	West	7	28.99	20.97	4.14	3.00	28%
Aug	South	7	31.60	20.64	4.51	2.95	35%
	West	7	31.15	20.30	4.45	2.90	35%
Dec	South	7	31.66	21.43	4.52	3.06	32%
	West	8	37.68	25.26	4.71	3.16	33%

Table 17. Plug load EUI.

Month	Orientation	Testing days	EUI (Wh/ft2)		Average daily EUI (Wh/ft2)		ZNE package savings
			Ref.	ZNE	Ref.	ZNE	
May	South	8	53.54	38.27	6.69	4.78	29%
	West	7	45.15	32.44	6.45	4.63	28%
Jun	South	7	44.81	32.54	6.40	4.65	27%
	West	7	44.95	32.51	6.42	4.64	28%
Aug	South	7	49.00	32.00	7.00	4.57	35%
	West	7	48.29	31.48	6.90	4.50	35%
Dec	South	7	49.09	33.23	7.01	4.75	32%
	West	8	58.41	39.16	7.30	4.90	33%

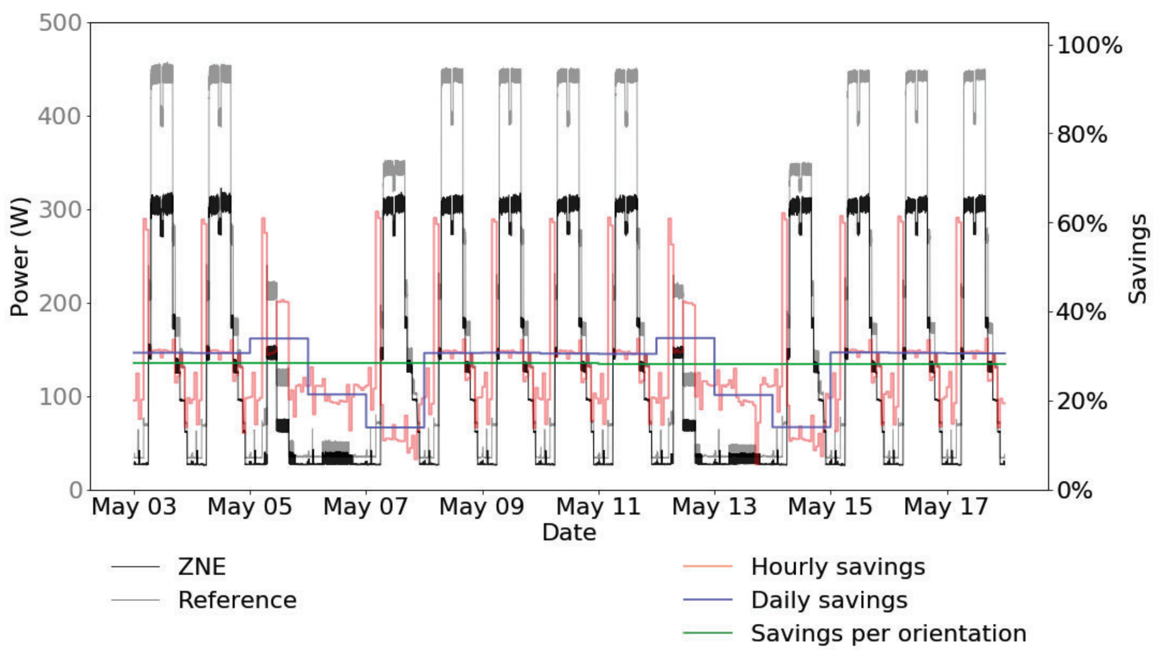

Figure 44. Hourly, daily and per-orientation plug load energy savings for May 2018 testing period.

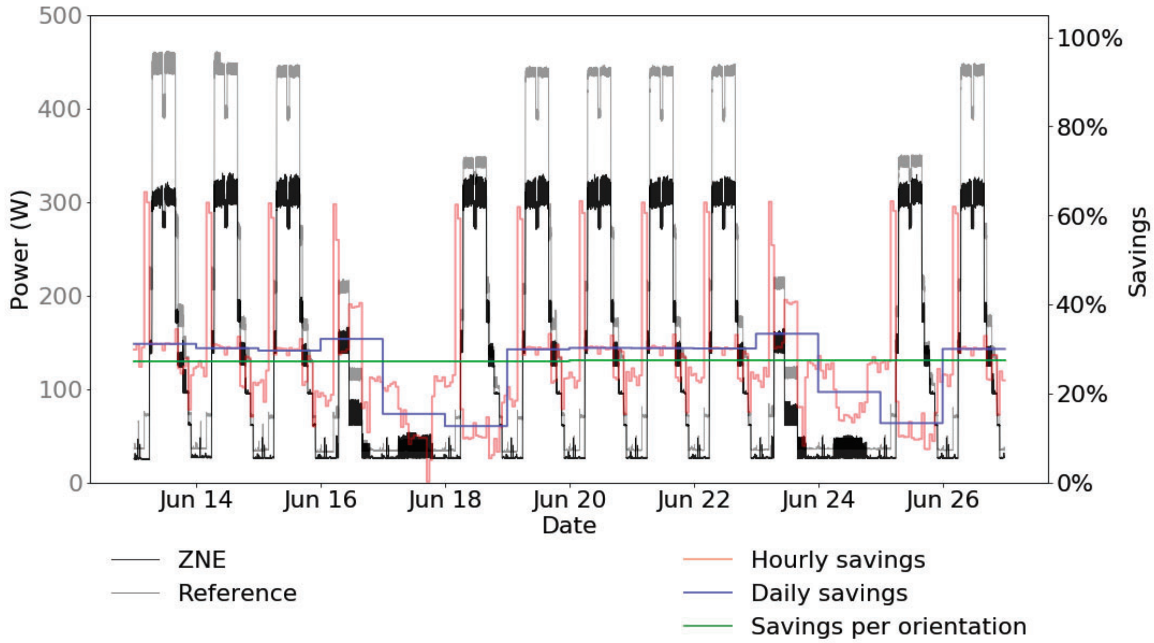

Figure 45. Hourly, daily and per-orientation plug load energy savings for June 2018 testing period.

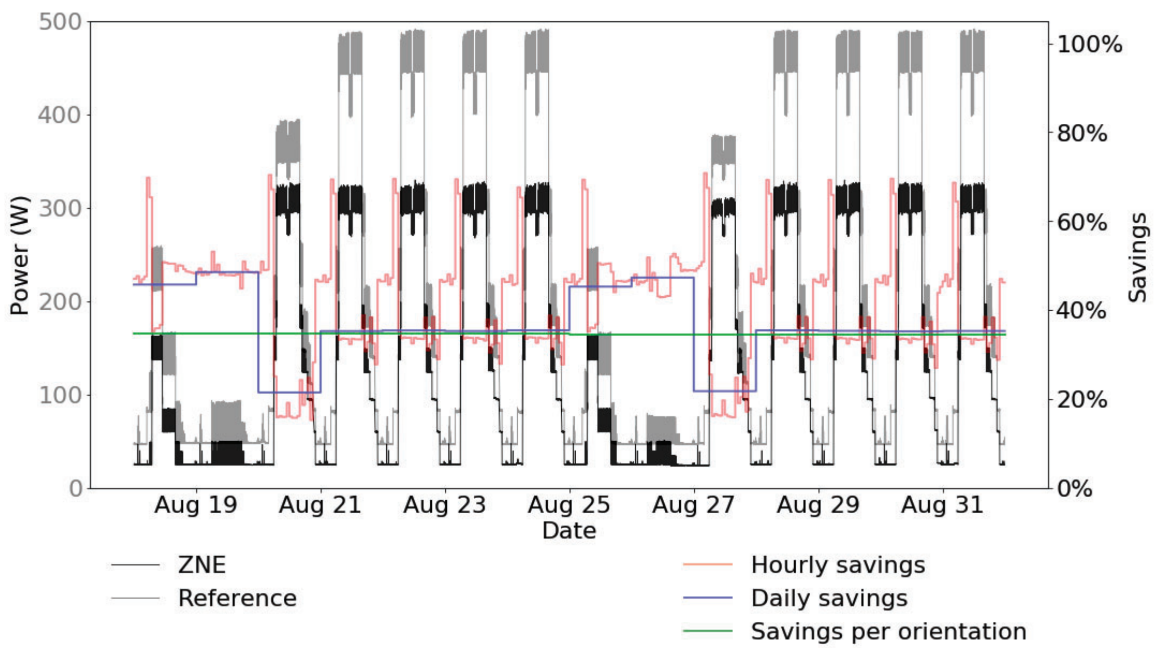

Figure 46. Hourly, daily and per-orientation plug load energy savings for August 2018 testing period.

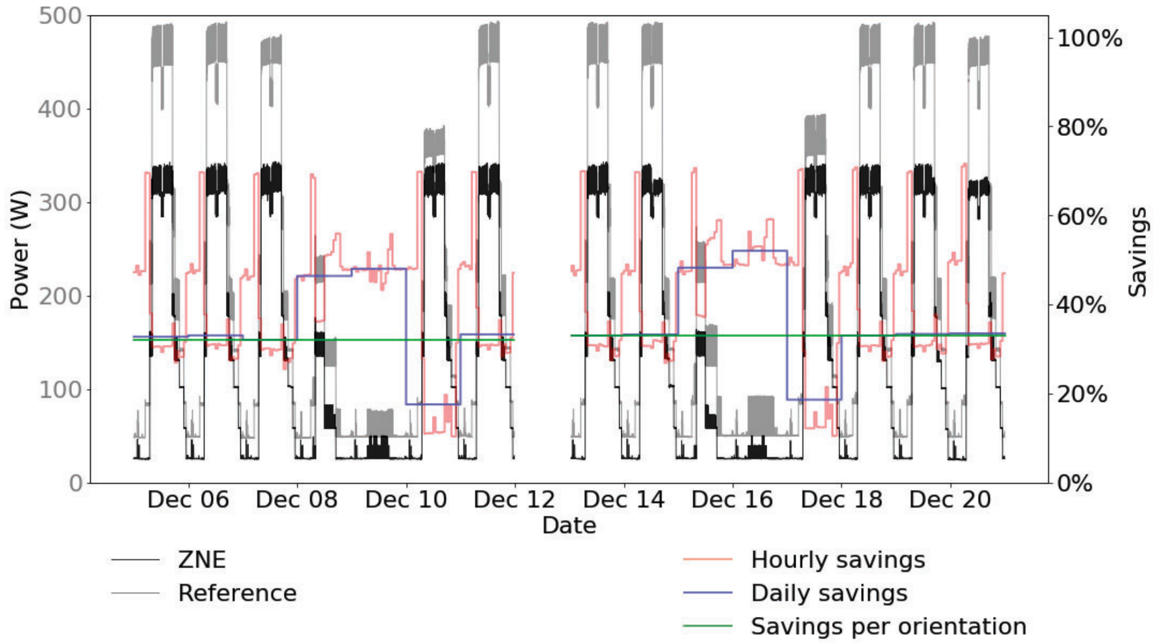

Figure 47. Hourly, daily and per-orientation plug load energy savings for December 2018 testing period.

3.1.5 Visual comfort

In the middle space of the ZNE package cell, measured DGP was well below the 0.35 threshold for perceptible glare. Figure 48 to Figure 51 show DGP data taken from the viewpoint that had the TDD in the field of view. From the point of view of the other workstation in that space, DGP was consistently at 0.1 or below (Figure 52 to Figure 55).

In the window spaces of both cells there were no substantial differences between cells in measured DGP. In May, June and August, when the cells were facing south, maximum DGP was in the vicinity of 0.35 facing the window, and in the 0.25-0.30 range when facing one of the side walls (Figure 57 to Figure 59). When the cells were facing west, DGP was in the 0.45-0.55 range for 2-3 hours in the afternoon when the weather was sunny, indicating the likelihood of disturbing or even intolerable glare (Figure 60 to Figure 64). In December, measured DGP with cells facing south peaked near 0.55 for measurements facing the window, and in the 0.35-0.40 range for measurements facing one of the side walls (Figure 59 and Figure 64). With the cells facing west, maximum DGP measured was in the 0.30-0.40 range for measurements facing the window and around 0.30 for measurements facing one of the side walls.

The occurrences of probable glare that were measured are mainly related to the nature of the shading device selected from the window – a generic, white venetian blind representative of what might be installed in many existing small commercial buildings; there was no substantial difference between the ZNE and reference cell in this regard. A blind with darker, or thicker slats would probably have provided better glare control, possibly with negative impacts on daylight availability in the spaces adjacent to the window.

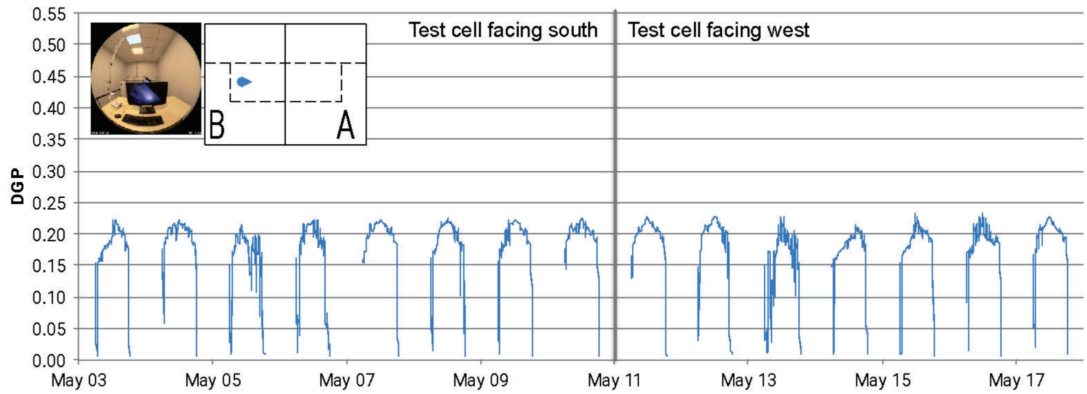

Figure 48. DGP in the enclosed office space in the ZNE package cell, with the TDD in view, for the May 2018 testing period.

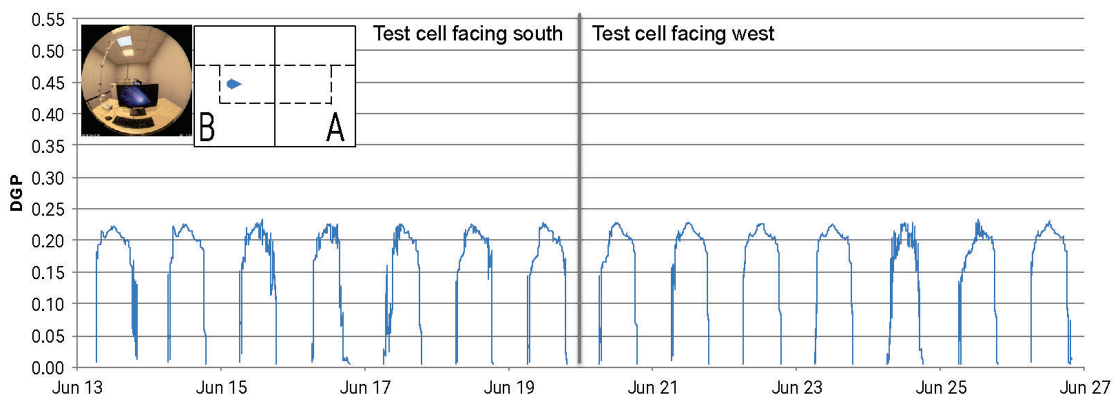

Figure 49. DGP in the enclosed office space in the ZNE package cell, with the TDD in view, for the June 2018 testing period.

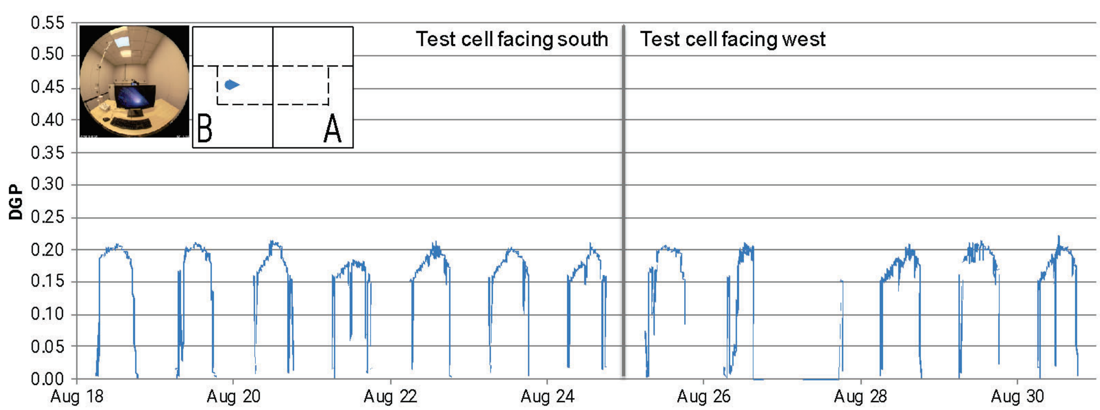

Figure 50. DGP in the enclosed office space in the ZNE package cell, with the TDD in view, for the August 2018 testing period.

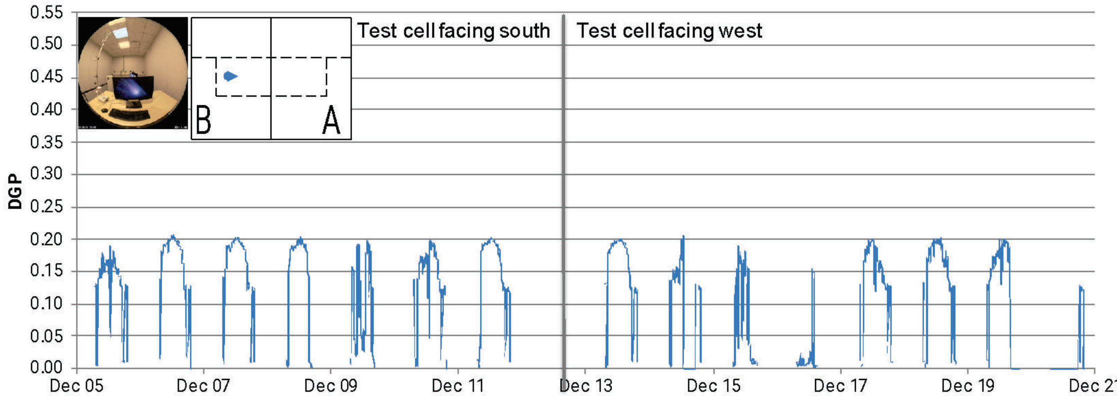

Figure 51. DGP in the enclosed office space in the ZNE package cell, with the TDD in view, for the December 2018 testing period.

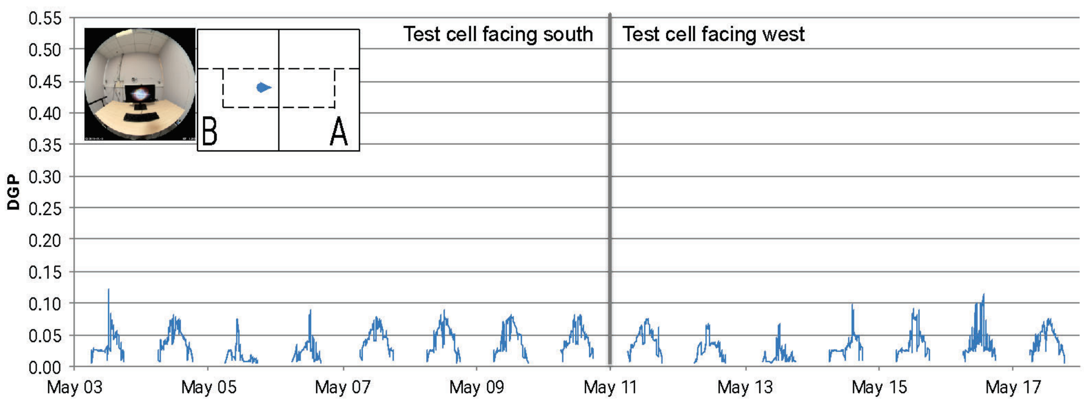

Figure 52. DGP in the enclosed office space in the ZNE package cell, workstation facing wall, for the May 2018 testing period.

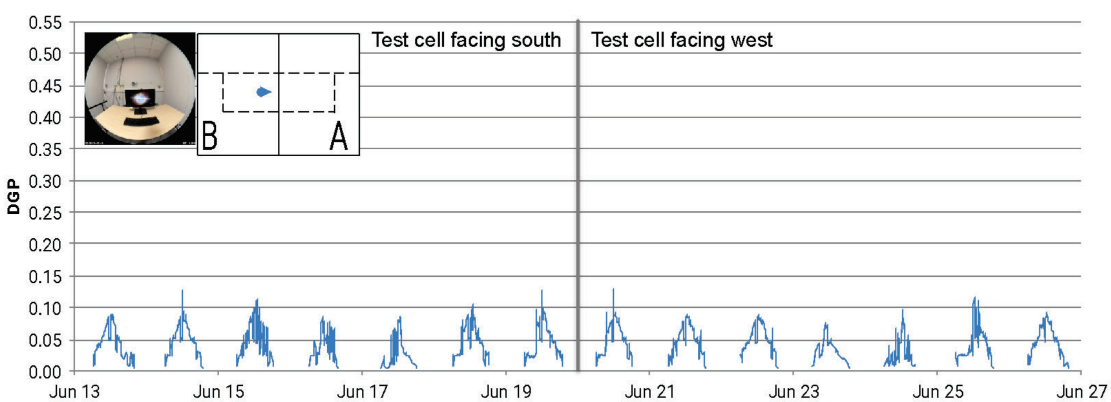

Figure 53. DGP in the enclosed office space in the ZNE package cell, workstation facing wall, for the May 2018 testing period.

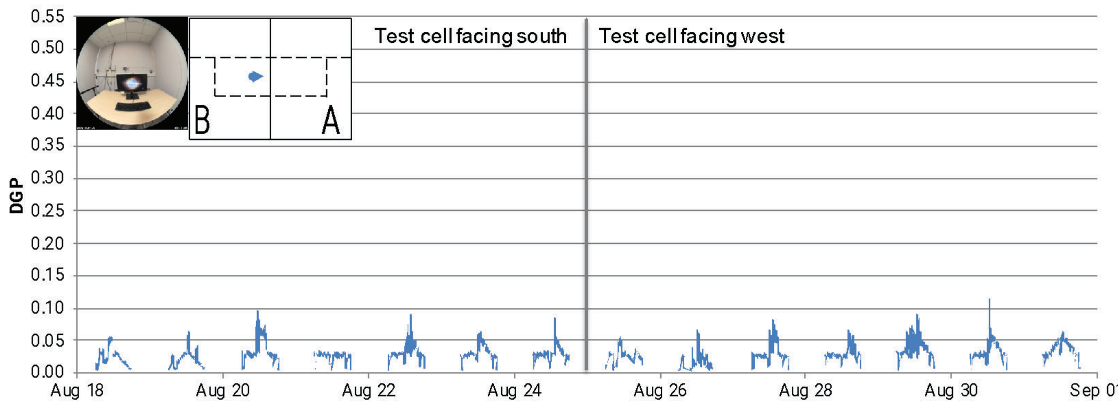

Figure 54. DGP in the enclosed office space in the ZNE package cell, workstation facing wall, for the August 2018 testing period.

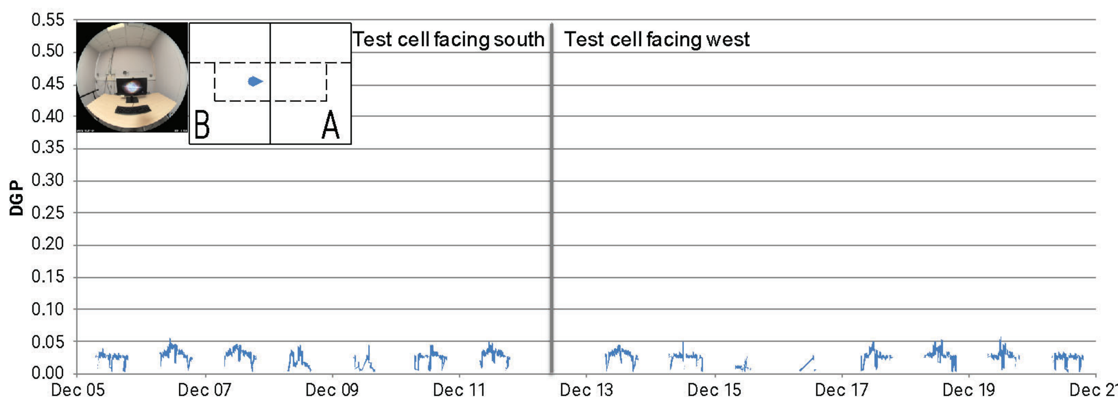

Figure 55. DGP in the enclosed office space in the ZNE package cell, workstation facing wall, for the December 2018 testing period.

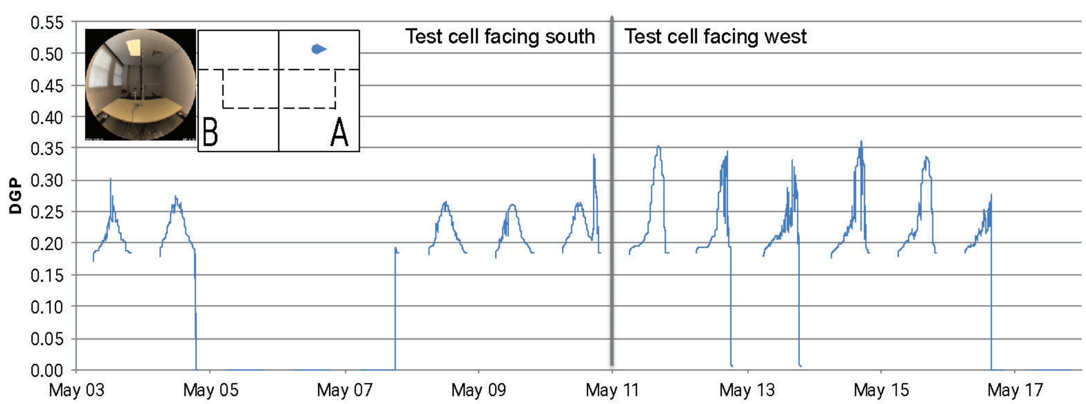

Figure 56. DGP in the window space in the reference cell, facing a side wall, for the May 2018 testing period. Gaps are due to equipment malfunction.

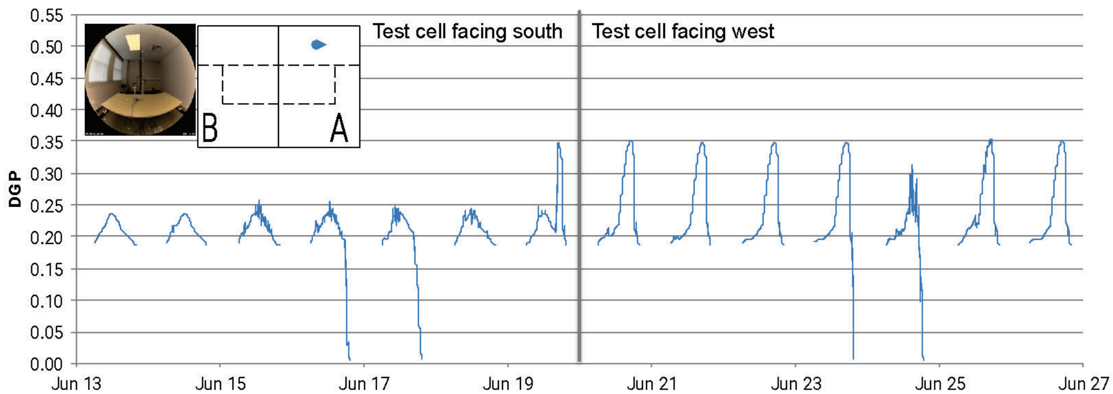

Figure 57. DGP in the window space in the reference cell, facing a side wall, for the June 2018 testing period.

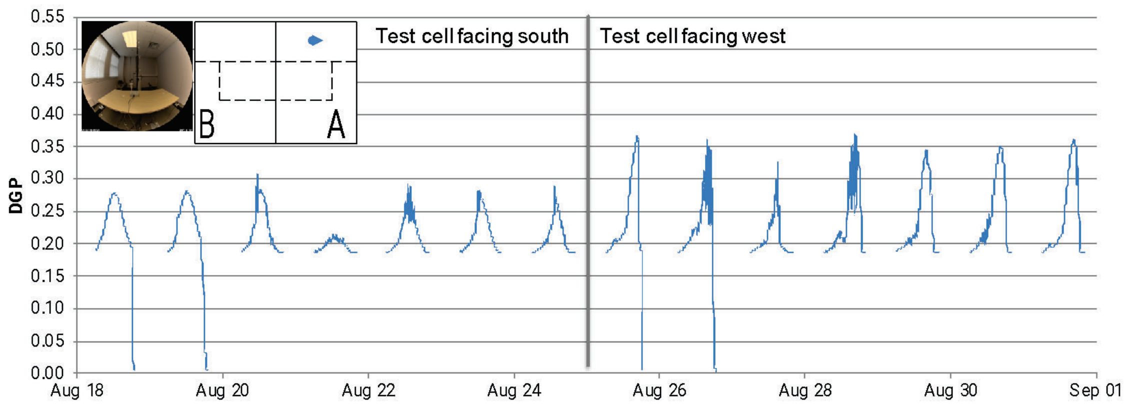

Figure 58. DGP in the window space in the reference cell, facing a side wall, for the August 2018 testing period.

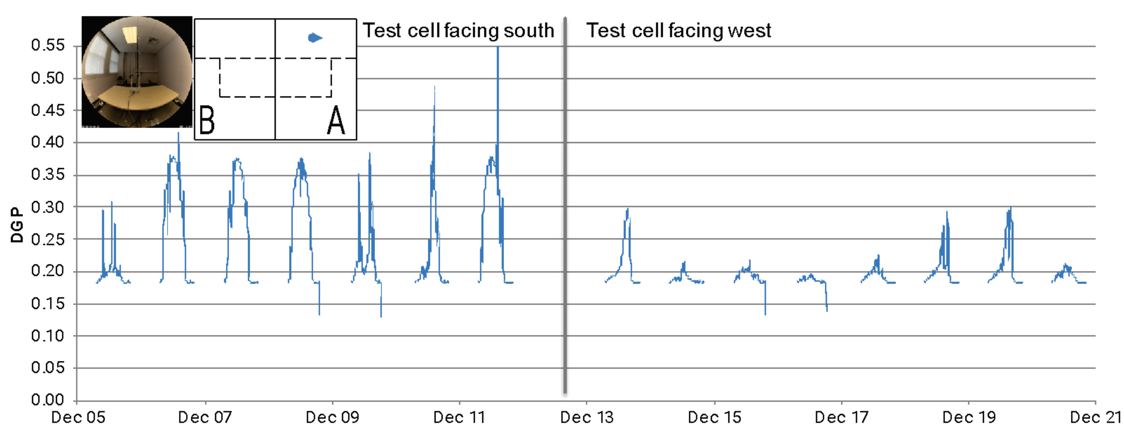

Figure 59. DGP in the window space in the reference cell, facing a side wall, for the December 2018 testing period.

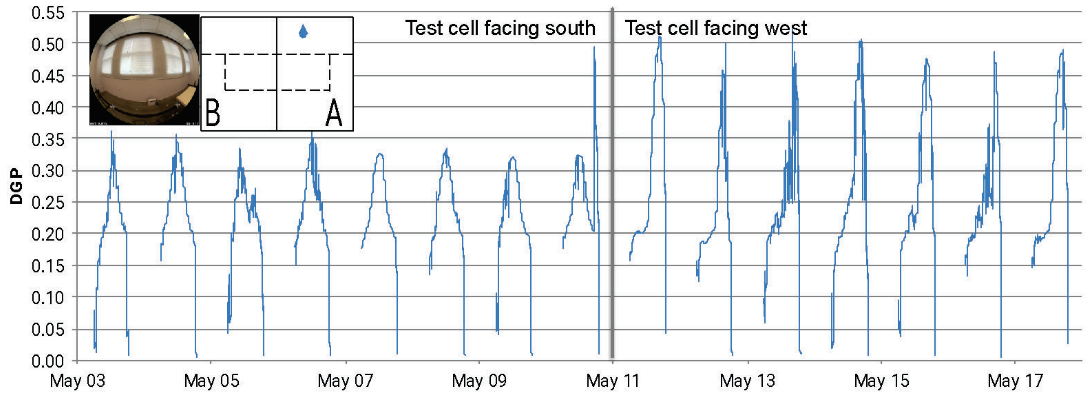

Figure 60. DGP in the window space in the ZNE cell package cell, facing the window, for the May 2018 testing period.

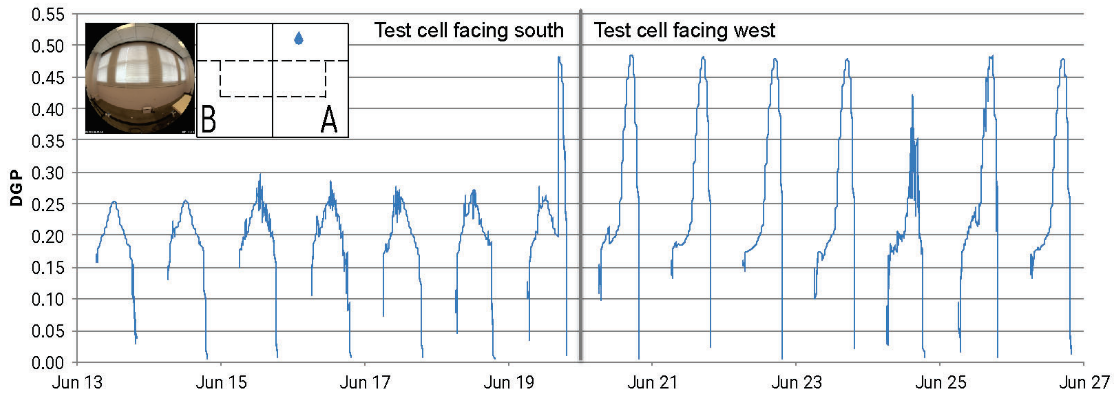

Figure 61. DGP in the window space in the ZNE package cell, facing the window, for the June 2018 testing period.

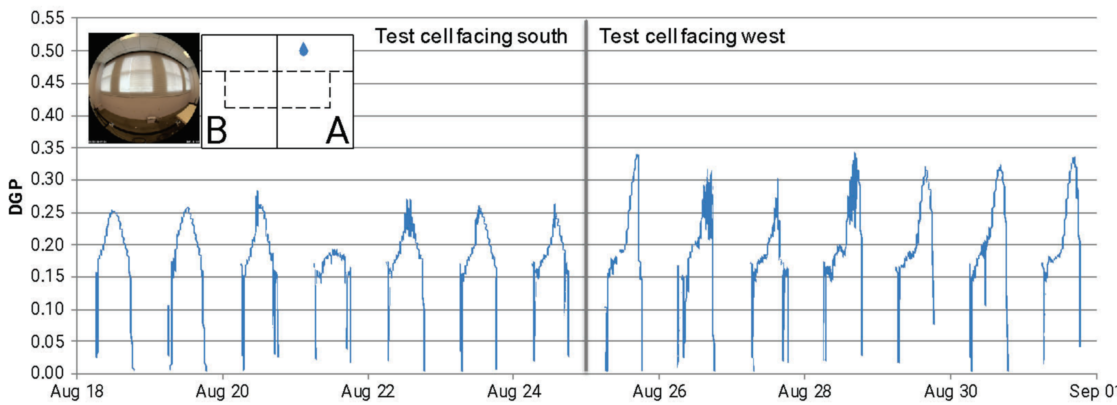

Figure 62. DGP in the window space in the ZNE package cell, facing the window, for the August 2018 testing period.

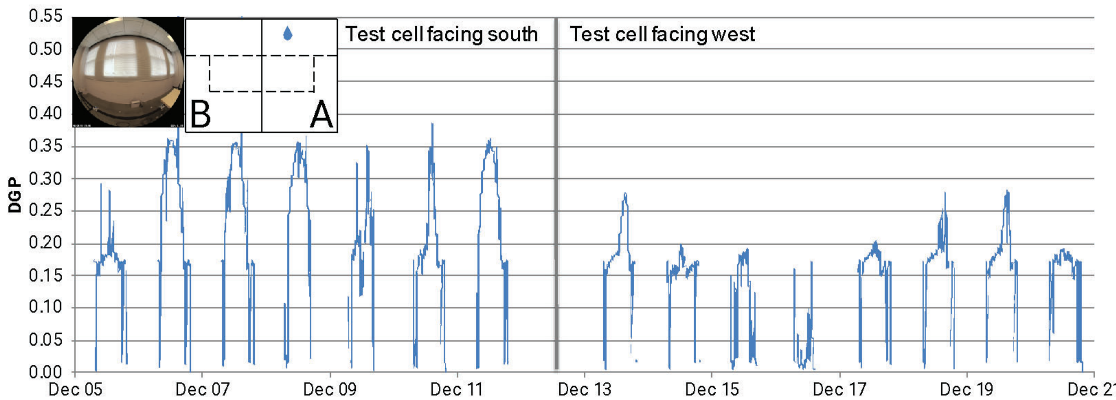

Figure 63. DGP in the window space in the ZNE package cell, facing the window, for the December 2018 testing period.

3.1.6 Total energy consumption

Total energy consumption was calculated by adding calculated HVAC energy (in the form of electricity and gas) use and measured lighting and plug load energy use. It is shown in Table 18 and Table 19. ZNE package savings were in the 59%-69% range for cooling-dominated test periods (May through August) and 22-25% range during the heating dominated test period (December). Hourly, daily and per-orientation variation in total energy savings is shown in Figure 64 through Figure 67.

Table 18. Total energy use.

Month	Orientation	Testing days	Total energy (kWh)		Average daily energy (kWh)		ZNE package savings
			Ref.	ZNE	Ref.	ZNE	
May	South	8	163.08	66.84	20.39	8.35	59%
	West	7	141.75	45.64	20.25	6.52	68%
Jun	South	7	152.94	49.15	21.85	7.02	68%
	West	7	169.18	54.53	24.17	7.79	68%
Aug	South	7	143.55	45.38	20.51	6.48	68%
	West	7	147.13	45.96	21.02	6.57	69%
Dec	South	7	194.62	152.62	27.80	21.80	22%
	West	8	184.68	138.68	23.08	17.33	25%

Table 19. Total EUI.

Month	Orientation	Testing days	EUI (Wh/ft2)		Average daily EUI (Wh/ft2)		ZNE package savings
			Ref.	ZNE	Ref.	ZNE	
May	South	8	252.84	103.62	31.61	12.95	59%
	West	7	219.76	70.77	31.39	10.11	68%

Jun	South	7	237.11	76.20	33.87	10.89	68%
	West	7	262.29	84.54	37.47	12.08	68%
Aug	South	7	222.55	70.36	31.79	10.05	68%
	West	7	228.11	71.26	32.59	10.18	69%
Dec	South	7	301.74	236.63	43.11	33.80	22%
	West	8	286.32	215.00	35.79	26.88	25%

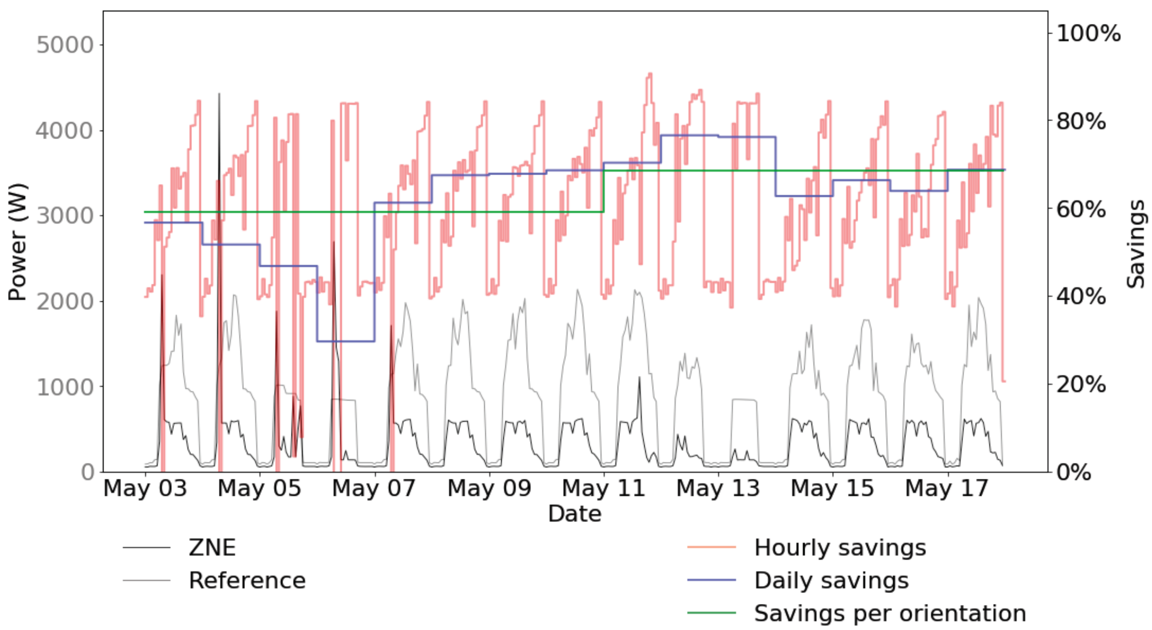

Figure 64. Hourly, daily and per-orientation total energy savings for the May 2018 testing period.

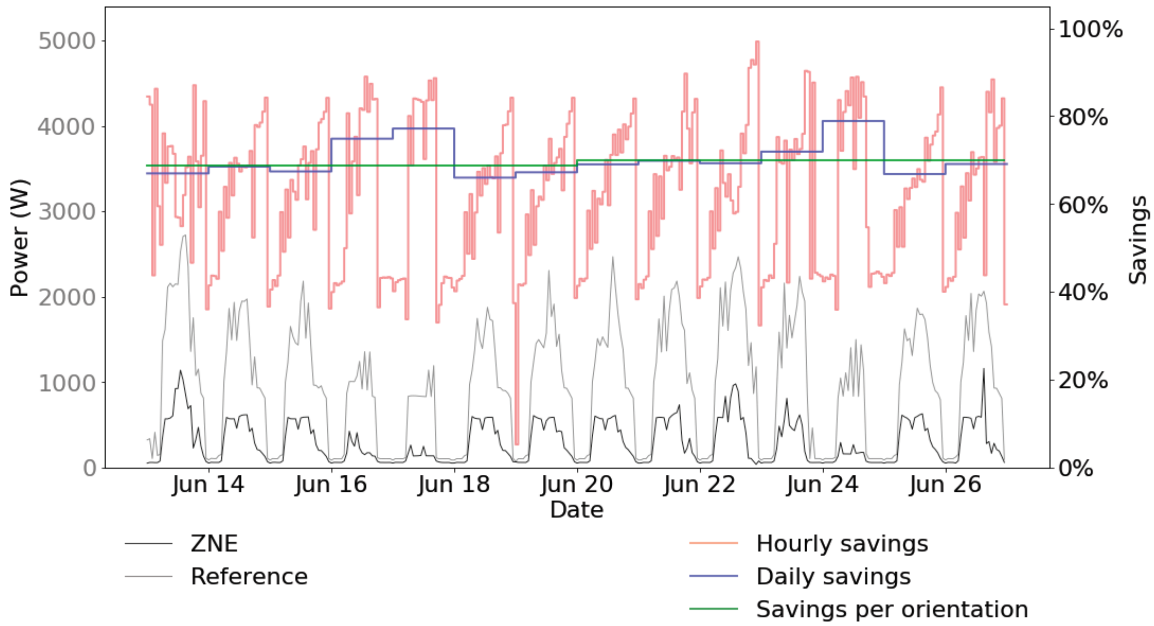

Figure 65. Hourly, daily and per-orientation total energy savings for the June 2018 testing period.

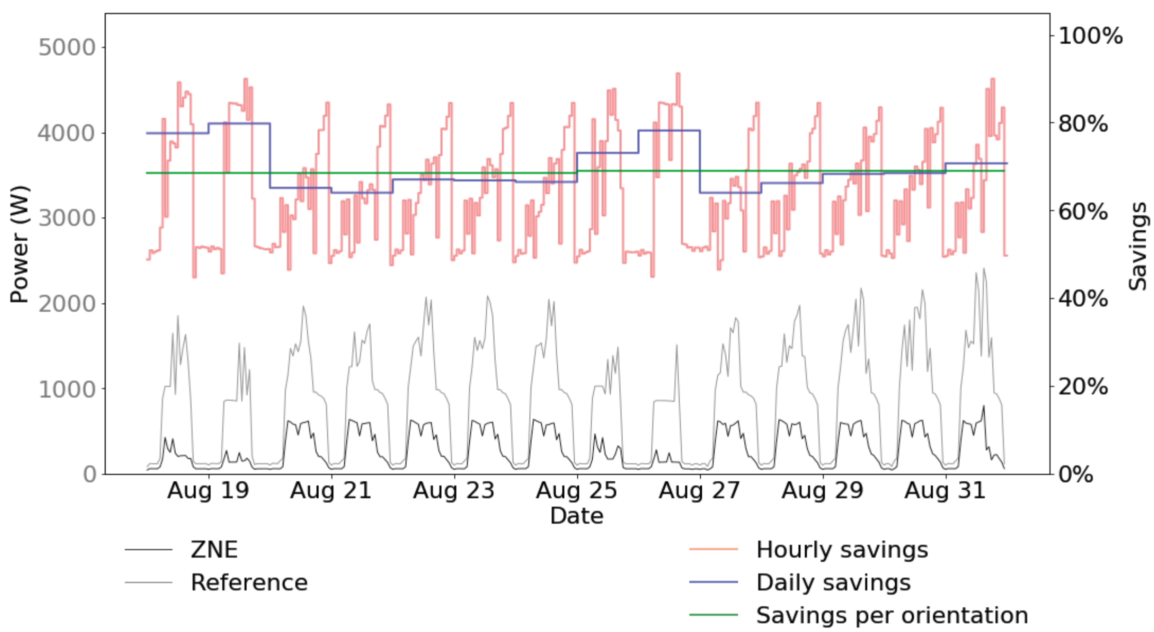

Figure 66. Hourly, daily and per-orientation total energy savings for the August 2018 testing period.

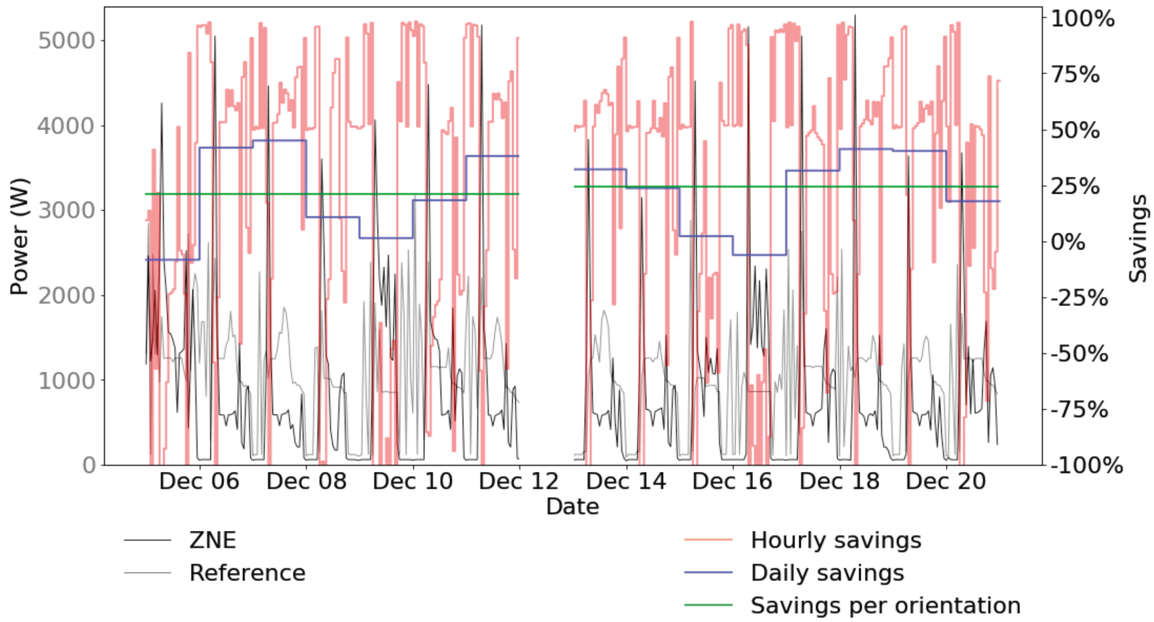

Figure 67. Hourly, daily and per-orientation total energy savings for the December 2018 testing period.

3.2 TDD tests

3.2.1 Light levels under clear sky

During the tests, indoor light levels provided by the TDDs varied substantially, depending on time of day, sky cover and TDD diameter and, to a lesser extent, type of TDD dome and diffuser. Figure 68 shows minimum, average, and maximum horizontal illuminance obtained with the TDD-SPF configuration during the February 2018, May 2018 and January 2019 tests under clear sky. Illuminance increases as solar altitude[2] increases, and that is evident both within each day and when comparing different times of the year.

[2] Solar altitude can be defined as the angle between 1) a line towards the sun originating at the observer's position and 2) a horizontal plane that includes the observer's position.

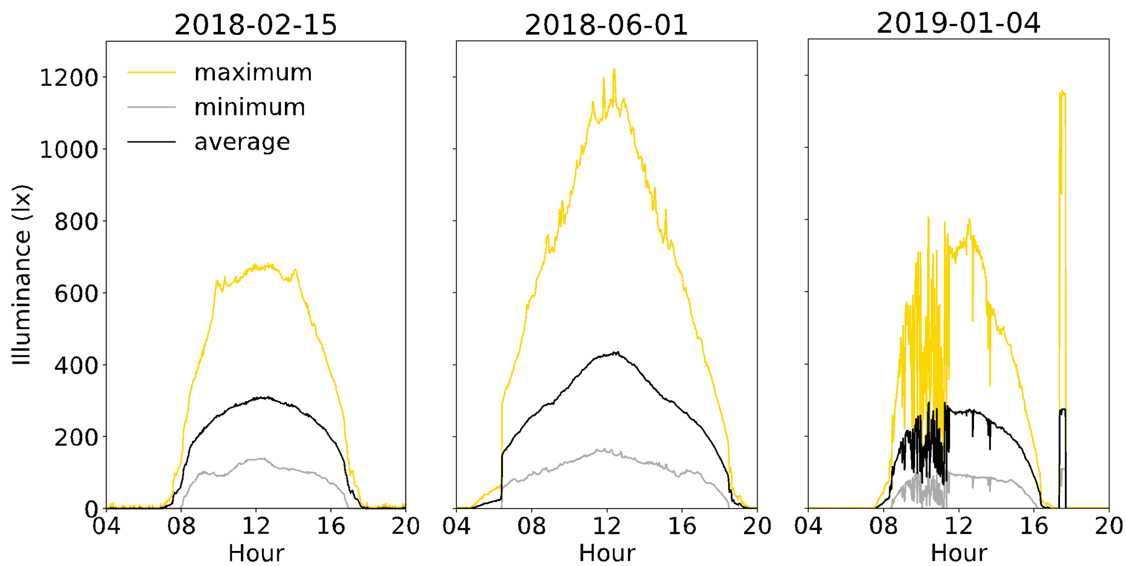

Figure 68. Minimum, average, and maximum horizontal illuminance obtained with the TDD-SPF configuration under clear skies during the February 2018, May 2018, and January 2019 tests. Note that 1) for January 4, 2019 the sky was not clear between 8 and 11 AM, approximately, and 2) the period of high illuminance after sunset on January 4, 2019 was due to electric lights being turned on for a short period; data for that period was not included in the analysis.

Within the interior space, illuminance is consistently higher towards the center of the room (Figure 69). This is expected because the TDD is situated in the center of the room. Similar trends were observed for other 21-inch TDD configurations as well as the 14-inch TDD configurations; however, the 14-inch TDD configurations had lower illuminance levels overall when compared to the 21-inch TDD configurations (Figure 70).

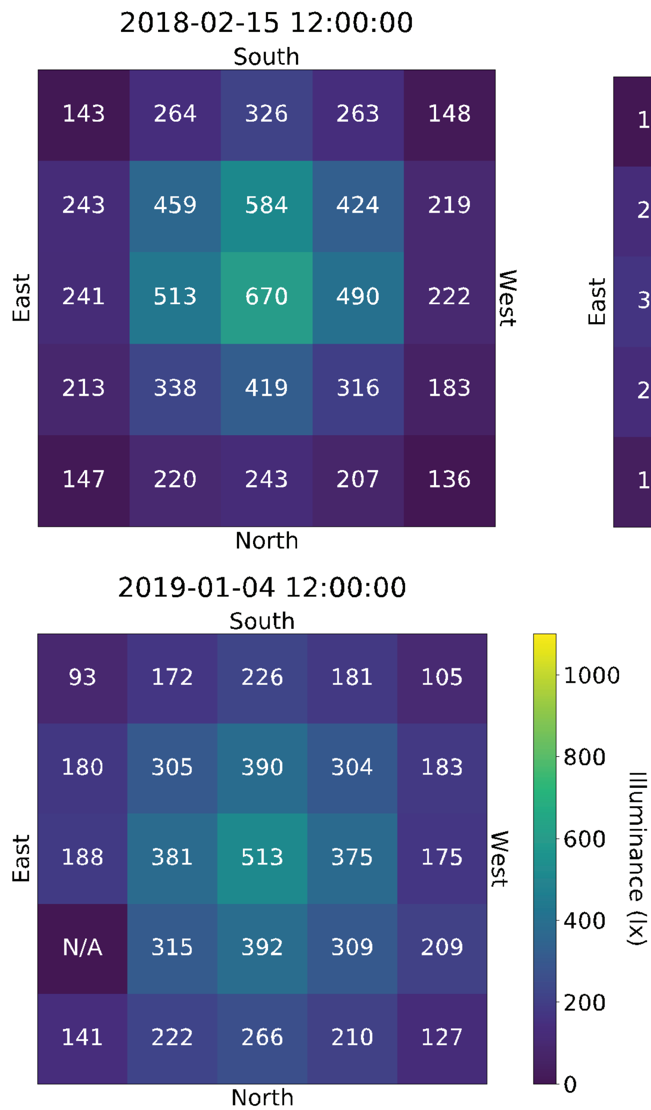

Figure 69. Illuminance distribution within interior space obtained with the TDD-SPF configuration under clear sky at noon during the February 2018, May 2018, and January 2019 tests. Note that one of the sensors along the eastern edge of the room malfunctioned during the January tests; a numerical value for that sensor is not shown.

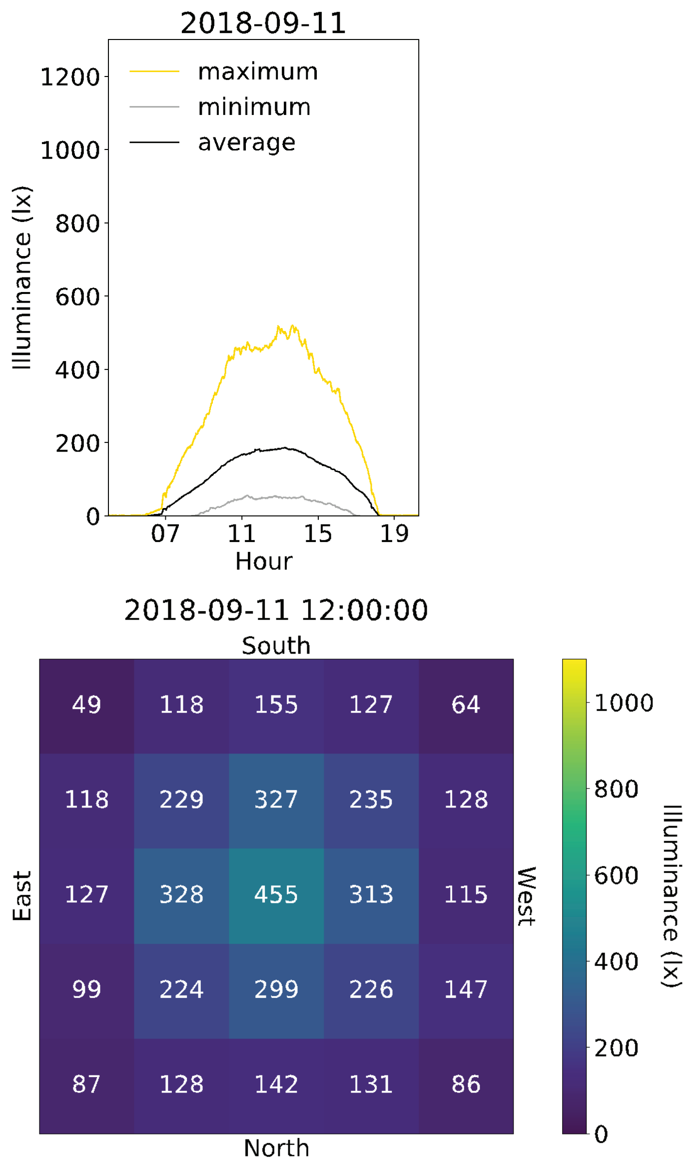

Figure 70. Horizontal illuminance under clear sky for 14” TDD (configuration TDD-14A) during the September 2018 test.

3.2.2 Lighting energy

Horizontal illuminance measurements taken throughout the TDD tests were used to calculate the amount of energy that would be saved by dimming electric lighting just enough to maintain each measurement at an illuminance of at least 300 lux, a commonly used horizontal illuminance setpoint in office lighting design. Assuming an installed power of 0.75 W/ft^2 – a reasonable assumption for LED luminaires and the maximum installed lighting power density in general office spaces allowed by the 2016 California building code for office spaces greater than 250 ft^2 [CEC, 2016] – annualized[3] energy consumption for each TDD configuration ranged between 0.61 and 1.53 kWh/ft^2-yr. This represents lighting energy savings between 22% and 69% (Figure 71). The results in Figure 71 are not weighted to account for the differences in sky cover observed between test configurations. In particular, the higher energy use obtained with the TDD-SPF configuration was due to higher occurrence of overcast sky during testing. The higher energy use observed with 14" TDDs is likely due to their smaller diameter relative to the 21" TDDs.

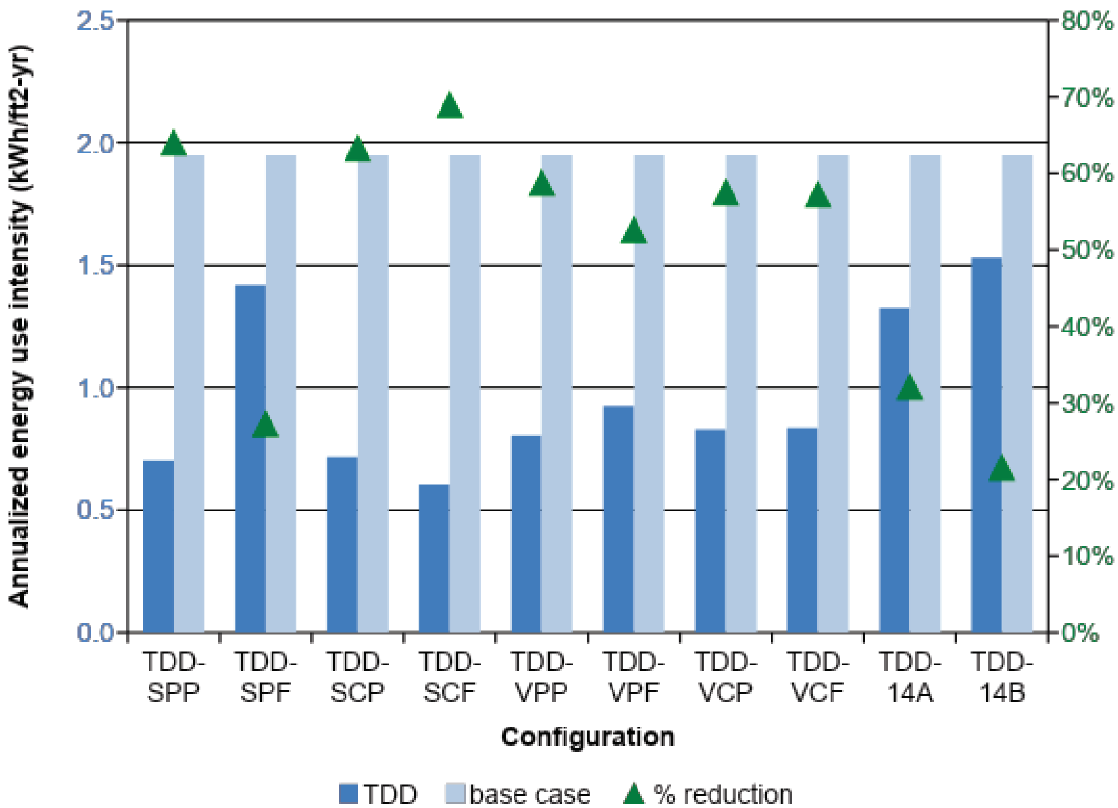

Figure 71. Annualized lighting energy use with the ten different TDD configurations. These results are not weighted to account for the differences in sky cover between test configurations. In particular, the higher energy use obtained with the TDD-SPF configuration was due to higher occurrence of overcast sky during testing.

[3] For each minute between 8 AM and 6 PM, the fraction of electric lighting installed power that was needed to supplement available daylight in order to achieve an average horizontal illuminance was calculated, assuming that 0.75 W/ft^2 provided 300 lx. For each TDD configuration, that fraction of electric lighting installed power was then averaged over the test period(s). To obtain the annualized energy use, that average power fraction was then multiplied by the installed lighting power density (0.75 W/ft^2) and by the number of annual hours of operation (2600 hours, equivalent to 50 hours per week).

To have a clearer view of TDD performance, it is helpful to separately examine performance under separate types of sky. Sky type was determined using the criteria in Table 20 [Fernandes, 2013]. Figure 72 shows lighting energy savings and average horizontal illuminance using the TDD-SFP configuration for typical clear sky days in February and June. Illuminance is higher in June than in February, as would be expected due to the higher solar altitude in June. Similar data for overcast skies is shown in Figure 73.

Table 20. Criteria for determining sky type based on irradiance measurements.

Sky type	**Criterion**
Clear	Direct normal irradiance is more than 200% of diffuse horizontal irradiance
Intermediate	Direct normal irradiance is between 5% and 200% of diffuse irradiance
Overcast	Direct normal irradiance is less than 5% of diffuse irradiance

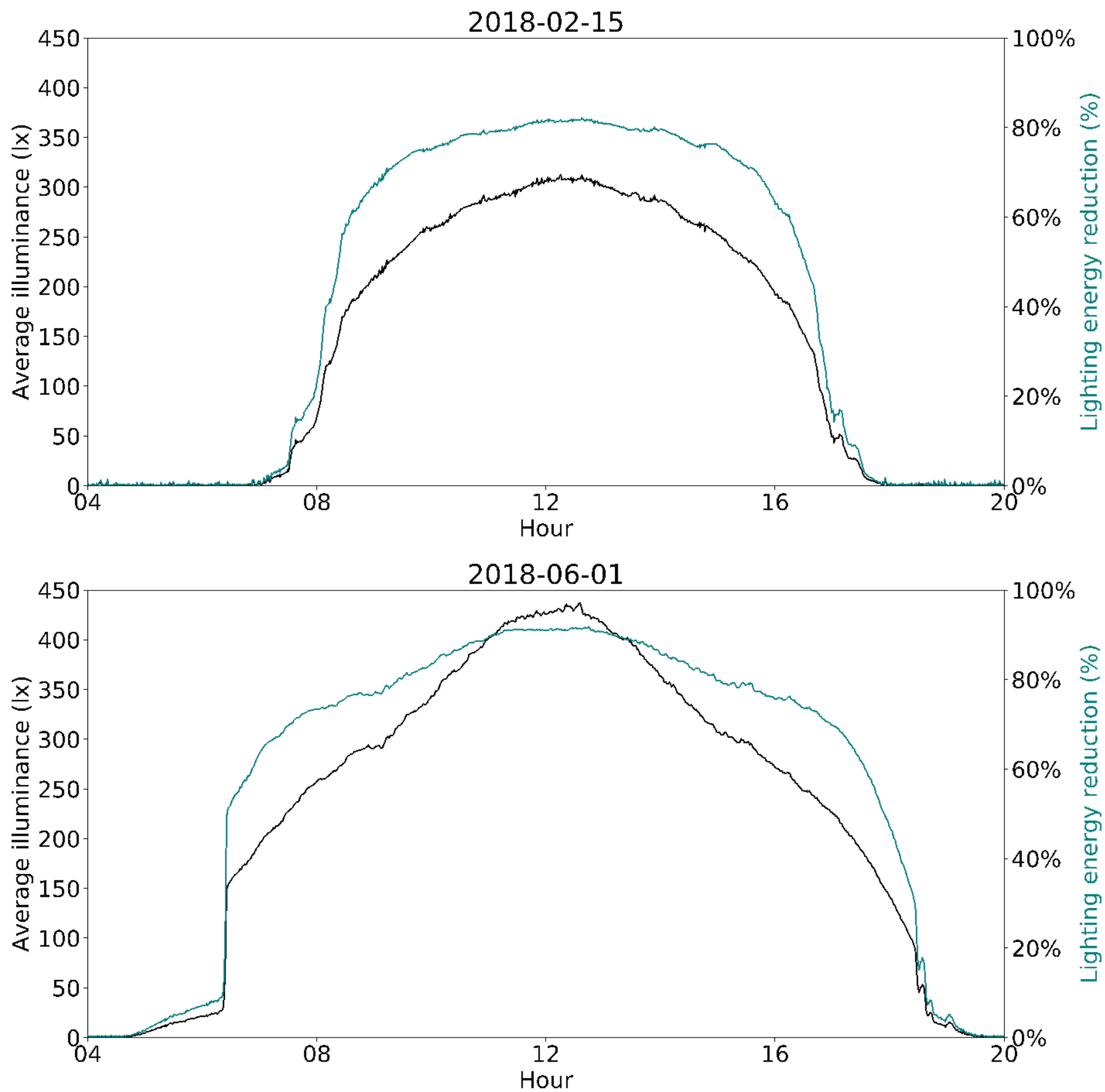

Figure 72. Average interior horizontal illuminance and estimated lighting energy savings for clear sky days during February and June 2018. Data shown for TDD-SFP configuration.

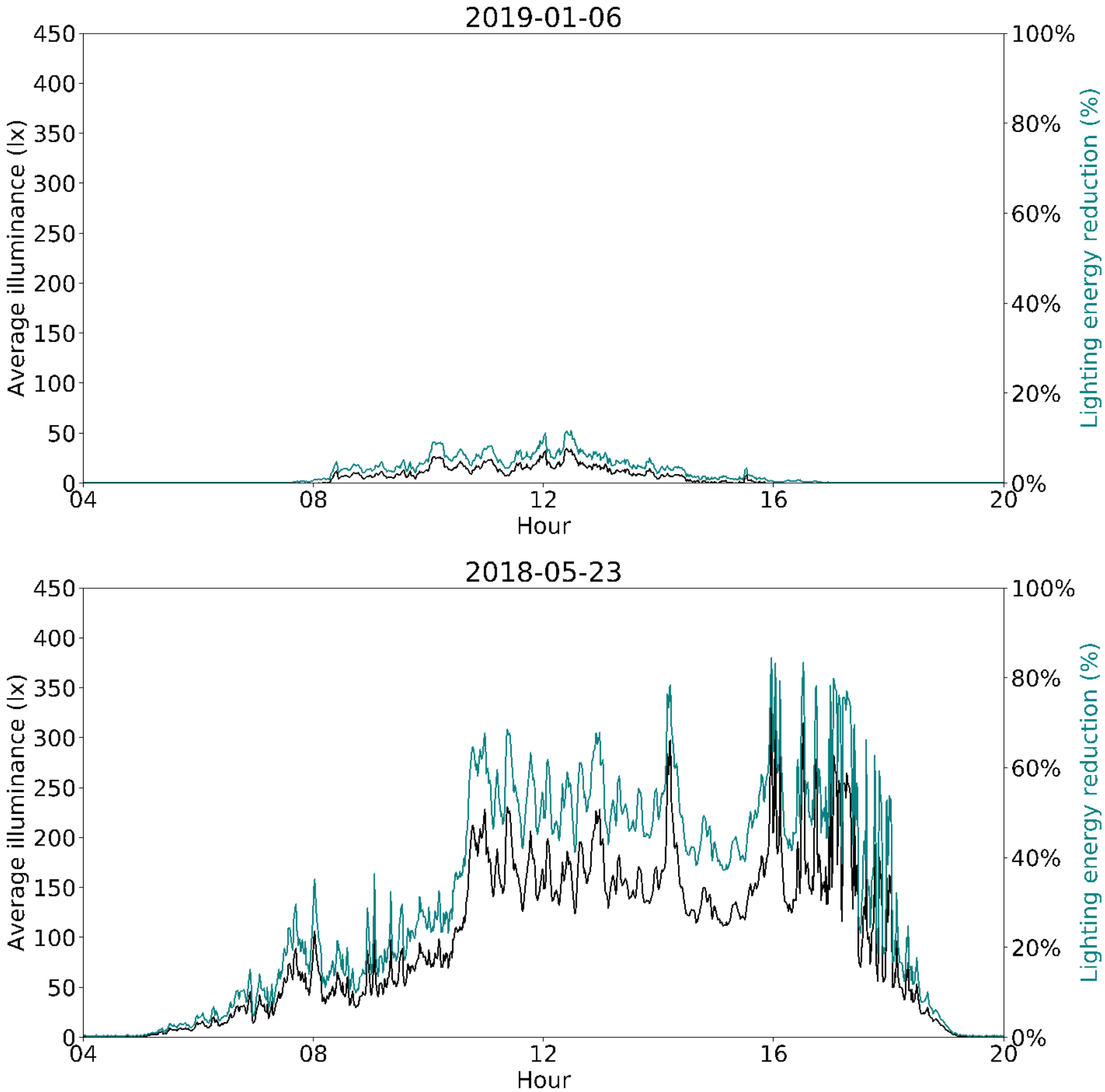

Figure 73. Average interior horizontal illuminance and estimated lighting energy savings for overcast sky days during January 2019 and May 2018. Data shown for TDD-SFP configuration.

Whole-day energy savings, calculated using the same methodology, are shown in Figure 74 for clear sky days. It should be noted that, in some cases, it was not possible to record data for a whole clear day, but only for half a day. This is mainly due to a weather pattern that commonly occurs at the test location, in which the sky is overcast in the morning and clear in the afternoon. For these cases, savings with clear sky were computed based on afternoon data only. Figure 75 shows corresponding results for overcast sky days. Similarly, in some cases savings were computed based on morning data only. These results indicate higher savings for clear skies, increasing with solar altitude.

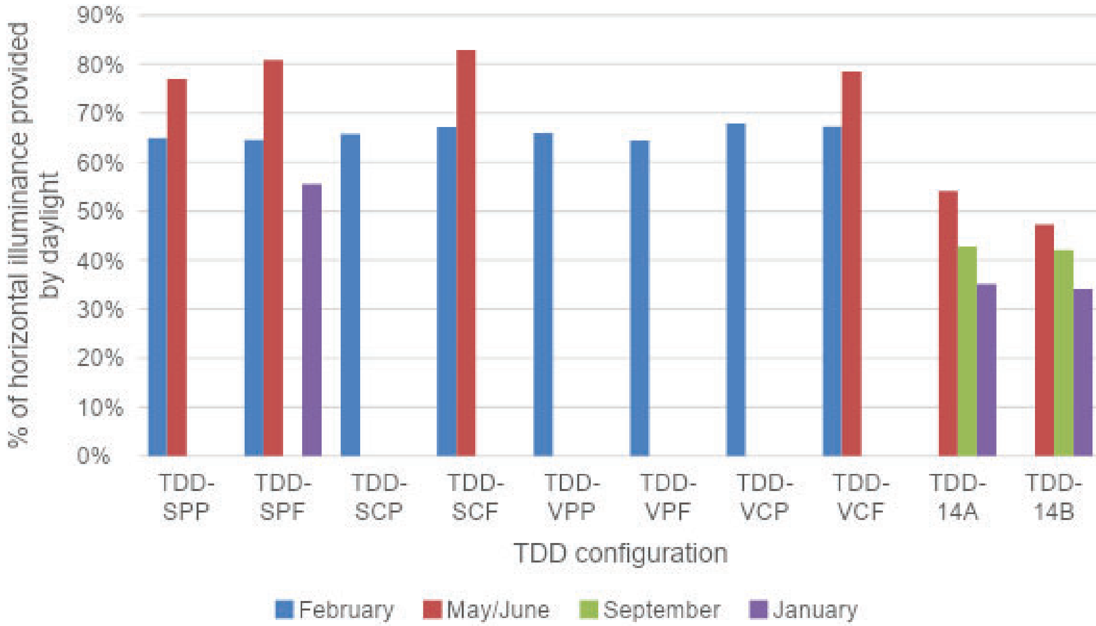

Figure 74 Estimated percentage lighting energy savings from TDD under clear sky. Values for TDD-VCP and TDD-VCF configurations in February, and TDD-SCF in January are based on afternoon data only.

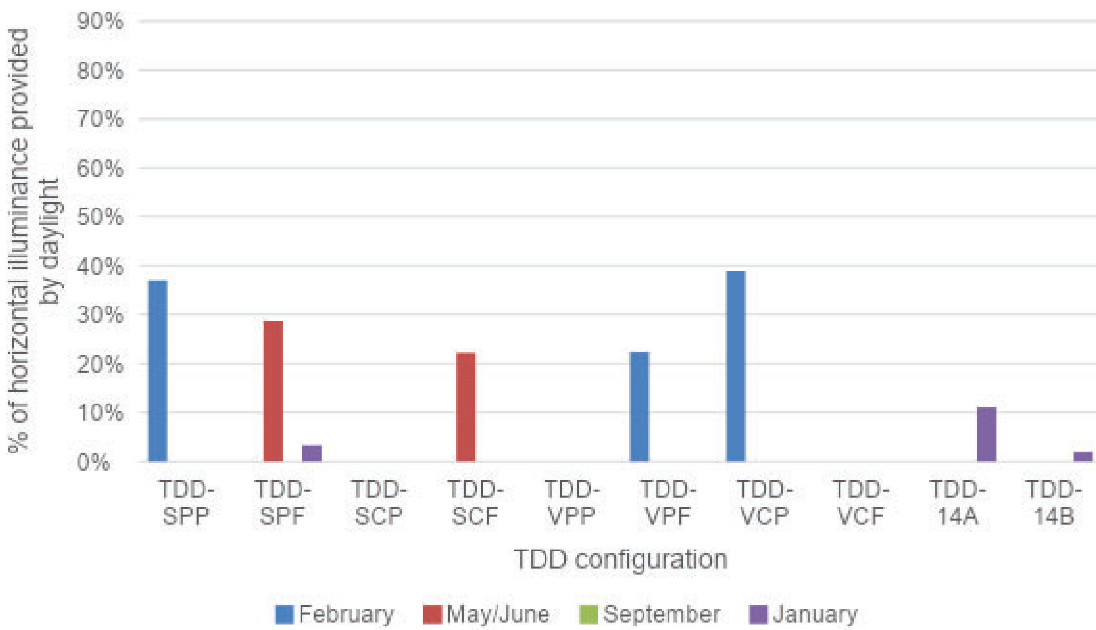

Figure 75. Estimated percentage lighting energy savings from TDD under overcast sky. Values for TDD-SPP and TDD-VCP configurations in February, TDD-SPF and TDD-SCF configurations in May/June, and TDD-14A in January are based on morning data only.

3.2.3 Visual comfort

All the TDD configurations tested were able to maintain conditions below the DGP 0.35 threshold for perceptible glare. Figures 79 to Figure 91 show DGP values throughout the four testing periods (see Figure 5 for measurement locations). The maximum DGP value recorded was 0.33, from position D (Figure 48), with the TDD-SCF configuration.

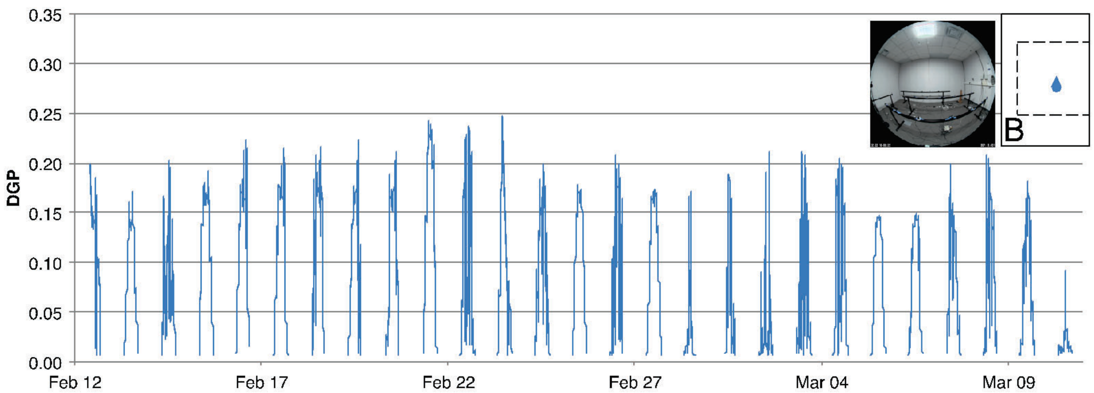

Figure 76. DGP measured from position A during the February-March 2018 testing period.

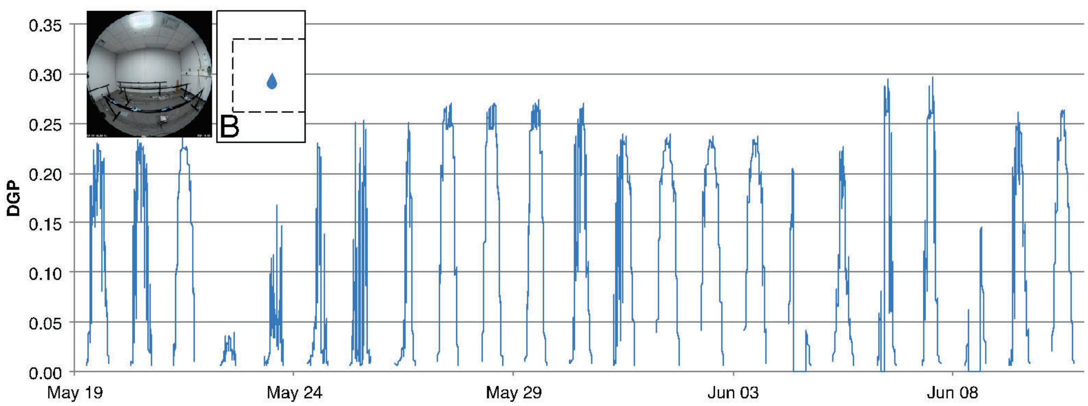

Figure 77. DGP measured from position A during the May-June 2018 testing period.

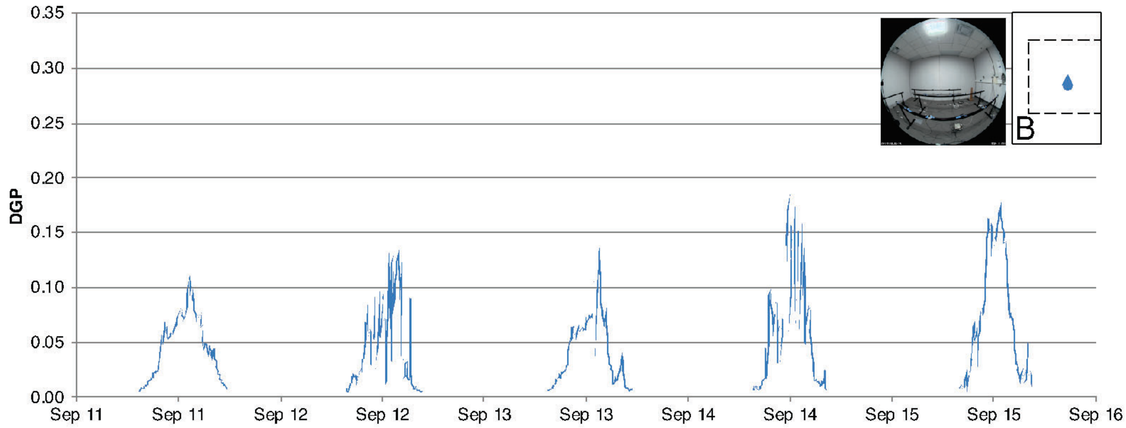

Figure 78. DGP measured from position A during the September 2018 testing period.

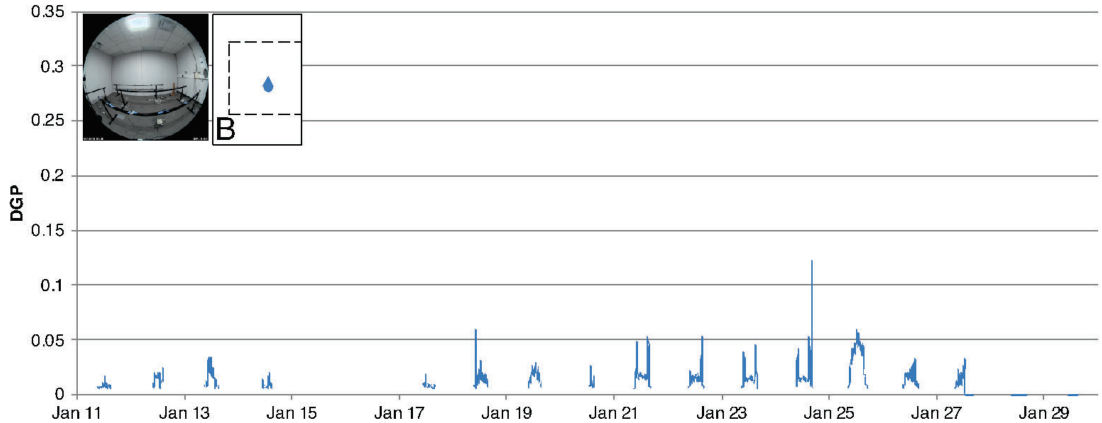

Figure 79. DGP measured from position A during the January 2019 testing period.

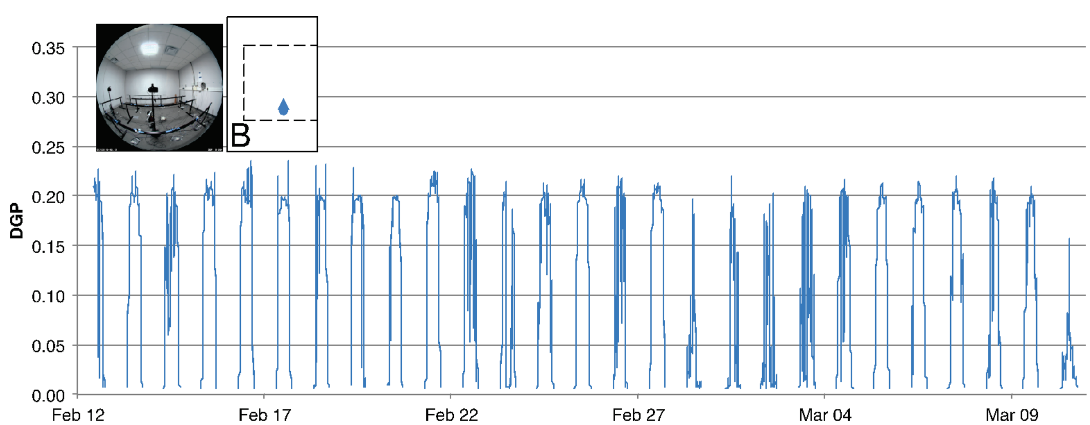

Figure 80. DGP measured from position B during the February-March 2018 testing period.

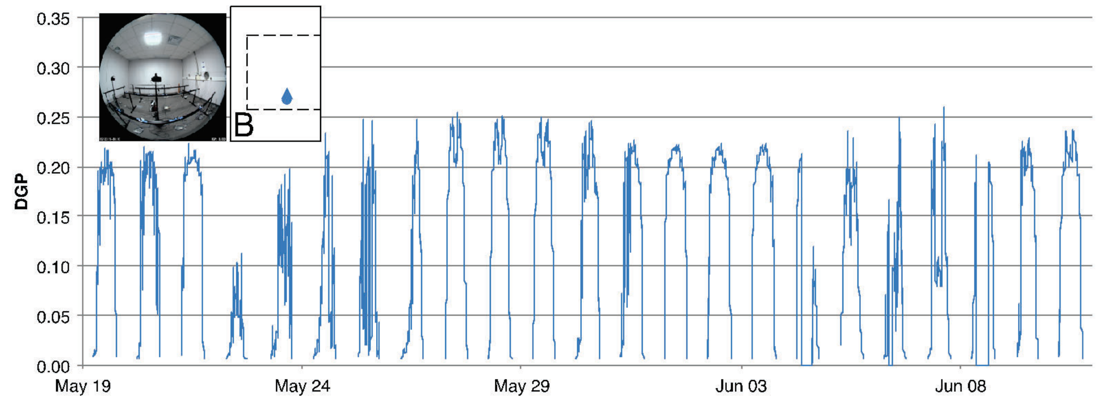

Figure 81. DGP measured from position B during the May-June 2018 testing period.

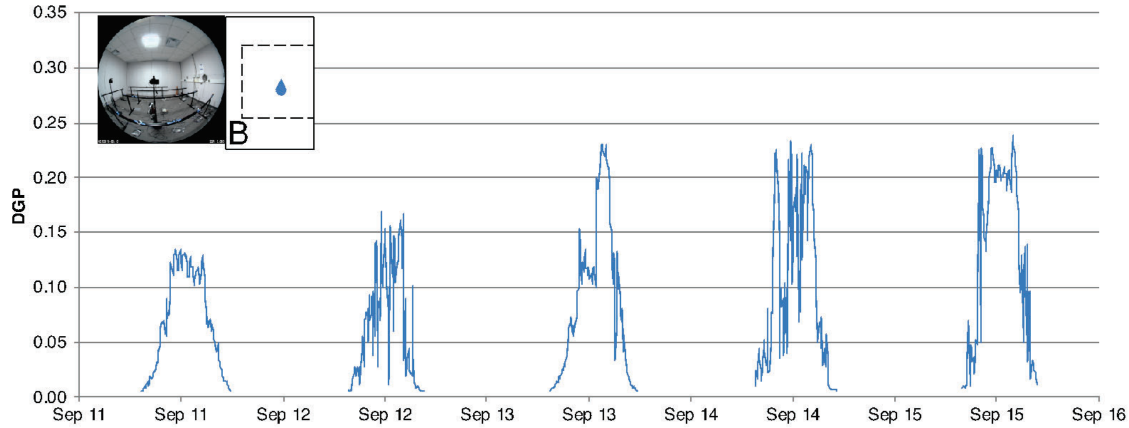

Figure 82. DGP measured from position B during the September 2018 testing period.

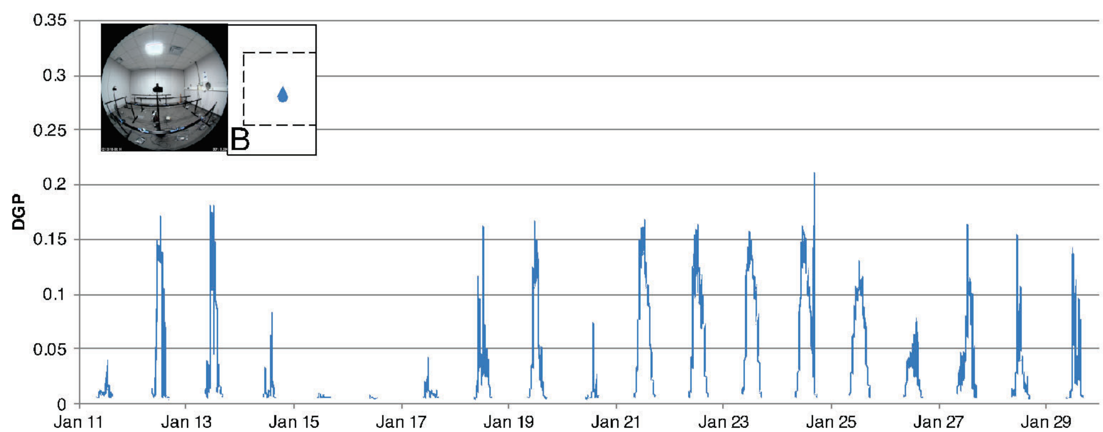

Figure 83. DGP measured from position B during the January 2019testing period.

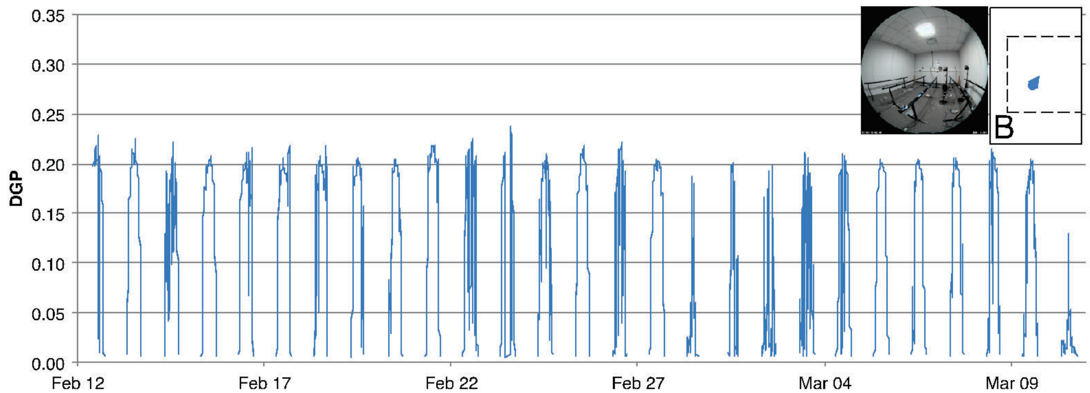

Figure 84. DGP measured from position C during the February-March 2018 testing period.

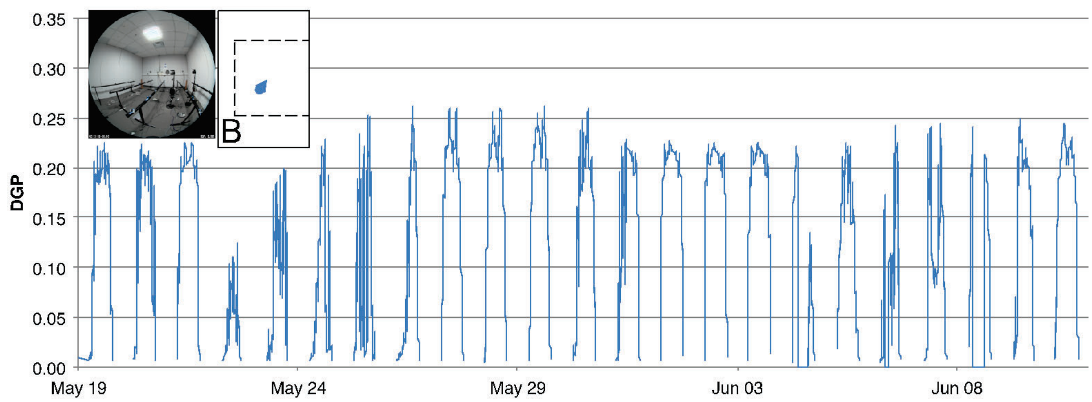

Figure 85. DGP measured from position C during the May-June 2018 testing period.

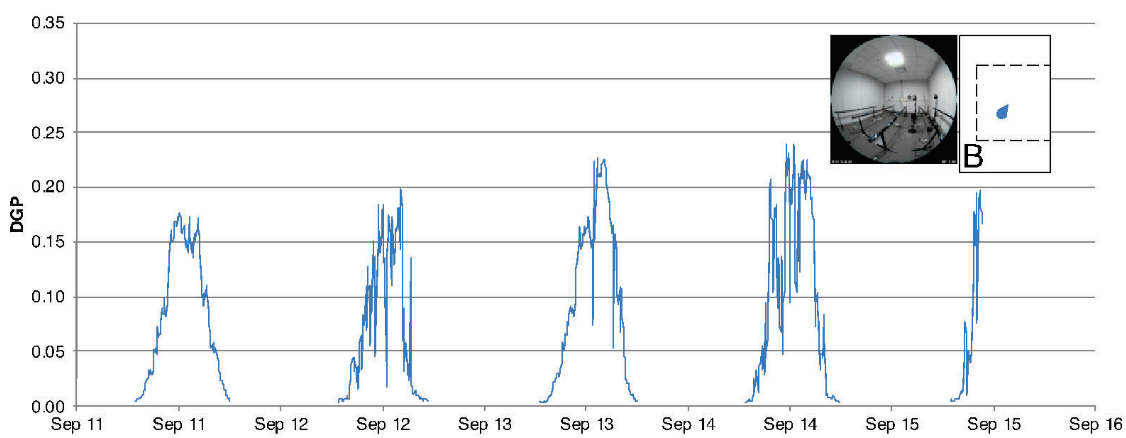

Figure 86. DGP measured from position C during the September 2018 testing period.

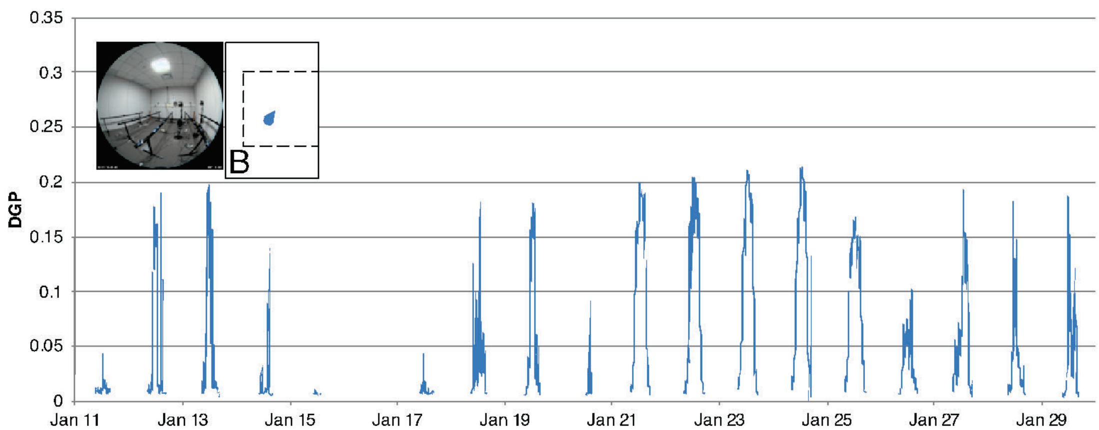

Figure 87. DGP measured from position C during the January 2019 testing period.

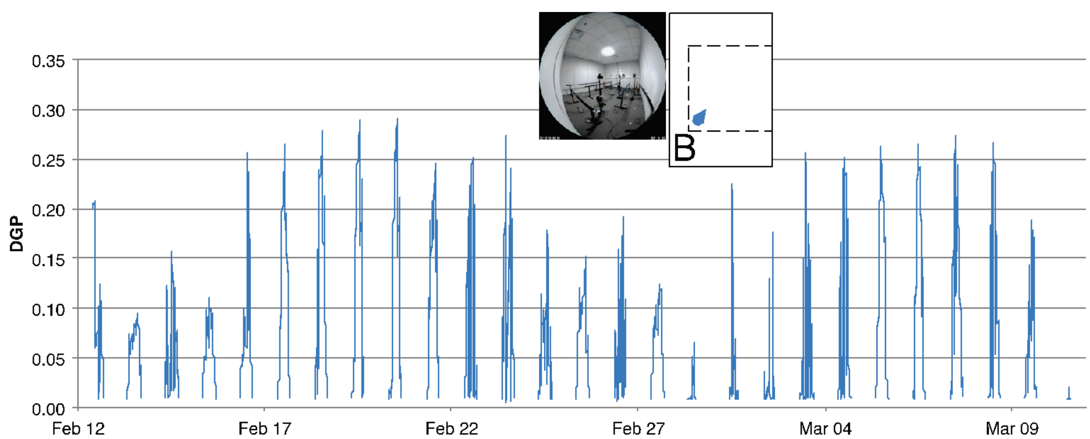

Figure 88. DGP measured from position D during the February-March 2018 testing period.

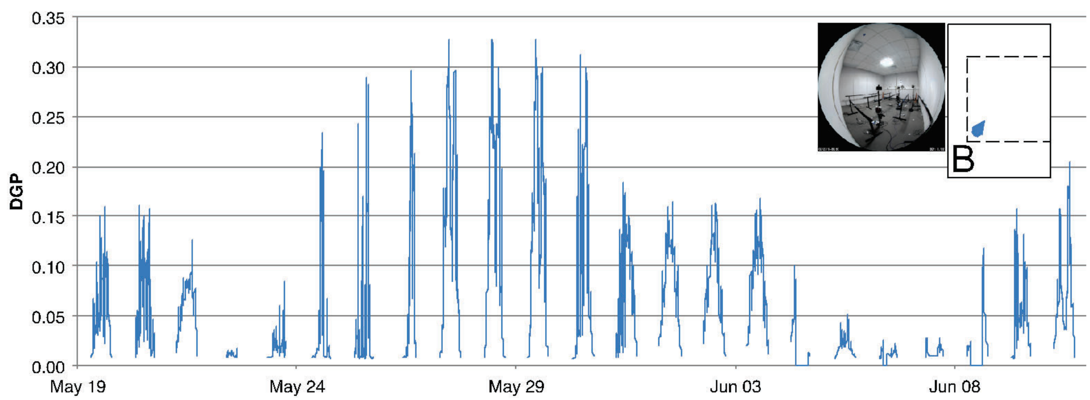

Figure 89. DGP measured from position D during the May-June 2018 testing period.

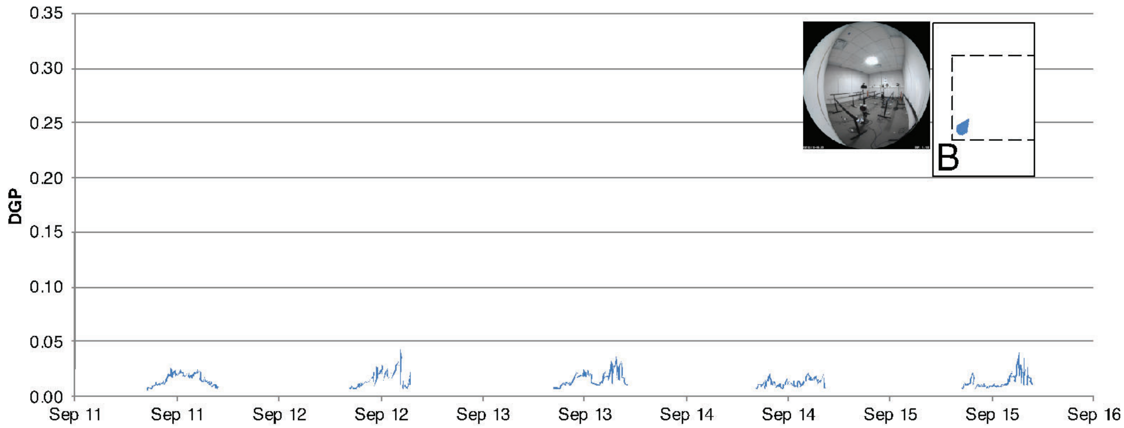

Figure 90. DGP measured from position D during the September 2018 testing period.

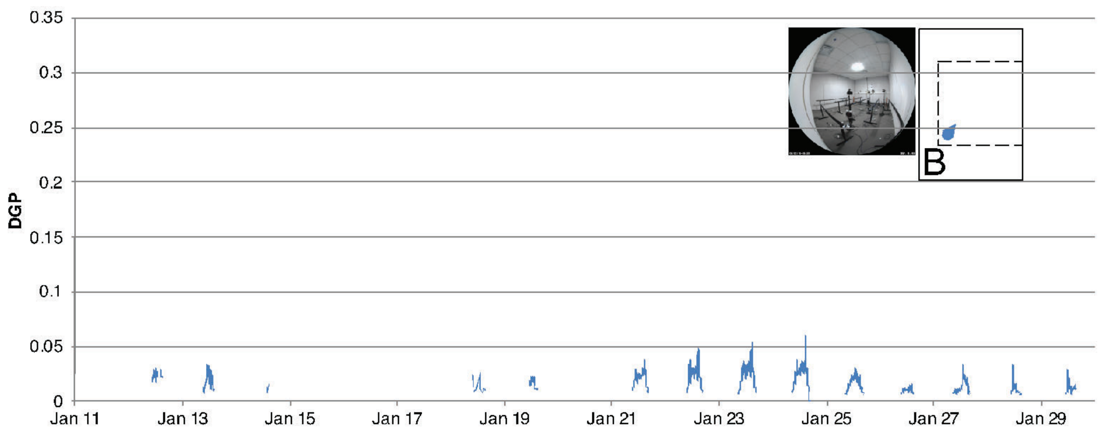

Figure 9. DGP measured from position D during the January 2019 testing period.

4 Conclusions

The testing conducted for this project shows that packages of ZNE measures resulting in substantial energy savings relative to standard practice. During cooling-dominated periods, total energy savings were 65% for south orientation and 68% for west orientation; during heating-dominated periods total energy savings were 22% for south orientation and 25% for west orientation.

During cooling-dominated periods, measured HVAC thermal energy savings were 79% for south orientation and 81% for west orientation. The corresponding values for heating-dominated periods are -25% and -49%, respectively; this increase in energy use is mainly due to an increase in the need for heating, as a consequence of reduced internal heat loads from lighting and plug loads. In terms of calculated actual HVAC energy use, for cooling-dominated periods savings were 49% for south orientation and 63% for west orientation; the corresponding values for heating-dominated periods are -41% and -77%, respectively. Lighting energy savings was 85% (a reduction from 17.7 to 2.6 Wh/ft^2-day) regardless of orientation. Plug load energy savings was 31% (a reduction from 6.8 to 4.7 Wh/ft^2-day), also independent from orientation. The introduction of the ZNE measures did not cause any measurable changes in visual comfort. Thermal comfort measurements results showed variations in thermal comfort between the two configurations, but within an acceptable range.

TDD-specific tests showed potential annual lighting energy savings of 27% to 69% (annualized EUI of 0.61 to 1.42 kWh/ft^2, assuming an installed LPD of 0.75 W/ft^2) for 22” TDDs and 22% to 32% (annualized EUI of 1.52 to 1.53 kWh/ft^2, assuming an installed LPD of 0.75 W/ft^2) for 14” TDDs, with no negative impacts on visual comfort. Note that these values do not take into account the fact that sky cover could vary substantially between tests with different configurations. For TDDs of the same diameter, tests did not show any clear differences in lighting energy and visual comfort performance across different TDD dome and diffuser types.

5 Acknowledgements

The authors wish to acknowledge LBNL colleagues Christian Fitting, Daniel Fuller, and Joshua Mouledoux for their invaluable contributions in setting up and maintaining the experiment; Eleanor Lee and Christoph Gehbauer for access to solar data; and also Jordan Shackelford for discussions on activating luminaire IR occupancy sensors.

The authors thank LBNL colleagues Robert Hosbach and Gerald Robinson for their thorough reading of a draft of this document and for their thoughtful comments on and edits to the same draft.

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7 Appendix A – Sensor Specifications

	Measurements	Sensors	Quantit y	Accuracy
Weather	Global and diffuse horizontal irradiance	Delta-T Devices SPN1-A990	1	+/- 5% | +/- $10W/m^2$
	Outside air dry bulb temperature	BAPI BA/10K-2(XP)-O-B B	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%)
Loads (per cell)	Cell lights, plug loads and occupant heat generators	Circuit breaker measurements	6	+/- 2% (typically +/- 1%)
Light levels (per cell)	Horizontal illuminance	Licor LI-210R	25	+/- 5%
Visual comfort (per cell)	Daylight glare probability	Custom-built package including Canon EOS SLR, Sigma fisheye lens, Mac Mini PC	4	+/- 10%
Thermal comfort (per cell)	Dry bulb air temperature	Thermistor		+/- 0.1°C
	Mean radiant temperature	Thermistor		+/- 0.1°C

	Air velocity			+/- 5%

8 Appendix B – Test Cell Calibration Conditions

The following were the conditions under which the calibration runs occurred from September 11, 2018 to September 13, 2018. During this period the test cells were only in cooling mode.

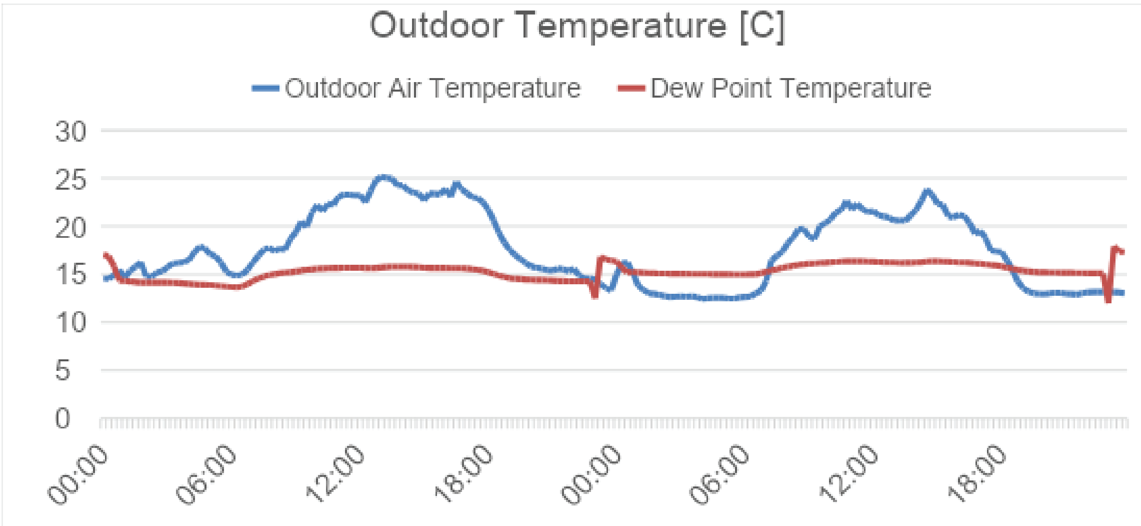

Figure B1. Outside air temperatures Sept 11 – Sept 13, 2018.

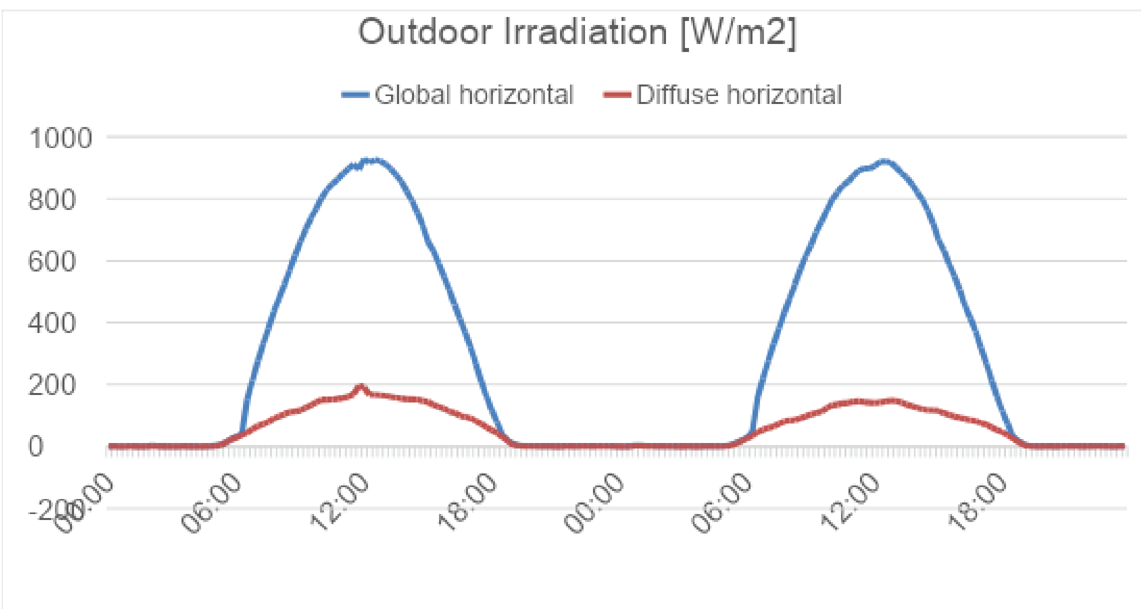

Figure B2. Outdoor Irradiation Sept 11 – Sept 13, 2018.

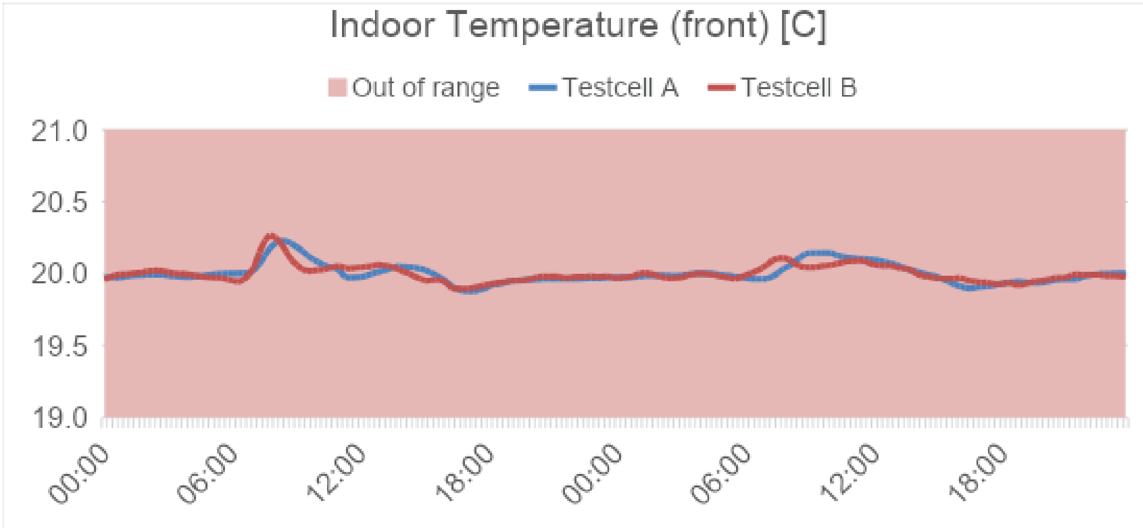

Figure B3. Cell interior temperatures Sept 11 – Sept 13, 2018.

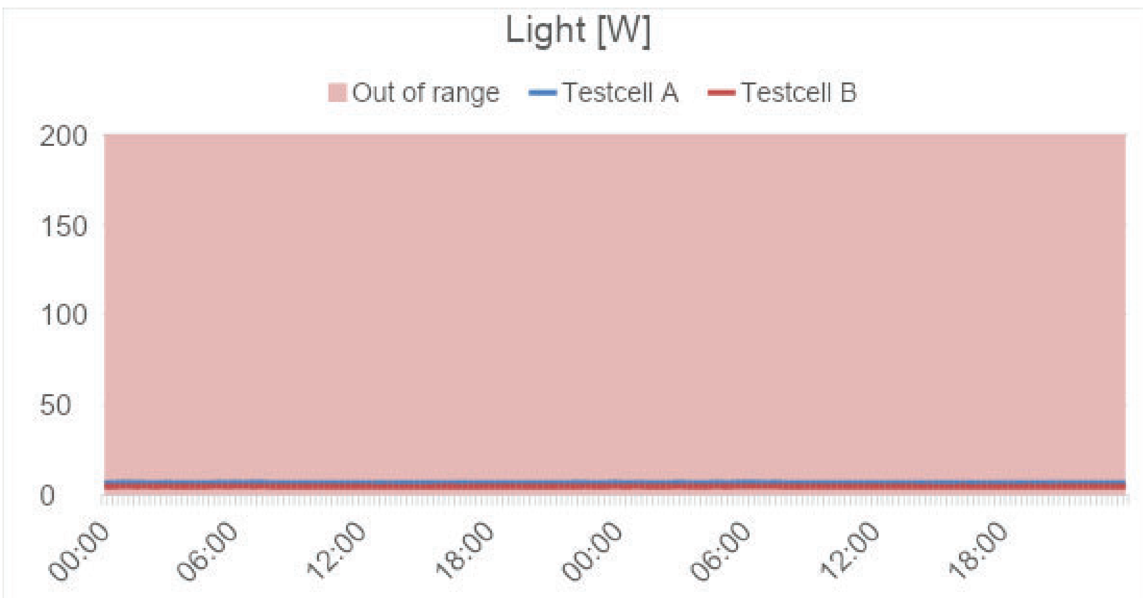

Figure B4. Cell interior light energy Sept 11 – Sept 13, 2018.

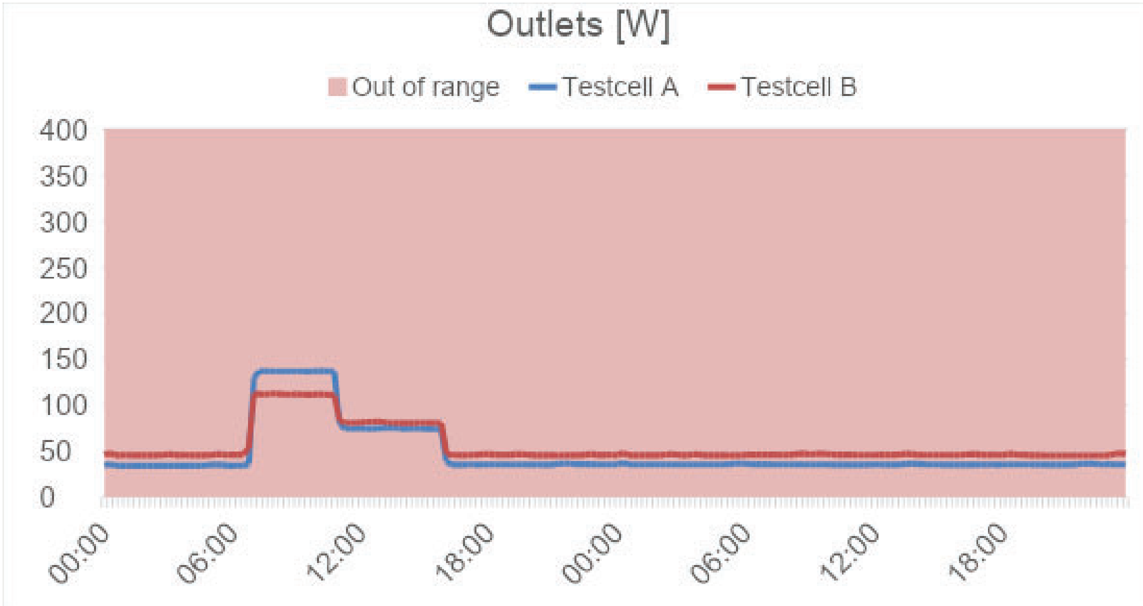

Figure B5. Cell electrical outlets energy Sept 11 – Sept 13, 2018.

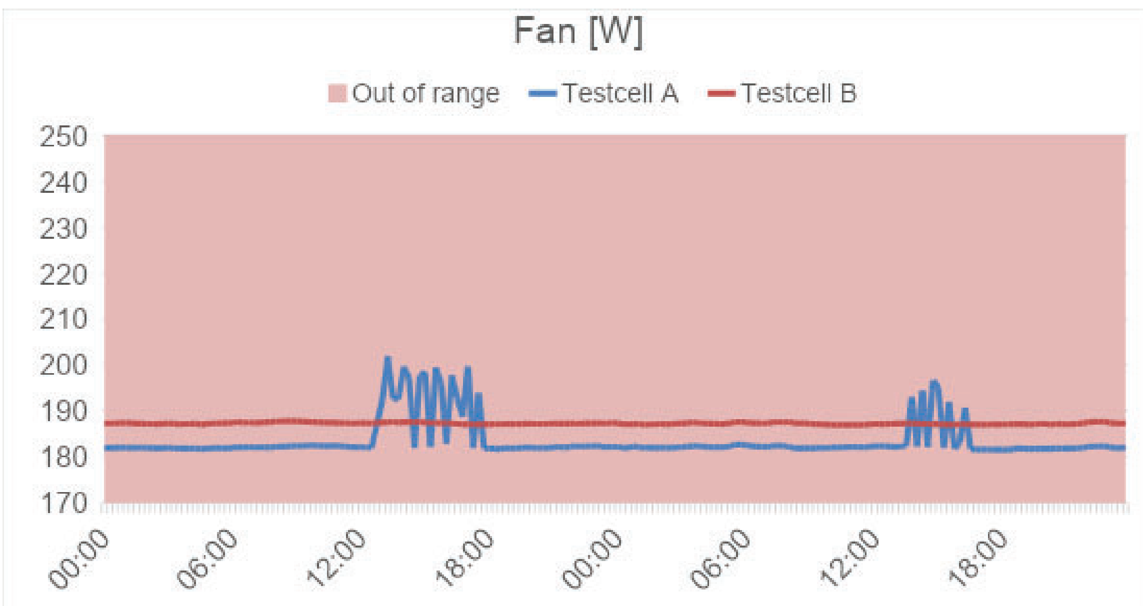

Figure B6. Cell fan energy Sept 11 – Sept 13, 2018.

In Figure B6, the small power spikes in Cell A correspond to a small fan on a VFD enclosure coming on due to some solar gains experienced on the west side of the test cell. Cell B's VFD enclosure did not experience this event. This is a small anomaly overall, but will be rectified with additional solar protection.

In the following Figures, the thermal energy comparison between the cells is presented. In each figure, and 'out of range' condition is defined. The acceptable differential between the measured loads has been defined as that provided by a whole building simulation model with the two cells under identical conditions. In this case, data that are more than 45W different between the two cells have been classified as 'out of range', however the data may still be within the accuracy range of the sensing devices for the given thermal load (ie at higher thermal loads the relative wattage error increase with increase temperature difference and/or increased water flow rates).

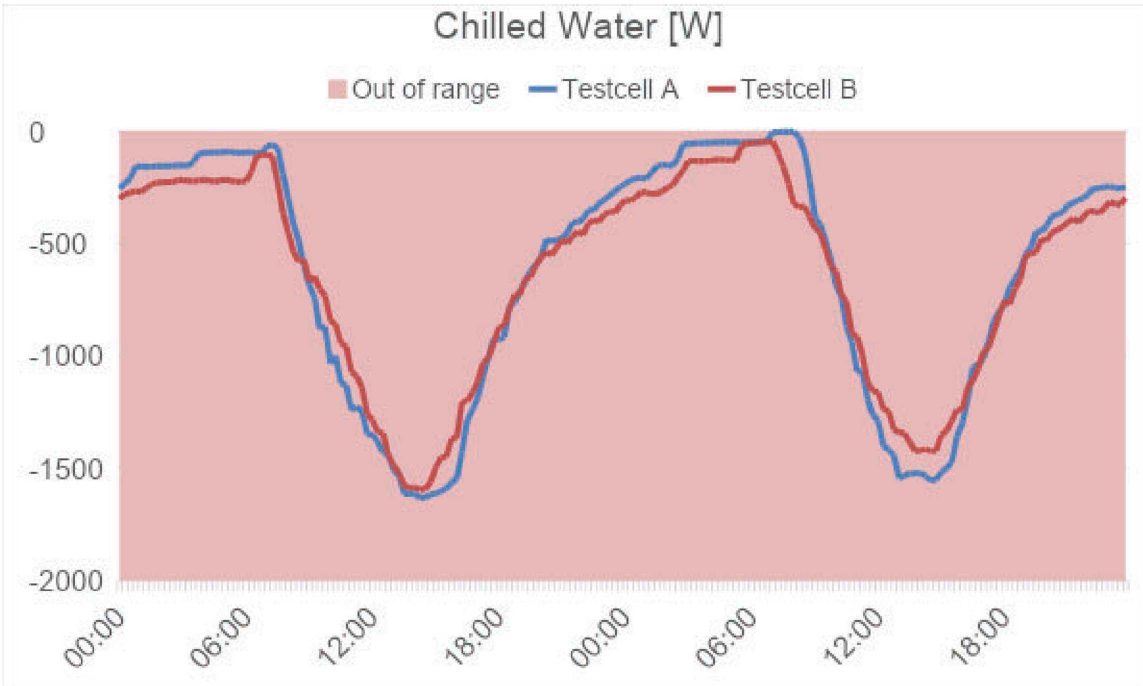

Figure B7. Cell chilled water thermal energy Sept 11 – Sept 13, 2018.

Figure B7 indicates that the measured chilled water thermal energy is below the differential threshold of 45 Watts for most of the daytime hours, but is above this for much of the night time hours. The out of range conditions though are on the order of 100 Watts or less though typically during night hours.

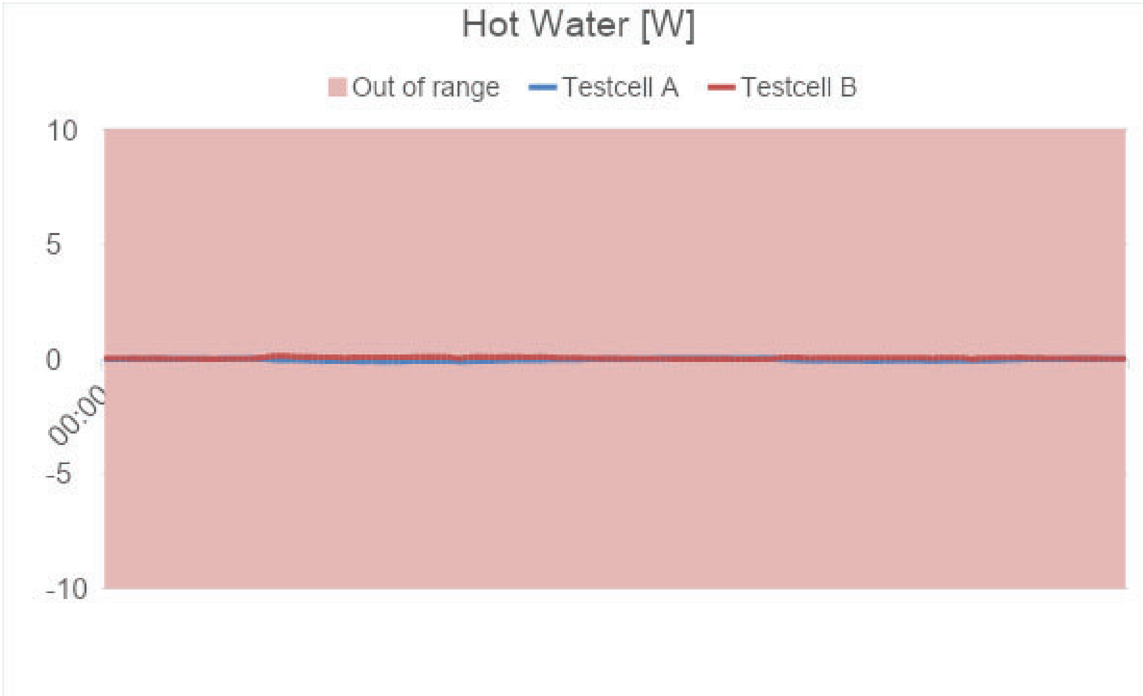

Figure B8. Cell hot water thermal energy Sept 11 – Sept 13, 2018.

Figure B8 indicates the cells were not in heating mode during the calibration period.

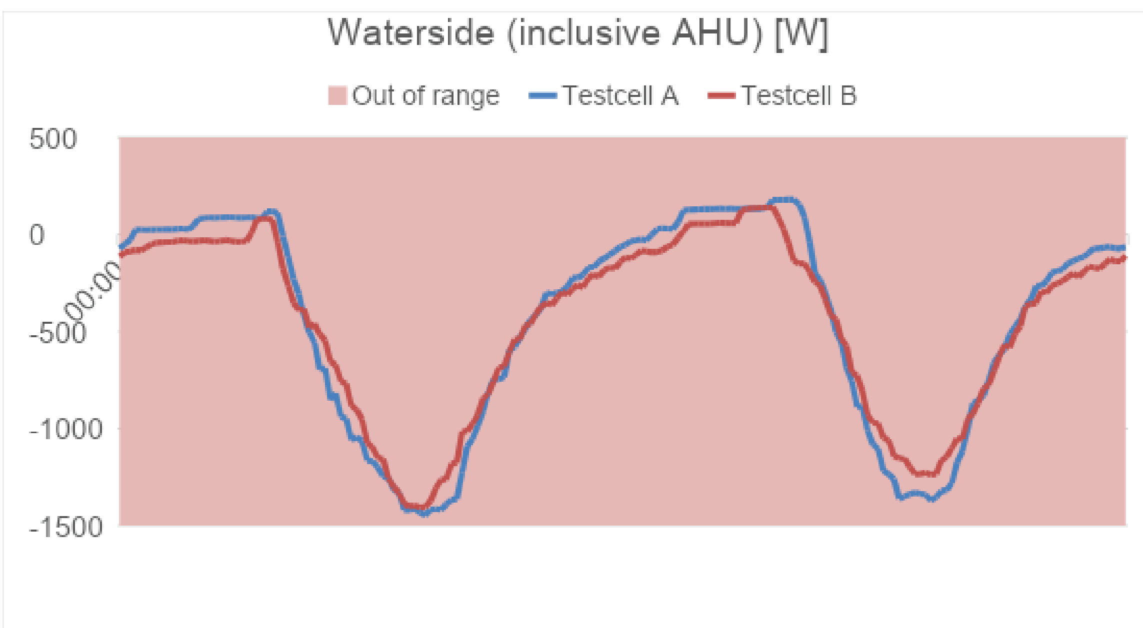

Figure B9. Cell waterside calculated thermal energy Sept 11 – Sept 13, 2018.

In Figure B9 we can see that the two cells operate within the expected accuracy range predominantly during the occupied hours of the test cells with a few periodic exceptions. The cells appear to be outside of the calibration range from ~10pm to 6am each day, corresponding to night time operation, however the discrepancy is on the order of ~100 Watts or less most of this time.