Zero Net Energy Retrofits for Small Commercial Offices:

ZNE Package and Tubular Daylighting Device (TDD) FLEXLAB Test Results Report

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Zero Net Energy Retrofits for Small Commercial Offices FLEXLAB Test Report

1 Introduction

This document is a part of the California Energy Commission (Energy Commission) EPIC study “Zero Net Energy Retrofits for Small Commercial Offices”. The project launched in January 2017 and is a 4-year research study involving 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 ZNE performance. The set of technologies are called the ZNE retrofit packages and documented in (Integral Group, 2018).

This document reports the results of the FLEXLAB testing of one ZNE package applicable to the Southern and Northern California climates, as well as the Berkeley demonstration site, consisting of Thermafusers with VAV control and ventilation only air, LED lighting and daylight dimming, reduced plug load power and Tubular Daylighting Devices (TDDs) to provide daylighting into core spaces. In addition, this document reports the results of the TDDs for both daylighting availability and lighting energy reduction potential. The test results report describes the test objectives and features, test cases, schedule, and measurements, as well as the energy, visual and thermal comfort performance of the ZNE package and TDDs.

2 Test methodology

2.1 Facility

Tests were conducted at LBNL’s FLEXLAB® facility located in Berkeley California (Figure 1). FLEXLAB (FLEXLAB.lbl.gov) 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 4 testbeds each consisting of two identical test cells calibrated to a high standard and 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 measurement systems. FLEXLAB can replicate the thermal loads of almost all U.S. climate zones and provides feedback on energy performance as well as thermal and visual comfort, and other indoor environmental performance targets.

Figure 1. LBNL's FLEXLAB, A Commercial Integrated Systems Test Facility

2.2 Test accuracy

High accuracy thermal and power measurements were used throughout the test period. Power measurements for example had an accuracy of +/- 1% typically, and +/- 2% for low loads. A full range of sensor specifications and accuracies is detailed in Appendix A.

In addition, a calibration run was conducted with both test cells in the same configuration to document the combined level of thermal accuracy between the two cells. In this case, the 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. One rounds of 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. Figure 2 illustrates the cumulative thermal load starting from midnight in each cell until 23:59h for each day, along with the outside air temperature for each of the days.

Figure 2. Calibration results – Cumulative thermal load comparison for each cell under identical conditions.

Table 1 provides the daily and average hourly thermal load difference between the two cells for each test day. In general the cells perform 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.

Table 1. Calibration results – Daily and average hourly thermal load differences

	Cumulative Daily Thermal Load Difference Between the Cells (Cell A – Cell B) (kWh)	Hourly Average Thermal Load Difference (W)
Sept 11, 2018	0.077	3.20
Sept 12, 2018	0.483	20.12

2.3 Test configurations

Two different configurations were tested:

1. ZNE package: This configuration was aimed at evaluating the overall performance of a package of energy-efficiency measures, including HVAC, lighting and plug loads.
2. TDD: This configuration was aimed at evaluating the daylight delivery and glare performance of tubular daylight devices.

Additional variations were tested for each configuration, for a total of 12 configurations. Table 2 details each configuration and its variations.

Table 2. Test configurations.

Test code	Test description	Cell B – Test Case	Cell A - Baseline

Pkg-S	ZNE package, south-facing	• Orientation: South
		• HVAC: VRF, DOAS, wide deadband, unocc. setbacks/shutoff
		• Façade:
		  ○ WWR 0.25
		  ○ Single-pane window w/ thermally broken (single break) aluminum frame
		  ○ metal stud wall w/ R-19 batt cavity insulation
		• Lighting: 0.4 W/ft², LED, occ. sensing, daylight harvesting
		• Plug loads: 0.539 W/sf is connected load, 90% diversity, 0.485 W/sf max operating load
			• Orientation: South
			• HVAC: PVAV with hydronic coils, to be translated to Gas Furnace energy in post processing
			• Façade:
			  ○ WWR 0.25
			  ○ Single-pane window w/ thermally broken (single break) aluminum frame
			  ○ metal stud wall w/ R-19 batt cavity insulation
			• Lighting: 1.19 W/ft², T8, no automated controls
			• Plug loads: 0.77 W/sf is connected load, 90% diversity, 0.70 W/sf max operating load

Pkg-W	ZNE package, west-facing	West orientation; all else same as Pkg-S	West orientation; all else same as Pkg-S
TDD-SPP	Solatube 22” TDD, Prismatic dome, Prismatic diffuser	• Windows blocked to simulate interior space • Interior partitions set up to create 16 x 14 ft enclosure • Solatube 22” TDD w/ prismatic dome, prismatic diffuser	• N/A
TDD-SPF	Solatube 22” TDD, Prismatic dome, Fresnel diffuser	• Same as TDD-SPP except: Solatube 22” TDD w/ prismatic dome, fresnel diffuser	• N/A
TDD-SCP	Solatube 22” TDD, Clear dome,	• Same as TDD-SPP except: Solatube 22” TDD w/ clear dome, prismatic diffuser	• N/A

Test code	Test description	Cell B – Test Case	Cell A - Baseline
	Prismatic diffuser		
TDD-SCF	Solatube 22" TDD, Clear dome, Fresnel diffuser	• Same as TDD-SPP except: Solatube 22" TDD w/ clear dome, fresnel diffuser	• N/A
TDD-VPP	Velux 22" TDD, Prismatic dome, Prismatic diffuser	• Same as TDD-SPP except: Velux 22" TDD w/ prismatic dome, prismatic diffuser	• N/A
TDD-VPF	Velux 22" TDD, Prismatic dome, Fresnel diffuser	• Same as TDD-SPP except: Velux 22" TDD w/ prismatic dome, fresnel diffuser	• N/A
TDD-VCP	Velux 22" TDD, Clear dome, Prismatic diffuser	• Same as TDD-SPP except: Velux 22" TDD w/ clear dome, prismatic diffuser	• N/A
TDD-VCF	Velux 22" TDD, Clear dome, Fresnel diffuser	• Same as TDD-SPP except: Velux 22" TDD w/ clear dome, fresnel diffuser	• N/A
TDD-14A	Solatube 14" TDD, 2'x2' Fresnel diffuser	• Same as TDD-SPP except: Solatube 14" TDD w/ prismatic dome, 2'x2' square fresnel diffuser	• N/A
TDD-14B	Solatube 14" TDD, 14" round frosted diffuser	• Same as TDD-SPP except: Solatube 14" TDD w/ prismatic dome, 14" round frosted ("Just Frost") diffuser	• N/A

2.4 Test calendar

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.

Table 3. Dates each configuration was tested or planned for testing.

Test code	Test description	Test 1	Test 2	Test 3	Test 4
Pkg-S	ZNE package, south-facing	May 3 - May 10	Jun 13 - Jun 19	Aug 18 - Aug 24	Dec 5 - Dec 11
Pkg-W	ZNE package, west-facing	May 11 - May 17	Jun 20 - Jun 26	Aug 25 - Aug 31	Dec 13 - Dec 20
TDD-SPP	Solatube 22" TDD, Prismatic dome, Prismatic diffuser	Feb 9 - Feb 14	May 19 - May 21		
TDD-SPF	Solatube 22" TDD, Prismatic dome, Fresnel diffuser	Feb 15 - Feb 16	May 22 - May 23	May 31 - Jun 3	Jan 4 - Jan 9
TDD-SCP	Solatube 22" TDD, Clear dome, Prismatic diffuser	Feb 17 - Feb 20			
TDD-SCF	Solatube 22" TDD, Clear dome, Fresnel diffuser	Feb 21 - Feb 22	May 25 - May 29		
TDD-VPP	Velux 22" TDD, Prismatic dome, Prismatic diffuser	Feb 24 - Feb 26			
TDD-VPF	Velux 22" TDD, Prismatic dome, Fresnel diffuser	Feb 27 - Feb 28			
TDD-VCP	Velux 22" TDD, Clear dome, Prismatic diffuser	Mar 7 - Mar 9			
TDD-VCF	Velux 22" TDD, Clear dome, Fresnel diffuser	Mar 10 - Mar 11	May 9 - May 10		
TDD-14A	Solatube 14" TDD, 2'x2' Fresnel diffuser	May 5	Sep 11 - Sep 12	Jan 11 - Jan 23	
TDD-14B	Solatube 14" TDD, 14" round frosted diffuser	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.

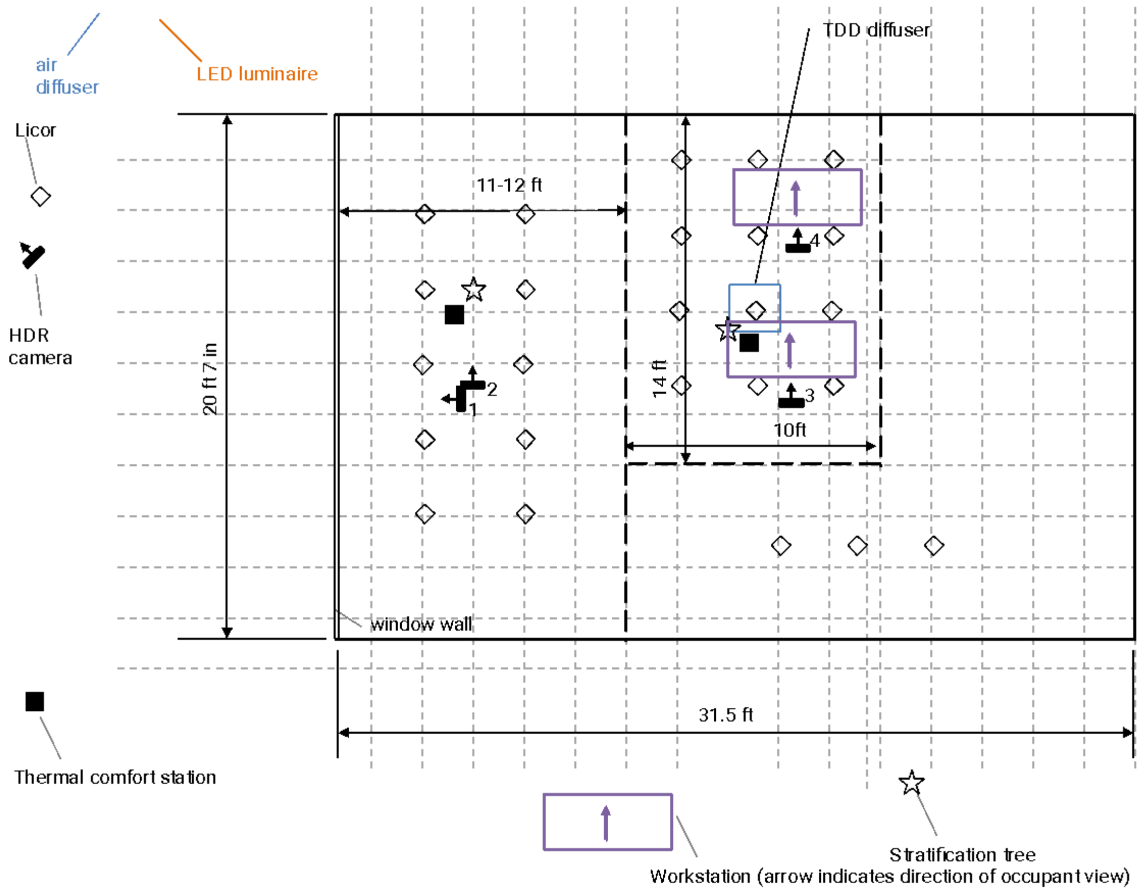

Figure 3. Layout for ZNE package tests in the test cell.

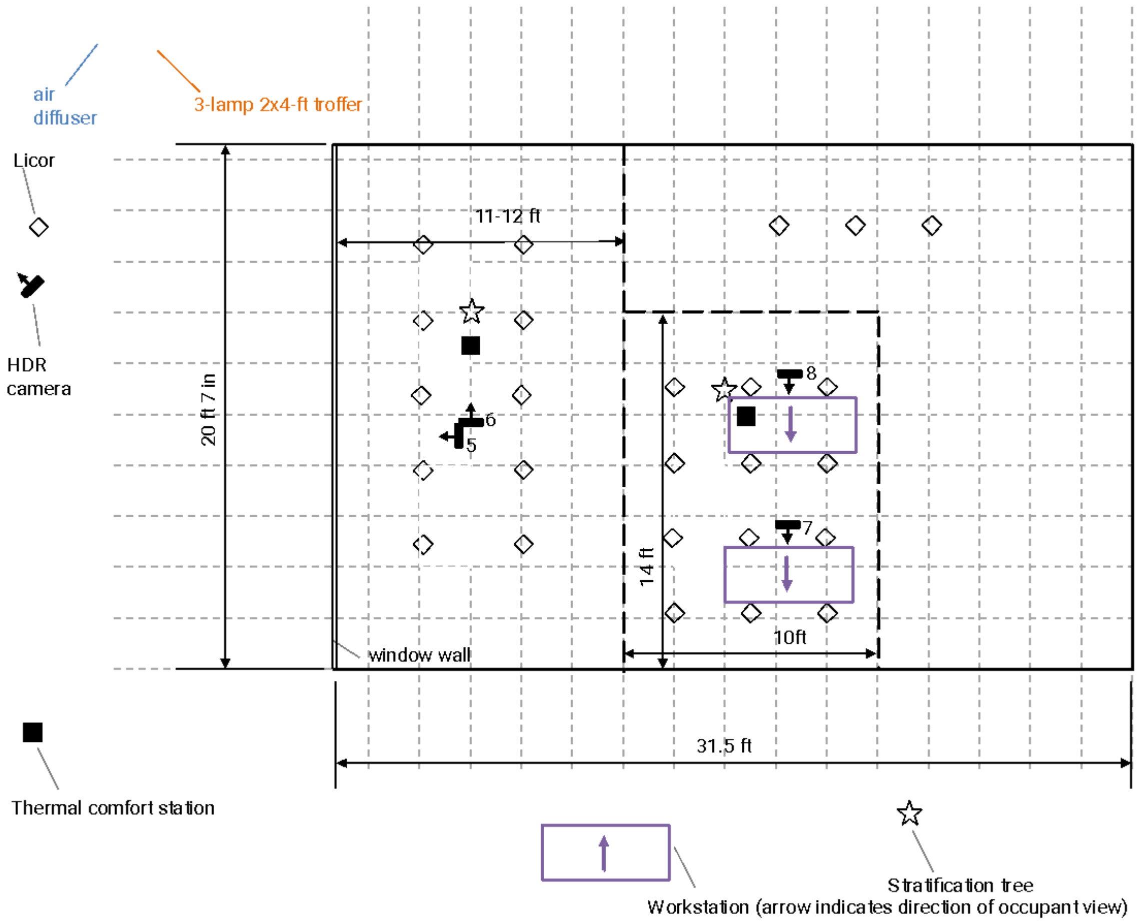

Figure 4. Layout for ZNE package tests in the baseline cell.

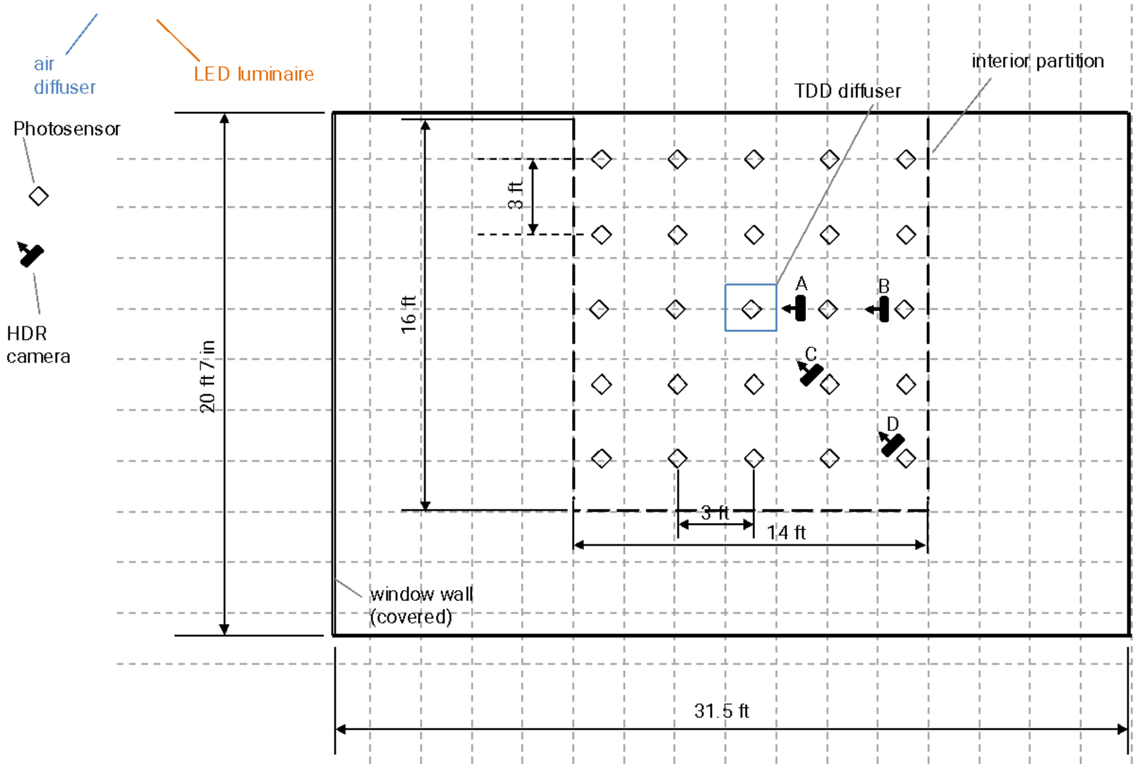

Figure 5. Layout for TDD tests.

2.6 Measurements

2.6.1 Weather

Exterior global and diffuse horizontal irradiance were measured using Hukseflux pyranometers, 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 that the difference between these data and data gathered at the test cell location was not significant.

2.6.2 Illuminance

Horizontal illuminance was measured using Licor LI-210 photometers, 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]. HDR images were captured using digital single-lens reflex cameras fitted with fisheye lenses, auxiliary sensors and computing equipment (Figure 7). These HDR images were processed in order to calculate a luminance map of the image, i.e., calculate the luminance of each pixel. A false-color luminance map taken in FLEXLAB is shown in Figure 8.

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

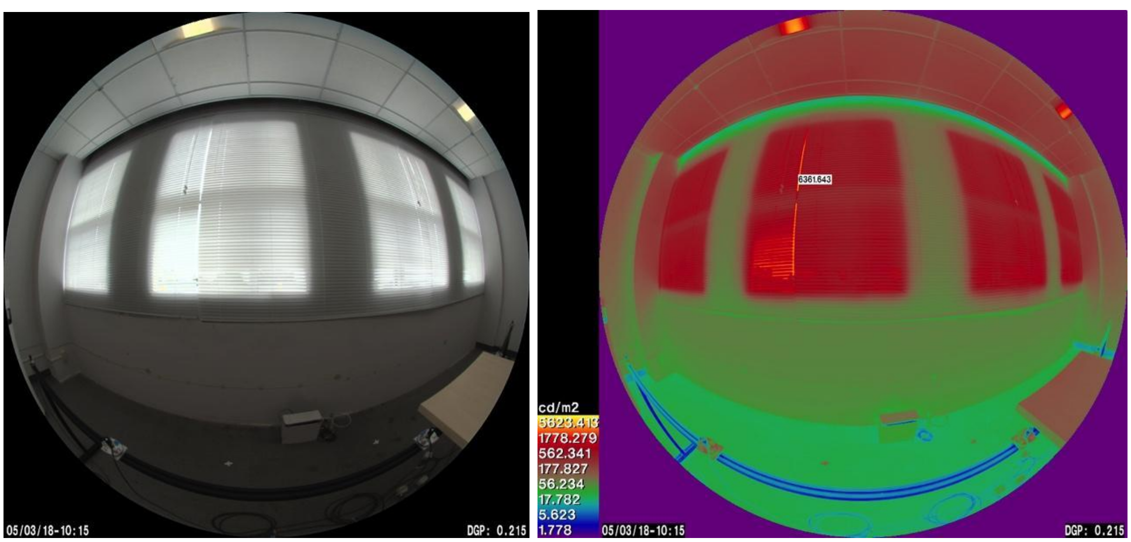

Figure 8. HDR image (*left*) and corresponding luminance map (*right*) of scene in FLEXLAB.

The DGP metric represents a probability, between 0 and 1, that occupants of 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, and that breaches above that level are of short duration and do not exceed 0.40.

2.6.4 Thermal comfort

Thermal comfort was evaluated using the Predicted Mean Vote/Percentage of People Dissatisfied (PMV/PPD) metric [ANSI/ASHRAE, 2013]. PMV is a value between -3 and 3 and 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, ASHRAE recommends that PPD be maintained under 20% and PMV between -0.5 and 0.5.

PMV/PPD are calculated from 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 in Figure 9.

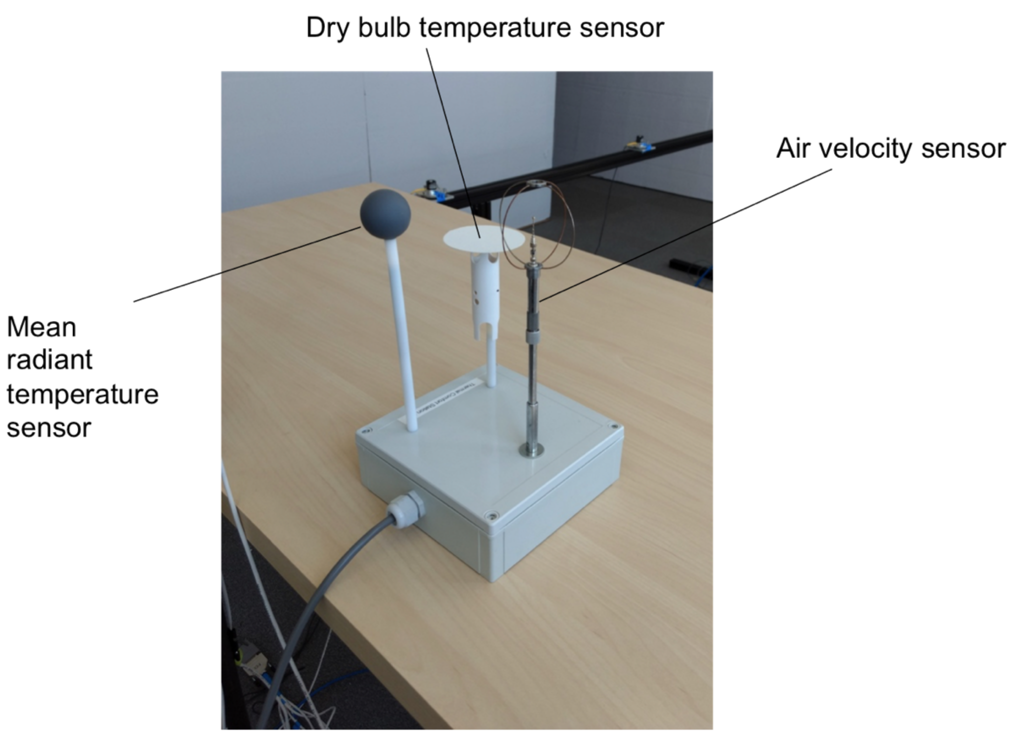

Figure 9. Thermal comfort measuring station.

2.6.5 HVAC

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 from water loop flow rate and temperature drop. Actual energy use for reference and ZNE configurations was calculated based on models of the HVAC system assumed for each configuration.

Electric energy use with fans and pumps was also monitored.

2.6.6 Lighting energy

Lighting energy consumption 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 adding up the energy consumption of each luminaire.

2.7 Systems

2.7.1 HVAC

The HVAC system to be evaluated consisted of a rooftop, 100% outside air high efficiency heat pump, with energy recovery on the relief air. The AHU has a VFD fan, and supplies to Thermafuser supply diffusers located throughout the conditioned zone. The controls strategy allowed for 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.

2.7.1.1 Thermafusers

Thermafusers™ are ceiling supply diffusers that are mounted in a ceiling grid that enable Variable Air Volume (VAV) control right at the diffuser. In general they 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 provided at the diffuser. Several models are available, including ones that have thermally actuated dampers, where a wax product expands or contracts to modulate the damper open or closed depending on the desired setpoints. Different models are available that also 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 workspaces over traditional single zone control strategies. In addition, by design they require a lower pressure drop duct design, which improves fan energy performance throughout all modes of operation.

In the ZNE cell, one 2’x2’ Thermafuser model TF-HC was provided for the enclosed office spaces, and two 2’x2’ Thermafusers model TF-HC for the perimeter space. Each Thermafuser tested was thermally actuated, with no connection to the centralized HVAC controls. The wax cylinder thermostats on each Thermafuser were set to 68F and 78F setpoints for heating and cooling mode respectively. Figure 3 shows the locations of the Thermafusers 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 cell.

2.7.2 HVAC AHUs

In the case of both the test and reference cells, the AHUs were programmed for an occupied schedule of 7am-midnight Mon-Fri, 7am-7pm Sat, and 7a-6pm Sun.

The reference cell AHU was selected to emulate a gas packaged DX air handler, 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 75F cooling setpoint, and a 70F heating setpoint. The supply air temperature setpoints were as follows:

- Cooling Supply Air Temp - 55F
- Heating Supply Air Temp - 95F

The test 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 is proven on. The Thermafusers were set for individual zone setpoints as noted above, and per the following setpoints:

1) Zone Cooling temperature setpoint shall be 78°F (all hours, year-round).
2) Zone Heating temperature setpoint shall shall be 70°F (all hours, year-round).

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

- MinCoolingSAT - 55°F
- MaxCoolingSAT - 68°F
- MinHeatingSAT - 76°F
- MaxHeatingSAT - 95°F

Both the reference and test cell AHUs were monitored for supply air flow, supply and return air temperatures, and each was served by individual hot and chilled water coils with flow metering and supply and return temperatures. In this way, thermal energy provided to each cell in heating and cooling was monitored. This data could then be translated to representations of the electrical energy performance of the base case and test systems by applying these provided thermal energies to the efficiency curves of these packaged equipment.

2.7.3 Electric lighting

In the ZNE cell, electric lighting was provided by ten 2'x2' Philips Spacewise LED luminaires, each rated at 26 W (Figure 10). Each of these luminaires has a passive infrared occupancy sensor and a photosensor, and can autonomously dim or turn off based on available daylight and/or detected occupancy. 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		
	Weekda y	Saturda y	Sunda y
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%

2.7.4 TDDs

The tubular daylight devices (TDDs) tested were manufactured by two different companies: Solatube and Velux. Each 22” TDD was tested with two different domes – a clear dome and a prismatic dome (Figure 11) – and two different diffusers at the bottom – a prismatic diffuser and a Fresnel diffuser (Figure 12). A smaller, Solatube 14” TDD was also tested. It had a prismatic dome; two bottom diffusers were tested: 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*).

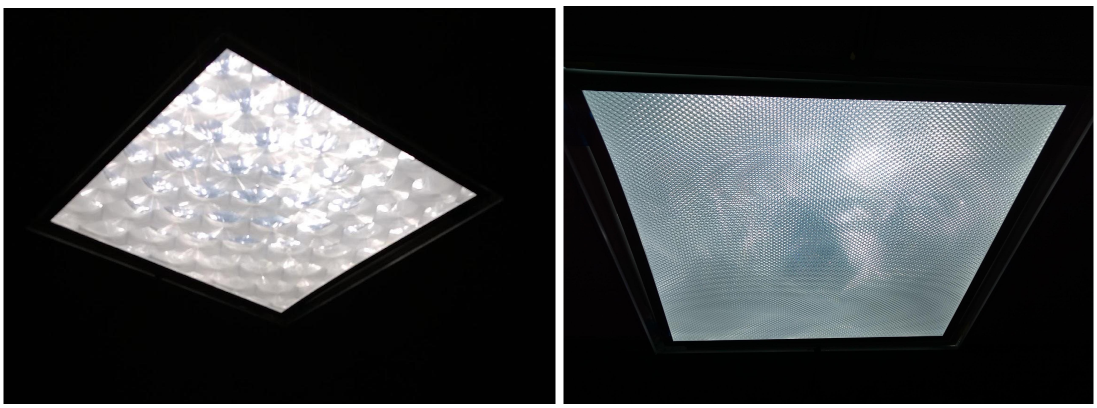

Figure 12. The two types of diffuser tested: prismatic (*left*) and Fresnel (*right*). Note that images are underexposed in order to show diffuser detail and aren't a good indicator of actual brightness.

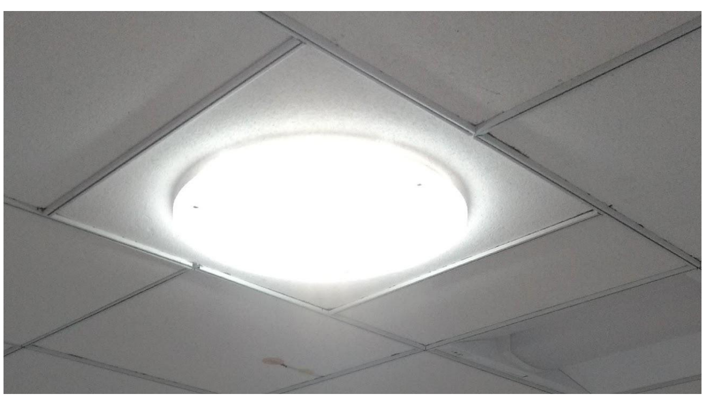

Figure 13. Fourteen-inch frosted round diffuser.

2.7.5 Plug loads

Plug loads were provided by desktop personal computers running custom software that allows setting 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 [ASHRAE, 2007] (Table 5), with a maximum target value of 497 W for the reference cell and 348 W for the ZNE cell.

Table 5.

Hour	Power level		
	Weekday	Saturday	Sunday
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

3.1 Introduction

Overall, the ZNE package (tested in cell/room B) resulted in significant energy savings relative to the reference configuration (tested in cell/room A), 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; the corresponding values for heating-dominated periods are -25% and -49%, respectively. 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. Plug load energy savings was in the 31% regardless of orientation. There were no measured differences in visual comfort between the ZNE package and reference condition. 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. No negative visual comfort impacts were measured during TDD testing. In general, for the same tube diameter, there were no significant differences in performance between TDD dome and diffuser types.

3.2 ZNE package tests

3.2.1 HVAC

3.2.1.1 Measured thermal energy use

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

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

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

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

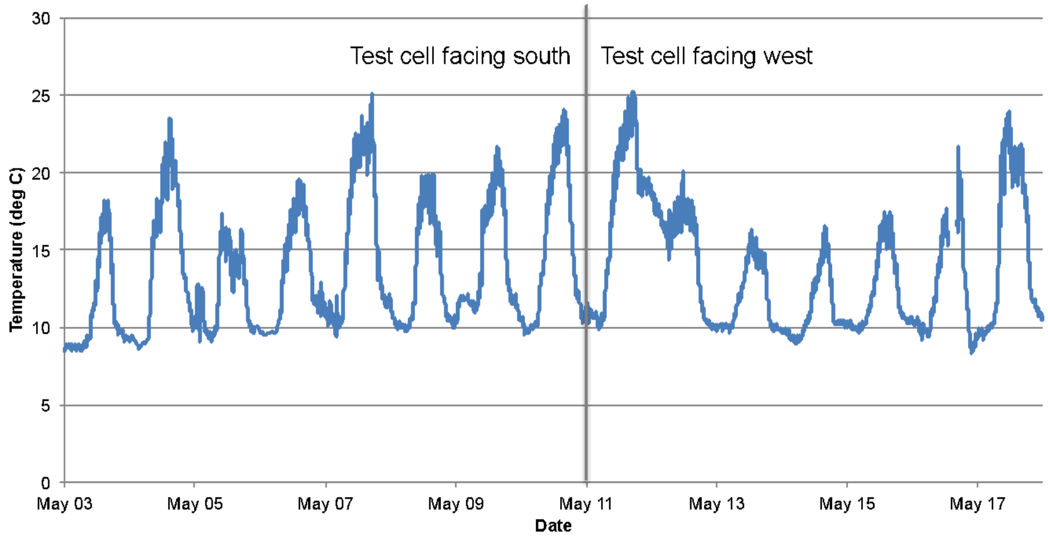

Figure 14. Outside air temperature during May test period.

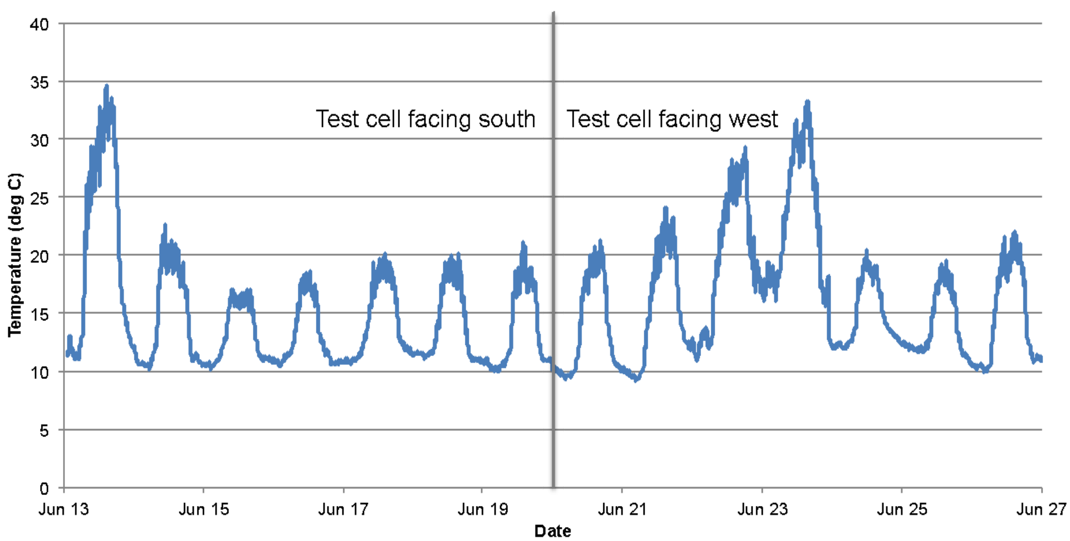

Figure 15. Outside air temperature during June test period.

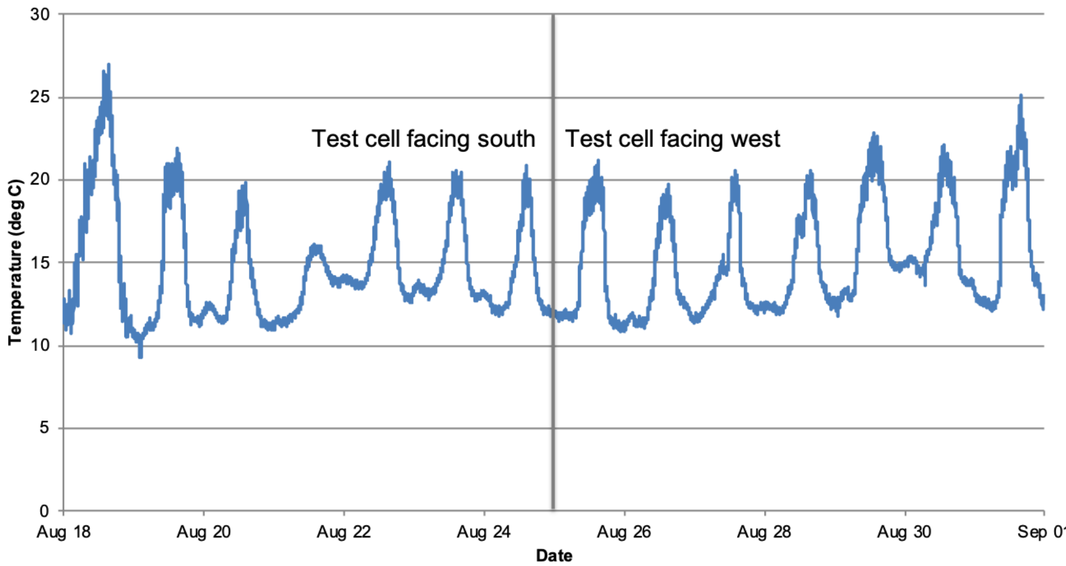

Figure 16. Outside air temperature during August test period.

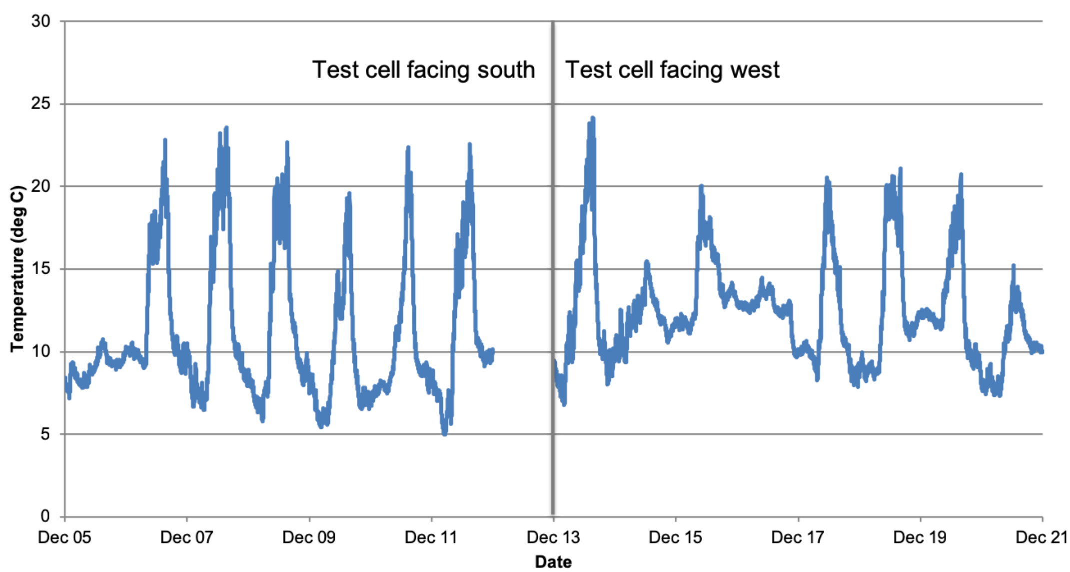

Figure 17. Outside air temperature during December test period.

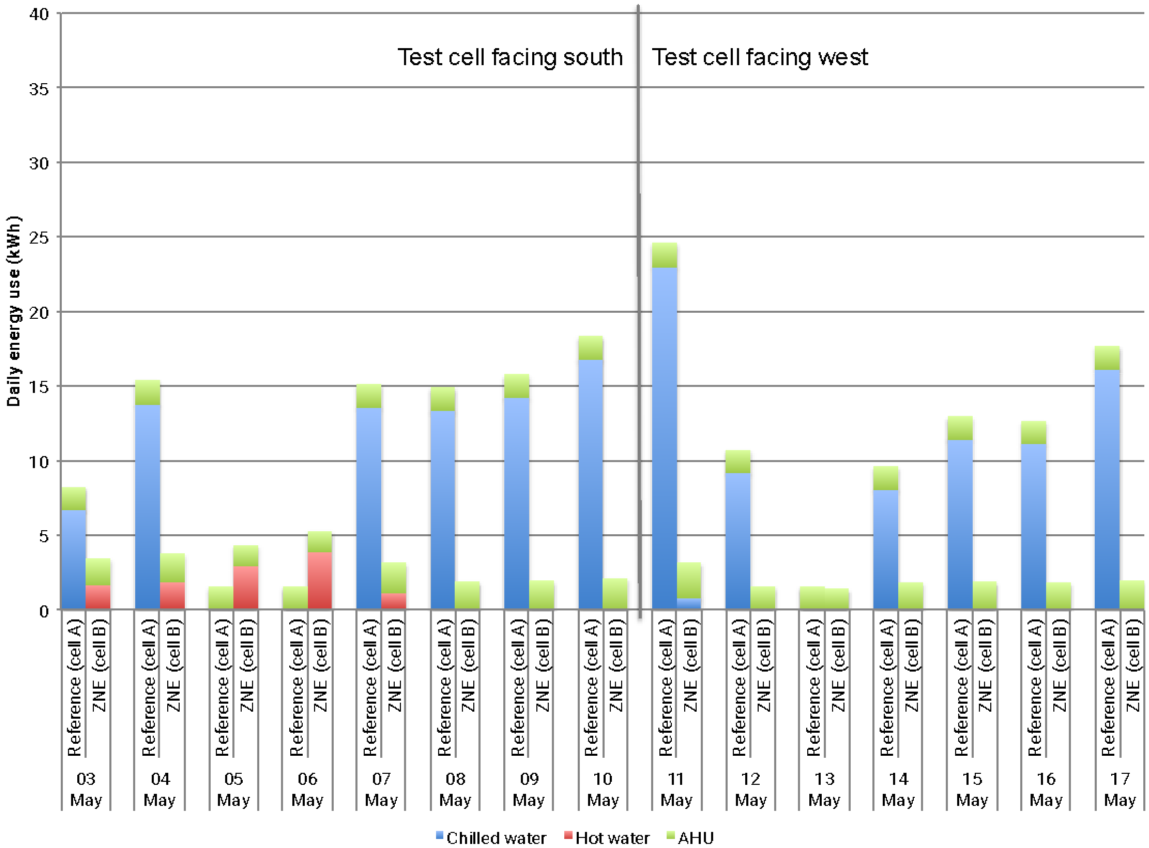

Figure 18. Daily HVAC energy consumption during May test period.

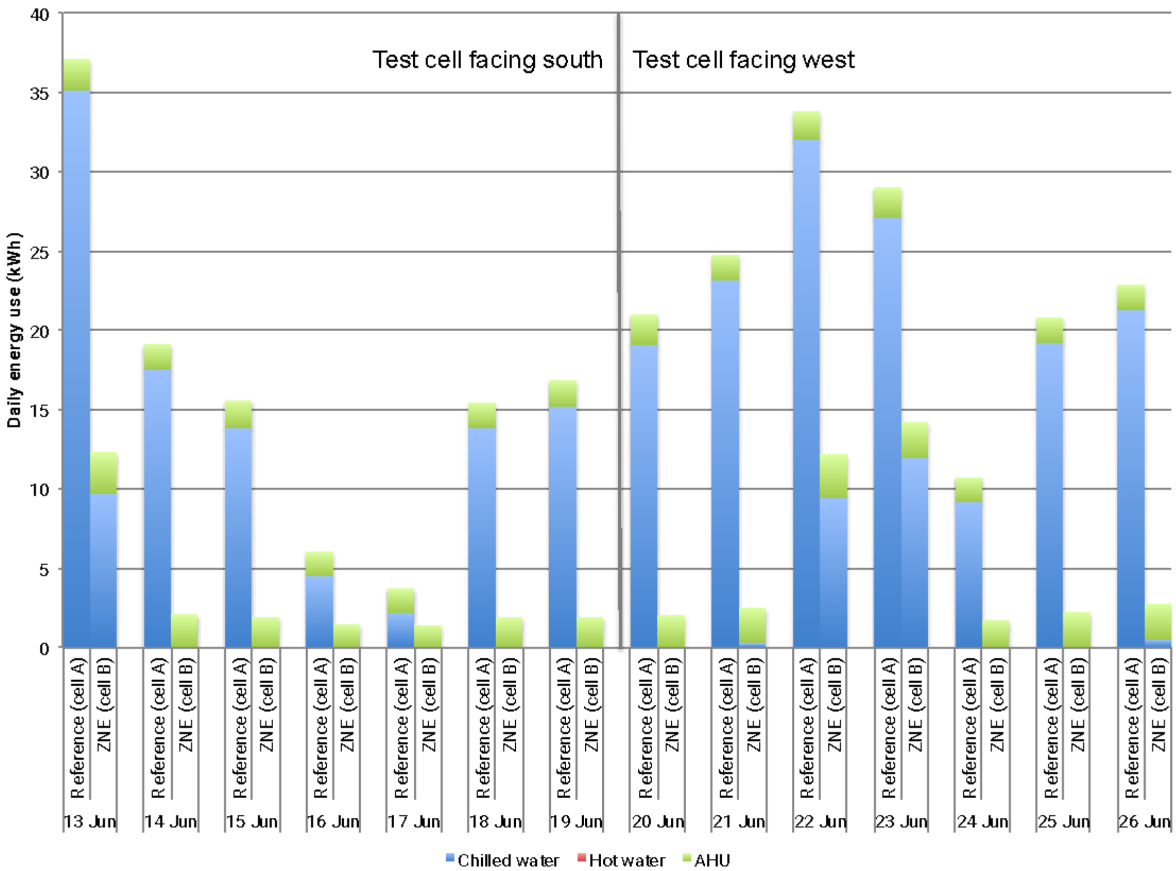

Figure 19. Daily HVAC thermal energy consumption during June test period.

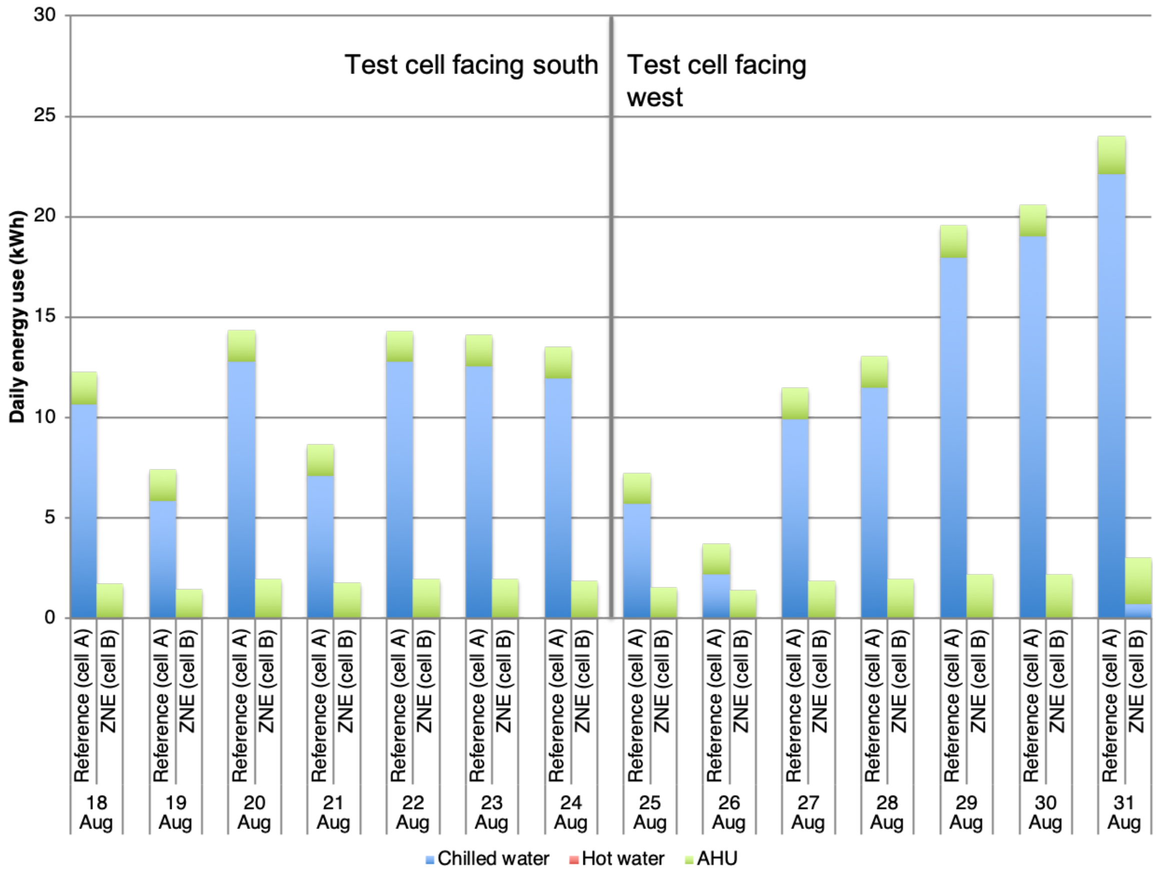

Figure 20. Daily HVAC thermal energy consumption during August test period.

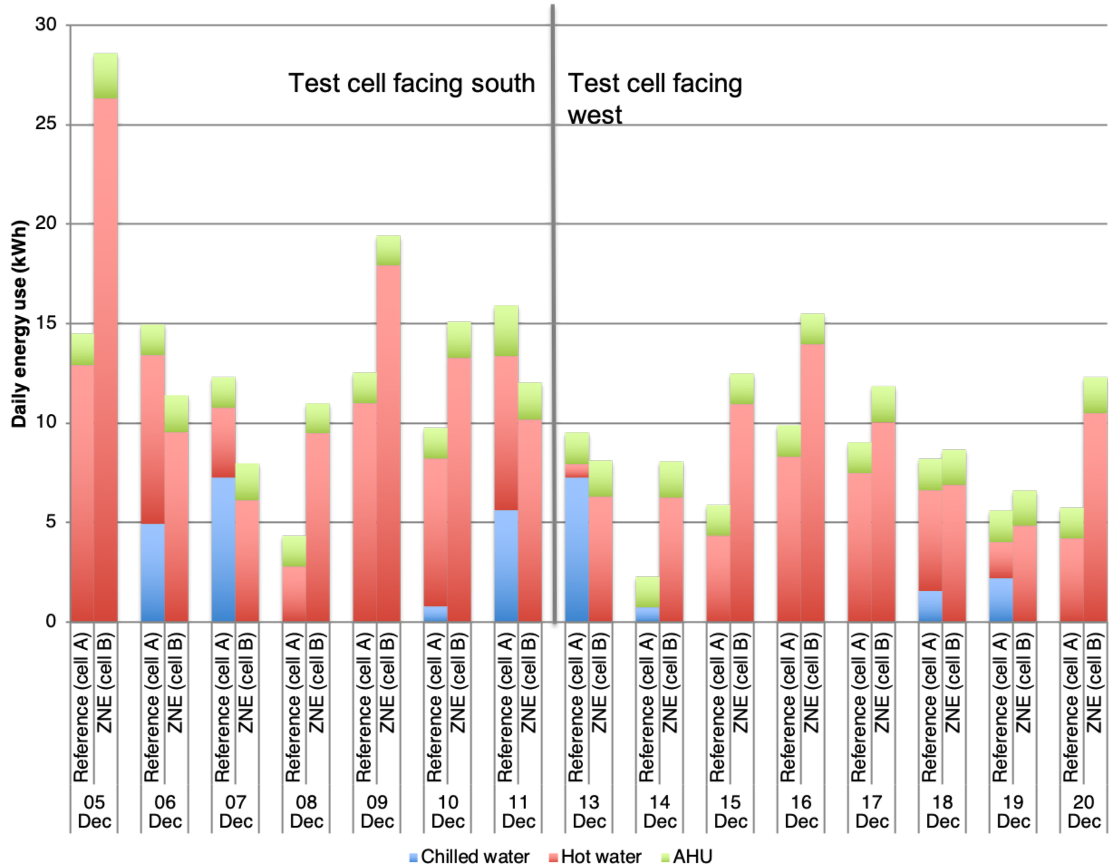

Figure 21. Daily HVAC thermal energy consumption during December test period.

Table 6. Total HVAC thermal energy.

Month	Orientation	Testing days	Total energy (kWh)								ZNE package savings
			Reference (Cell A)				ZNE (Cell B)				
			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	Orientatio n	Testing days	Average daily energy (kWh)								ZNE packag e savings
			Reference (Cell A)				ZNE (Cell B)				
			Chille d water	Hot water	AHU	Total	Chille d 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%

3.2.1.2 Calculated energy use

This subsection shows results from the calculations of actual energy consumption needed in order to provide the measured levels of thermal energy detailed in the previous subsection. Figures 22-25 show daily energy use for each of the four testing periods; Tables 8-11 show total and daily average energy use and energy use intensity. As for measured thermal energy, the reference cell was in cooling mode for the May, June and August tests, whereas the ZNE 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 significantly in comparison to cooling energy needs. For May, June and August combined, calculated HVAC energy use was 115 and 59 kWh in the reference and ZNE cells respectively, for south orientation, resulting in a savings of 49%; the corresponding values for west orientation are 133 kWh, 50 kWh and 63%. During the December test, HVAC energy use with south orientation was 85 kWh and 120 kWh for the reference and ZNE cells, respectively; a 41% increase; the corresponding values for west orientation are 56 kWh, 99 kWh and 77%. Hourly, daily and per-orientation variation in lighting energy savings is shown in Figures 26-29.

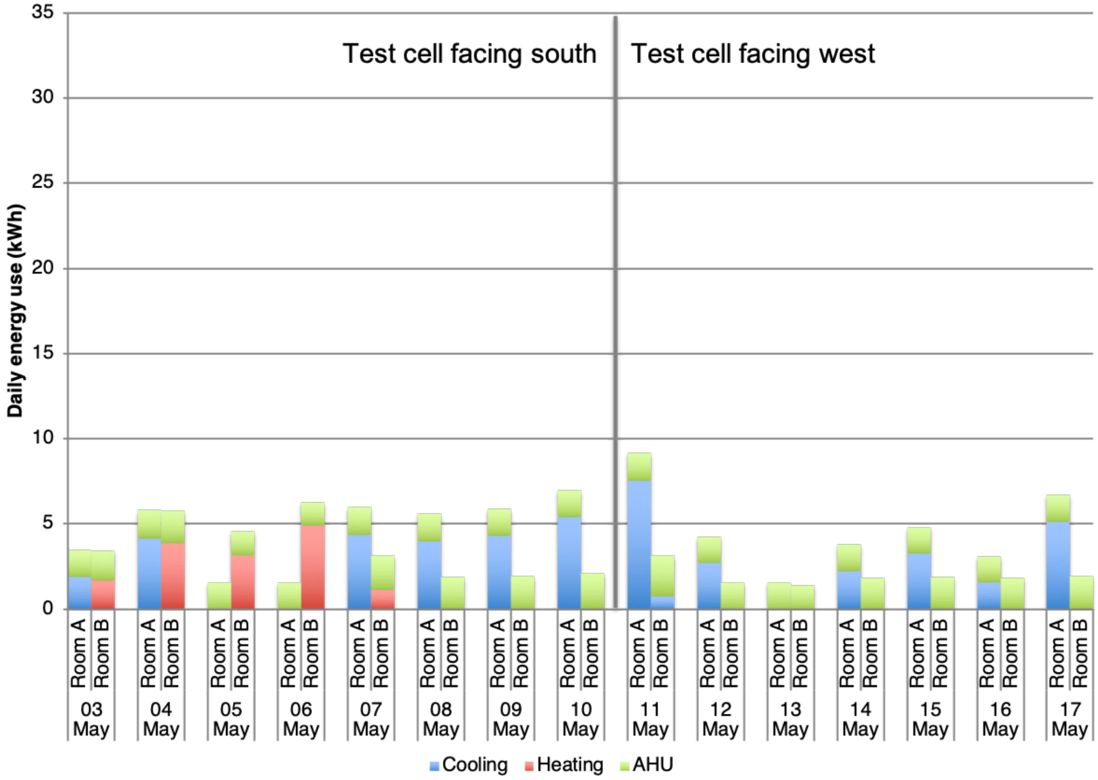

Figure 22. Daily HVAC energy consumption during May test period.

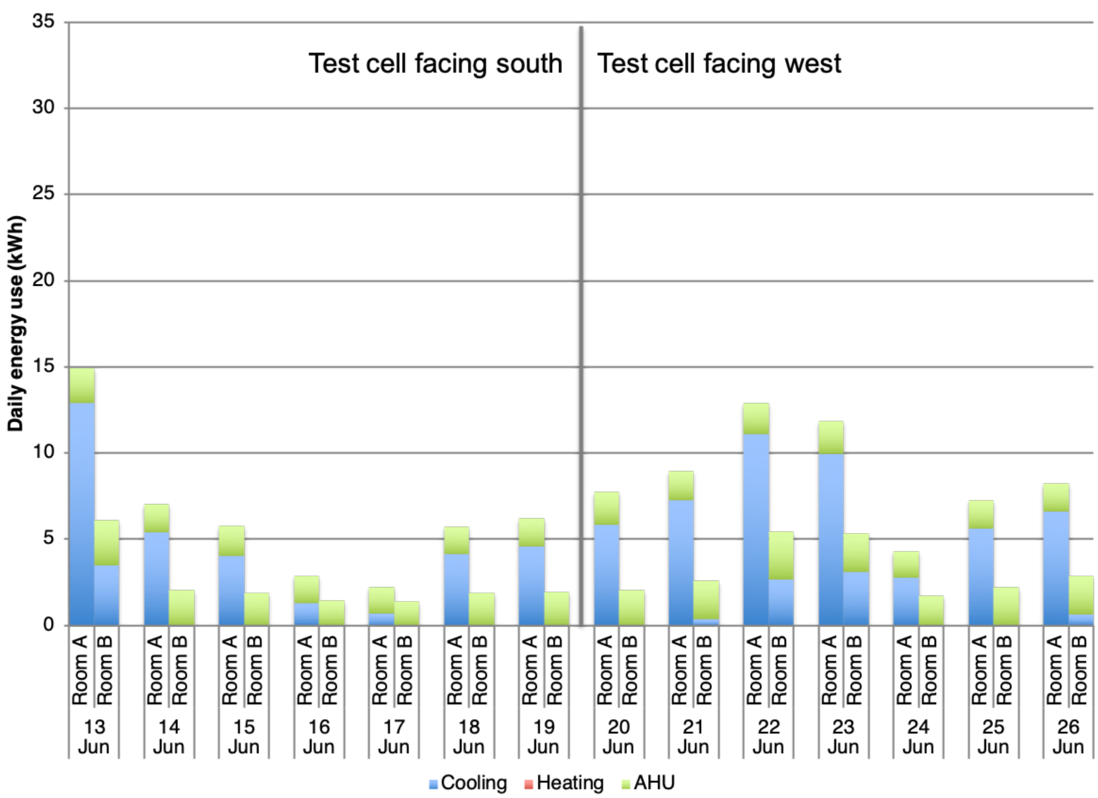

Figure 23. Daily HVAC energy consumption during June test period.

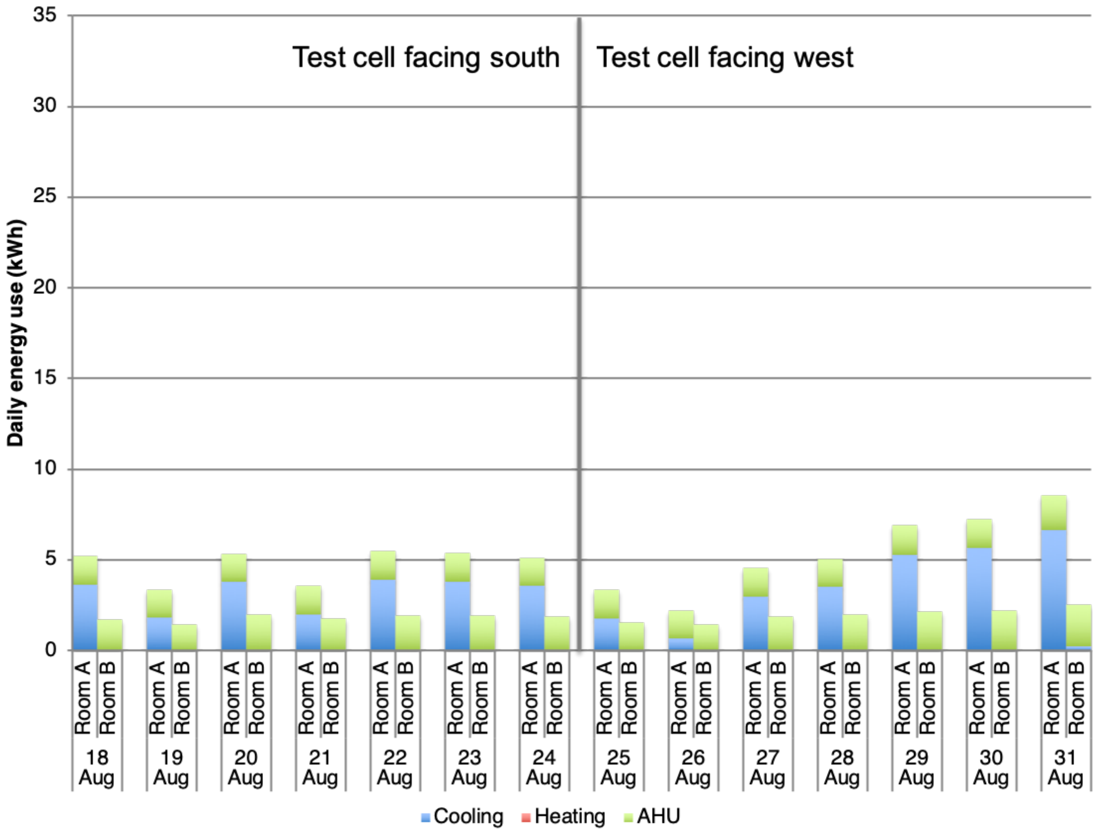

Figure 24. Daily HVAC energy consumption during August test period.

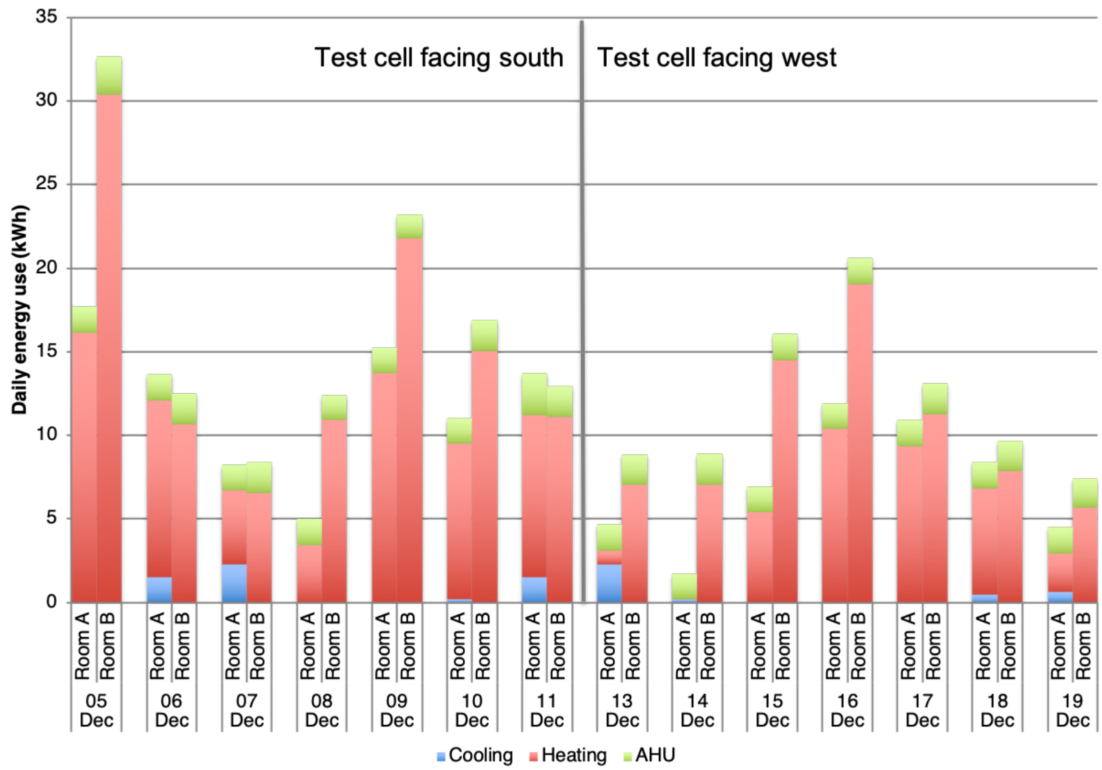

Figure 25. Daily HVAC energy consumption during December test period.

Table 8. Total HVAC energy use.

Month	Orientation	Testing days	Total energy (kWh)								ZNE package savings
			Reference (Cell A)				ZNE (Cell B)				
			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	Orientatio n	Testing days	Average daily energy (kWh)								ZNE packag e savings
			Reference (Cell A)				ZNE (Cell B)				
			Coolin g	Heatin g	AHU	Total	Coolin g	Heatin g	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	Orientatio n	Testing days	EUI (Wh/ft^2)								ZNE packag e savings
			Reference (Cell A)				ZNE (Cell B)				
			Coolin g	Heatin g	AHU	Total	Coolin g	Heatin g	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	184.7 4	-41%
	West	8	5.6	61.9	19.3	86.8	0.0	131.6	21.7	153.3 3	-77%

Table 11. Average daily HVAC EUI.

Month	Orientatio n	Testing days	Average daily EUI (Wh/ft^2)								ZNE packag e savings
			Reference (Cell A)				ZNE (Cell B)				
			Coolin g	Heatin g	AHU	Total	Coolin g	Heatin g	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%

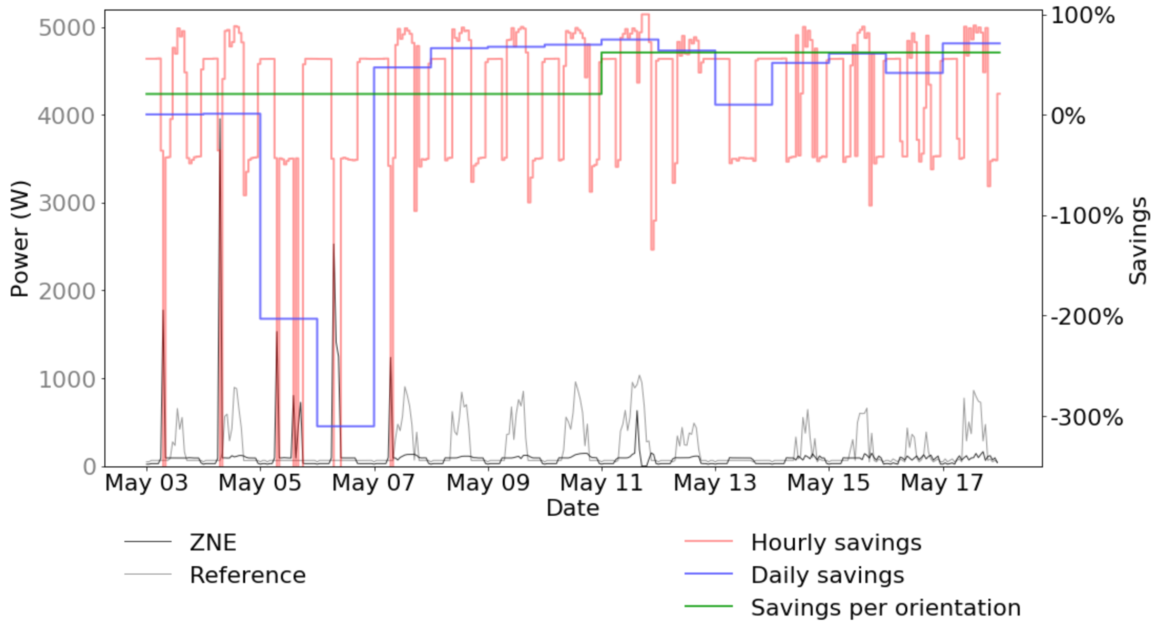

Figure 26. Hourly, daily and per-orientation HVAC energy savings for May testing period.

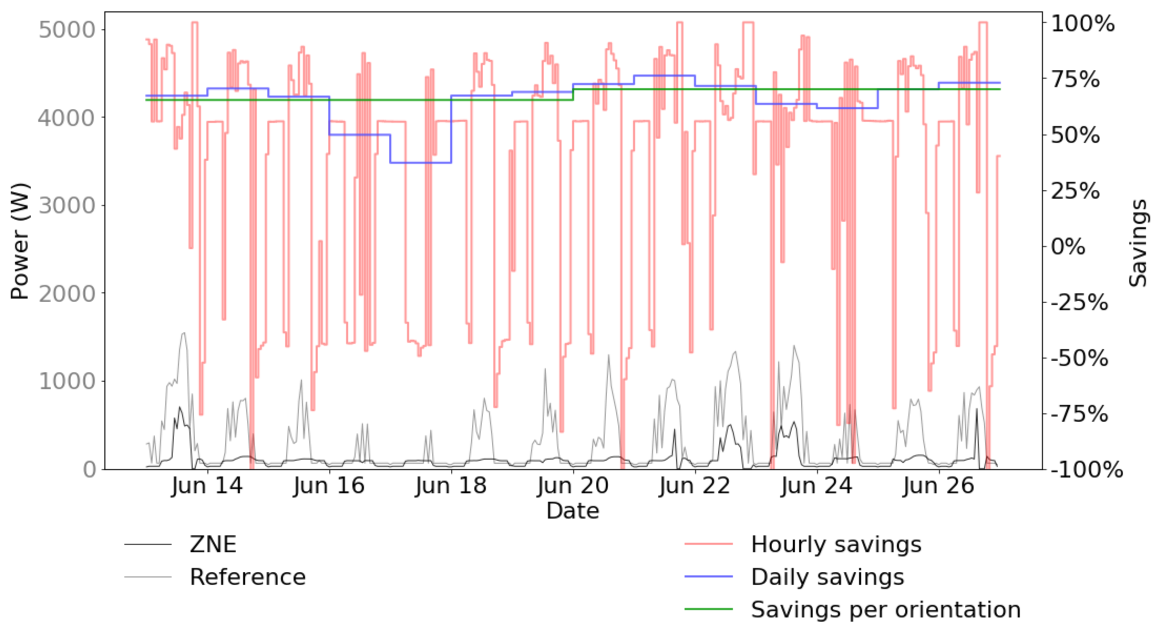

Figure 27. Hourly, daily and per-orientation HVAC energy savings for June testing period.

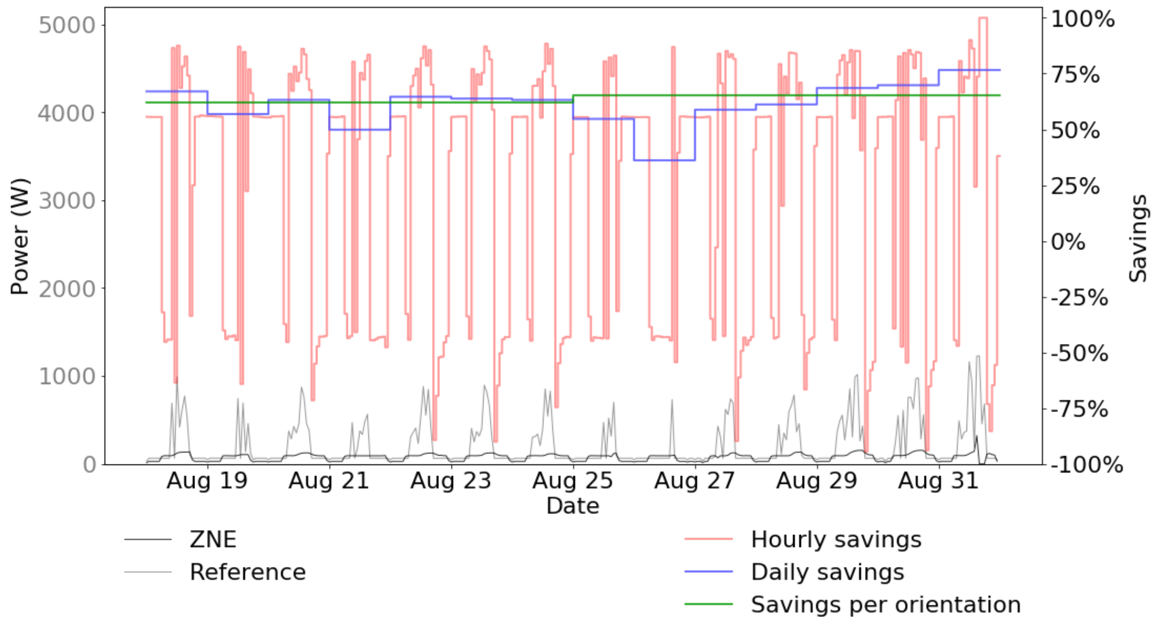

Figure 28. Hourly, daily and per-orientation HVAC energy savings for August testing period.

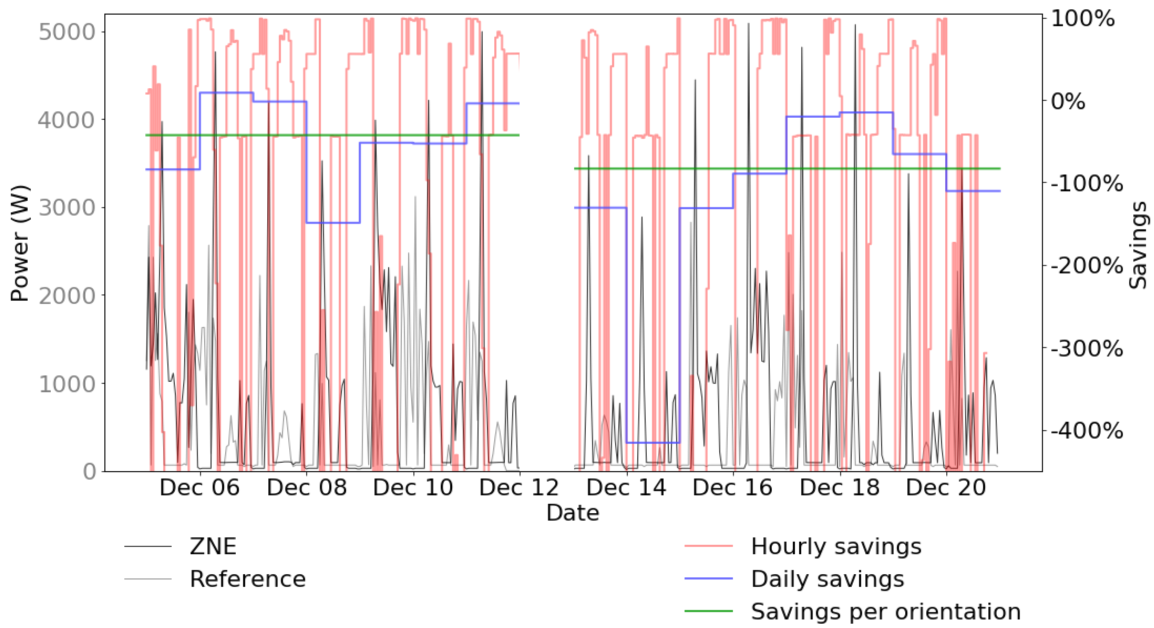

Figure 29. Hourly, daily and per-orientation HVAC energy savings for December testing period.

3.2.2 Thermal comfort

PMV and PPD distributions for the middle and window spaces of the reference and ZNE cells are in Figures 30 to 31, for the times of greater occupancy - between 8 AM and 6 PM. The values measured by the velocity sensors were found to not be reliable; the air velocity was determined from the manufacturers' specifications for the conventional and Thermafuser diffusers for the reference and ZNE 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 cell, respectively.

During the cooling season (May, June, and August), the ZNE cell appears warmer than the reference cell, with perhaps some overcooling in the window space of the reference cell (PMV around -0.5 to -1). As a consequence, there is a significant occurrence of PPD values in that space that are above the 20% limit, unlike in other spaces. During the heating season (December), the ZNE 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%. Here it is possible that the single-pane window plays a part in making the space less comfortable than it would be with a better insulating window, such as a low-emissivity double-pane window.

All in all, the ZNE package can be said to maintain 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 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.

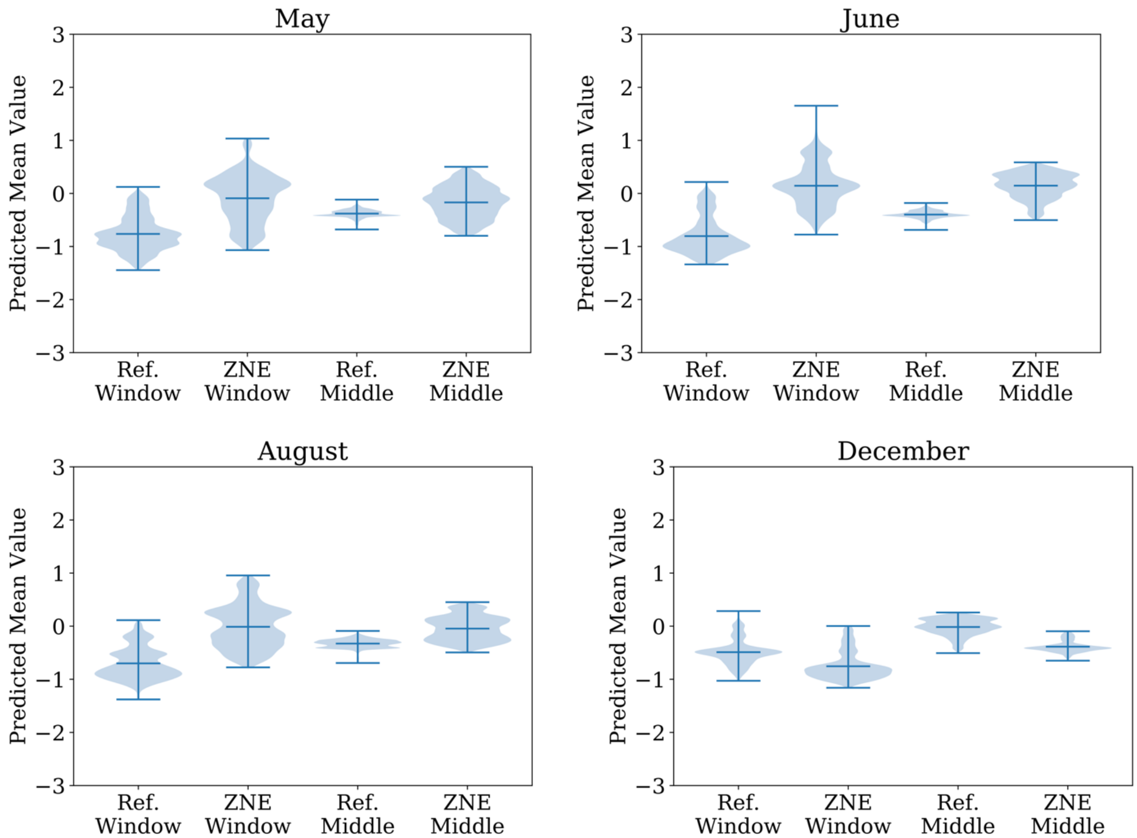

Figure 30. Kernel-density estimator distribution plots of Predicted Mean Value for each of the four tests. Each plot contains the distribution for the window and middle spaces both in the reference and in the ZNE cells.

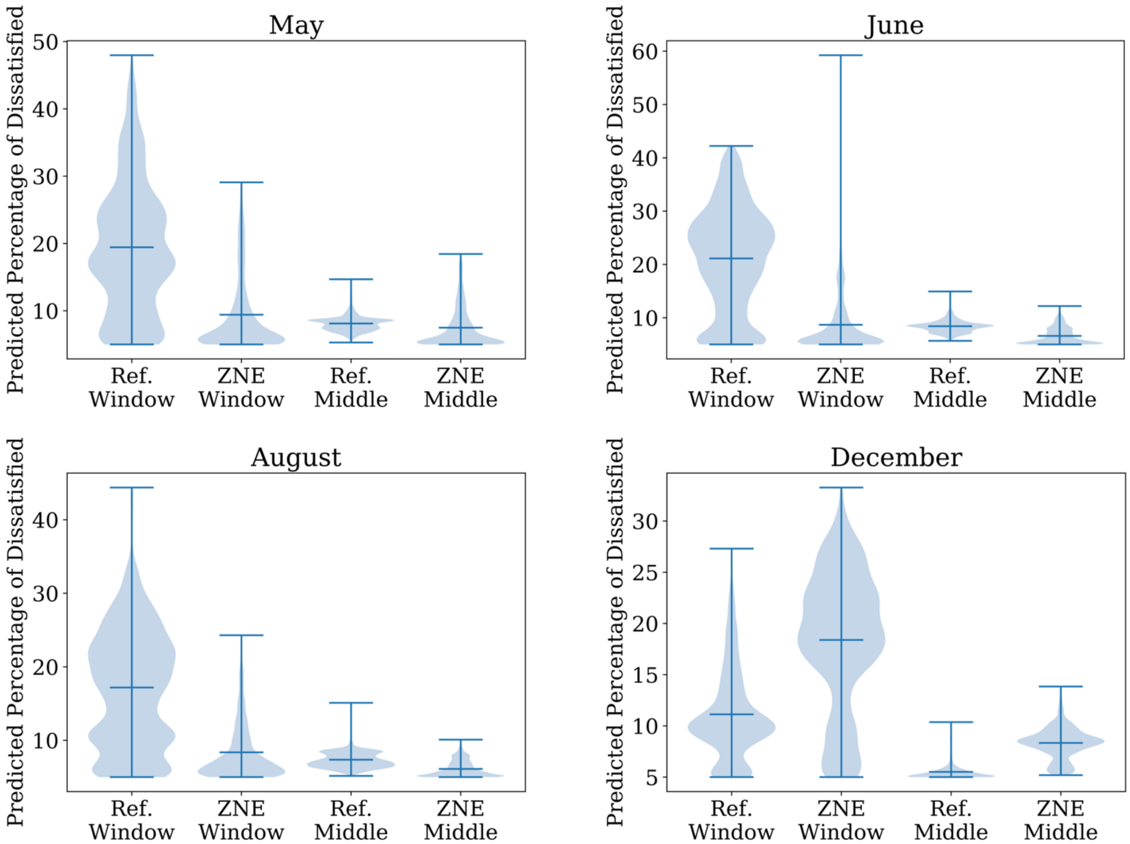

Figure 31. Kernel-density estimator distribution plots of Predicted Percentage of Dissatisfied for each of the four tests. Each plot contains the distribution for the window and middle spaces both in the reference and in the ZNE cells.

3.2.3 Lighting energy

Lighting power consumption throughout the four testing periods was significantly lower in the ZNE cell (Cell B) than in the reference cell (Cell A) (Figures 27 to LE2). For south orientation, total lighting energy use was 85% lower in the ZNE cell when compared to the reference cell (48 versus 328 kWh, respectively). For west façade orientation the lighting energy use reduction was also 85% (49 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 south orientation; for west orientation the corresponding values are very similar: 90%, 89%, 77%. More detail is shown in Table 8. These results are presented in terms of average daily energy use in Table 9 and EUI in Tables 10 and 11. Hourly, daily and per-orientation variation in lighting energy savings is shown in Figures 36-39.

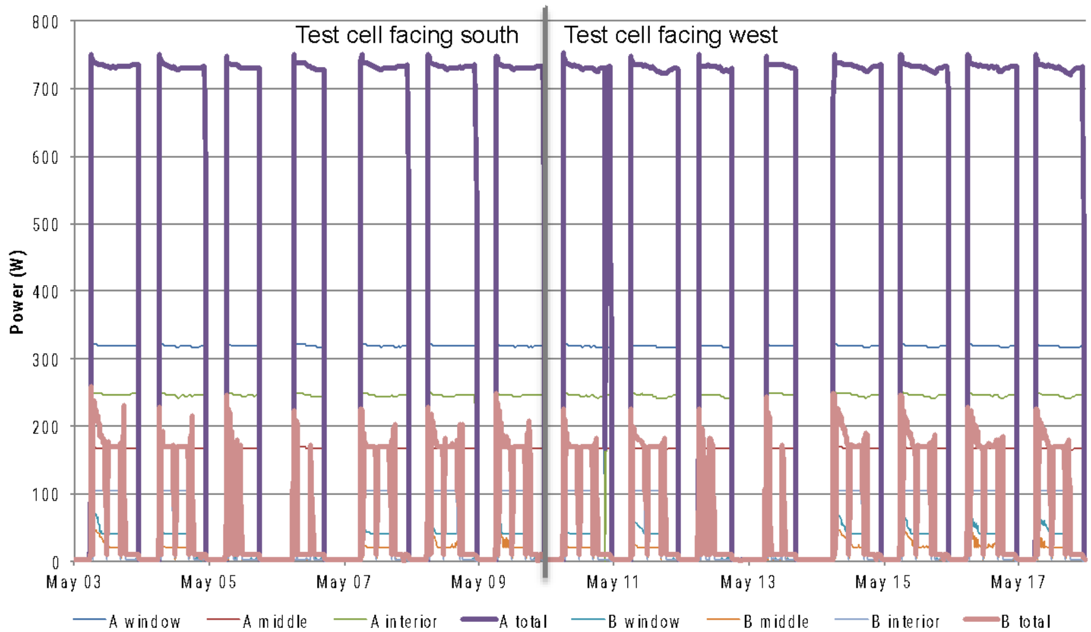

Figure 32. Lighting power consumption during May test period.

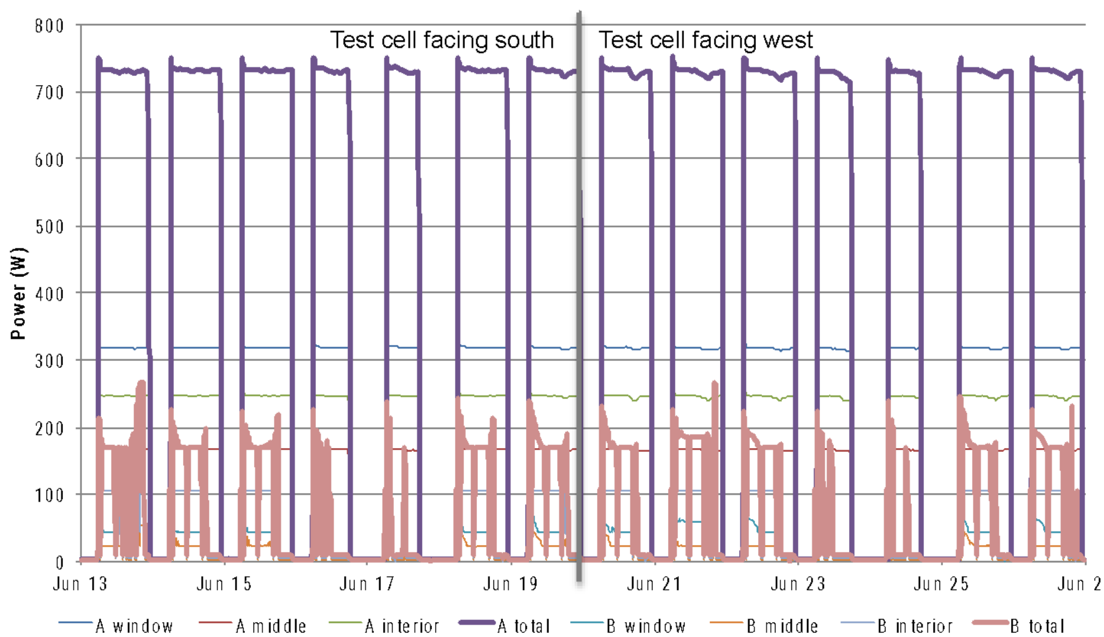

Figure 33. Lighting power consumption during June test period.

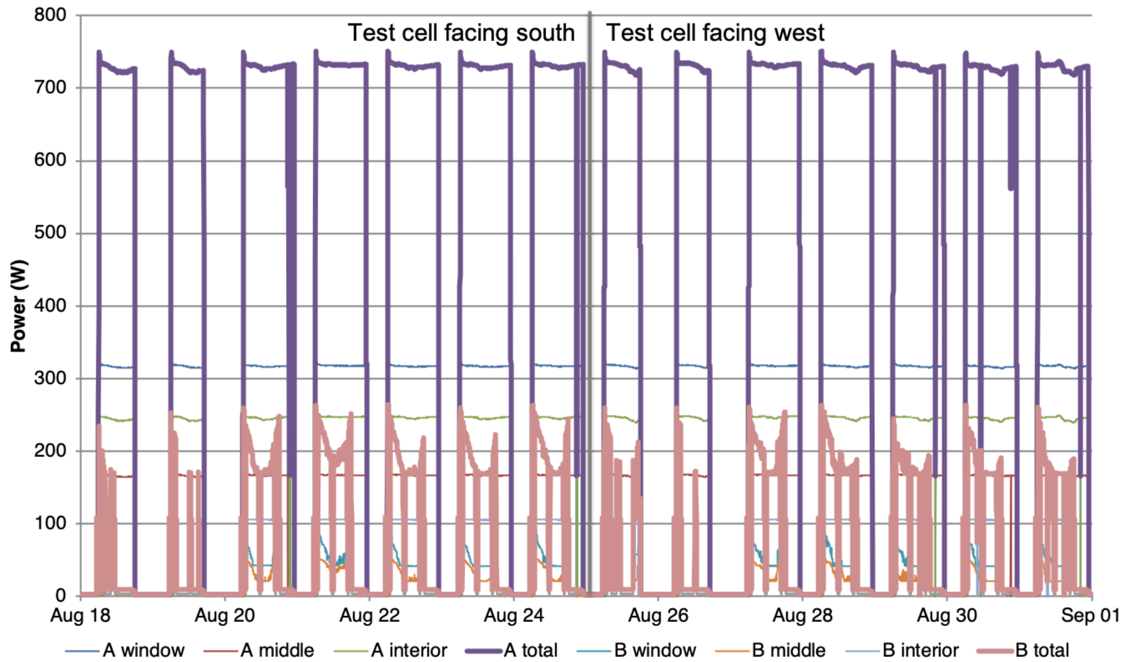

Figure 34. Lighting power consumption during August test period.

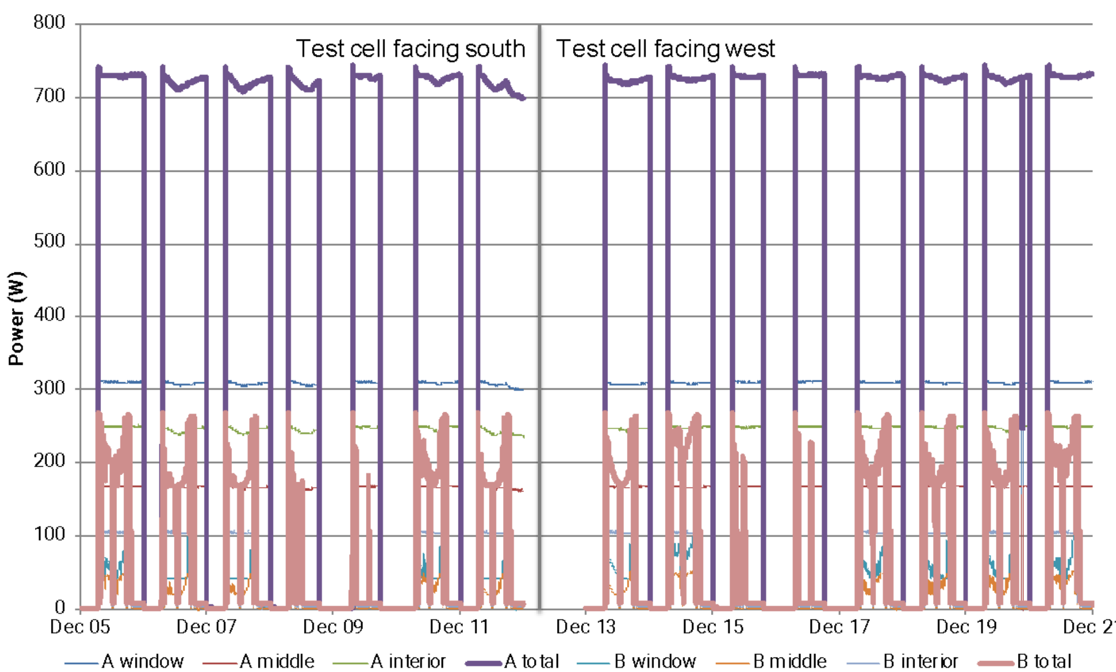

Figure 35. Lighting power consumption during December test period.

Table 12. Total lighting energy consumption.

Mo.	Orient.	Testing days	Total energy (kWh)								ZNE package savings			
			Reference (Cell A)				ZNE (Cell B)							
			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 (Cell A)				ZNE (Cell B)							
			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 (Cell A)				ZNE (Cell B)							
			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%
Jun	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%
Aug	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%
Dec	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 (Cell A)				ZNE (Cell B)							
			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%
May	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%
Jun	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%
Aug	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%
Dec	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

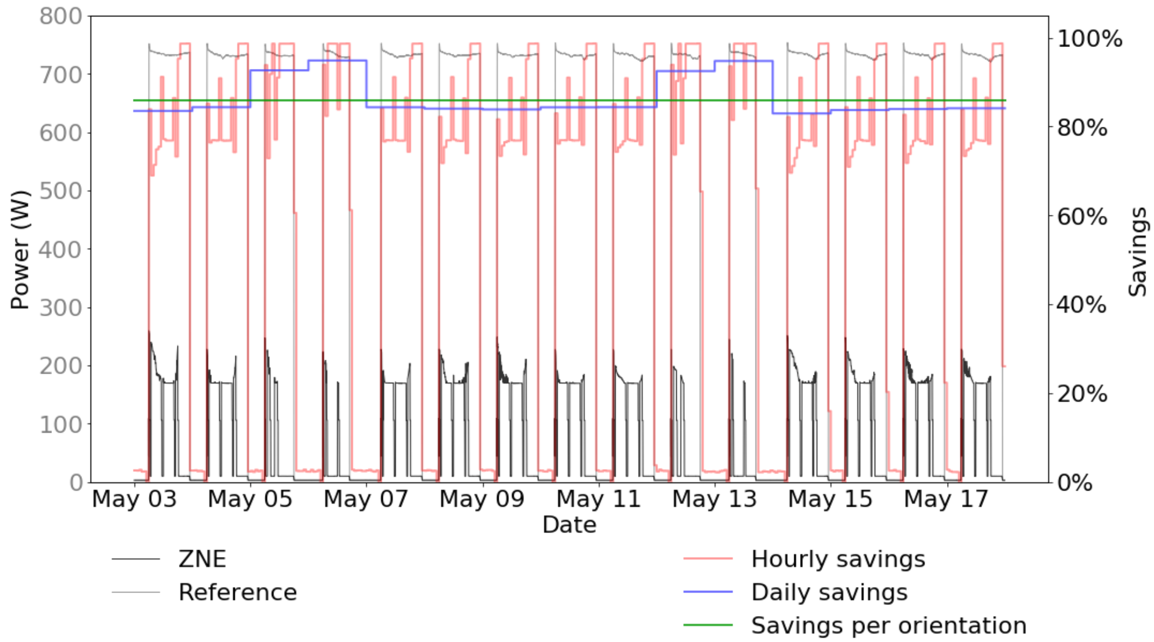

Figure 36. Hourly, daily and per-orientation lighting energy savings for May testing period.

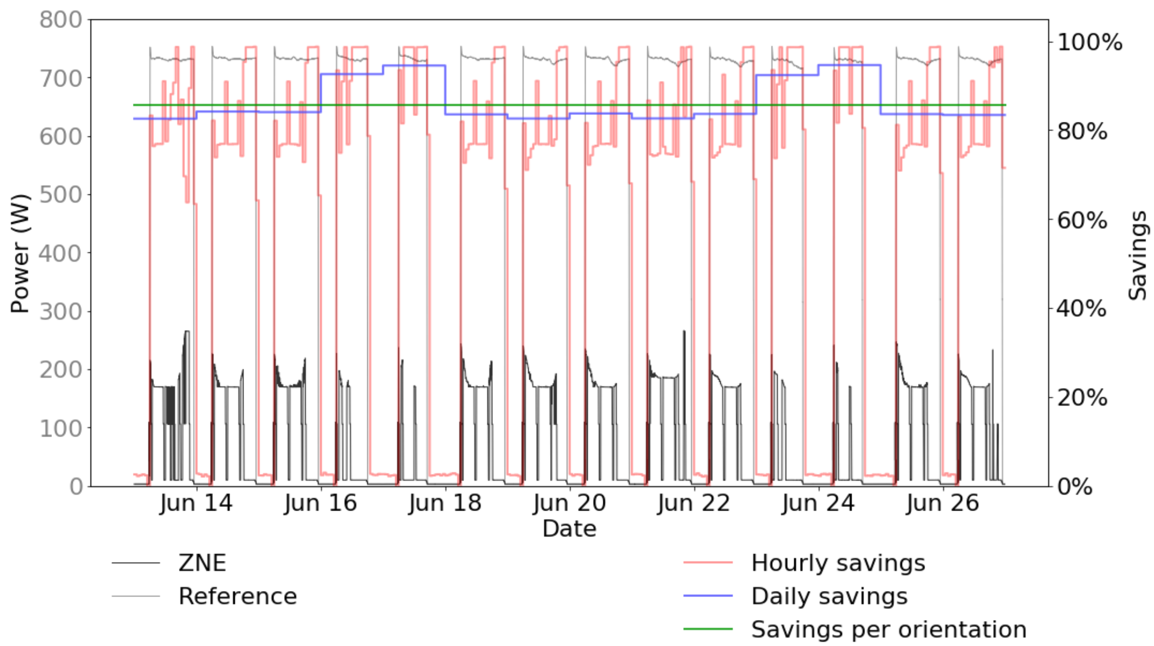

Figure 37. Hourly, daily and per-orientation lighting energy savings for June testing period.

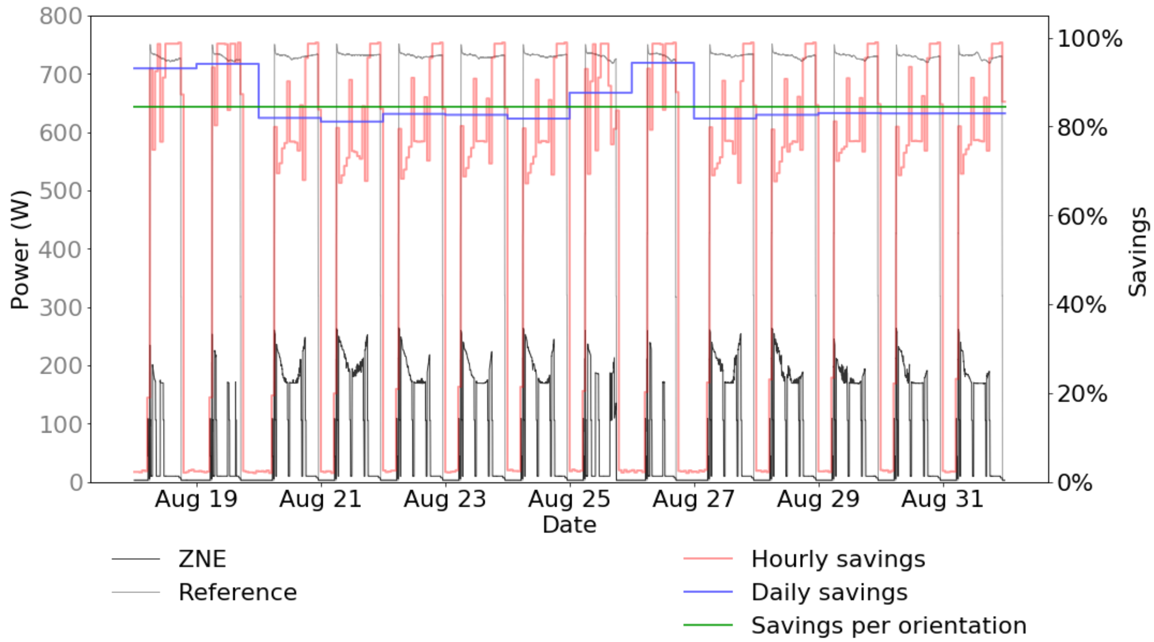

Figure 38. Hourly, daily and per-orientation lighting energy savings for August testing period.

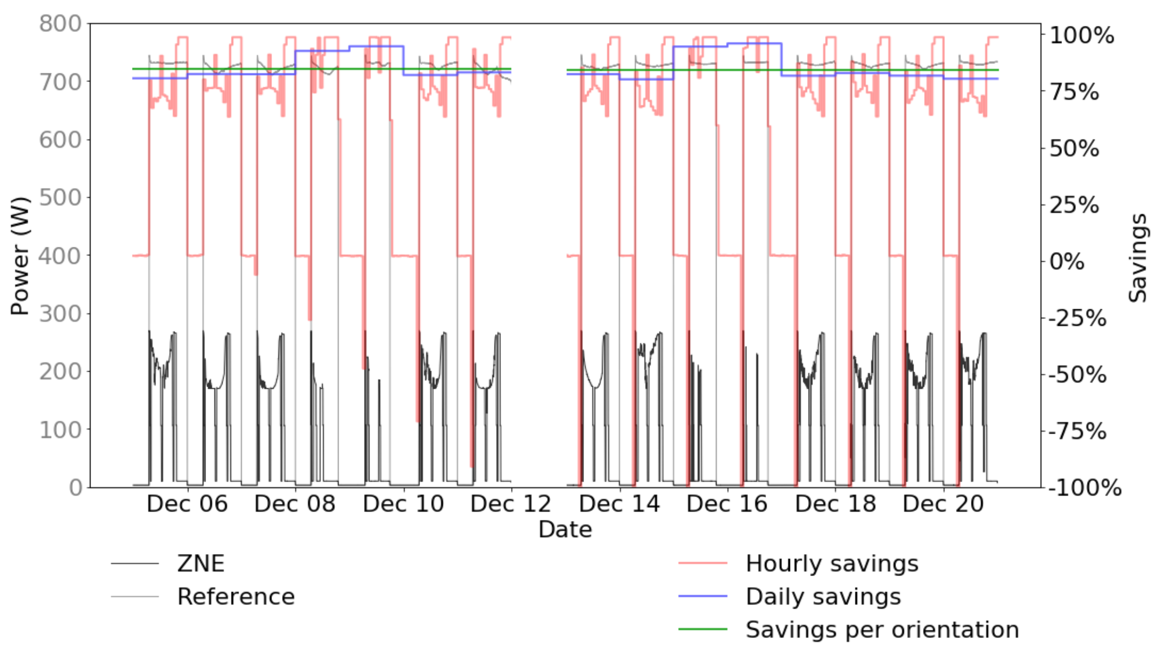

Figure 39. Hourly, daily and per-orientation lighting energy savings for December testing period.

3.2.4 Plug loads

Plug load energy use was 31% lower in the ZNE cell than in the reference cell (88 versus 127 kWh). Figures 29 to 43 show plug load power consumption during the test periods; energy use is shown in Tables 12 and 13. Hourly, daily and per-orientation variation in lighting energy savings is shown in Figures 44-47.

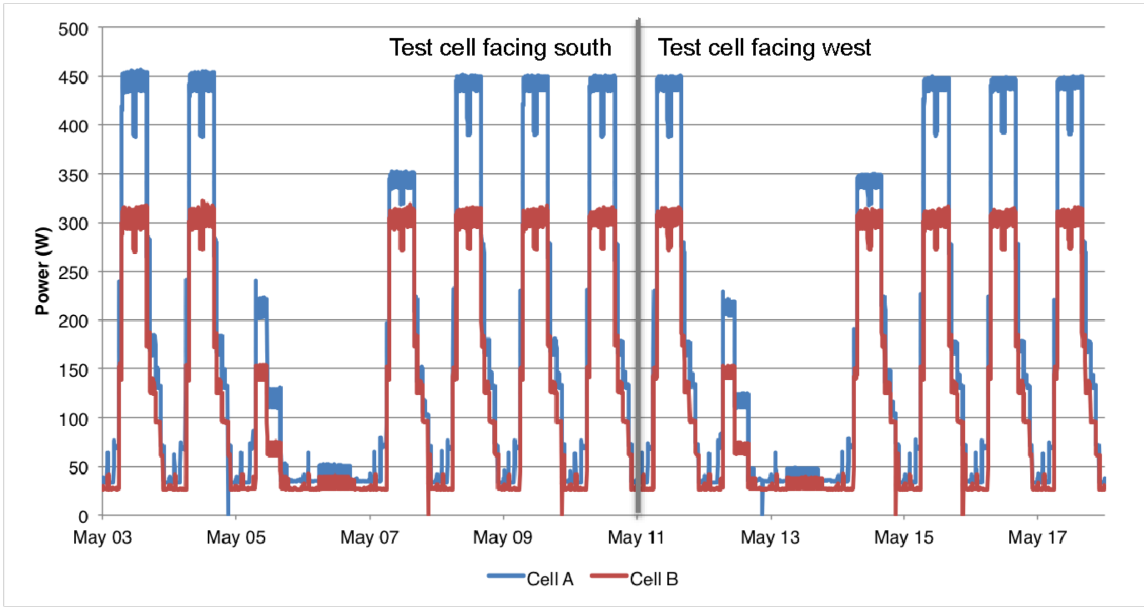

Figure 40. Plug load power consumption during May test period.

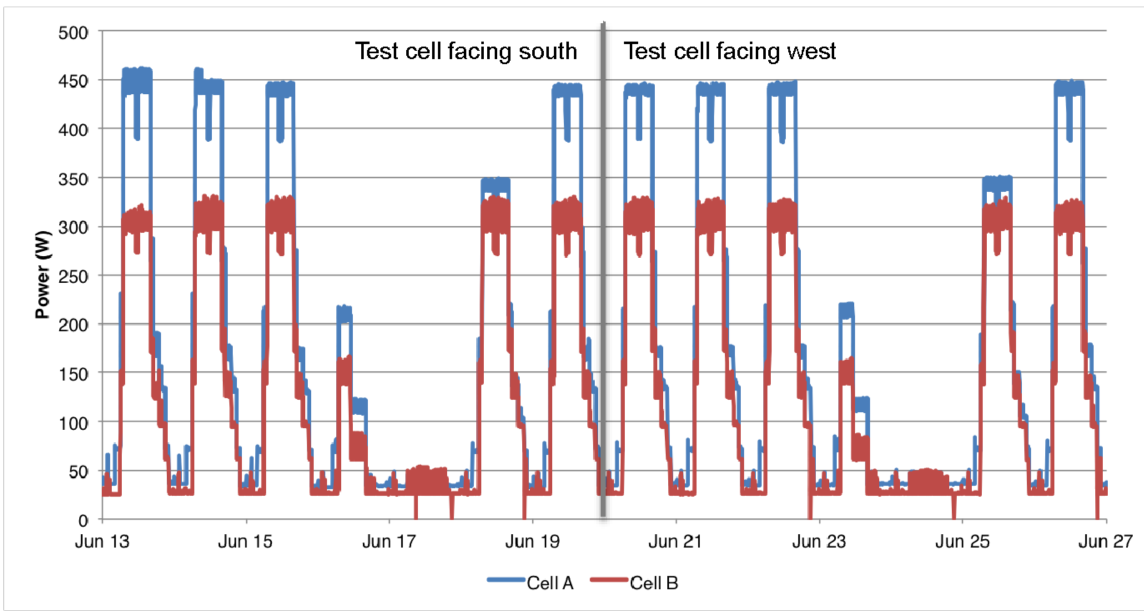

Figure 41. Plug load power consumption during June test period.

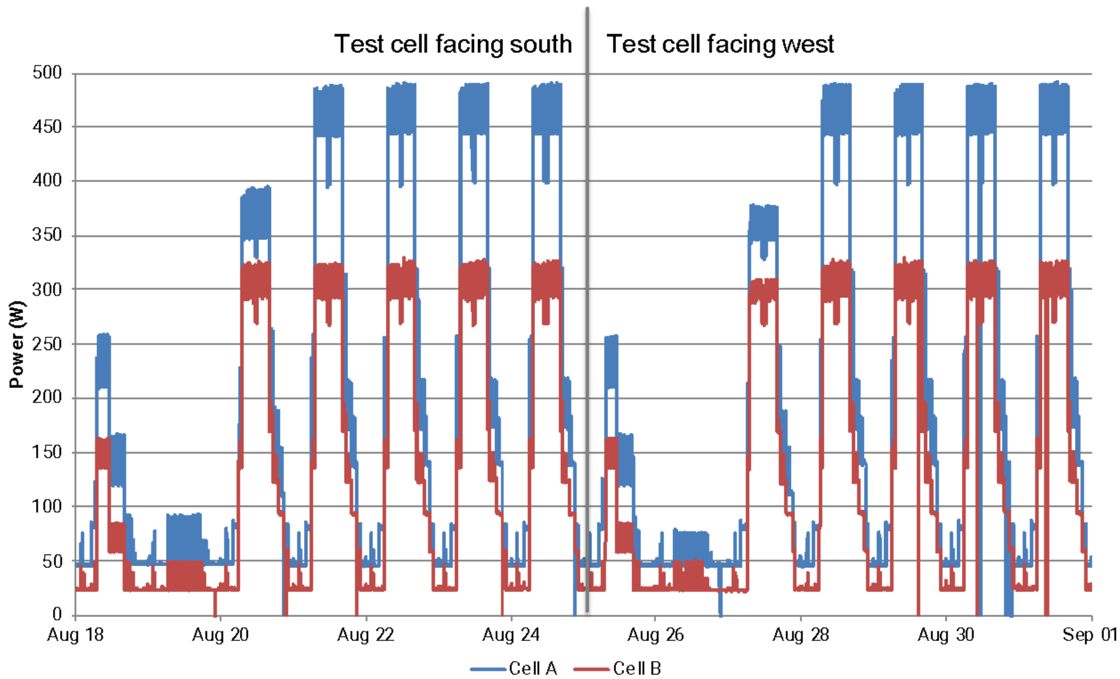

Figure 42. Plug load power consumption during August test period.

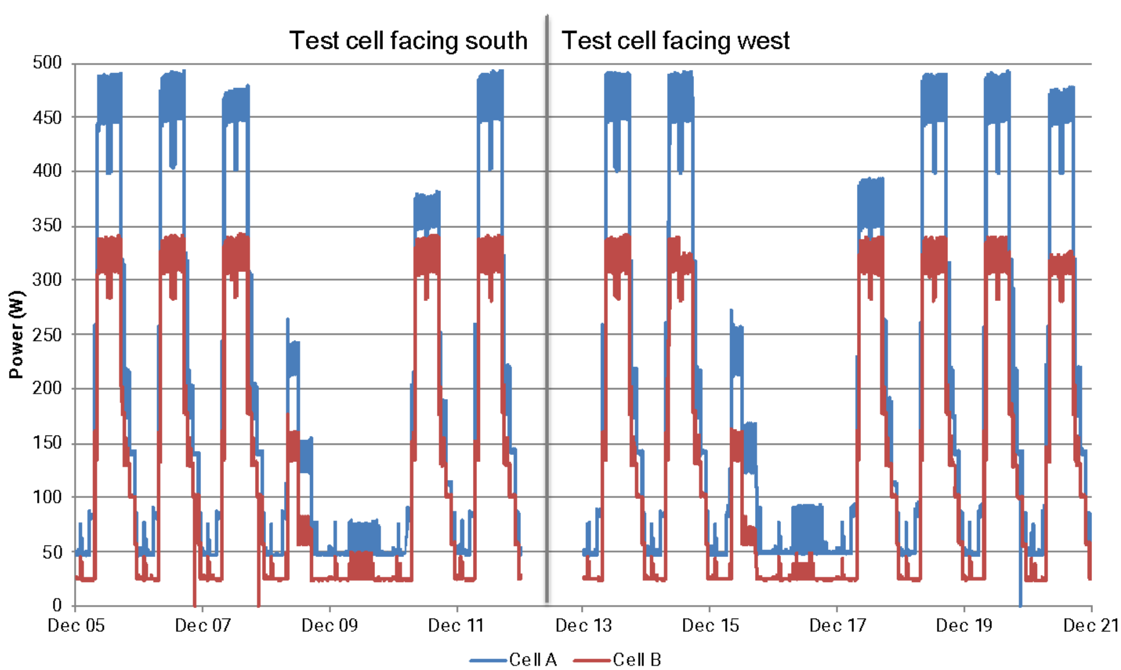

Figure 43. Plug load power consumption during December test period.

Table 16. Plug load energy use.

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

			Cell A	Cell B	Cell A	Cell B	
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
			Cell A	Cell B	Cell A	Cell B	
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%

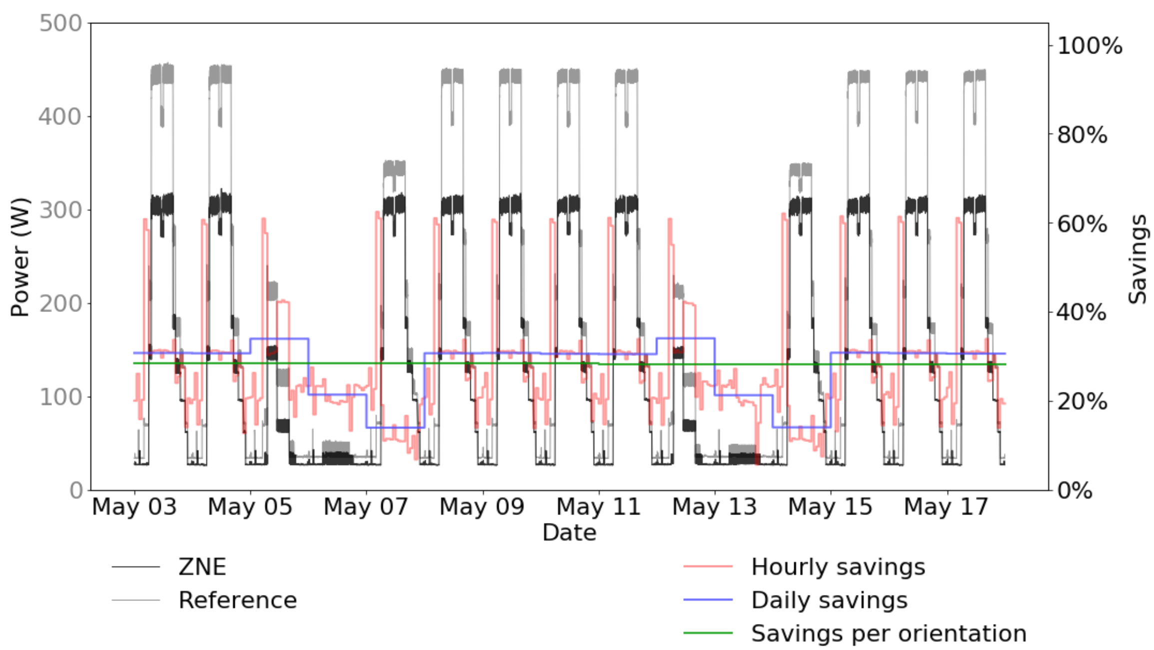

Figure 44. Hourly, daily and per-orientation plug load energy savings for May testing period.

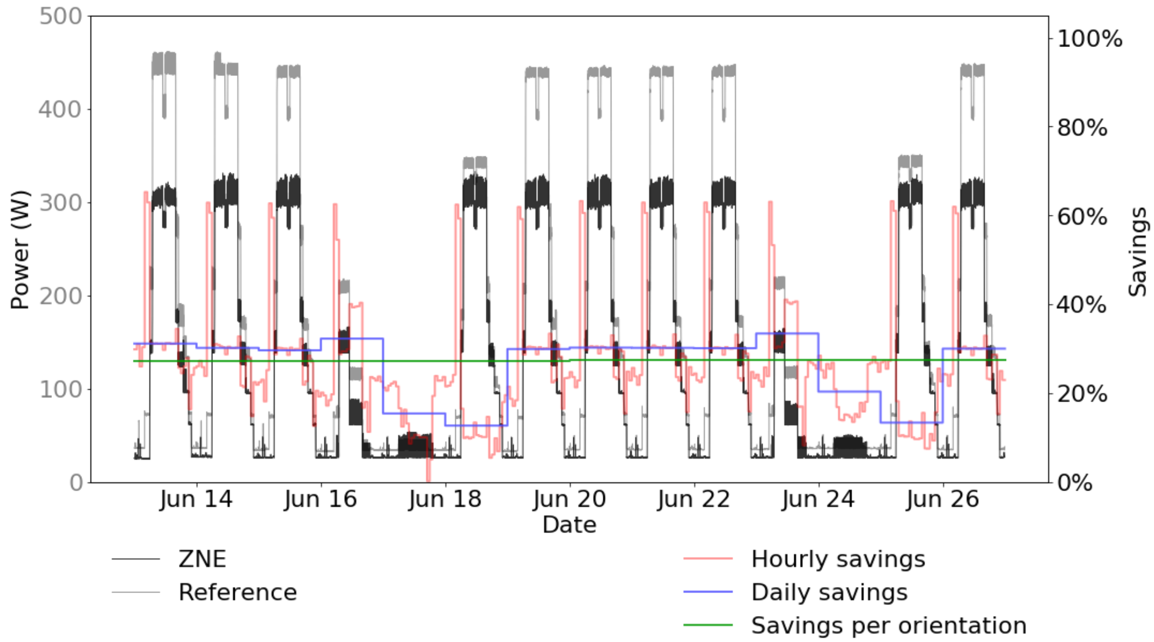

Figure 45. Hourly, daily and per-orientation plug load energy savings for June testing period.

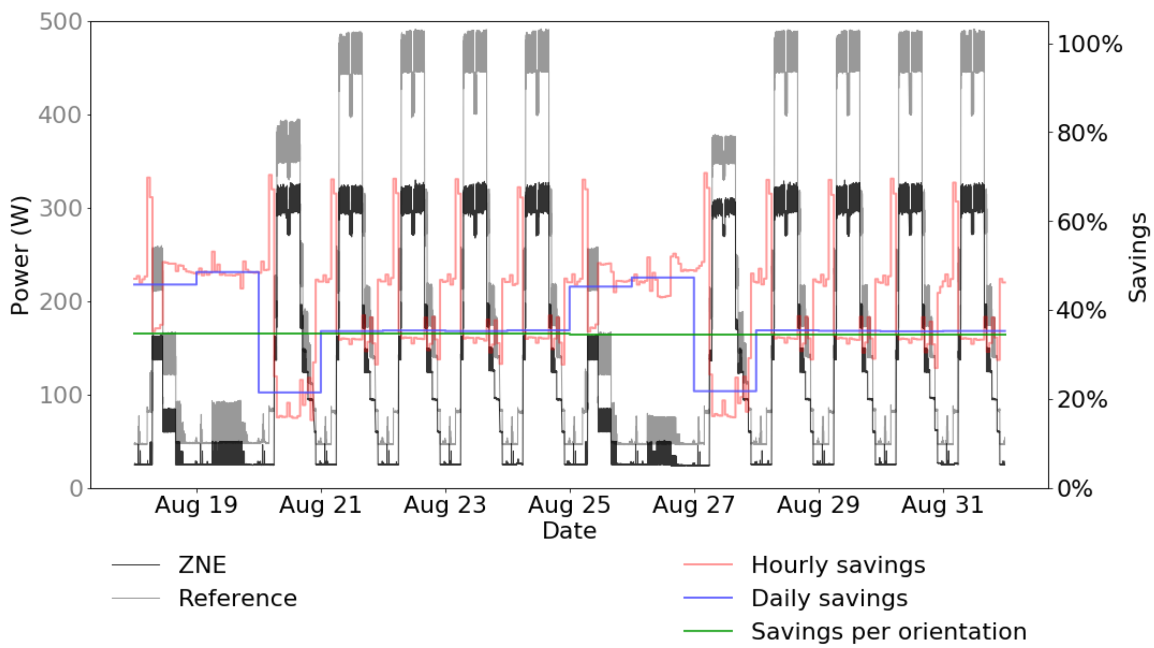

Figure 46. Hourly, daily and per-orientation plug load energy savings for August testing period.

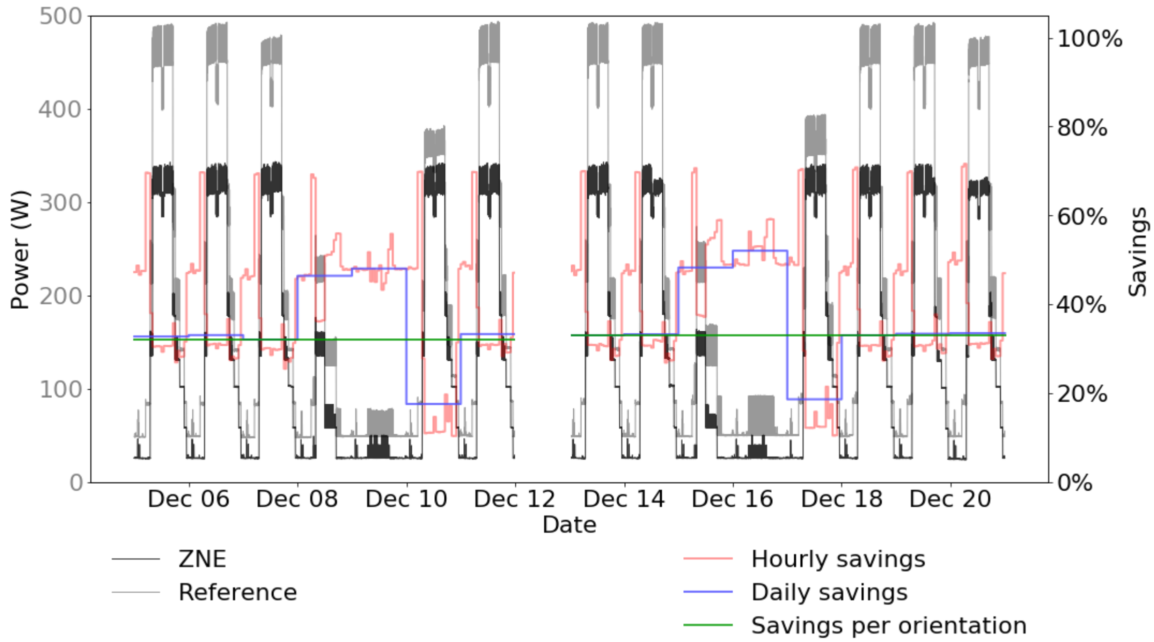

Figure 47. Hourly, daily and per-orientation plug load energy savings for December testing period.

3.2.5 Visual comfort

In the TDD space, measured TDD was well below the 0.35 threshold for perceptible glare. Figures 31 to 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 (Figures 33 to 55). Results from the equivalent space in cell A show similar DGP values.

In the window spaces of both cells there were no significant 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 (Figures 35 to 58). 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 (Figures 37 to 62). 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 (Figures 59 and 63). 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 significant 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.

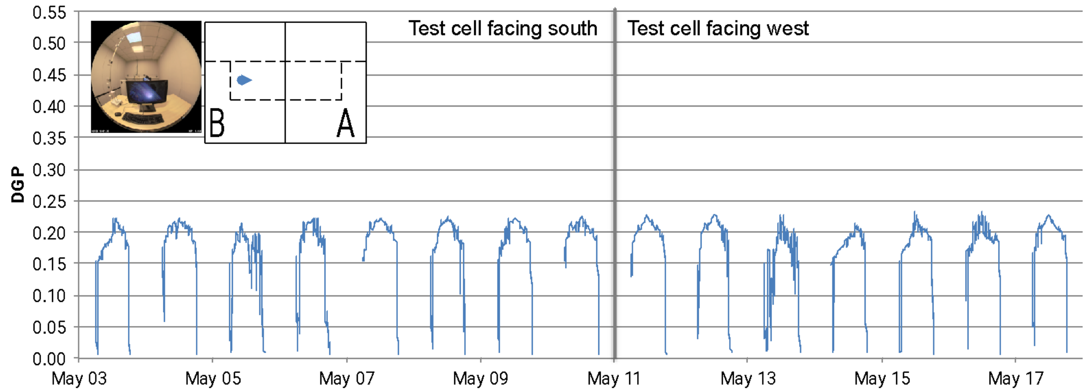

Figure 48. DGP in the enclosed office space in the ZNE cell (cell B), with the TDD in view, for the May testing period.

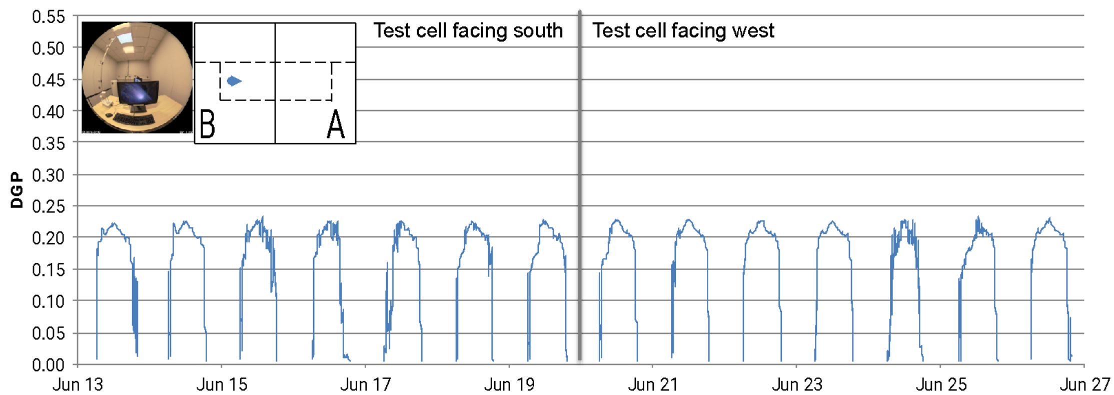

Figure 49. DGP in the enclosed office space in the ZNE cell (cell B), with the TDD in view, for the June testing period.

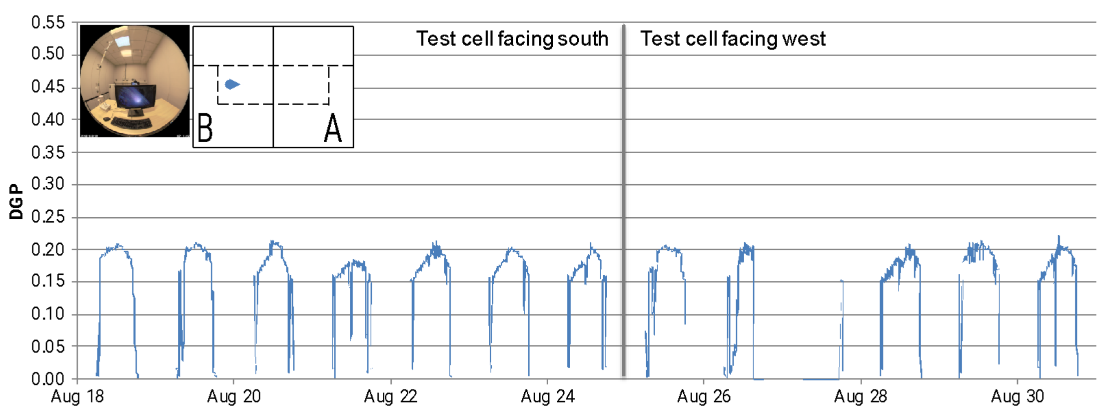

Figure 50. DGP in the enclosed office space in the ZNE cell (cell B), with the TDD in view, for the August testing period.

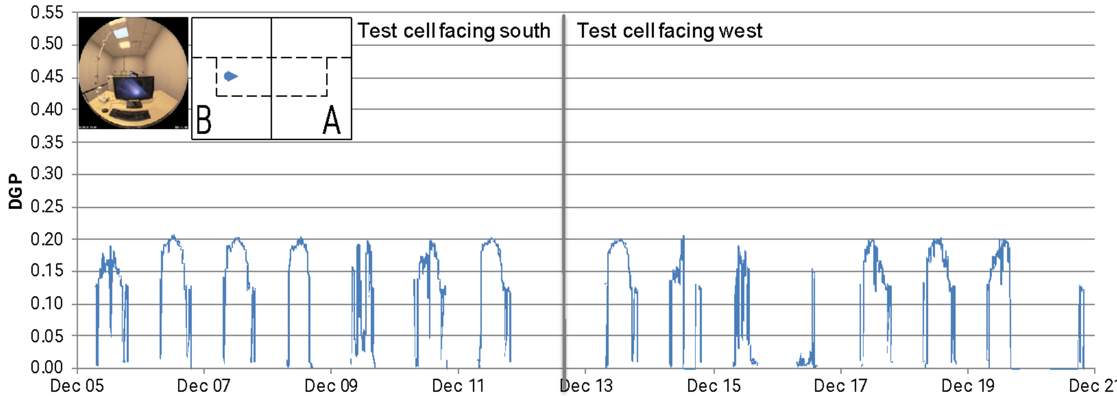

Figure 51. DGP in the enclosed office space in the ZNE cell (cell B), with the TDD in view, for the August testing December.

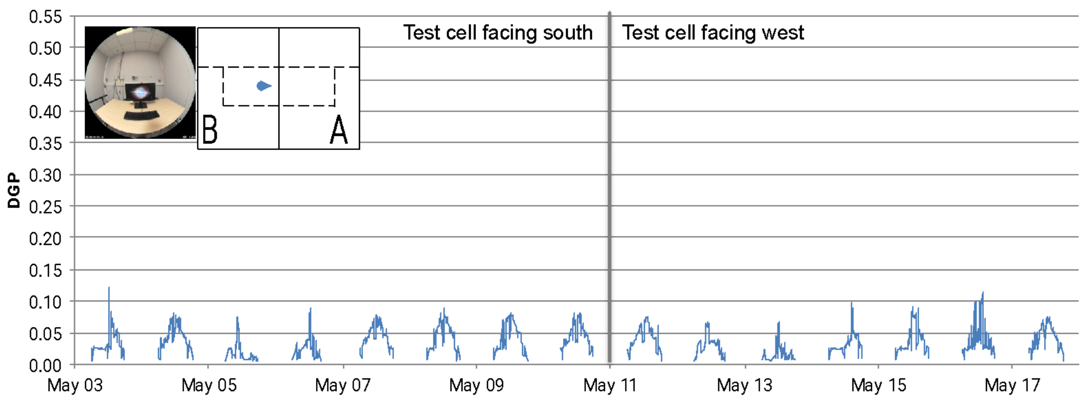

Figure 52. DGP in the enclosed office space in the ZNE cell (cell B), workstation facing wall, for the May testing period.

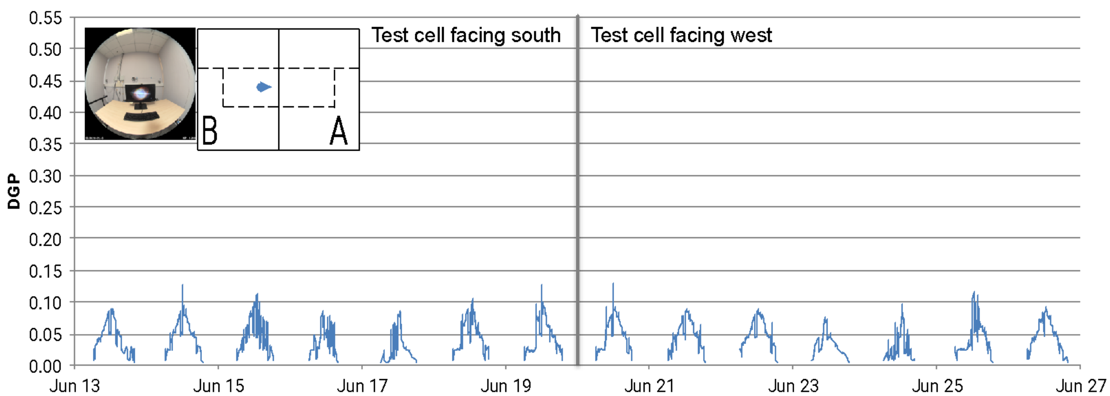

Figure 53. DGP in the enclosed office space in the ZNE cell (cell B), workstation facing wall, for the May testing period.

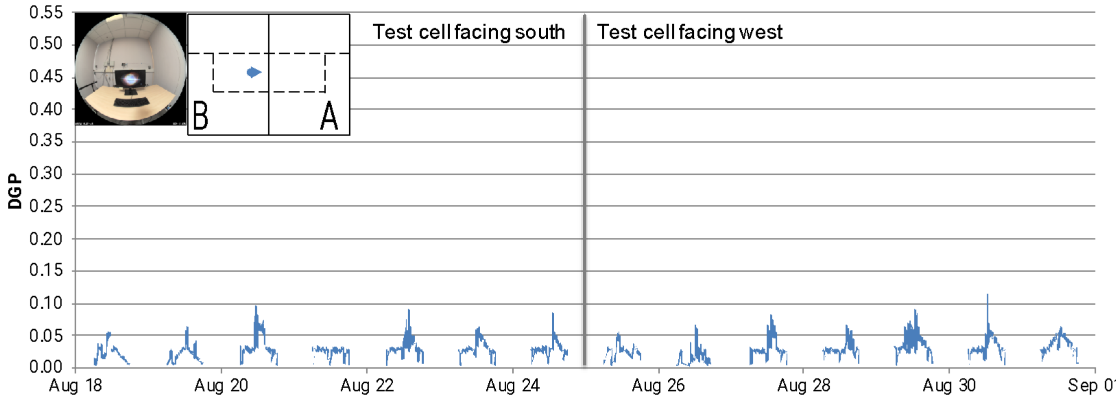

Figure 54. DGP in the enclosed office space in the ZNE cell (cell B), workstation facing wall, for the August testing period.

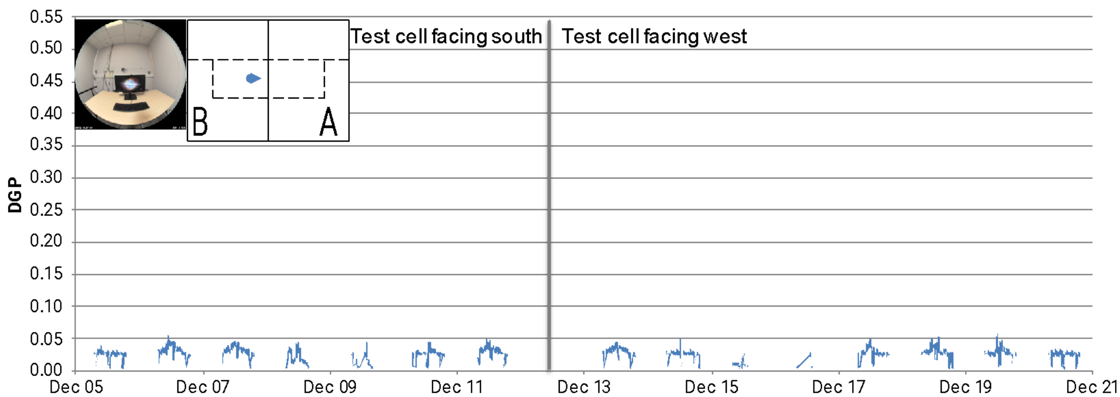

Figure 55. DGP in the enclosed office space in the ZNE cell (cell B), workstation facing wall, for the December testing period.

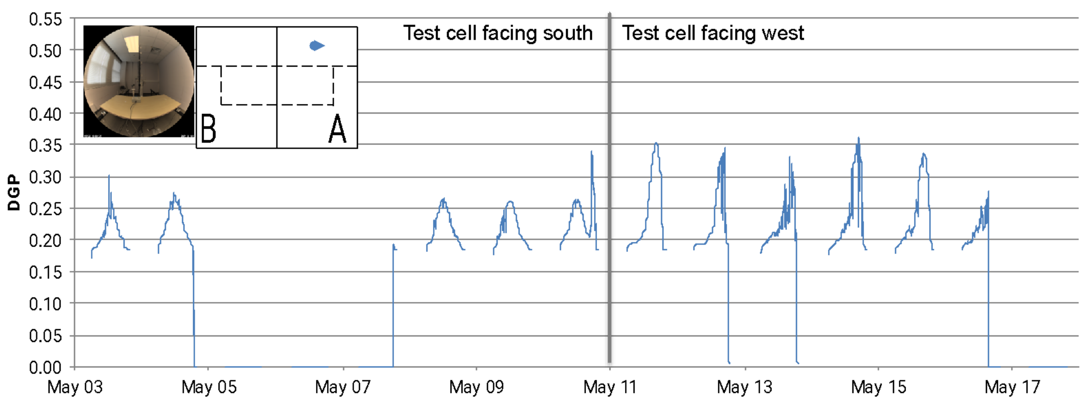

Figure 56. DGP in the window space in the reference cell (cell A), facing a side wall, for the May testing period. Gaps are due to equipment malfunction.

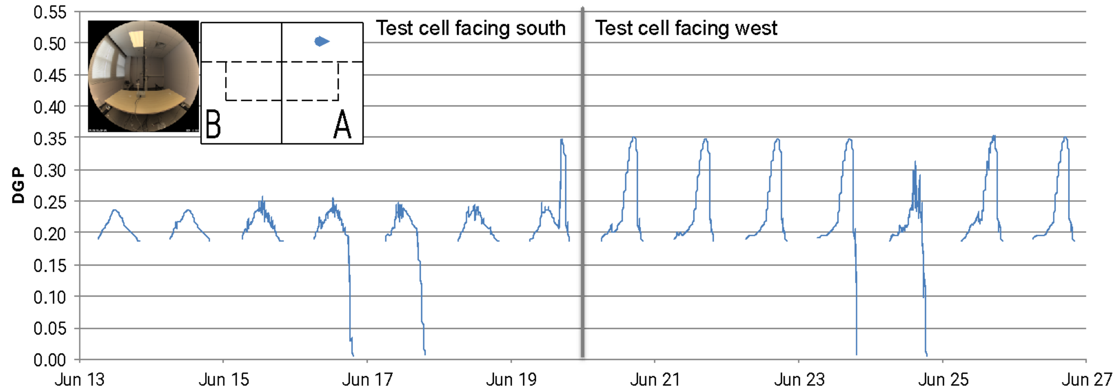

Figure 57. DGP in the window space in the reference cell (cell A), facing a side wall, for the June testing period.

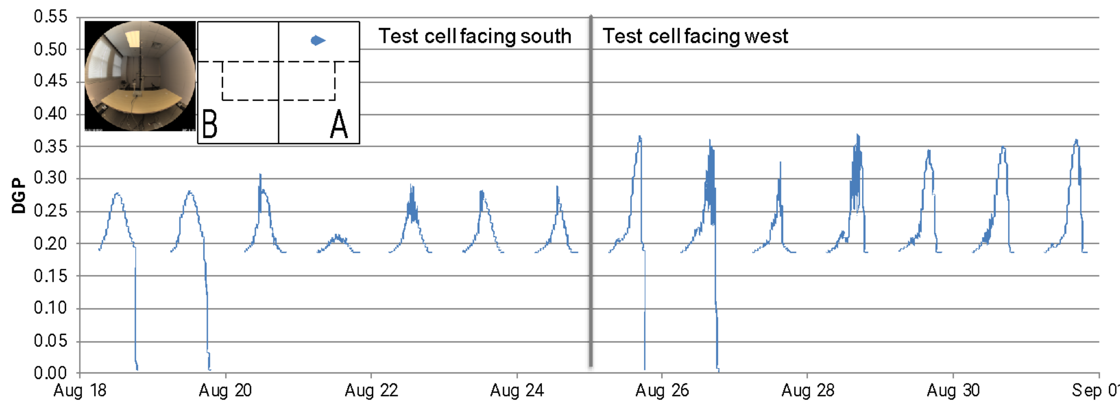

Figure 58. DGP in the window space in the reference cell (cell A), facing a side wall, for the August testing period.

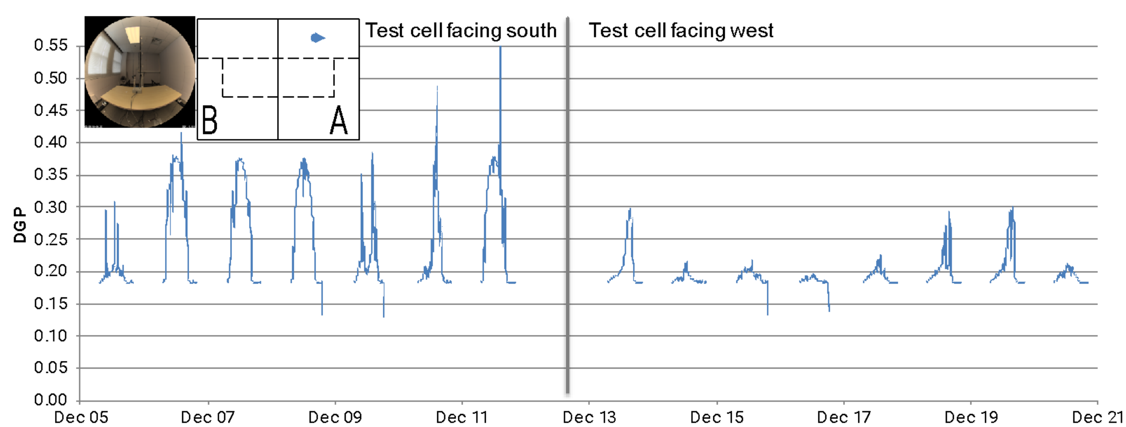

Figure 59. DGP in the window space in the reference cell (cell A), facing a side wall, for the December testing period.

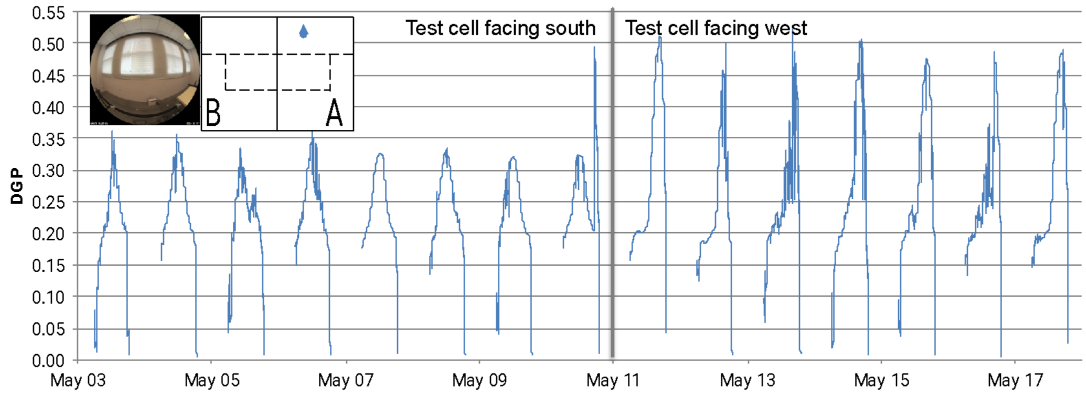

Figure 60. DGP in the window space in the ZNE cell (cell B), facing the window, for the May testing period.

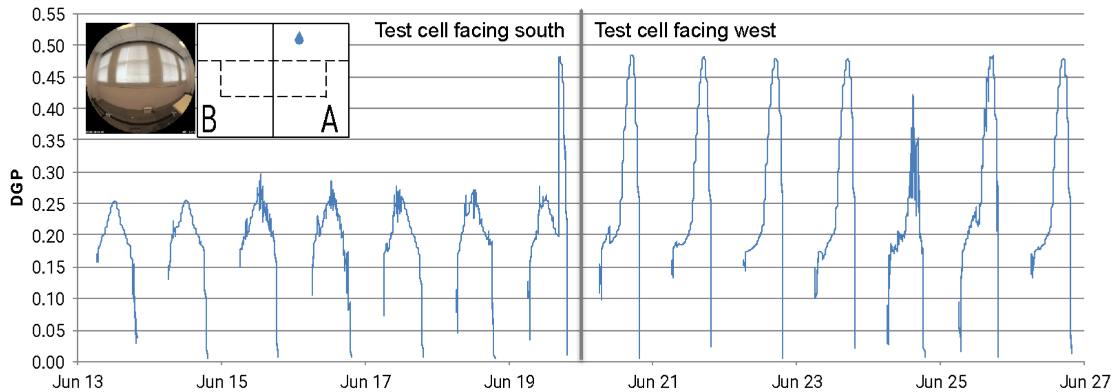

Figure 61. DGP in the window space in the ZNE cell (cell B), facing the window, for the June testing period.

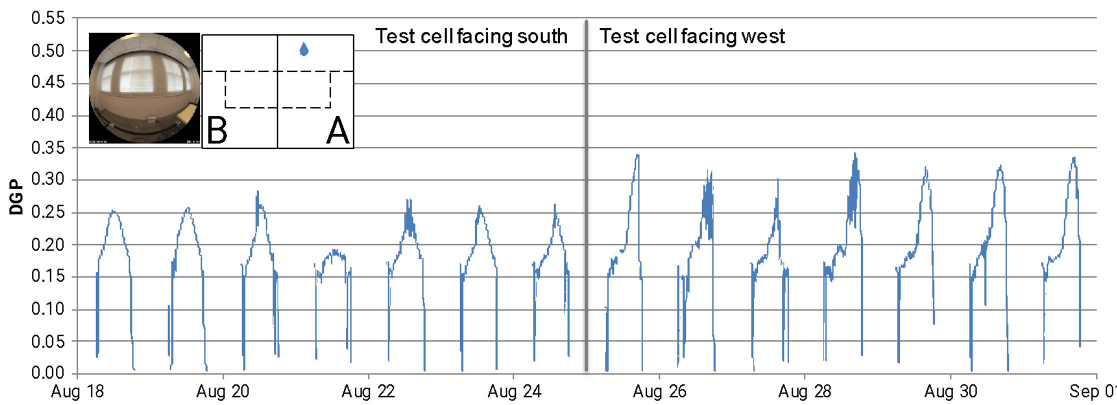

Figure 62. DGP in the window space in the ZNE cell (cell B), facing the window, for the August testing period.

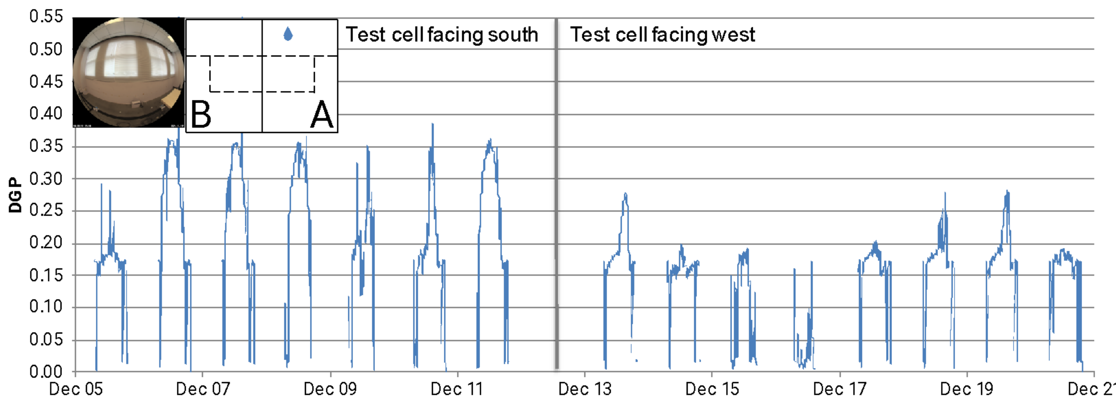

Figure 63. DGP in the window space in the ZNE cell (cell B), facing the window, for the December testing period.

3.2.6 Total energy consumption

Total energy consumption was calculated by adding calculated HVAC energy use and measured lighting and plug load energy use. It is shown in tables 18 and 19. ZNE package savings were in the 59%-69% range for cooling-dominated test periods and 22-25% range during heating dominated test periods. Hourly, daily and per-orientation variation in total energy savings is shown in Figures 64-67.

Table 18. Total energy use.

Month	Orientation	Testing days	Total energy (kWh)		Average daily energy (kWh)		ZNE package savings
			Cell A	Cell B	Cell A	Cell B	
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
			Cell A	Cell B	Cell A	Cell B	
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%

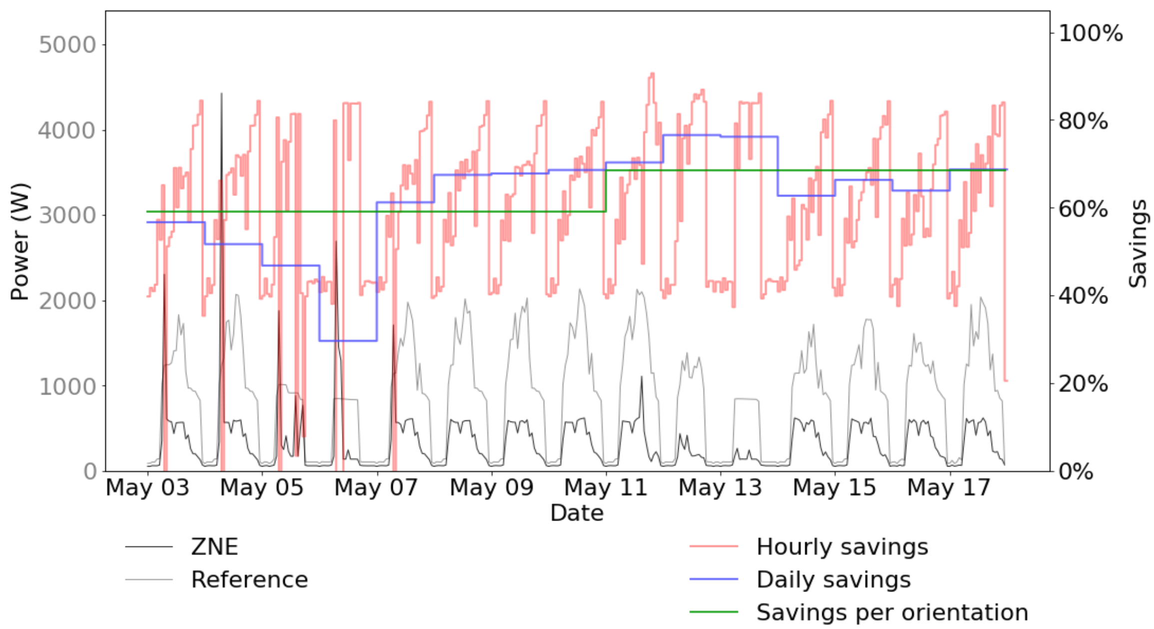

Figure 64. Hourly, daily and per-orientation total energy savings for May testing period.

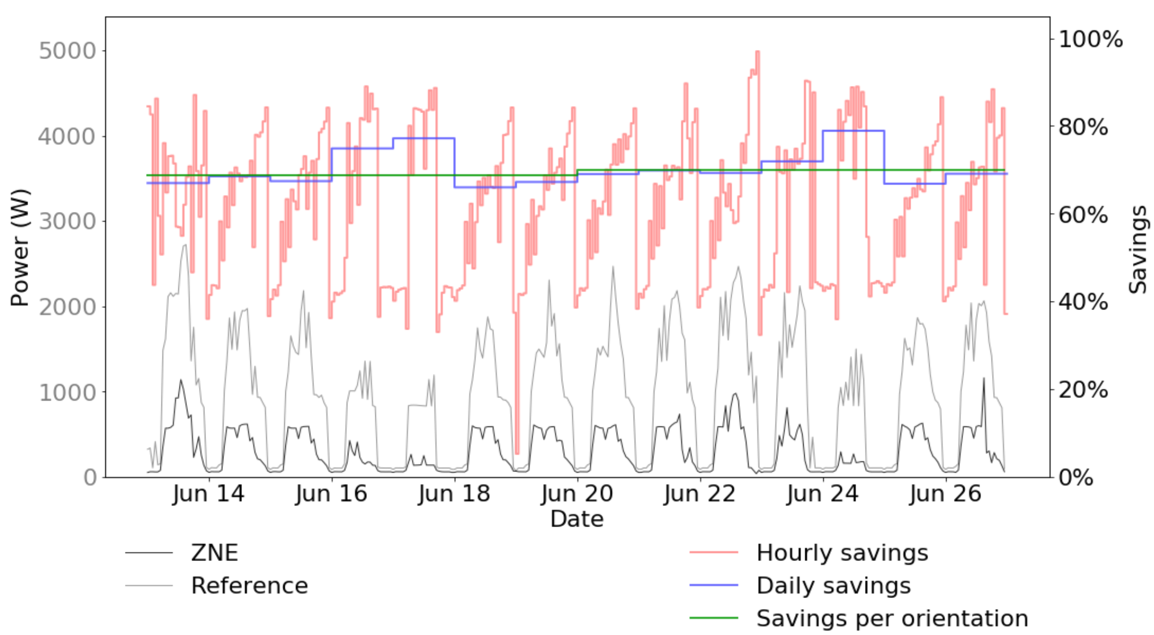

Figure 65. Hourly, daily and per-orientation total energy savings for June testing period.

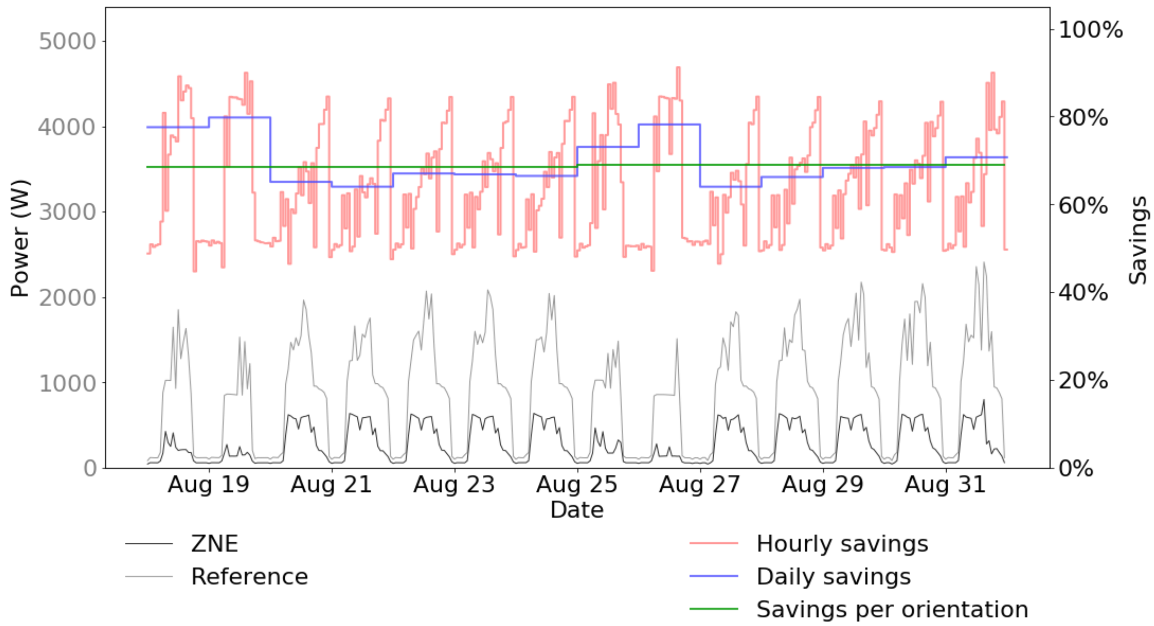

Figure 66. Hourly, daily and per-orientation total energy savings for August testing period.

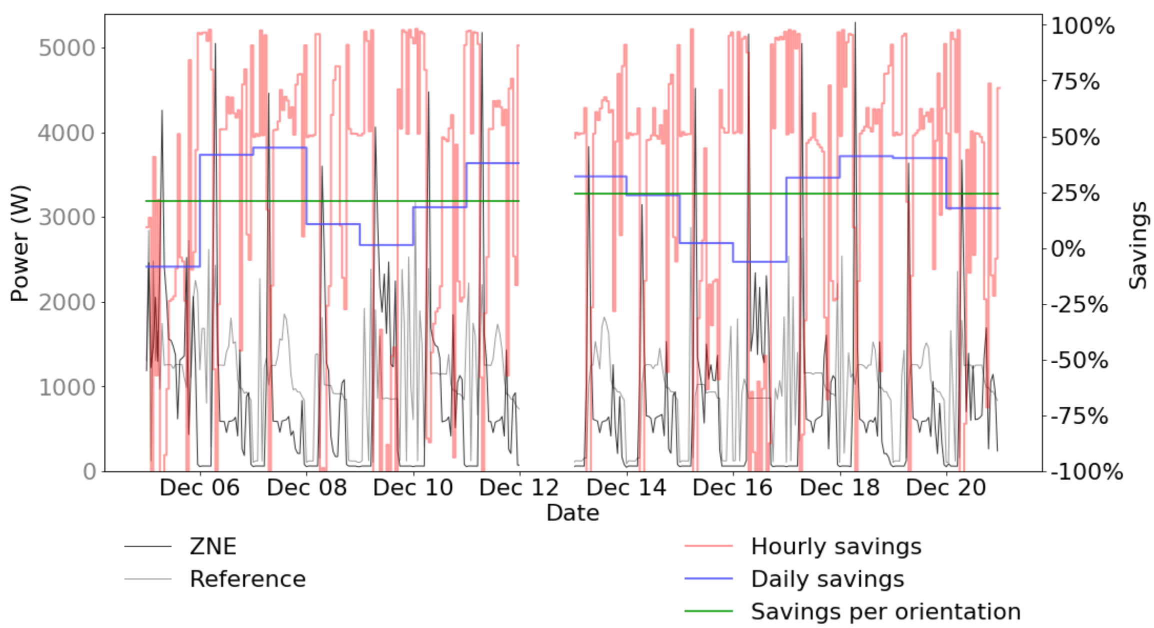

Figure 67. Hourly, daily and per-orientation total energy savings for December testing period.

3.3 TDD tests

3.3.1 Light levels under clear sky

During the tests, indoor light levels provided by the TDDs ranged from minimal to substantial, depending on time of day, sky cover and TDD diameter. To a lesser extent, type of TDD dome and diffuser. Figure 68 shows average, maximum and minimum horizontal illuminance obtained with the TDD-SPF configuration during the February, May and January tests under clear sky. Illuminance increases as solar altitude increases, and that is evident both within each day and when comparing different times of the year. Within the interior space, illuminance is consistently higher towards the center of the room (Figure 69). Similar trends were observed for other 21-inch TDD configurations. 14-inch TDD also showed the same trends, although at lower illuminance levels overall (Figure 70).

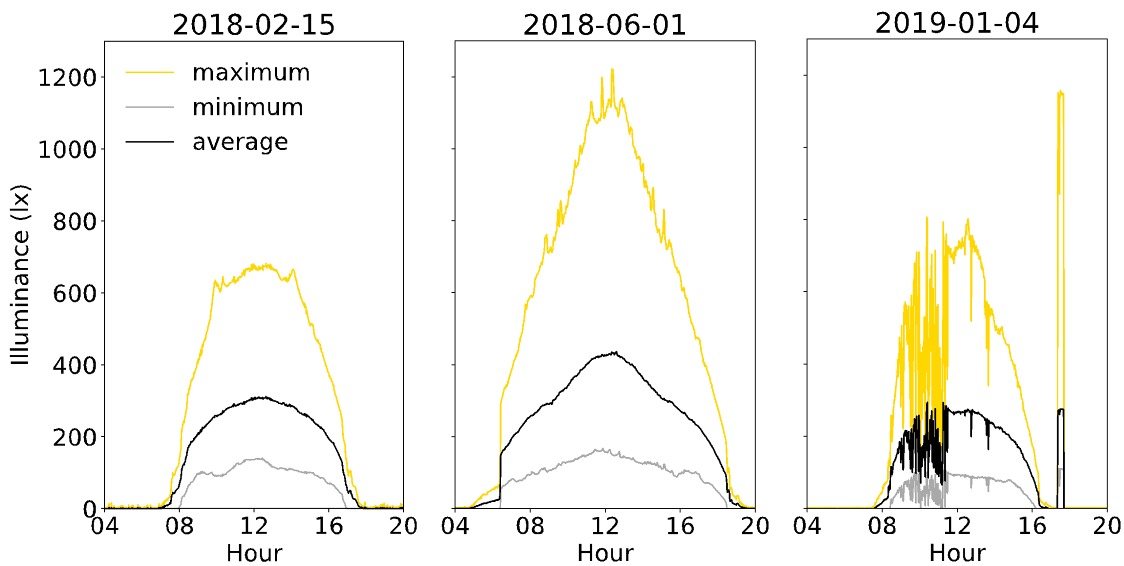

Figure 68. Average, maximum and minimum horizontal illuminance obtained with the TDD-SPF configuration under clear skies during the February, May and January tests (note that for January 4, 2019 the sky was not clear between 8 and 11 AM, approximately). Illuminance generally increased with solar altitude, both within each day and also with the time of the year. Note: the period of high illuminance after sunset on January 4 was due to electric lights being turned on for a short period; data for that period was not included in the analysis.

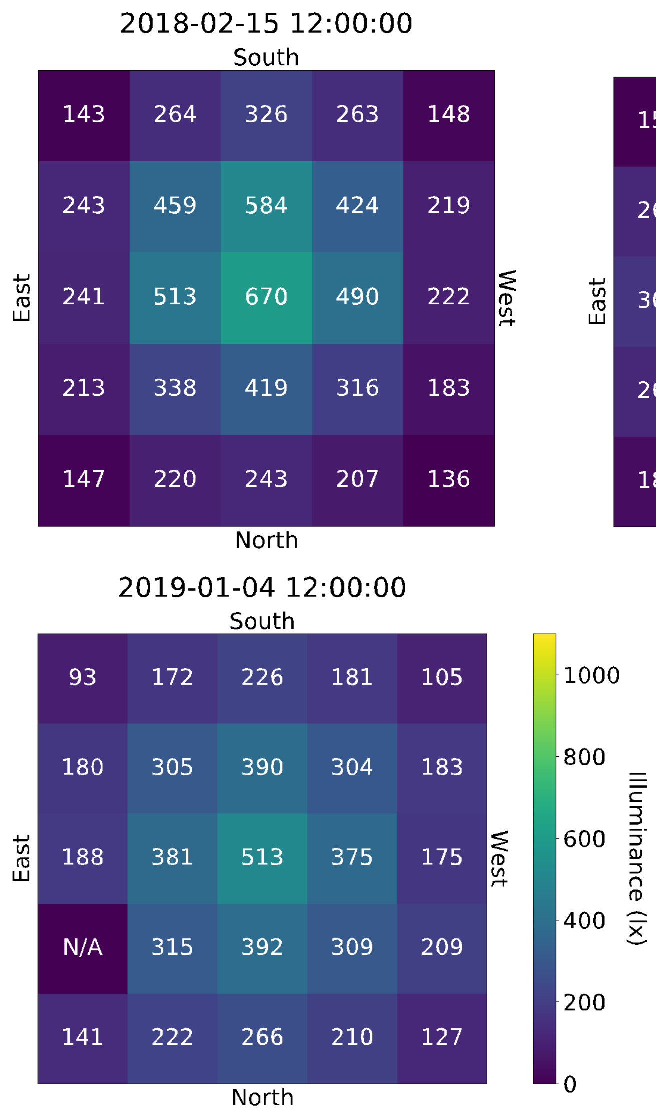

Figure 69. Illuminance distribution within interior space obtained with the TDD-SPF configuration under clear sky at noon during the February, May and January tests. Illuminance increased towards the center of the room. Note that one of the sensors along the eastern edge of the room malfunctioned during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

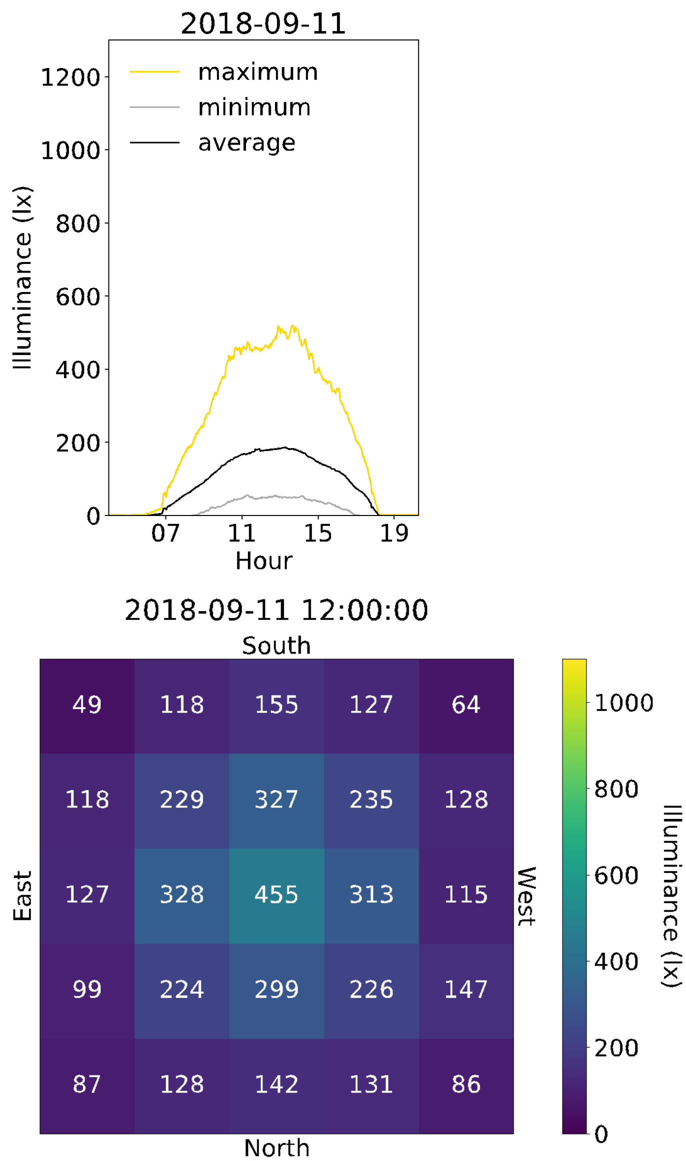

Figure 70. Horizontal illuminance under clear sky for 14” TDD (configuration TDD-14A) during the September tests. Tests with 14” TDDs showed similar trends to tests with 21” TDDs, at lower illuminance levels.

3.3.2 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. 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 areas greater than 250 ft^2 [CEC, 2016], annualized energy consumption for each TDD configuration ranged between 0.61 and 1.53 kWh/ft^2-yr, representing a range of between 22% and 69% lighting energy savings (Figure 71). It should be noted that the results shown in Figure 71 are not normalized 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.

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 and, correspondingly, savings, are higher in June than in February, as it would be expected since solar altitude is also higher in June than in February. Similar data for overcast skies is shown in Figure 73 for overcast sky.

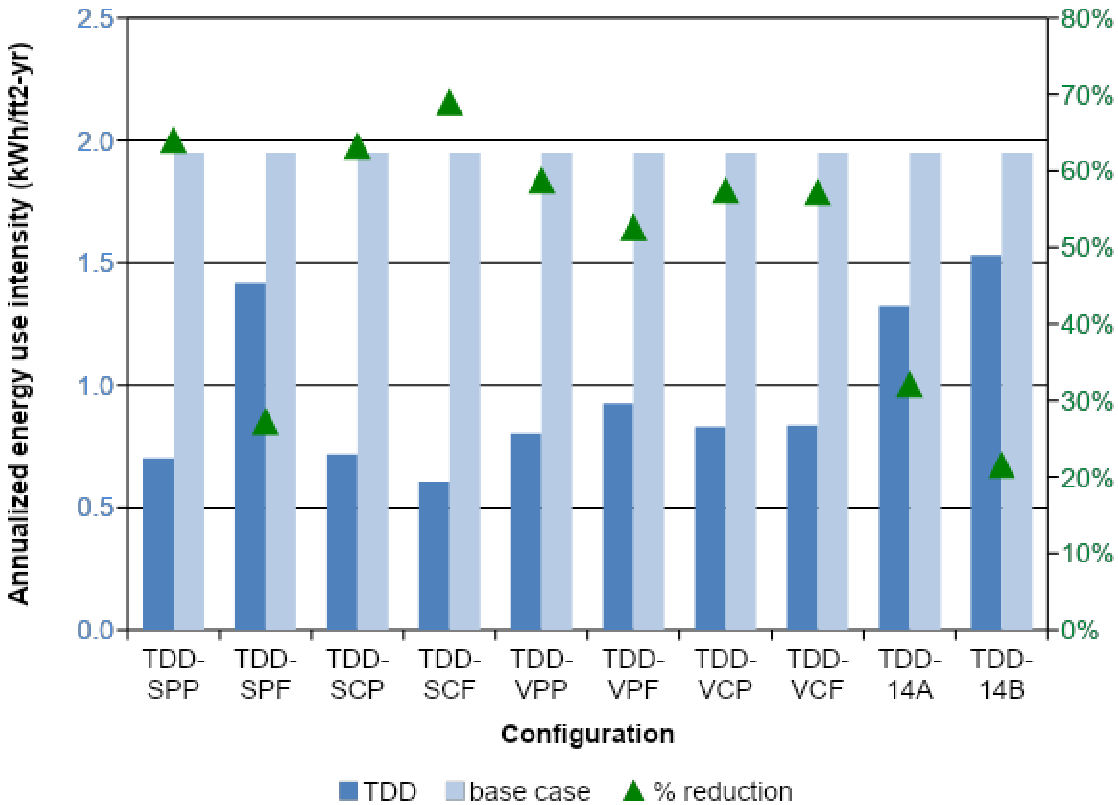

Figure 71. Annualized lighting energy use with the ten different TDD configurations. These results are not normalized to account for the differences in sky cover between test configurations. In particular, the higher energy use obtained with the TDD-SPF configuration was due to higher occurrence of overcast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

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
Intermediate	Direct normal is between 5% and 200% of diffuse

Overcast	Direct normal is less than 5% of diffuse

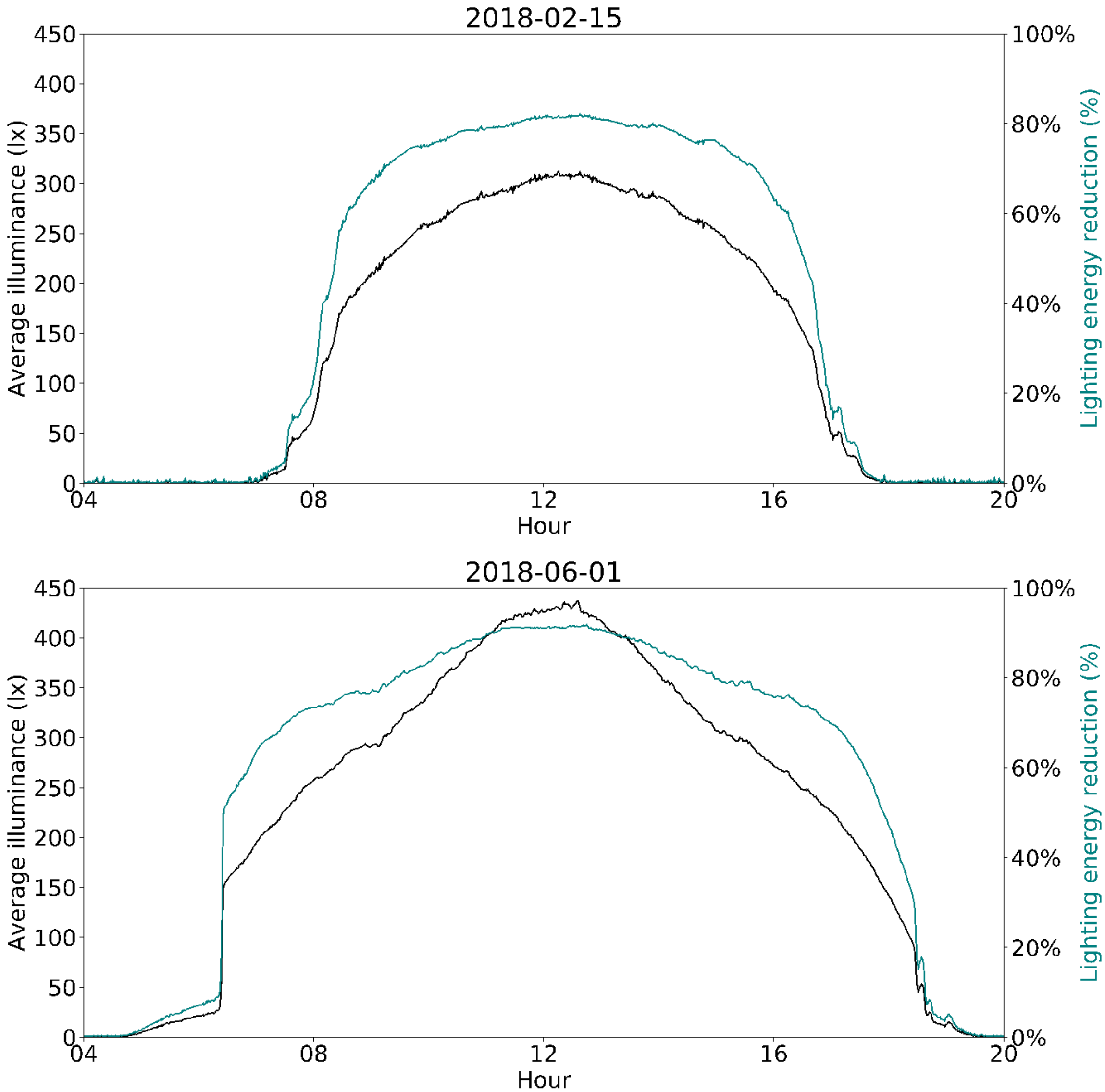

Figure 72. Average horizontal illuminance and estimated lighting energy savings for clear sky days during February and June. Data shown for TDD-SFP configuration.

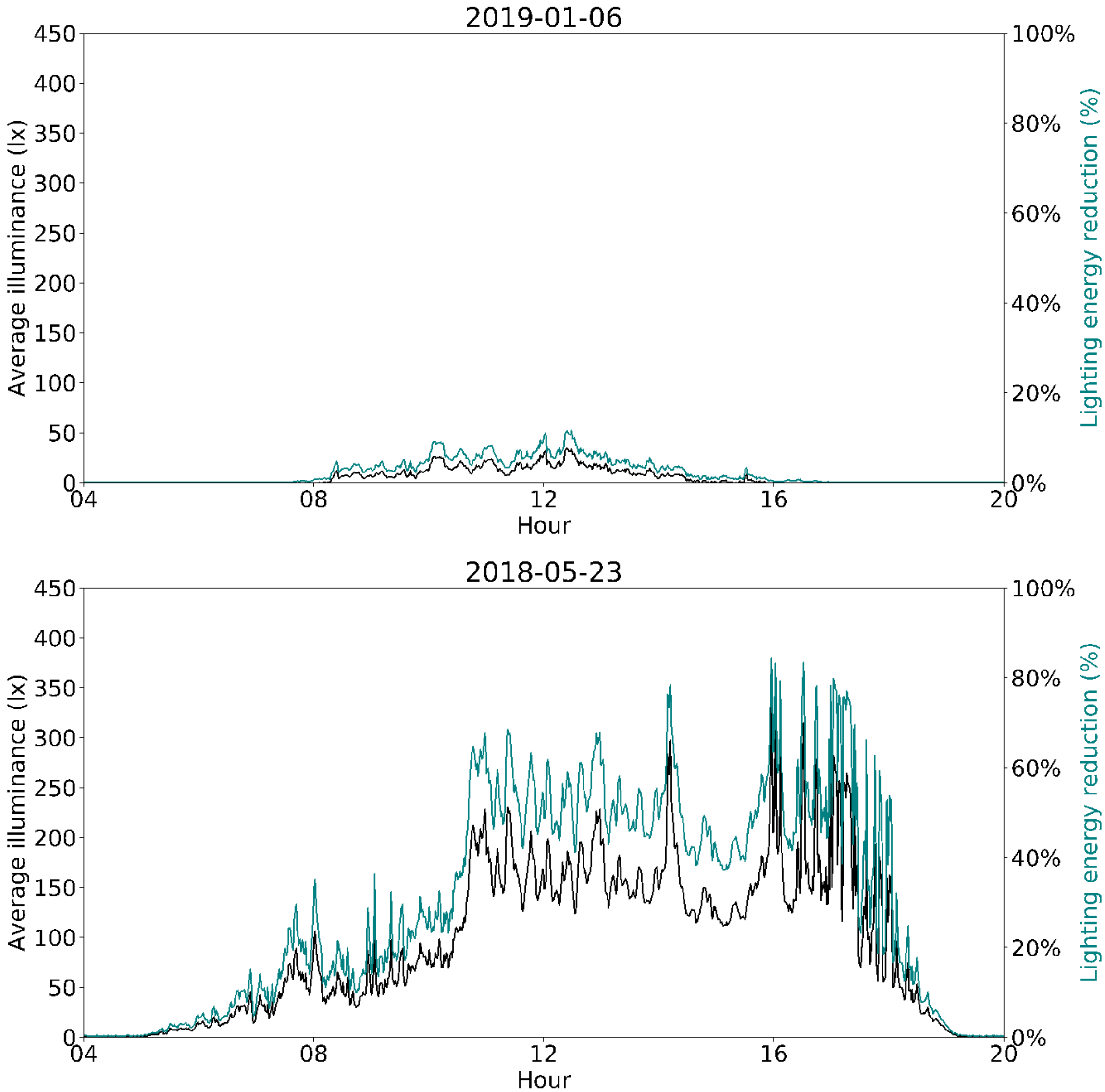

Figure 73. Average horizontal illuminance and estimated lighting energy savings for overcast sky days during January and May. Data shown for TDD-SFP configuration.

Whole-day energy savings, calculated using the same methodology, are shown in Figure 74for 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. Figure75 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.

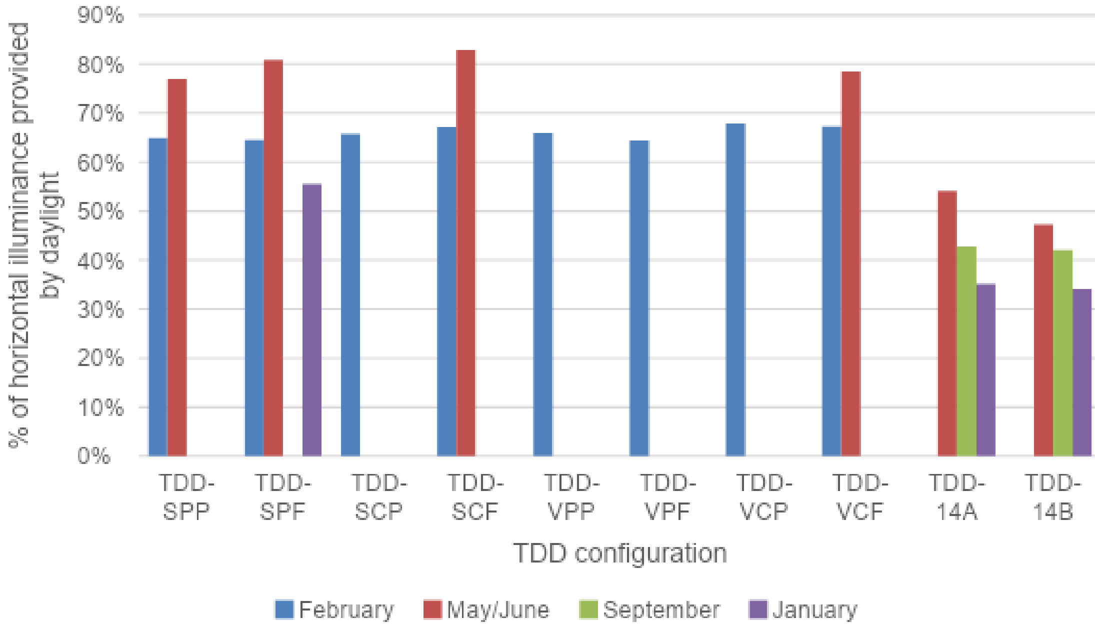

Figure 74 Estimated percentage lighting energy savings from TDD under clear sky. Values for TDD-VCP and TDD-VCF configurations in February, and TDD-SCF in January are based on afternoon data only.

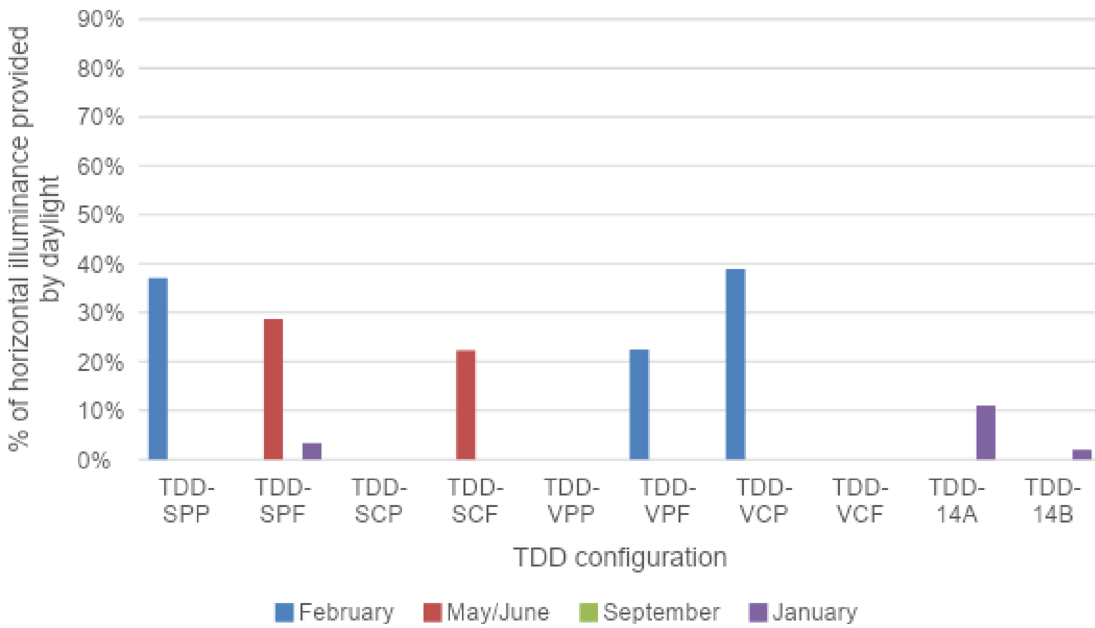

Figure 75. Estimated percentage lighting energy savings from TDD under overcast sky. Values for TDD-SPP and TDD-VCP configurations in February, TDD-SPF and TDD-SCF configurations in May/June, and TDD-14A in January are based on morning data only.

3.3.3 Visual comfort

All the TDD configurations tested were able to maintain conditions below the DGP 0.35 threshold for perceptible glare. Figures 42 to 49 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.

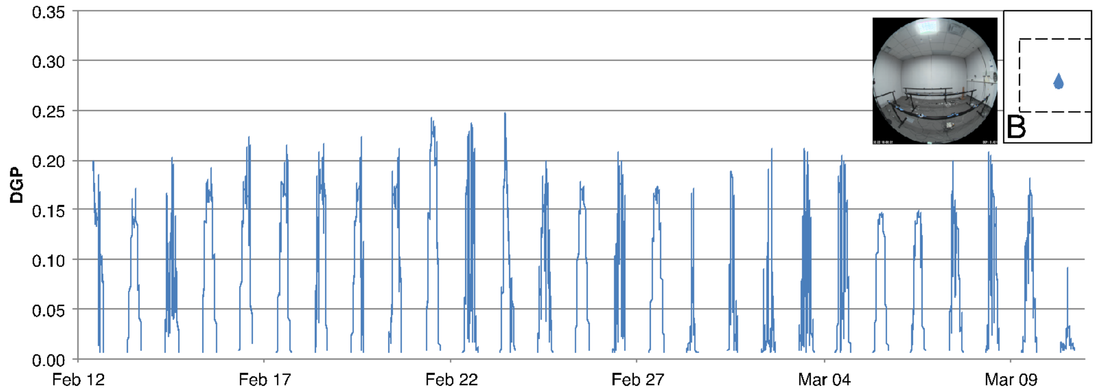

Figure 76. DGP measured from position A during the February-March testing period.

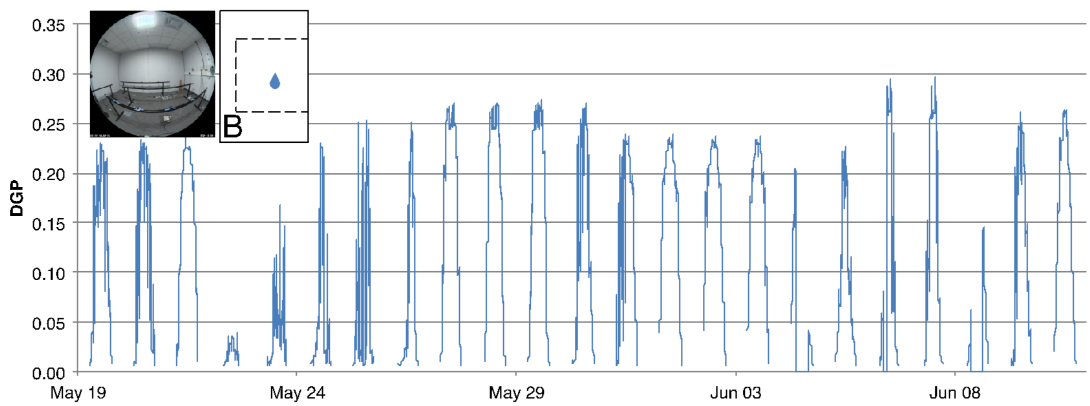

Figure 77. DGP measured from position A during the May-June testing period.

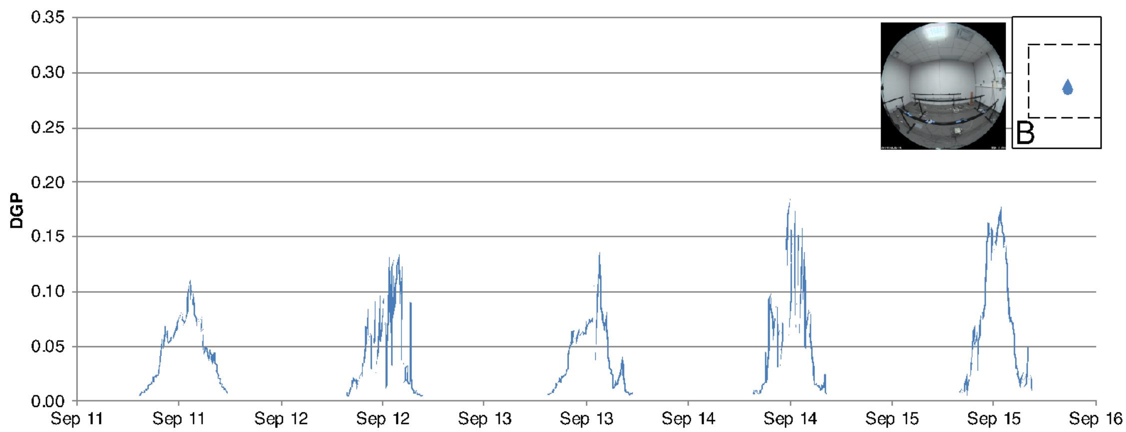

Figure 78. DGP measured from position A during the September testing period.

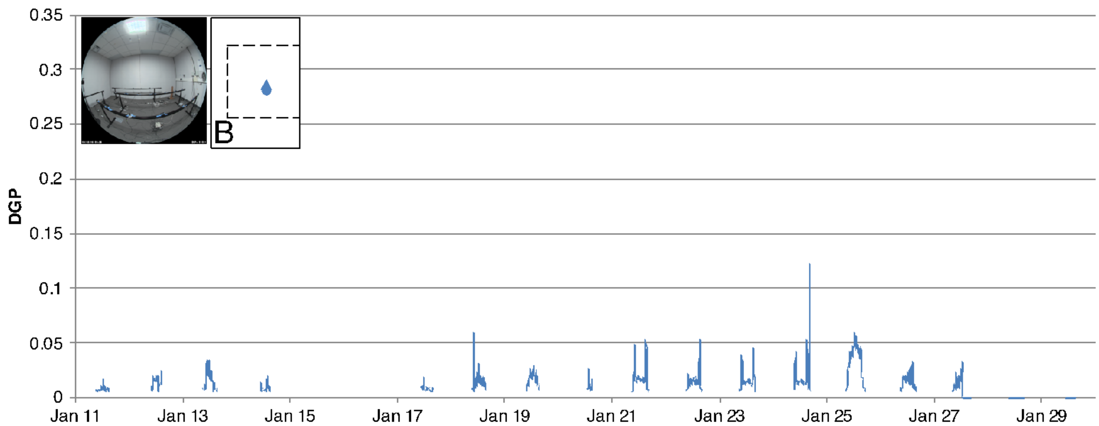

Figure 79. DGP measured from position A during the January testing period.

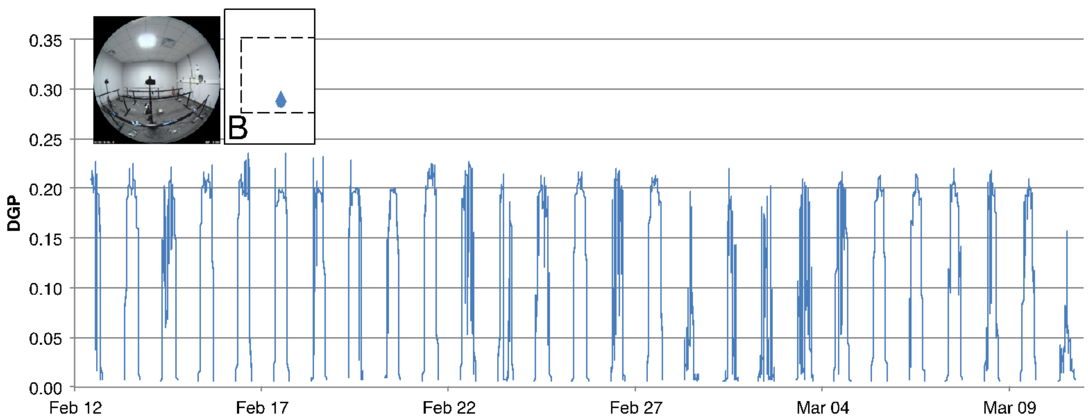

Figure 80. DGP measured from position B during the February-March testing period.

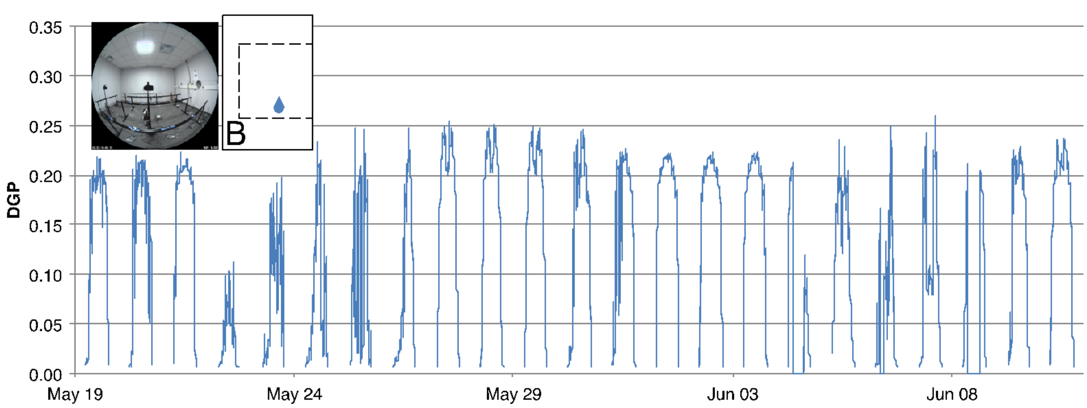

Figure 81. DGP measured from position B during the May-June testing period.

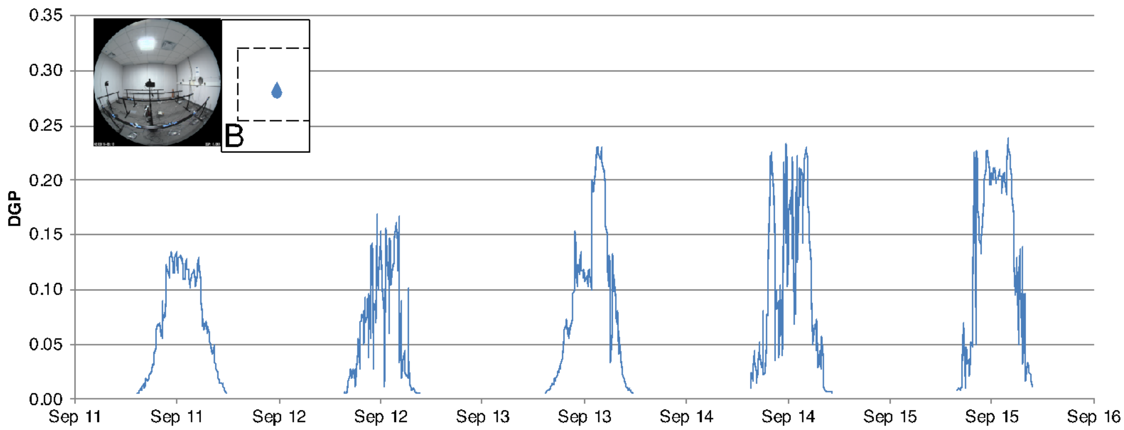

Figure 82. DGP measured from position B during the September testing period.

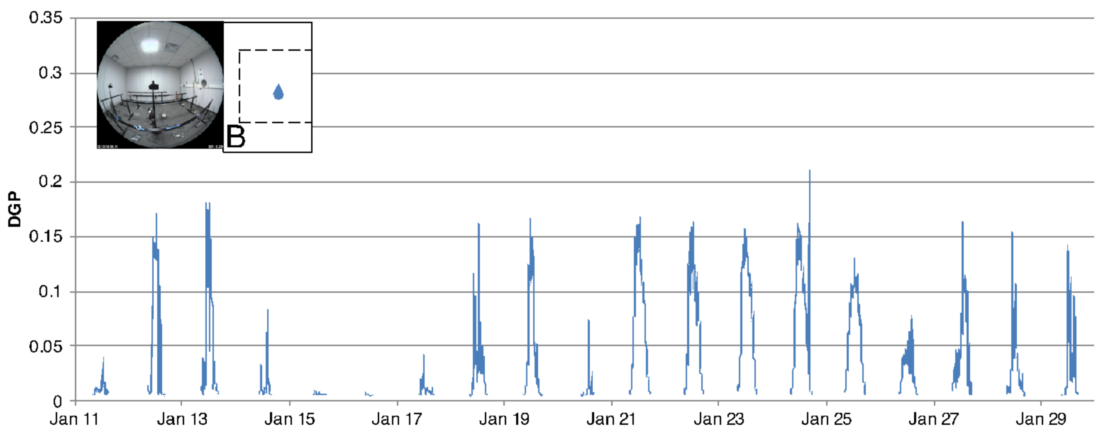

Figure 83. DGP measured from position B during theJanuary testing period.

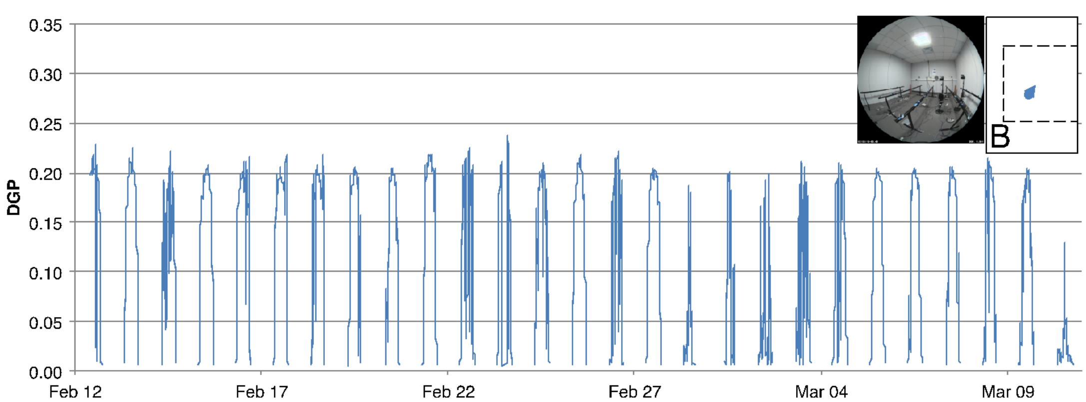

Figure 84. DGP measured from position C during the February-March testing period.

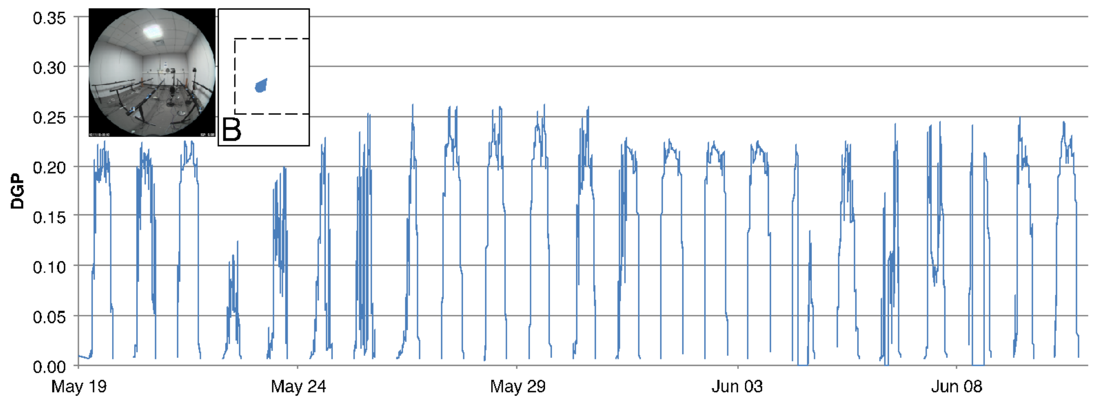

Figure 85. DGP measured from position C during the May-June testing period.

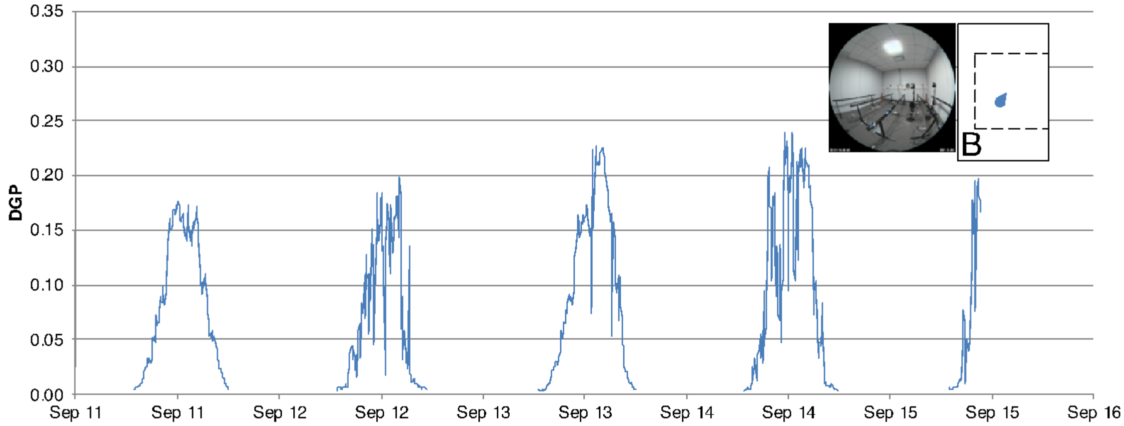

Figure 86. DGP measured from position C during the September testing period.

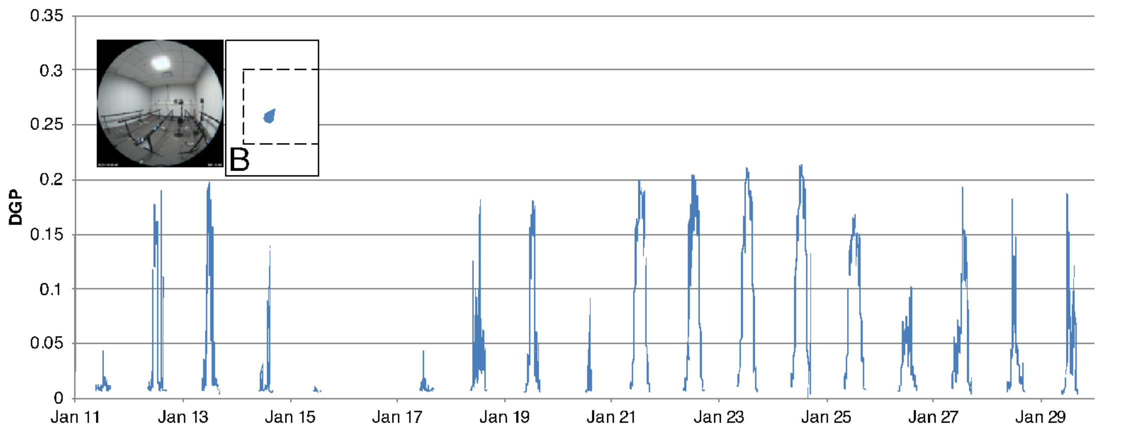

Figure 87. DGP measured from position C during the January testing period.

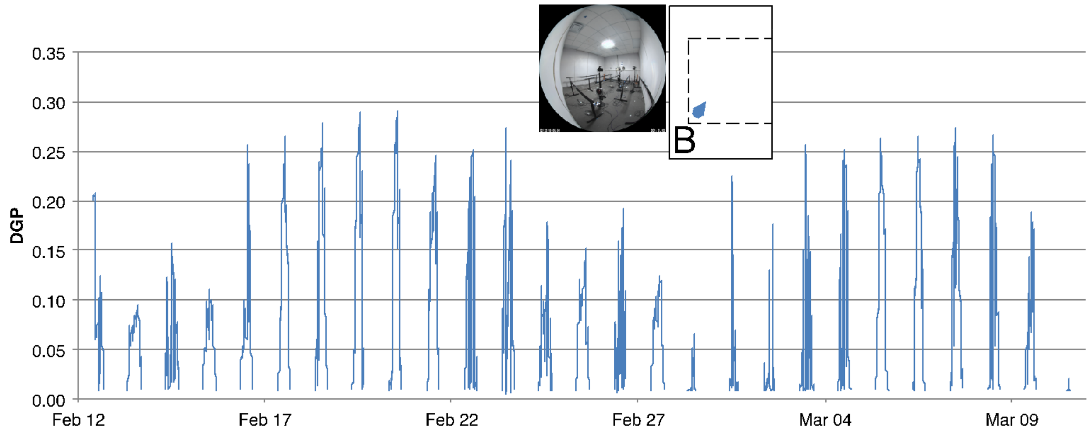

Figure 88. DGP measured from position D during the February-March testing period.

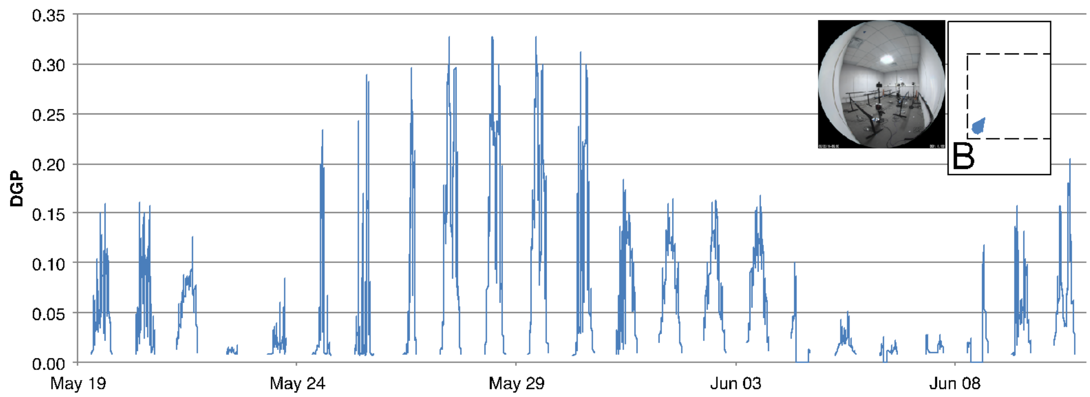

Figure 89. DGP measured from position D during the May-June testing period.

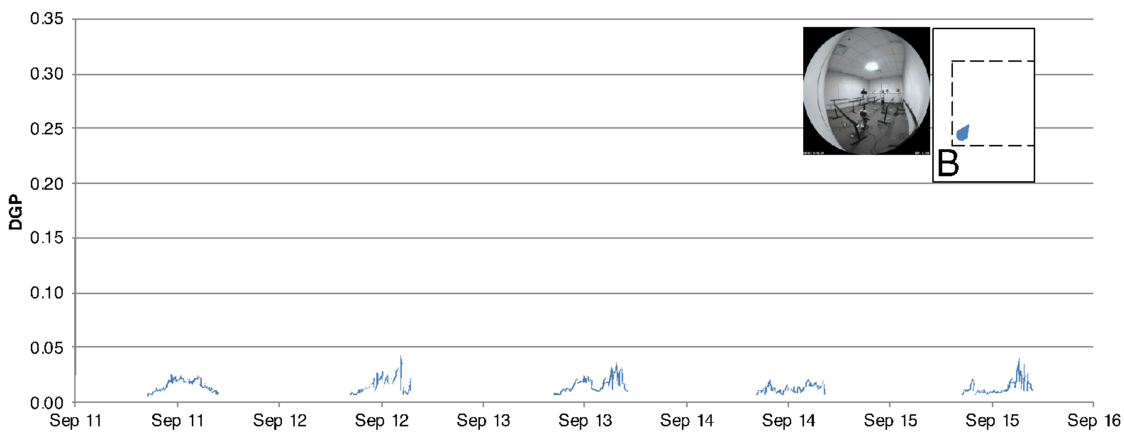

Figure 90. DGP measured from position D during the September testing period.

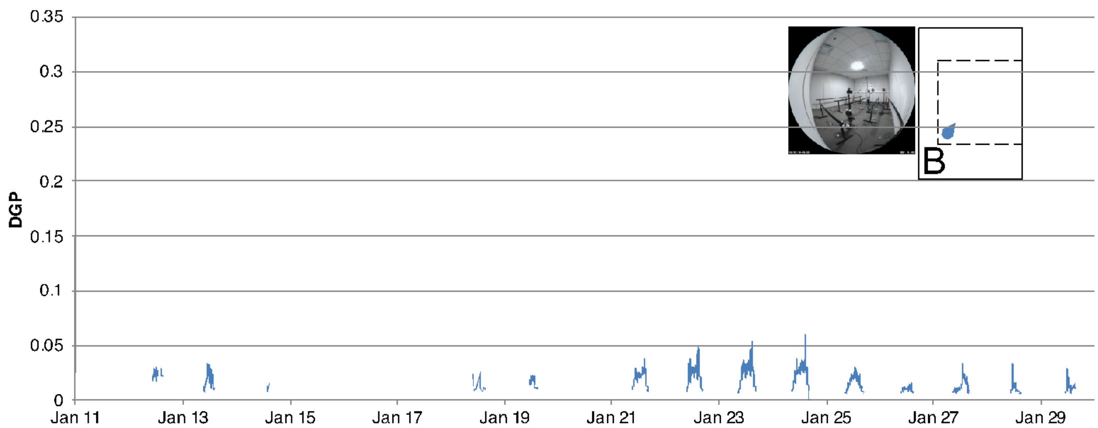

Figure 9. DGP measured from position D during the January testing period.

4 Conclusions

The testing conducted for this project shows packages of ZNE measures resulting in significant 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. 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 significantly 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

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6 References

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7 Appendix A – Sensor Specifications

	Measurements	Sensors	Quantity	Uncertainty
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-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%)
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 Sept 11, 2018 00:00hr to Sept 13, 2018 00:00hr. During this period the test cells were only in cooling mode. A calibration run will be conducted in the winter to capture the heating mode conditions.

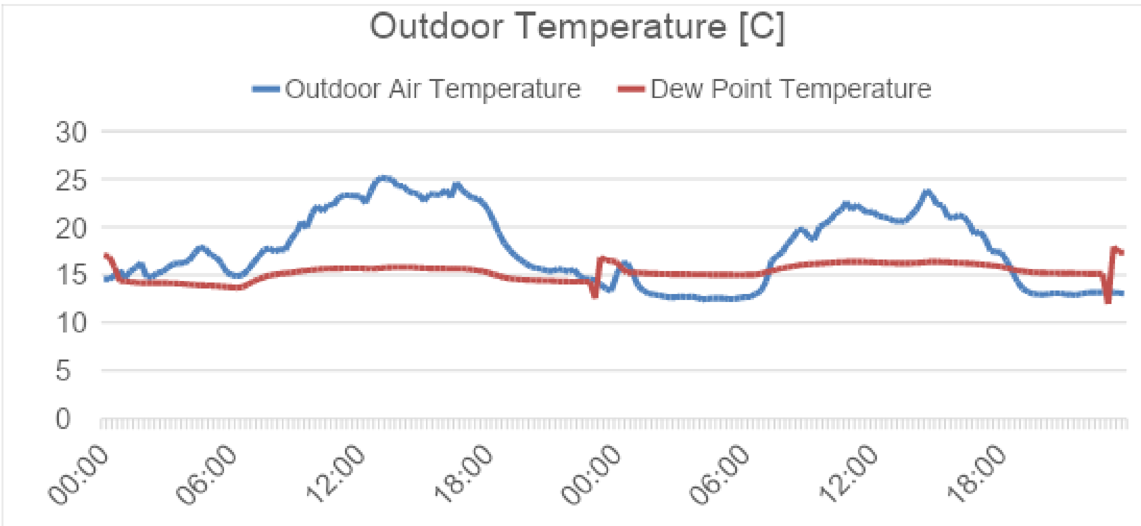

Figure B1. Outside air temperatures Sept 11 – Sept 13, 2018.

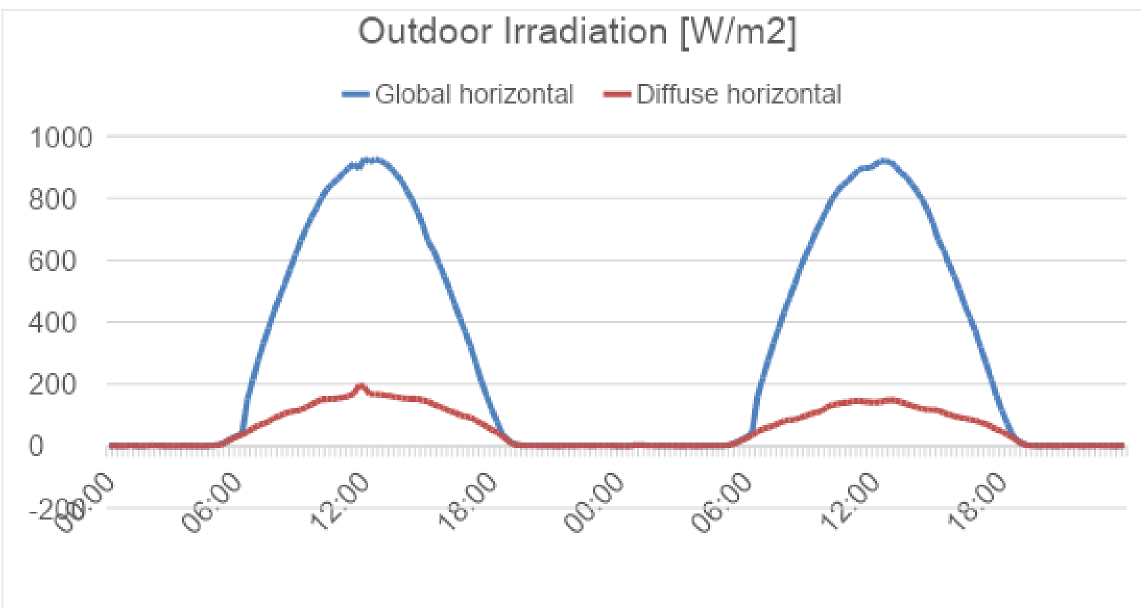

Figure B2. Outdoor Irradiation Sept 11 – Sept 13, 2018.

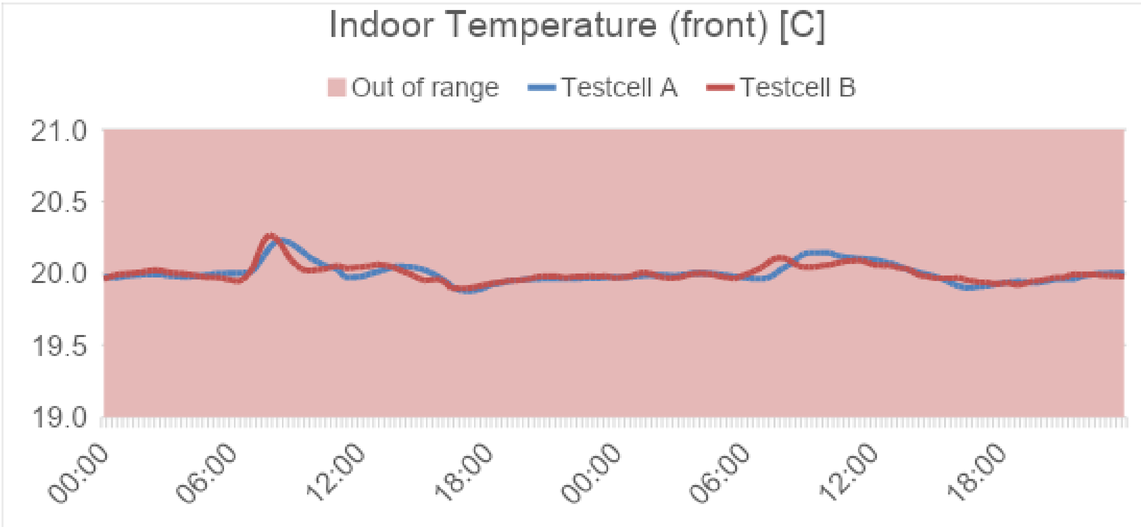

Figure B3. Cell interior temperatures Sept 11 – Sept 13, 2018.

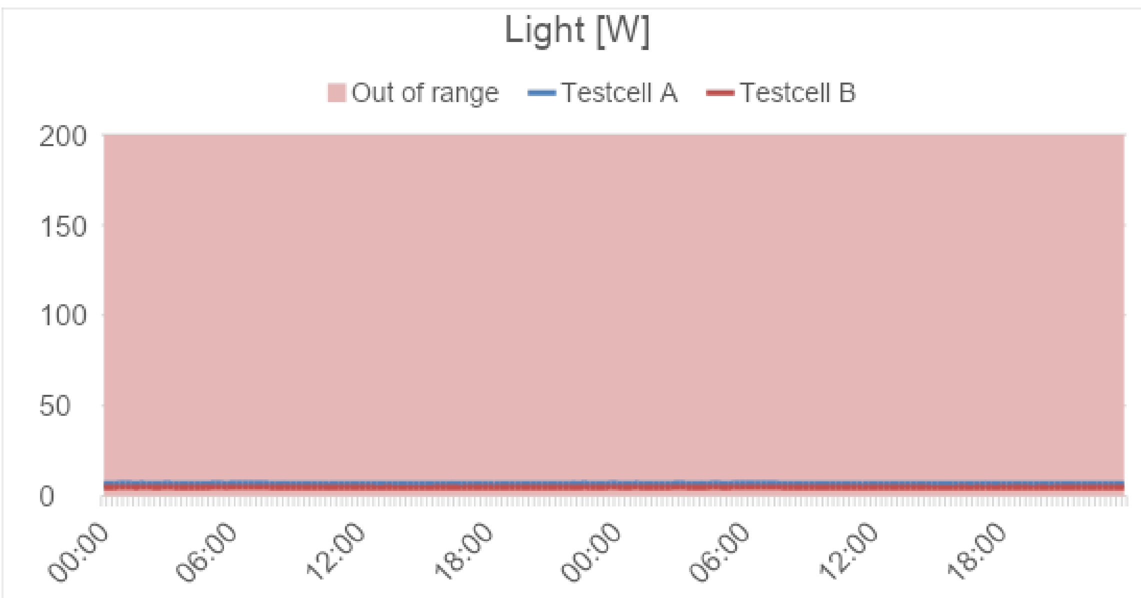

Figure B4. Cell interior light energy Sept 11 – Sept 13, 2018.

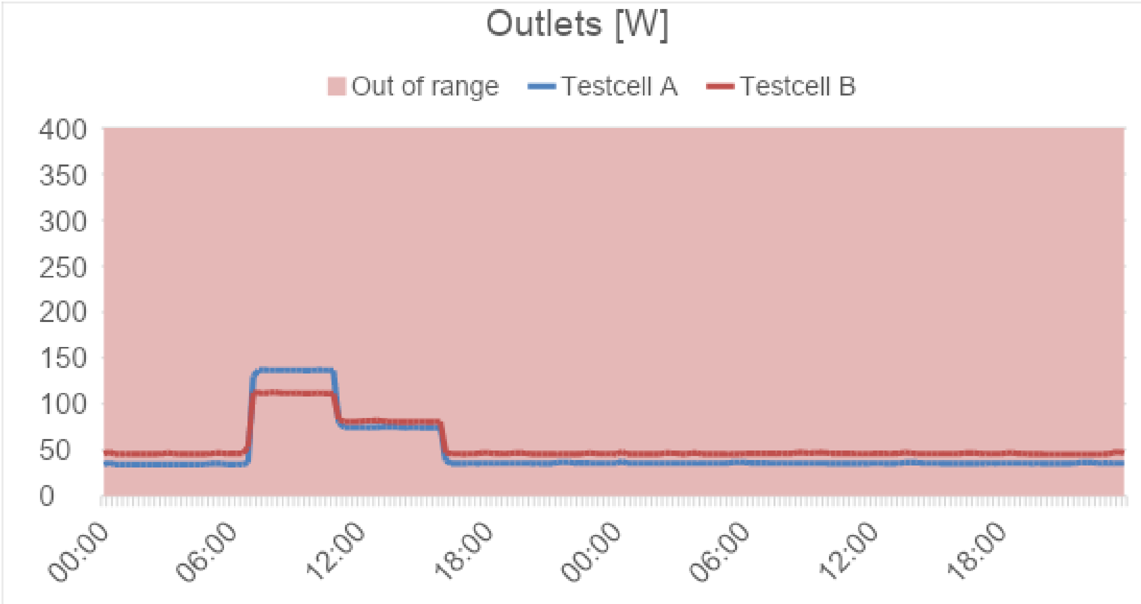

Figure B5. Cell electrical outlets energy Sept 11 – Sept 13, 2018.

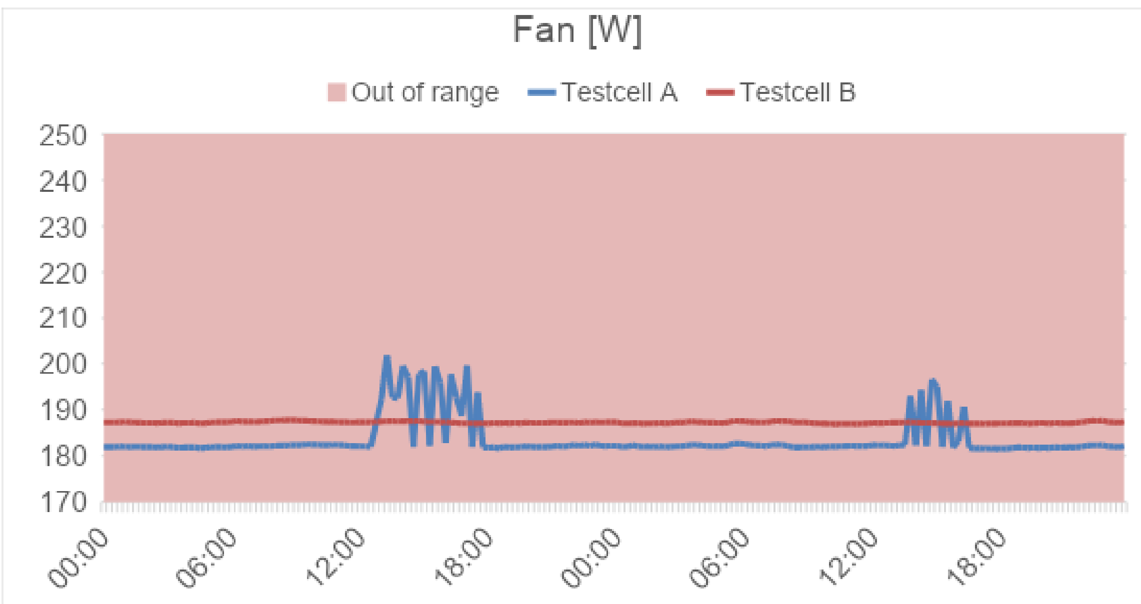

Figure B6. Cell fan energy Sept 11 – Sept 13, 2018.

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).

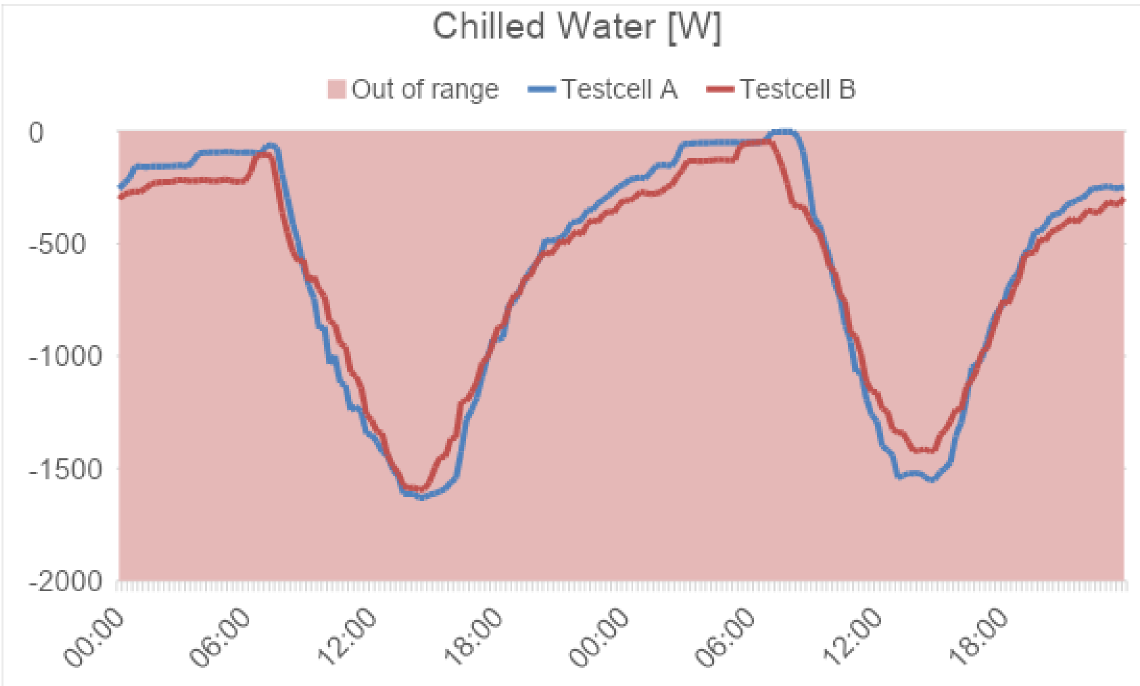

Figure B7. Cell chilled water thermal energy Sept 11 – Sept 13, 2018.

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.

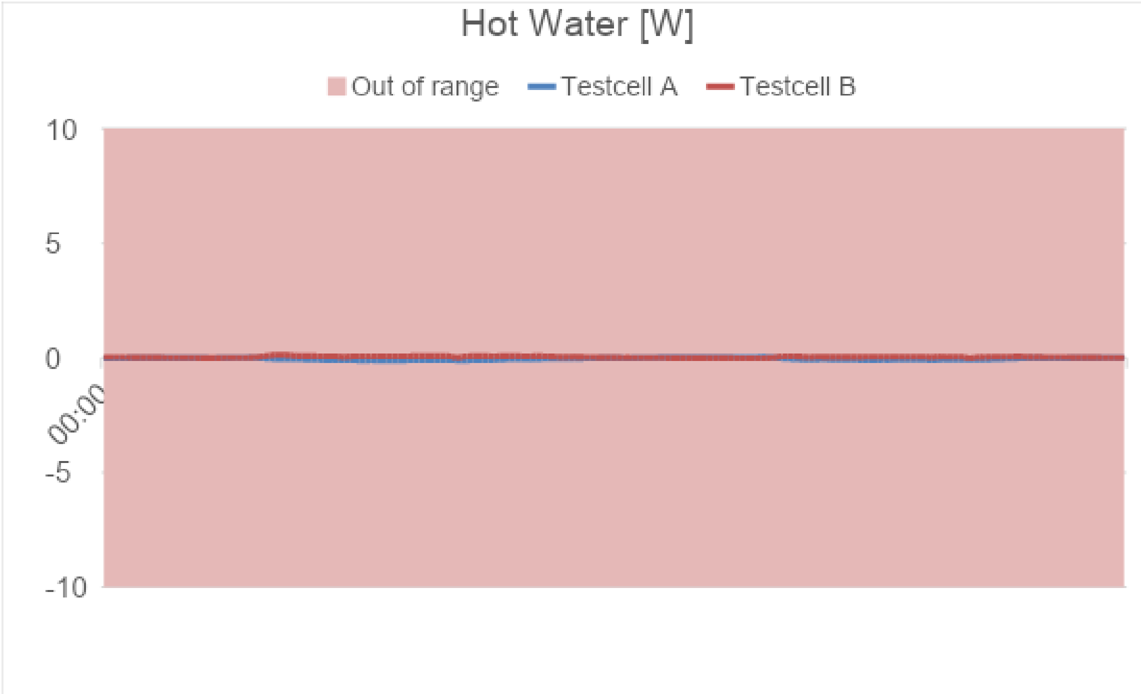

Figure B8. Cell hot water thermal energy Sept 11 – Sept 13, 2018.

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

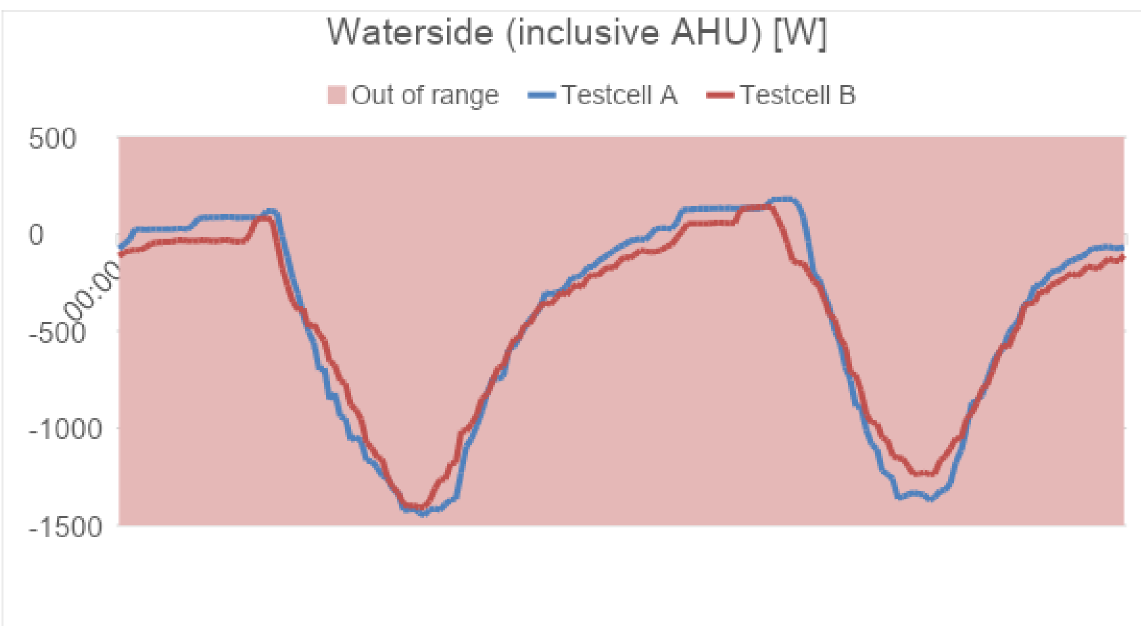

Figure B9. Cell waterside calculated thermal energy Sept 11 – Sept 13, 2018.

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.