Amplified Farms 2017

Indoor Horticulture Lighting Study

Sacramento Municipal Utility District

SMUD™

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1. Executive Summary

1.1 Introduction

With the recent legalization of adult use cannabis in California, SMUD has received numerous requests for electrical service upgrades from commercial customers planning to operate indoor cultivation facilities. Some of these facilities are large and have significant power requirements. For example, during the flowering stage, commercial cultivators often use one 1,000-watt high pressure sodium (HPS) light fixture for every 16 to 25 sq. ft. of planted area (i.e., canopy). A facility with 10,000 sq. ft. of flowering space can draw up to 550 kW of power for just lighting alone. For comparison purposes, a modern 10,000 sq. ft. commercial office space would require only around 8 kW for lighting. On an annual basis, the energy consumption to support just one cannabis plant is about the same as seven residential refrigerators.

Because the City of Sacramento is the only local government within SMUD's service territory that allows indoor cannabis cultivation operations, these new facilities will be concentrated into a relatively small geographical area. Based on permitting requirements and forecasted growth, certain areas in this region will likely require infrastructure upgrades. This is part of SMUD's normal grid planning process, and SMUD does this type of work for all business customers.

Because cannabis cultivation is now legal in California, SMUD treats cannabis cultivators just like any other commercial customer and works with them to provide the electricity they need to operate their business. SMUD works with them to save energy and money when possible, while ensuring such operational and environmental cost savings do not impact overall cultivation and business productivity (i.e. plant yield and quality).

Recently, LED manufacturers have started to offer products for horticulture applications. While these products are expected to reduce lighting energy consumption by up to 40%, few case studies exist for using these products to cultivate cannabis and validate them as a viable option that will produce the same (or better) results than incumbent technologies, often HPS. Offering incentives to commercial cultivators to use LEDs can help lessen the impacts on the grid and provide SMUD with more flexibility and time to upgrade its infrastructure. Furthermore, establishing a successful local case study will provide useful information for developing energy efficiency incentive programs.

1.2 Project Objectives

The primary objectives for this study were:

- Determine if LED technology is a viable option for cultivating cannabis through the flowering stage (producing the same, if not better, results in place of industry-standard HPS fixtures) and how much energy and demand savings potential may exist.
- Learn more about the energy loads required for indoor horticulture operations, including those for cooling, heating, dehumidification, fan energy, and plug loads, and how they are impacted when growing with HPS versus LED.
- Report any observed energy efficiency opportunities for commercial indoor cannabis cultivation facilities.

1.3 Results

Cadmus monitored two flowering rooms at Amplified Farms throughout the flowering cycles of the housed plants, one room lit by HPS fixtures and the other by LEDs. After analyzing all collected data, we calculated the following savings when comparing the LED results to HPS (see Figure 1):

- Overall energy savings of 20% (7,628 kWh)
- Lighting energy savings of 34% (5,344 kWh)
- Overall demand savings of 7% (4.2 kW)
- Lighting demand savings of 33% (7.3 kW)
- Simple payback of 3.3 years for the LED upgrade

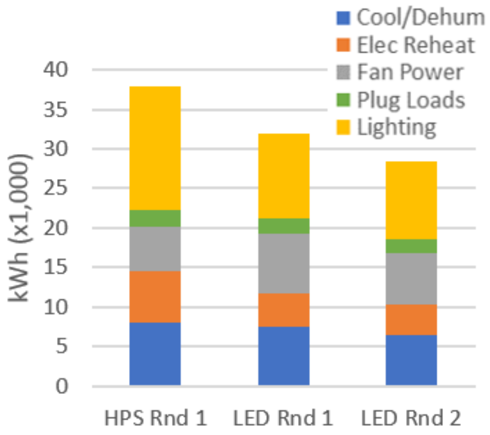

Figure 1: Total energy use during monitored flowering cycles. Cooling & dehumidification and electric reheat values are weather-normalized.

We verified the center-of-fixture, canopy-level photosynthetic photon flux density (PPFD) for the LED fixtures aligned with the manufacturer-reported values. The crop production characteristics for strains grown in Room 2 (LED) were positive overall. These plants realized high potency, with THC (tetrahydrocannabinol) levels above average, and in many cases above the expected range, for all strains. Plant yields varied from below the expected range to above for both rooms.

We also determined that dehumidification loads drive the HVAC demand; therefore, optimizing dehumidification mode sequencing (and all controls) may impact energy use substantially. We calculated a simple payback as short as 3.3 years for a 100% hot gas reclaim unit when compared to the current operation of the single-stage hot gas reclaim with stage 2 electric heat units we monitored.

We found some dependency of cooling and reheat load on weather, despite the closed-system operation. Data also suggested the reduced loads in the LED room would allow for HVAC equipment downsizing compared to the HPS room.

1.4 Recommendations

The findings from this study suggest LEDs can provide the necessary lighting to successfully cultivate cannabis through the flowering phase while reducing energy use and costs. However, with numerous variables impacting the energy use of each system, it is difficult to determine whether interactive effects can be attributed to the lighting system upgrade. Additional research is necessary to determine interactive effects the lighting may have on other energy systems as well as the response of crops. Specific lessons learned and recommendations are detailed in Section 4 - Conclusion.

While additional research is necessary, SMUD is currently offering custom incentives for LED and other technologies for indoor cultivation facilities. For more information, please send an email to indoorcultivation@smud.org or visit the websites below:

- Custom Incentive Program (retrofit projects)
  https://www.smud.org/en/Business-Solutions-and-Rebates/Business-Rebates/Custom-Incentives
- Savings by Design (new construction)
  https://www.smud.org/en/Business-Solutions-and-Rebates/Business-Rebates/Savings-by-Design

1.5 Acknowledgements

While many people contributed to this project, we particularly appreciate the cooperation and efforts of the staff at Amplified Farms; Joe Stanger of Stang Air; as well as Allen Lee, John Walczyk, Tom Davies, and Alex Trueblood from Cadmus.

2. Project Description

2.1 Background

Indoor cannabis cultivation is an energy intensive process. As mentioned earlier, the lighting demand alone may be near 70 times the lighting demand for a typical office space. Not only are demand loads high, but hours of use for lighting typically range from 12 to 24 hours per day, depending on the stage of life the plants are in. These high lighting loads result in corresponding cooling and equipment loads to maintain the environmental conditions desired by the cultivators. Although targets vary, each cultivator has preferred photosynthetic photon flux density (PPFD), space temperature, relative humidity, and CO_2 ranges for the plants throughout their growth cycle and maintaining these conditions are critical to plant production and crop yields. Many lighting types are commonly used throughout the cultivation process such as compact fluorescent (CFL), T5 fluorescent, metal halide (MH), HPS, and LED. Typical industry ranges for these parameters are summarized in Table 1.

		Clone	Vegetative	Flower	Harvest	Drying
Duration		1-2 weeks	2-5 weeks	8-12 weeks	n/a	4-14 days
Lighting Type		CFL, T5, LED	T5, MH, LED	HPS, LED	n/a	n/a
Light Schedule (hrs on)		24	18-24	12	n/a	0
PPFD (µmoles/m^2/s)		75-150	300-600	600+	n/a	n/a
Airflow		Sometimes	Yes	Yes	n/a	Sometimes
Relative Humidity (%)		60-80	55-75	50-60	45-55	45-60
CO_2 (ppm)		400	400-800	800-1400	n/a	n/a
Temperature (F)	Lights on	72-80	74-84	68-84	65-75	n/a
	Lights off	70-78	68-76	68-78	65-75	60-75

Table 1: Typical environmental targets for cannabis cultivation by plant growth stage.[1]

As can be seen in Table 1, the flowering stage requires high PPFD output for 12 hours a day and cooler space temperatures while lights are on, and this stage may last up to 12 weeks. The flowering rooms also make up a higher percentage of the facility's floor area, generally occupying at least three times the area occupied by plants in their

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[1] Fluence Bioengineering High PPFD Cultivation Guide v1.2 and general knowledge sources.

vegetative phase. For these reasons, the flowering phase was the target for this study and analysis.

Photosynthetically Active Radiation (PAR)

As reported in Table 1, PPFD is one of the metrics closely tracked by cultivators due to its high impact on plant growth and photosynthesis. Typically, the higher the PPFD, the higher the yields. The following terms are commonly used in horticulture lighting applications and may be referenced throughout this report:

- **Photosynthetically active radiation (PAR)** is light that falls between the spectral wavelengths 400nm – 700nm (basically the visible light range and illustrated in Figure 2), and it is required for photosynthesis.
- **Photosynthetic photon flux (PPF)** is the total amount of PAR produced by a light fixture every second (micromoles/s).
- **Photosynthetic photon flux density (PPFD)** is the amount of PAR that reaches the plant surface (micromoles/m^2/s).

Differentiating between PPF and PPFD is critical to understand lighting performance. For example, a fixture rated at a high PPF value (producing a lot of PAR) may have a recommended mounting distance to the canopy greater than a fixture with a lower PPF rating and, therefore, provide less PPFD than the other fixture. It is important to note that PPFD values are specific to a location and distance from the fixture. A single PPFD value or measurement cannot be extrapolated and applied to the entire canopy area.

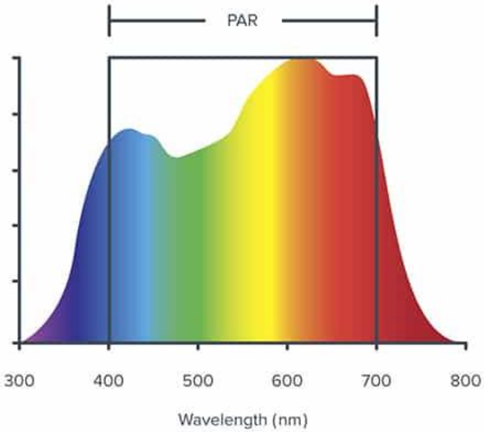


Figure 2: PAR wavelength range.

2.2 Project Objectives

The main objective for this project was to test the viability and potential benefits of using LED lighting for cannabis cultivation at local, commercial indoor cultivation facilities. Specifically, we wanted to gain understanding about how using LED lighting in place of the industry standard HPS fixtures during the flowering cycle may impact the following:

- The quality of the product, including yield and potency, as well as any observations on coloring, smell, structure, density, or other industry metrics.
- The energy use (kWh) and electrical demand (kW) of each space including lighting and interactive effects on the plug load and HVAC systems. In addition,

any insights on end-use and load profiles required for indoor horticulture operations such as lighting, plug loads, cooling, dehumidification, reheat, and fan energy may help inform potential future studies.

- The PPFD or amount of PAR received by the plants. Since PAR levels are critical to photosynthesis and growth, many cultivators have concerns about the light output or photosynthetic photon flux (PPF) capacity of LEDS compared to HPS fixtures.
- The customer's finances, including simple payback of any upfront incremental costs or continuous maintenance expenses.

In addition to the direct comparison between spaces with the competing lighting technologies, SMUD hoped to gain insight on these issues:

- Whether the LED technology is viable for this application and, if so, what market barriers and potential pathways to wider adoption exist.
- Whether SMUD may want to consider additional research regarding potentially providing energy efficiency incentives or developing a custom program for LED technology specific to indoor agriculture customers.
- Common energy efficiency opportunities observed in commercial indoor cannabis cultivation operations to provide education to the market as customers continue to invest in existing and new cultivation facilities.

2.3 Project Scope

Cadmus monitored two similar flowering rooms at Amplified Farms, one with HPS light fixtures and one with LED fixtures. The monitoring took place throughout one flowering cycle in Room 1 (HPS) and two flowering cycles in Room 2 (LED). The monitoring period timeline is summarized in Table 2. SMUD requested the second round of monitoring following some system start-up commissioning setbacks observed in Room 2 (LED) after the installation of the new lighting and HVAC systems. We did not conduct a second round of monitoring in Room 1 (HPS) due to impending room configuration adjustments that were too significant to make comparisons for this study feasible.

Monitoring Period	RM1 (HPS)	RM2 (LED) Round 1	RM2 (LED) Round 2
Start	8/27/17	7/11/17	9/30/17
End	10/30/17	9/14/17	11/30/17
Total Days	65	66	62

Table 2: Site monitoring schedule.

The flowering rooms at Amplified Farms monitored for this study had the same footprint and nearly identical equipment installed. Even the HVAC had been newly installed with matching 10-ton Aaon packaged heat pump units with electric reheat. The lighting fixtures were the only equipment that differed. Fixture details are shown in Table 3.

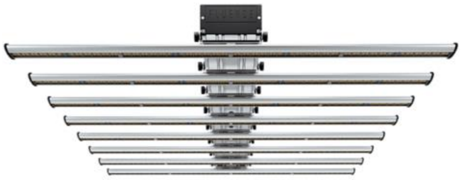
	Room 1	**Room 2**
Quantity	21	21
Image		
Model	Nanolux Super DE HPS	Fluence SPYDRx Plus LED
Rated Input	1000 W	660 W
Max Measured Input	1048 W	700 W
Recommended distance to canopy	36”	6”
Reported output	800 min. / 1,200 max.[2] [µmol/m^2/s]	1,030 µmol/m^2/s (average over 4 ft. x 4 ft. area)
Efficacy	Not reported	2.3 µmol/J (reported)
Equipment Useful Lifespan	Fixture & Ballast: 4-5 years Bulb & Reflectors: 8-9 months	70,000 hours for L70 (8-16 years) (L70 = 70% light output remaining)

Table 3: Lighting fixture details.[3]

Each room measured 21 x 58 feet with approximately 384 sq. ft. of canopy. Inventories and details of the installed equipment, including model numbers, are provided in Table 6 in Appendix A. Figure 3 and Figure 4 show Room 1 and Room 2, respectively.

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[2] These values were reported at nanoluxtech.com/super-de-double-ended-fixture, however they were listed with units of micromoles and no area or duration was provided. Based on the description from the website, we have assumed this is for a 5’ on center installation. We also assume they intended these maximum and minimum values to be micromoles/m^2/s, the standard PPFD units.

[3] Images from Nanolux Technology Inc. (nanoluxtech.com) and Fluence Bioengineering (fluence.science).

Figure 3: Nanolux HPS fixtures installed in Room 1.

Figure 4: Fluence LED fixtures installed in Room 2.

2.4 Research Methodology

Cadmus monitored space conditions and lighting levels within two similar flowering rooms at Amplified Farms. We also monitored the power demand and energy consumption of all equipment in, or serving, each room. We installed a variety of sensors and loggers, throughout the spaces, and the type, model number, and locations of the sensors are reported in Table 7, Table 8, and Figure 14 in Appendix B. In summary, we monitored the following:

- Energy consumption of:
    - Lighting systems in each room
    - Plug loads in each room
    - HVAC units serving each room.
- PPFD and total PAR at locations in each room
    - Manufacturer-recommended distance to canopy:
        - 36 inches in Room 1 (HPS)
        - 6 inches in Room 2 (LED)
    - Two plant-bed locations per room
- Temperatures and relative humidity levels
    - Throughout each room
    - Supply air in each room
    - Return air in each room
- CO_2 levels in each room

We collected the data at one-minute intervals throughout the monitoring periods. We viewed and/or exported the data to discuss any questions or concerns with the project team on a near weekly basis. This was to ensure the rooms operated as intended and to identify any potential issues as early as possible for the duration of the study.

At the end of each monitoring period, Cadmus exported and compiled all data. The total energy consumption calculations for the plug loads and lighting systems were straightforward; however, the HVAC analysis was slightly more involved. First, we disaggregated consumption results by end-use (fan energy, cooling and dehumidification, and electric reheat); see Figure 18 in Appendix C for an example 24-hour period. Then we normalized the heating and cooling loads for weather. Since these sites operate the HVAC as a closed system, meaning no outside air ventilation, and due to the high internal gains from the lights and dehumidification loads from plant transpiration, we were not sure whether the loads would show much dependency on weather. However, trends for heating and cooling in both rooms suggested they were weather dependent, illustrated by Figure 16 and Figure 17 in Appendix C. Therefore, it was necessary for us to normalize the consumption results for comparison since the flowering cycles in each room did not occur simultaneously. This also allowed us to compare results from both flowering cycles in Room 2 (LED) to the cycle in Room 1 (HPS). The results were not normalized for the number of days in the flowering cycle because reduced cycle durations are commonly achieved using LED technology.

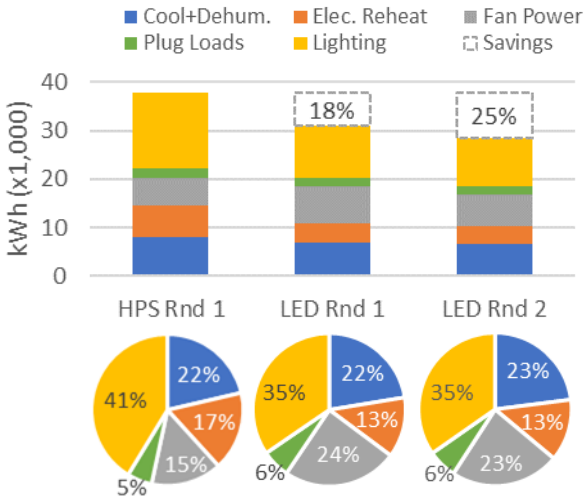

Figure 5: Total energy consumption and end-use breakdown during monitored flowering cycles. Cooling & dehumidification and electric reheat values are weather-normalized.

Lastly, we collected yield results, cost information, and feedback from the cultivators at Amplified Farms.

3. Project Results

3.1 Energy Savings

The observed total energy usage for each flower cycle monitored in Room 2 (LED) was significantly less than the usage observed during the monitored Room 1 (HPS) flower cycle (Figure 5). Room 2 (LED) saw a **total energy consumption reduction of 18% and 25%** (6,816 kWh and 9,407 kWh) in round 1 and round 2, respectively, when compared to the Room 1 (HPS) totals. As can be seen in Figure 6, most of the energy savings is directly attributable to the decrease in lighting power demand. About 72% of the total savings is attributed to lighting reductions in round 1 and nearly 61% in

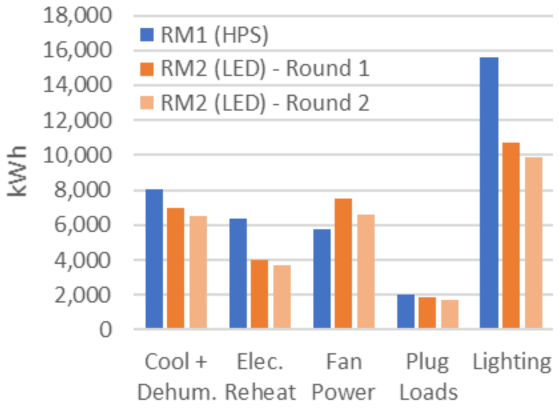

Figure 6: Total energy consumption for each monitored flowering cycle by end use. Cooling & dehumidification and electric heating loads are weather-normalized.

round 2. Approximately 26% of the total savings is attributable to HVAC reductions for round 1 and 36% for round 2. Room 2 (LED) used less energy for cooling and reheat compared to Room 1 (HPS); however, some of these savings were offset by an increase in fan energy. The discrepancy in fan energy appears to be due to the Room 1 (HPS) supply fan operating at a reduced speed compared to the Room 2 (LED) supply fan. Additional savings may be achievable with corresponding fan speeds.

The Room 1 (HPS) lighting energy consumption accounted for 41% (15,632 kWh) of the overall energy use, while it only accounted for 35% (10,716 kWh for round 1 and 9,860 kWh for round 2) in Room 2 (LED). This represents a **26%-36% lighting energy savings** that was achieved from the use of LED lighting versus HPS. Round 2 in Room 2 (LED) saw an increase in lighting savings compared to round 1 due to the use of dimming throughout the cycle as well as a reduction in flowering cycle duration. Hourly lighting demand for each cycle can be seen in Figure 20 through Figure 22 in Appendix C.

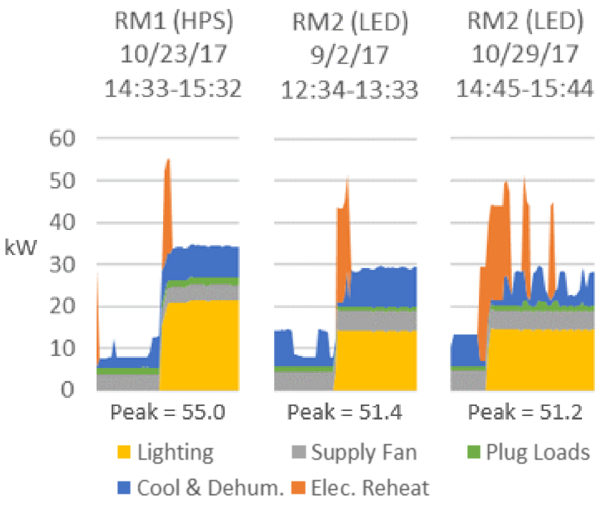

Figure 7: Measured coincident peak demand, one hour shown for each monitored flowering cycle.

The Room 2 (LED) measured overall coincident **peak demand was 6-7% less** (3.6 kW for round 1 and 3.8 kW for round 2) compared to Room 1 (HPS). Figure 7 shows the measured loads the hour demand peaked for each cycle. The lighting peak demand for Room 2 (LED) was 33%, or 7.3 kW less than that of Room 1 (HPS).

Using the energy savings results above and the assumptions listed below, Cadmus determined a simple **payback period of 3.2 years or 16 flowering cycles** for the installation of LED fixtures:

- SPYDRx PLUS LED = $1,465 each (x21)
- Nanolux Super DE 1000W = $375 each (x21)
- HPS DE bulb replacements = $60 each
- Lifespan of HPS DE bulb = three cycles
- Blended utility rate $0.125 per kWh

Results are shown below in Table 4.

Total Use (kWh)	RM1 (HPS)	RM2 (LED)	
		Rnd 1	Rnd 2
Cooling + Dehum.	8,073	7,476	6,528
Electric Reheat	6,399	4,262	3,722
Fan Power	5,719	7,532	6,571
Plug Loads	2,007	1,995	1,742
Lighting	15,632	10,716	9,860
Total	**37,830**	**31,981**	**28,423**

Peak Demand (kW)	RM1 (HPS)	RM2 (LED)	
		Rnd 1	Rnd 2
All HVAC	33.4	36.0	35.6
Plug Loads	4.1	4.8**	4.8
Lighting	22.0	14.7	14.7
Total (Non-Coincident)	**59.5**	**55.5**	**55.1**
Total (Coincident)*	**55.0**	**51.4**	**51.2**

*Measured values.

** Round 2 peak demand value (kW) was assumed for Round 1 since Round 1 plug load data was not collected. Round 2 consumption value (kWh/day) was used to estimate Round 1 total energy use (kWh).

Table 4: Results summary by end-use. Weather-normalized cooling and dehumidification and electric reheat values.

3.2 HVAC Findings

We gained several insights regarding cultivation facility HVAC operation and loads throughout the monitoring periods and during the data analysis for this project. We summarize below our findings on load weather dependency, equipment sizing, the role of dehumidification and potential savings, and the importance of controls commissioning.

Load Weather Dependency

As we previously mentioned, after disaggregating the HVAC loads into fan energy, cooling and dehumidification (basically compressor and condenser energy), and electric reheat, we discovered that cooling and reheat loads showed some dependency on weather, specifically outdoor air temperature. Graphs showing these trends are in Appendix C, Figure 16 and Figure 17. Figure 8 shows the impact of weather dependency on energy consumption during a flowering cycle and potential savings between Room1 (HPS) and Room 2 (LED). The site may see more than an 11% swing between summer and winter in total consumption per flower cycle for both Room 1 and Room 2. Although the values vary slightly, the expected savings between Room 1 (HPS) and Room 2 (LED) should be about 20% any time of year.

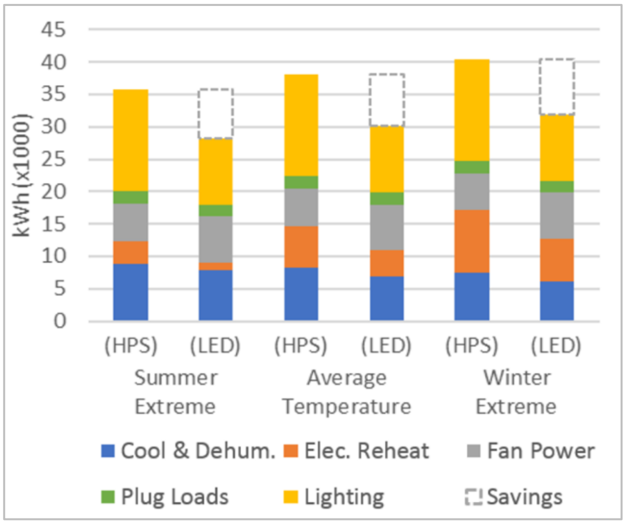

Figure 8: Seasonal Effects Results

Equipment Sizing

We also found evidence that there could be HVAC equipment-sizing benefits when installing LEDs compared to HPS fixtures. When comparing the space temperatures for Room 1 (Figure 9) and Room 2 (Figure 10), it is clear that temperatures trend upward in Room 1 (HPS) and remain flat in Room 2 (LED) during periods when lights are on. This suggests Room 1 (HPS) loads may be maxing out the capacity of the HVAC unit, while Room 2 (LED) loads are well within system capacity, allowing for a constant room temperature within the desired setpoints. Further evidence of the capacity benefit was provided following this study when Amplified Farms reconfigured the two rooms to accommodate an additional row of lighting in each and were required to install an additional 5-ton unit in Room 1 (HPS) while Room 2 (LED) continued normal operation with the existing unit.

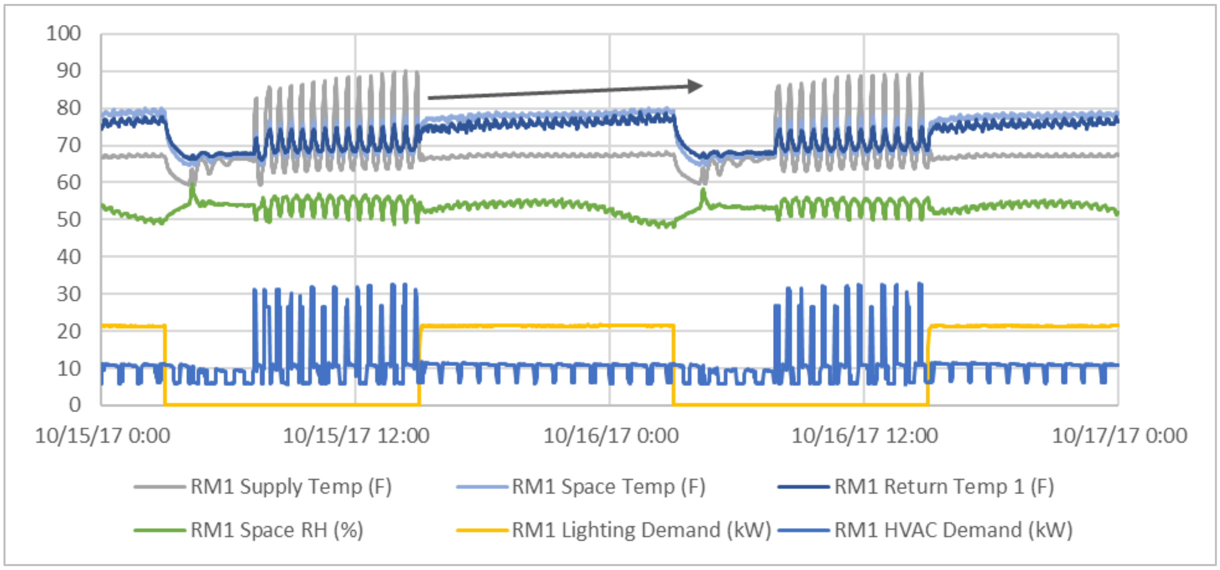

Figure 9: Room 1 (HPS) logged data for a two-day period near the end of the monitored flower cycle. Upward slope suggests Room 1 loads are approaching the maximum capacity of the HVAC equipment.

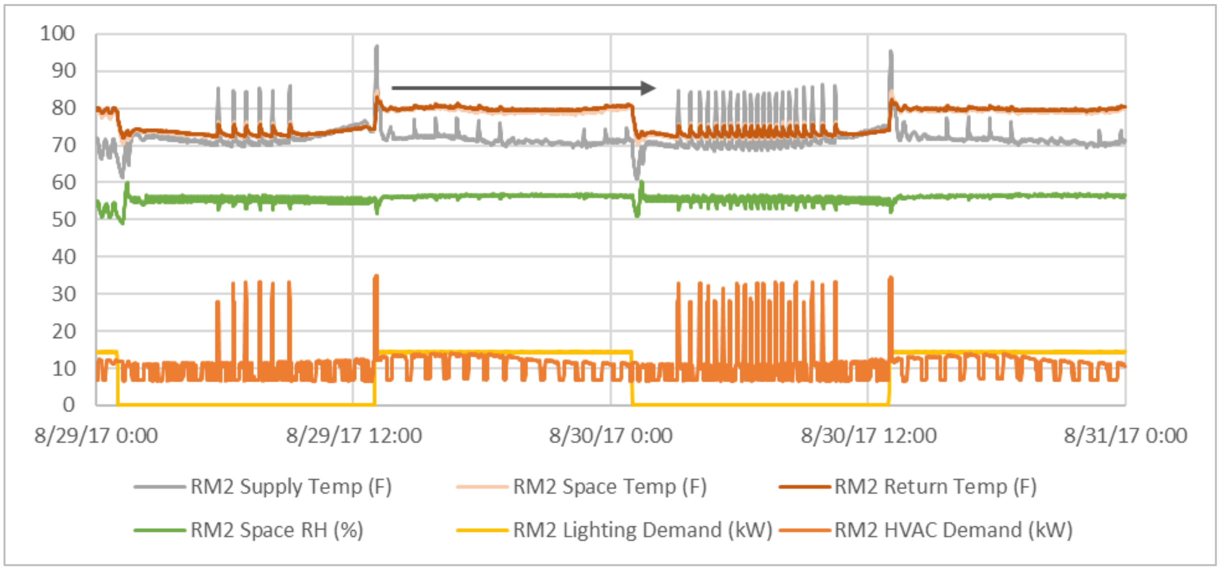

Figure 10: Room 2 (LED) logged data for a two-day period near the end of the first monitored flower cycle. Horizontal slope confirms Room 2 loads are within the capacity of the HVAC equipment.

Dehumidification

As this study progressed, it became evident that dehumidification loads drive much of the HVAC demand. This is because dehumidification is an energy-intensive process often requiring over-cooling the air to remove the moisture, and then reheating it to keep the space temperature within the setpoints. The installed Aaon units provide a single stage of hot gas reclaim, which means the waste heat coming from the compressor (while the equipment is in cooling mode) is captured and used to reheat the airstream for “free.” In this case, the units have a single-row coil allowing only a fraction of the heat to be reclaimed. However, the single stage does not provide sufficient heating capacity, so a second stage of electric resistant heat is installed as well, 22.5 kW per unit. This is a significant demand load, more than the total lighting demand in Room 1 or Room 2. This configuration is typical for many units this size because additional coils for 100% reclaim increase equipment costs significantly—by an estimated 30% according to Stang Air, the HVAC contractor for this project.

According to our findings from the energy analysis, the average flowering cycle will consume 6,399 kWh of reheat in Room 1 and 3,992 kWh in Room 2. Eliminating these loads completely would save 17% of the total energy consumption per flower cycle in Room 1 (HPS), and 13% in Room 2 (LED). Using the assumptions listed below, we calculated the **simple payback of 3.3 years** for installing a unit with 100% hot gas reclaim in Room 1 (HPS) and 5.2 years in Room 2 (LED):

- Installed costs of a 10-ton unit
    - Single-stage hot gas reclaim = $30,000
    - Full condensing hot gas reclaim = $43,000
- Flowering cycles per room per year = 5
- Blended utility rate = $0.125 per kWh

Another option for reducing the reheat load is to optimize the fan speed. Currently, the HVAC units serving Room 1 and Room 2 appear to run at a near-constant, high fan speed 24 hours per day. However, the loads vary substantially between “day” (lights on) and “night” (lights off) so different sequencing may improve performance. During the day, there are both dehumidification and sensible cooling loads (from the lights being on), so the high fan speed may be necessary to meet the cooling load. During lights-off, dehumidification is the primary load, with very little sensible heat gain in the rooms. Slowing the fan speed during lights-off would reduce the supply air temperature, improving dehumidification (extracting more moisture per unit of air), while requiring less reheat. Less reheat is required because even though the supply air temperature may be lower, it will contain less moisture and there is less airflow overall due to the fan speed reduction.

Controls Commissioning

While reviewing the logged data, SMUD and Cadmus noticed some peculiar behavior from the HVAC equipment. The reheat appeared to kick on momentarily right when the lights turned on (see Figure 11). Although we did not confirm the root cause of this behavior, the monitored space relative humidity values do not suggest there was a call for dehumidification. This behavior would not be easily identified without investigating the trend data as we did during this study, which illustrates the importance of commissioning new equipment and reviewing setpoints and controls regularly, especially if changes are being made often.

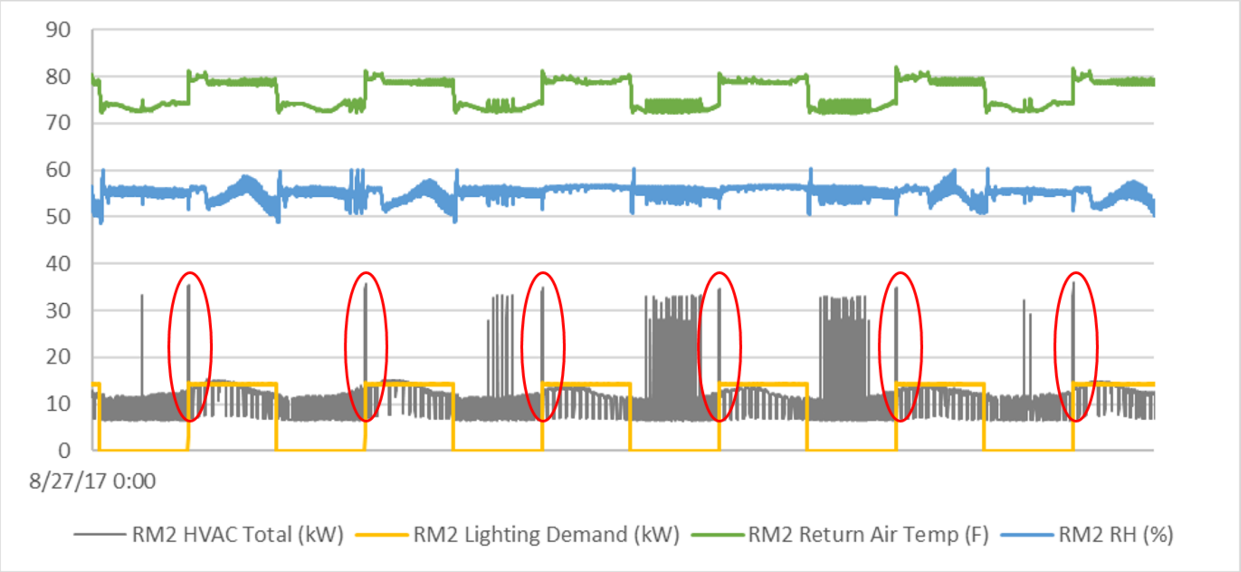

Figure 11: Unnecessary reheat spikes when lights turn on may be avoided with additional commissioning.

3.3 PAR Summary

Throughout the monitoring periods, Cadmus collect PPFD readings using LICOR 190R Quantum sensors. We placed three sensors in each room, two on the plant beds and one at the canopy level. The canopy sensor was located below the center of the fixture at the manufacturer recommended distance to canopy, 36 inches from the HPS fixture in Room 1 and 6 inches from the LED fixture in Room 2.

Table 5 shows our recorded canopy-level maximum PPFD values (center-of-fixture). Figure 23 through Figure 25 in Appendix C show the hourly PPFD readings for all sensors throughout all cycles. We observed similar PPFD trends at the plant-bed level suggesting comparable penetration for both rooms.

3.4 Yield Results

Amplified Farms provided measured crop yield results for all strains grown in Room 1 and Room 2 through the duration of our study. For monitoring period 1, the same number of plants were grown in each room for each strain, so the results are directly comparable. All results are summarized in Figure 12, with triangles representing the Room 1 (HPS) results and circles representing Room 2 (LED) results. The dashed lines indicate the expected range (provided by the cultivator) for results based on values the cultivator has historically seen for flowering under HPS fixtures. The results show three of the seven strains yielded less weight than expected in Room 2 (LED). However, the Room 2 yield was greater than the Room 1

Monitoring Period	RM1 (HPS)	RM2 (LED)	RM2 (LED)
Maximum canopy (center-of-fixture) PPFD (µmol/m^2/s)	715	1,323	1,323

Table 5: PPFD measurements.

(HPS) yield for one of these strains (White Cookies) and achieved substantially higher THC levels. In all cases, the strains grown in Room 2 (LED) realized THC levels higher than the historical average value, and only two of the seven strains were less than the historical maximum value. The three strains grown in Room 1 (HPS) were all at the historical average or less for percent THC. This suggests the LED fixtures may be outperforming HPS technology for optimizing THC production.

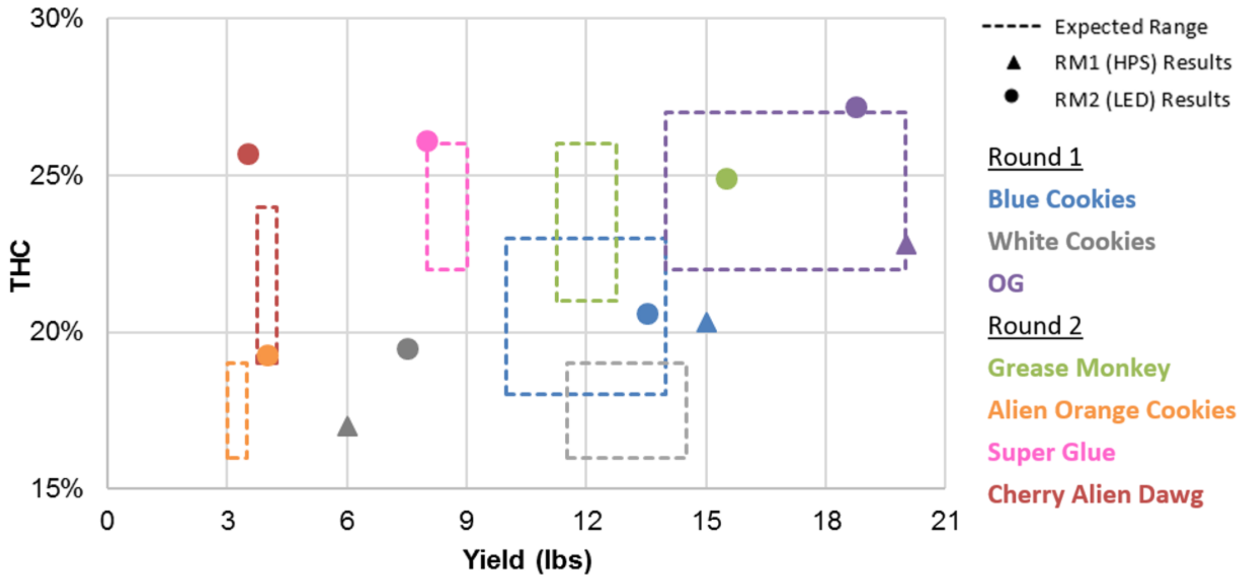

Figure 12: Measured yield and potency results for all strains in study. Also, multipliers have been applied to some or all of these values (no effect on results) for privacy concerns and visual clarity. Note: Round 2 started with two additional strains, but all the plants were damaged or missing following a break-in at the site.

Although we made our best effort to keep the room conditions equal throughout the study, there were some uncontrollable events, such as the HVAC outage and lighting timer issues at the beginning of Room 2 monitoring period 1. For this reason, cultivator feedback is a valuable supplement to the objective results.

For Room 2 (LED) monitoring period 1, the cultivator made the following comments:

- Both the Blue Cookies and OG strains were within expected ranges for yield and THC “despite a very challenging run.”
- For White Cookies, “Yield was only around 60% of normal. THC was very high, despite a very challenging run.”

For Room 2 monitoring period 2, the cultivators made the following comments:

- Yield and potency were within range for all four strains.
- Color was better than usual for Alien Orange Cookies and Super Glue, and within range for other strains.

- "Nose a bit light," meaning less odorous smell than usual, for Grease Monkey and Cherry Alien Dawg. Smell was within range for other strains.

Overall, Amplified Farms cultivators were pleased with the crop results from the Room 2 (LED) grows and felt they could improve future grows as they become more familiar with the lighting system.

3.5 Additional Benefits of LED Technology

With the LED installation at the study site, the cultivator became increasingly confident in the potential of LED technology to achieve yields comparable to plants grown under HPS fixtures. In addition to energy and cost savings, they realized other benefits. Many of these benefits were related to the reduced power demand required by the LEDs and the flexibility that offers for installations.

Since many sites are facing power capacity restraints, installing LEDs rather than HPS in new cultivation spaces is allowing facilities to increase the canopy area more quickly than they can with HPS (rather than waiting for power capacity upgrades). Following our study, Amplified Farms installed an additional row of plants and LEDs in Room 2 to increase the canopy to floor area ratio. They are in the process of installing an additional row of plants and HPS fixtures in Room 1; however, this required also installing an additional 5-tons of cooling, which is an added expense and has caused delays.

The cultivators also noted the cooler operating temperatures of the LED fixtures make expanding vertically an option, which would not be possible with HPS. This is because the LED fixtures can be installed with the distance to the canopy as little as 6 inches (at some points Amplified Farms had plant growth through the fixtures without damage), where the HPS require nearly 36 inches to prevent scorching the plants. Again, this benefits future expansion—a facility that installs LEDs in a vertical, multitier configuration may be able to fit two to three times the canopy area that would fit in the same building using HPS.

Figure 13: Example of vertical farming. Photo courtesy of Fluence.

The technology also provides the benefit of having precise control of the spectral distribution the plants receive, as well as dimming capabilities. Generally, any additional control of environmental parameters available to the cultivator are going to improve their ability to determine and achieve the optimum conditions for successful cultivation. The cultivators can also improve conditions within the spaces for workers, who noted their preference for working under the LEDs (white light/broad spectrum) compared to the HPS (orange light).

4. Conclusion

The findings from this study suggest LEDs can provide the lighting necessary to successfully cultivate cannabis through the flowering phase while reducing energy use and costs. However, with numerous variables impacting the energy use of each system in this study, it was difficult to determine whether interactive effects could be attributed to the lighting system upgrade. There may be steps to take with future studies to obtain more detailed values, which we have outlined in the following subsections.

From the perspective of the cultivators, the LED fixtures were a positive addition to their process. Amplified Farms cultivators were pleased with the crop results, the savings, and the versatility of the fixtures. They are purchasing more of the same LED fixtures to be used in future flowering rooms at the site.

4.1 Lessons Learned

From this and other field studies, we have gained many insights regarding how indoor cannabis cultivation facilities operate, and these insights may impact future research studies. However, it is difficult to conduct a controlled, side-by-side study for the following reasons:

- Flowering cycles rarely occur simultaneously, so it is likely that monitoring periods will be staggered in different rooms.

- Many processes are conducted manually and typically cannot be controlled automatically throughout the cycles. These may include watering, fertigation, lighting control, additional humidification or dehumidification by portable or fixed units, trimming, and others.

- Because plants are living things, cultivators often adjust as needed (in an effort to optimize production) based on their experience, instead of adhering to an unchanging schedule through each cycle.

- To optimize production, cultivators often try different strategies throughout their facility. They may try a different grow media or soil, switch nutrients, or reconfigure a space between cycles (or sometimes mid-cycle) to improve their crop. Unfortunately, these changes can significantly impact a research study.

Another challenge that arose during these studies was the impact of facility start-up. Because of the rapid growth in this sector due to the recent California legalization of commercial cannabis for recreational use, all facilities are essentially new. This means that cultivators are not only determining their process, but often have all new lighting, HVAC, and supporting equipment, much of which they may by unfamiliar with. As with any building, there is typically a commissioning period that occurs before all the bugs are worked out of the system, and this period is not ideal for conducting research. However, the studies need to be conducted in a timely manner so that findings can be published before many facilities are built-out.

Lastly, we discovered that improved comparison metrics may result from asking more specific questions regarding yield and crop production, such as fresh and dry weights for total plants and flowers only.

For future side-by-side field studies we recommend the following:

- Conducting a pre-test of equipment to ensure equivalent operation, especially at new facilities or in new spaces. Check items such as the following:
    - Fan speeds
    - Reheat sequencing
    - Lighting schedules
    - Set-points (if hoping to keep them equal)

- Request room setup be as similar as possible including:
    - The same quantities and model numbers of equipment be installed where possible
    - Circuit breakers are properly labeled for all items in the spaces
    - Plant spacing and density be equal between the spaces (rather than focusing on overall canopy size)

- Request a grow plan upfront for all comparison rooms including:
    - Outlined strategies for all variables including type, amount, and schedule for: fertigation, watering, media, nutrients, trimming, light dimming, temperature and humidity setpoints, CO_2 level setpoints, etc. Also request a plan and schedule for any expected adjustments to these setpoints (such as reducing the lighting for the final week or trimming plants at 5 weeks).
    - Get the cultivator's commitment to follow the plan as closely as circumstances will allow.

- Collect detailed plant and crop production information:
    - Type of plant (indica or sativa)

  - Which strains
  - Number of plants of each strain
  - Measured yield values
    - Total THC (%)
    - Total plant fresh weight
    - Flower fresh weight
    - Trim fresh weight
    - Dry flower weight
    - Terpene analysis

4.2 Recommendations and Next Steps

After demonstrating that LEDs can successfully be used in cannabis flowering applications while reducing energy use, additional data collection and research is necessary to understand the interactive effects between energy systems. We hope to investigate the following:

- How using LEDs compared to HPS impacts energy and demand with different HVAC systems
- How different HVAC control strategies (particularly reheat) impact energy consumption and demand
- How different LED lighting technologies compare to each other

With the challenges faced throughout this and other field studies, we hope to collect additional data in a laboratory environment or, possibly, a site with LED and HPS technology installed within the same room. Although this would not allow for further investigation into interactive system effects, it would ensure space conditions, schedules, and any other events were consistent between the two testing areas so the crop response could be more accurately determined.

While additional research is necessary, SMUD is currently offering custom incentives for LED and other technologies for indoor cultivation facilities. For more information, please send an email to indoorcultivation@smud.org or visit the websites below:

- Custom Incentive Program (retrofit projects)
  https://www.smud.org/en/Business-Solutions-and-Rebates/Business-Rebates/Custom-Incentives
- Savings by Design (new construction)
  https://www.smud.org/en/Business-Solutions-and-Rebates/Business-Rebates/Savings-by-Design

Appendices

Appendix A – Room Inventories

The equipment installed in, or serving, each space is summarized below in Table 6. Most equipment is operated on similar schedules or to meet similar setpoints between rooms, however, some equipment such as floor fans and portable humidifiers are only present in the room and operated as needed. For this equipment, a range is provided in the quantity columns representing the variability throughout the cycle.

Table 6: Equipment details and quantities by room.

	Equipment Description	Flowering Room 1 (HPS) Quantity	Flowering Room 2 (LED) Quantity
	Nanolux Super DE 1000W HPS Light Fixture	21	0
	SPYDRx PLUS 660W LED Light Fixture	0	21
	EcoSmart ECS GP 19 Green NDM 120 BL 2 Watt Light	8	8
	Hurricane 16” Classic Wallmount Fan Product #736503	12	12
	Hurricane 24” High Velocity Drum Fan Product #736470 and/or Hurricane 20” High Velocity Floor Fan Product #736476	0-3	0-3
	Air King 9020 High Velocity Air Circulator	4	4

	Equipment Description	Flowering Room 1 (HPS) Quantity	Flowering Room 2 (LED) Quantity
	Titan Controls ARES 8 NG CO_2 Generator and Atlas 3 CO_2 Controller	2	2
	Can-Fan EL 014 E4 01	2	2
	Liberty Pumps Pro 380 4/10hp Pump	1	1
	Sentinel GPS BHC-1a PB Basic Humidity Controller Product #703240	1	1
	Hunter I-CORE Sprinkler Controller	1	1
	Ideal-Air™ GSH200 Portable Humidifier	0-2	0-2
	Aaon RN-010-8-0-EP09-132 Packaged Heat Pump with • 10-ton Cooling Capacity • 22.5 kW 2-Stage Electric Heat • Variable Capacity, Compressor • Modulating Hot Gas Reheat • 5hp Variable Speed Supply Fan • Variable Speed Condenser Fan	1	1

The Aaon HVAC units operated according to the following sequencing:

- **Supply Fan Control**: The supply fan runs continuously and will run at the high speed setpoint (adj.). The supply fan is maintained by minimum on and off timers.

- **Cooling Mode** (Hysteresis +/- 1.5F): The cooling mode will be enabled when the space temperature rises above the occupied cooling mode setpoint. During the cooling mode, the controller will modulate and stage cooling to maintain the space temperature at the occupied cooling mode setpoint. The supply air temperature is continuously reset as needed but is not allowed to be maintained below the low supply air temperature limit setpoint. The cooling mode will remain active until the space temperature falls below the occupied cooling mode setpoint.

- **Dehumidify Mode** (Hysteresis +/-5%RH): The dehumidify mode will be enabled when the space humidity rises above the occupied dehumidify setpoint. During the dehumidify mode, the controller will modulate and stage cooling to maintain the space humidity at the occupied dehumidify setpoint. Reheat stage 1 and 2 will be modulated sequentially to maintain the space temperature at .5°F below the occupied cooling control setpoint. An additional electric heat stage will be activated as needed to supplement reheat to maintain space temperature. The dehumidify mode will remain active until the space humidity falls below the occupied dehumidify setpoint.

Appendix B – Monitoring Equipment

Cadmus monitored the space conditions within the rooms using a mix of temperature, temperature & relative humidity, PAR, and CO2 sensors. We monitored power demand of the lighting, HVAC, and plug loads at their respective panels using current transducers, Onset Wattnodes, pulse adapters, TRMSA modules, and Hobo RX3000 loggers. The RX3000 provided a cellular connection so all data points were visible from the online portal at Hobolink.com. A summary of installed metering devices is below in Table 3 and Table 2. Note that the summary below is the final installation list, some meters were added throughout the project as additional end-use disaggregation was desired, so not all the devices listed below were installed for the entire duration of the cycle.

Table 7. Power Monitoring Devices

	Device Description	Location (Panel), Service	Quantity
	Current Transformers	PB-C, RM1 Lighting PB-C, RM2 Lighting PB-C, RM2 Lighting Control Panel PB-C, RM1 & RM2 Plug Loads PB-A, RM1 HVAC PB-A, RM2 HVAC PB-A, RM2 HVAC PB-C, Main Supply	6 6 3 8 1 1 3 3
 	Continental Control Systems WattNode AC Energy Meters Onset S-UCC-M006 Electronic Switch Pulse Input Adapters	PB-C, Main Supply PB-C, LED Controls PB-A, RM2 HVAC	1 1 1
	Onset S-FS-TRMSA 2-Channel FlexSmart TRMS Modules	PB-A, RM1 & RM2 HVAC PB-C, RM1 & RM2 Lighting & Plug Loads	2 10
	Hobo RX3000 Remote Monitoring Station Data Logger	PB-A, RM1 & RM2 HVAC PB-C, RM1 & RM2 Lighting & Plug Loads RM1, RM1 Space Conditions RM2, RM2 Space Conditions	1 3 1 1

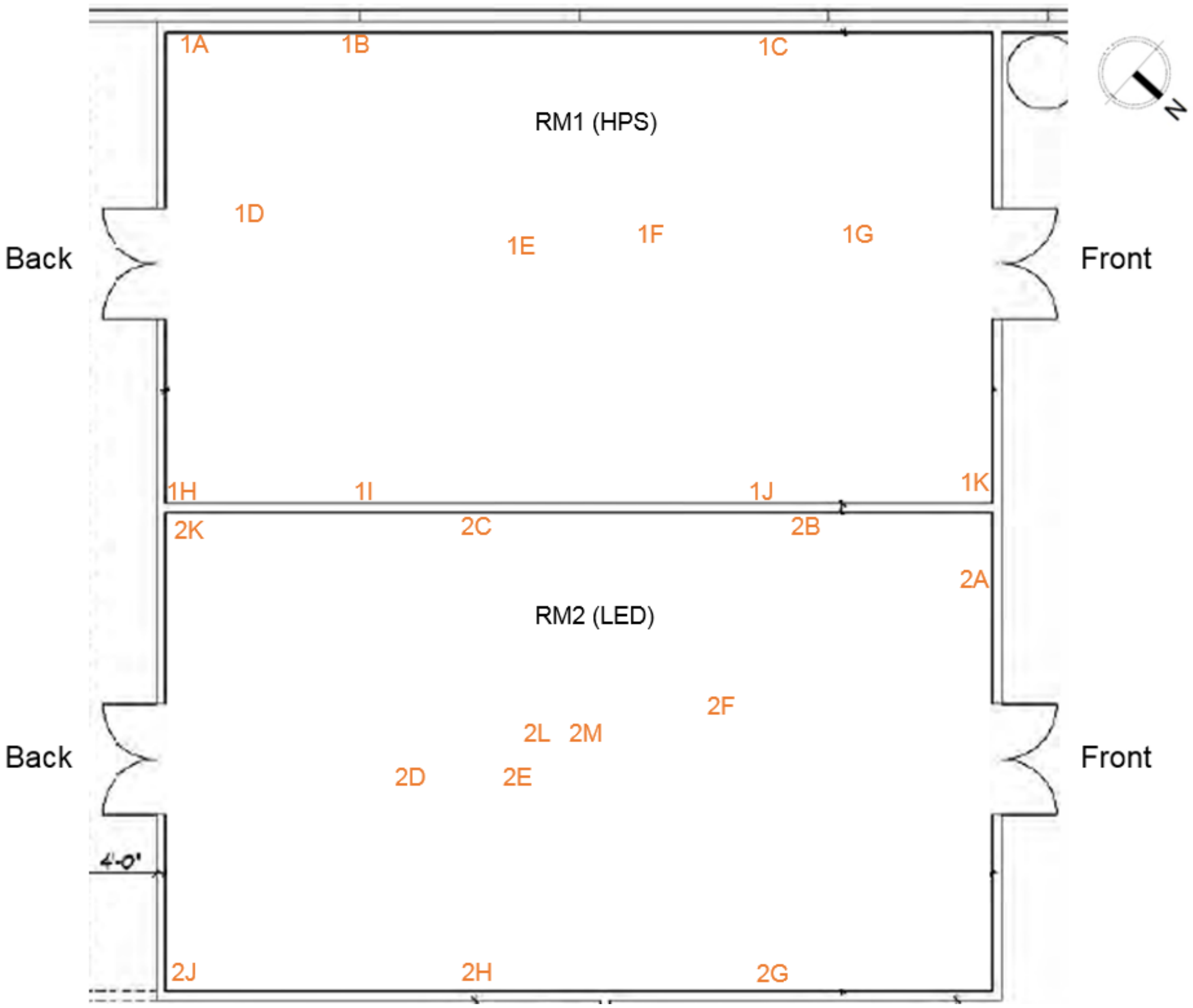

Figure 14: Sensor Locations

Table 8. Space Condition Monitoring Devices

	Device Description	Flowering Room 1 (HPS) Qty/Location	Flowering Room 2 (LED) Qty/Location
	Onset S-THB 12-bit Temperature/Relative Humidity Smart Sensor	Quantity: 5 1A: Back-Right 1C: Front-Right 1E: Mid-Mid 1F: Supply Air 1H: Return Air	Quantity: 4 2D: Back-Mid 2J: Left Return 2K: Right Return 2M: Supply Air
	Onset S-TMB 12-Bit Temperature Smart Sensor	Quantity: 5 1B: Mid-Right 1D: Back-Mid 1G: Front-Mid 1I: Back-Left 1J: Mid-Left	Quantity: 6 2B: Front-Right 2C: Back-Right 2E: Mid-Mid 2F: Front-Mid 2G: Front-Left 2H: Back-Left
	Telaire TEL-7001 CO_2 Sensor	Quantity: 1 1K: Front-Left	Quantity: 1 2A: Front Right
	LICOR LI-190R Quantum PAR Sensor + EME Systems 2.5V Output Universal Transconductance Amplifier (UTA) + Onset S-VIA-CM14 12-bit Voltage Input Adapter Sensor	Quantity: 3	Quantity: 3

Appendix C – Supplementary Data

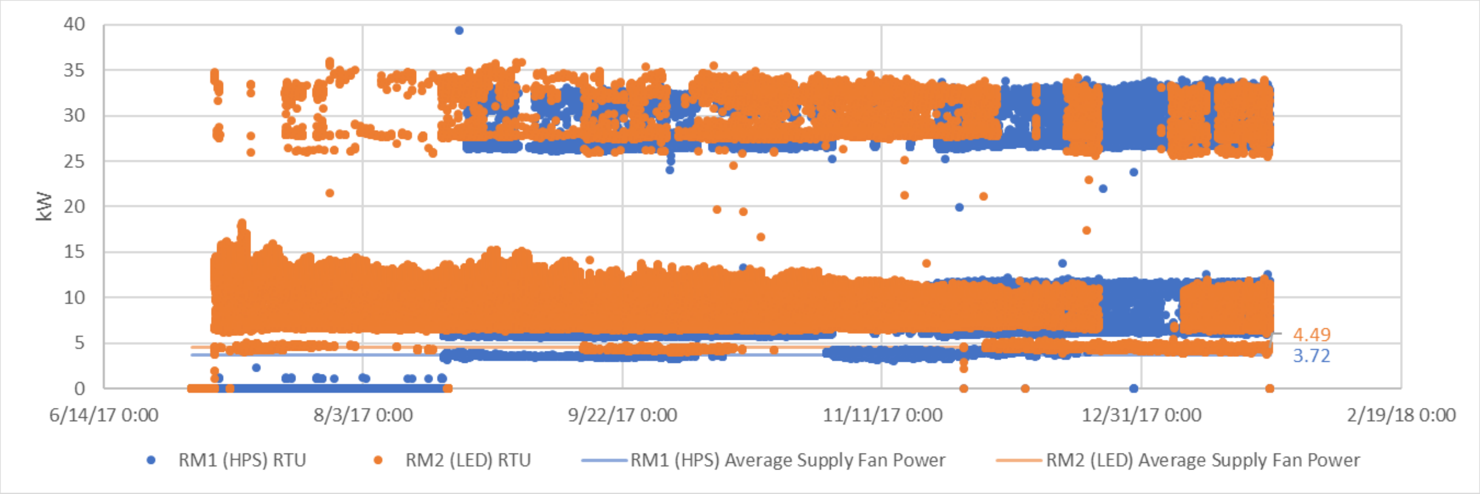

Figure 15: Room 1 (HPS) RTU supply fan may run slightly slower than Room 2 (LED) RTU. This may have slightly improved the dehumidification process in Room 1 (HPS) as well as reduced the need for reheat.

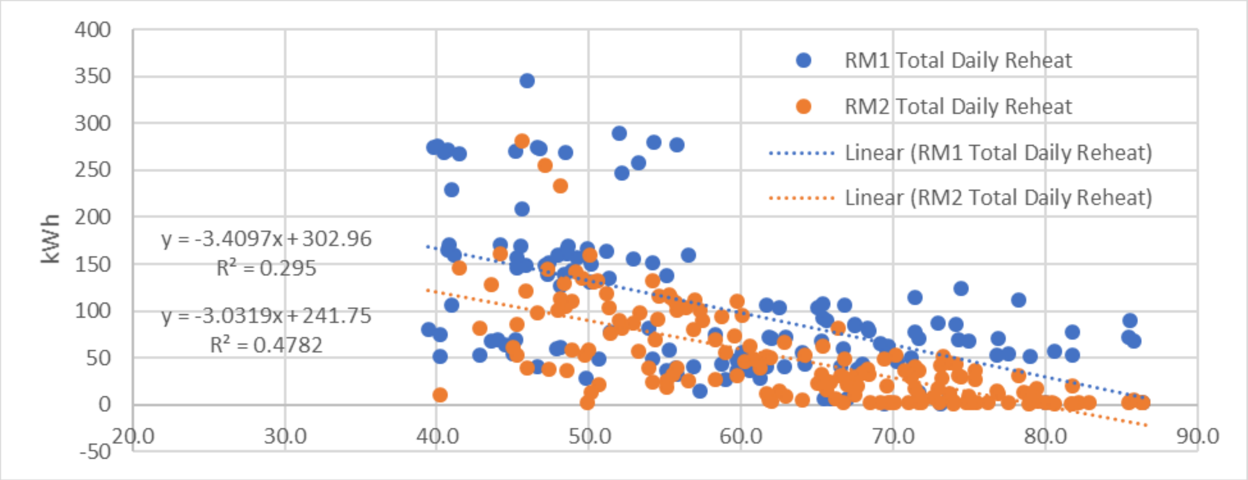

Figure 16: Room 1 (HPS) showed slightly higher reheat requirements for the same average daily temperatures than Room 2 (LED) did.

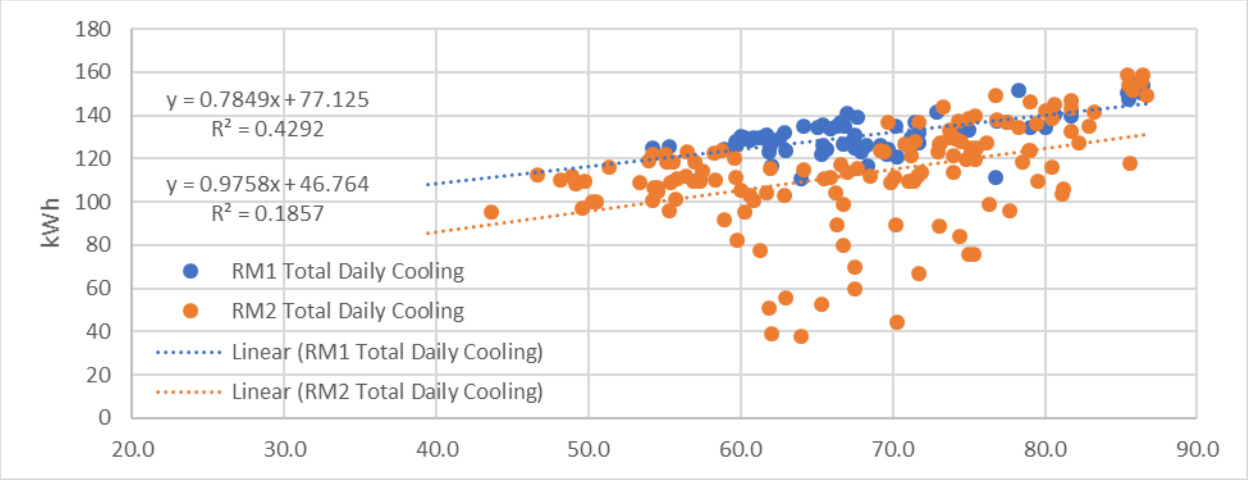

Figure 17: Room 1 (HPS) also showed higher cooling requirements at the same average daily temperature.

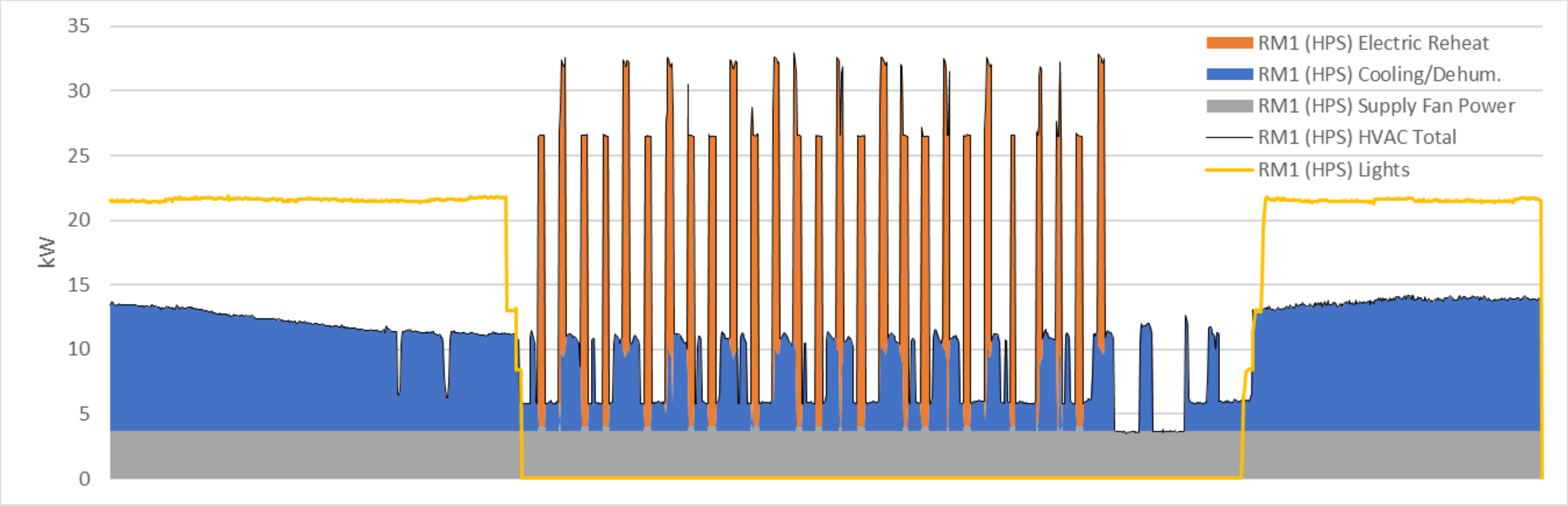

Figure 18: 24-hours period example of HVAC operation. RM1 (HPS) on first day of flower. 8/27/17 at 6pm – 8/28/17 at 6pm.

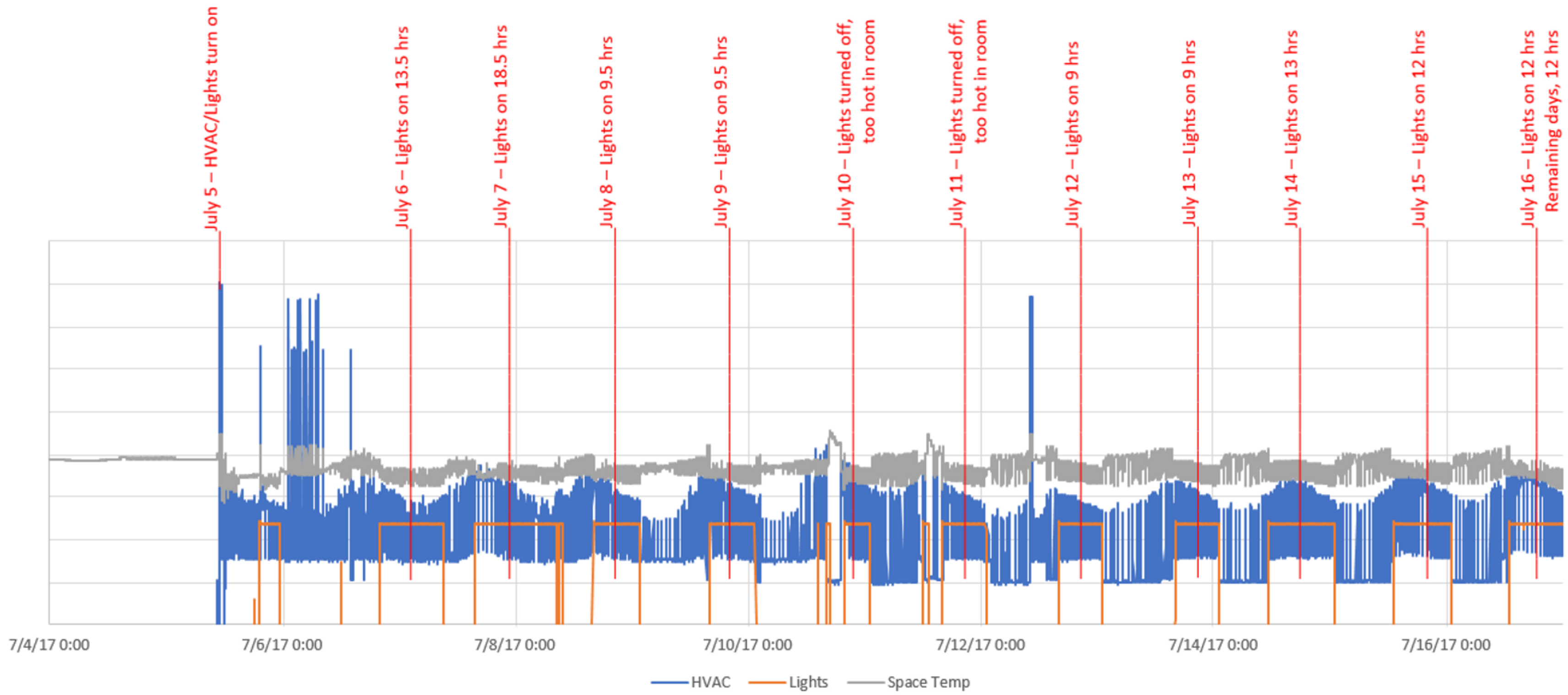

Figure 19: At the start of the first monitoring period in Room 2 (LED), there were multiple issues resulting in non-ideal growing conditions. With the newly installed LED fixtures in place, the plants were moved into the room to continue their vegetative phase on July 6th (lights on for 18 hours, off for 6 hours). Later, it was discovered the lighting control timer had been set improperly, resulting in 'daytime' (lights on) periods lasting only 9.5 hours rather than the expected 18 hours. After multiple days of 9.5 hour 'daytime' periods, the plants had transitioned into their flowering phase prematurely, and could not go back to vegetative phase. In addition, there were two days, July 10-11th, where the cultivators were forced to turn off the lights during the intended 'daytime' period due to excessively high temperatures in the space. This was caused by an outage of their also newly installed HVAC unit. It was not until July 15th that the lighting schedule and HVAC equipment were both operating as planned for the flowering phase. For the purpose of this study, we considered day 1 of flowering to be July 11th.

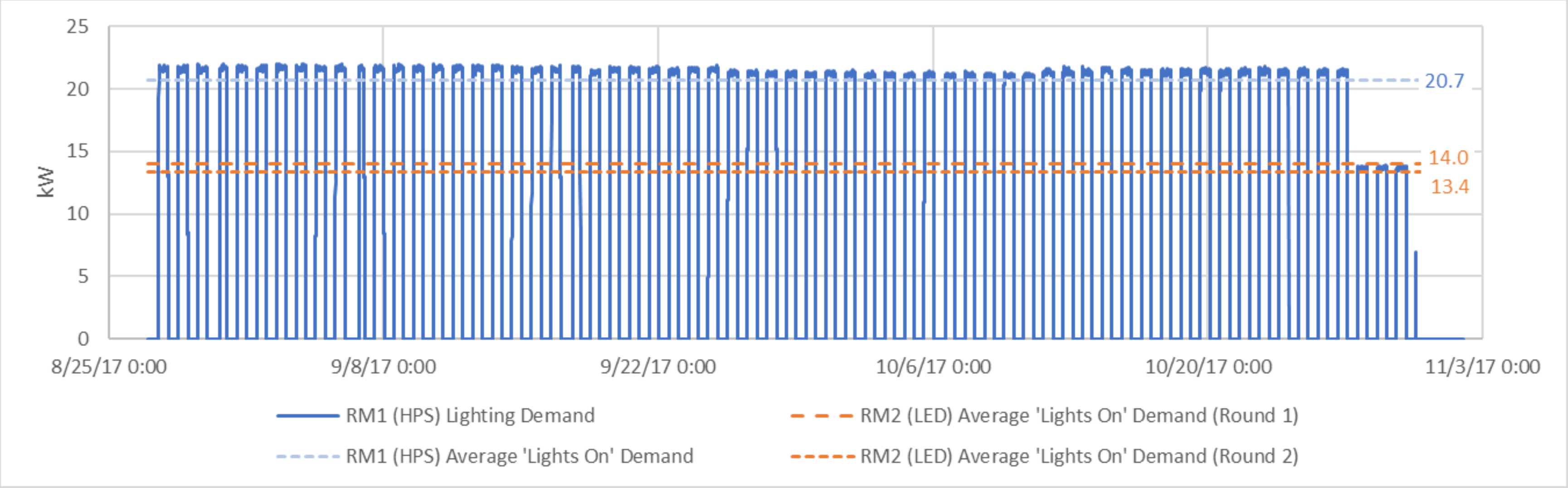

Figure 20: Room 1 (HPS) lighting power demand.

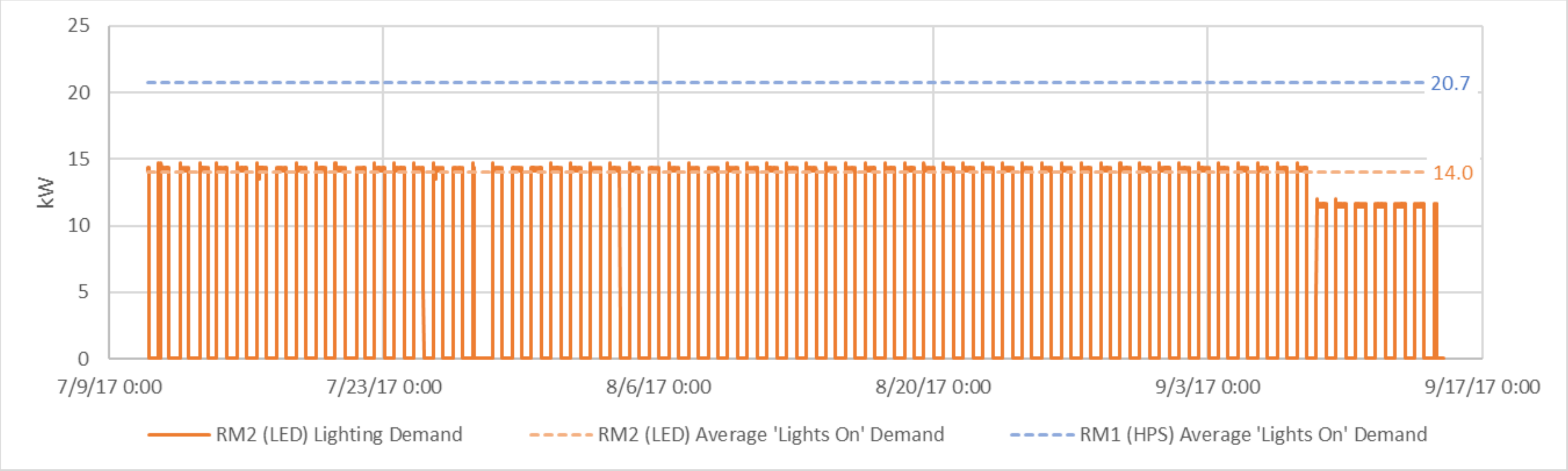

Figure 21: Room 2 (LED) lighting power demand throughout monitoring period 1.

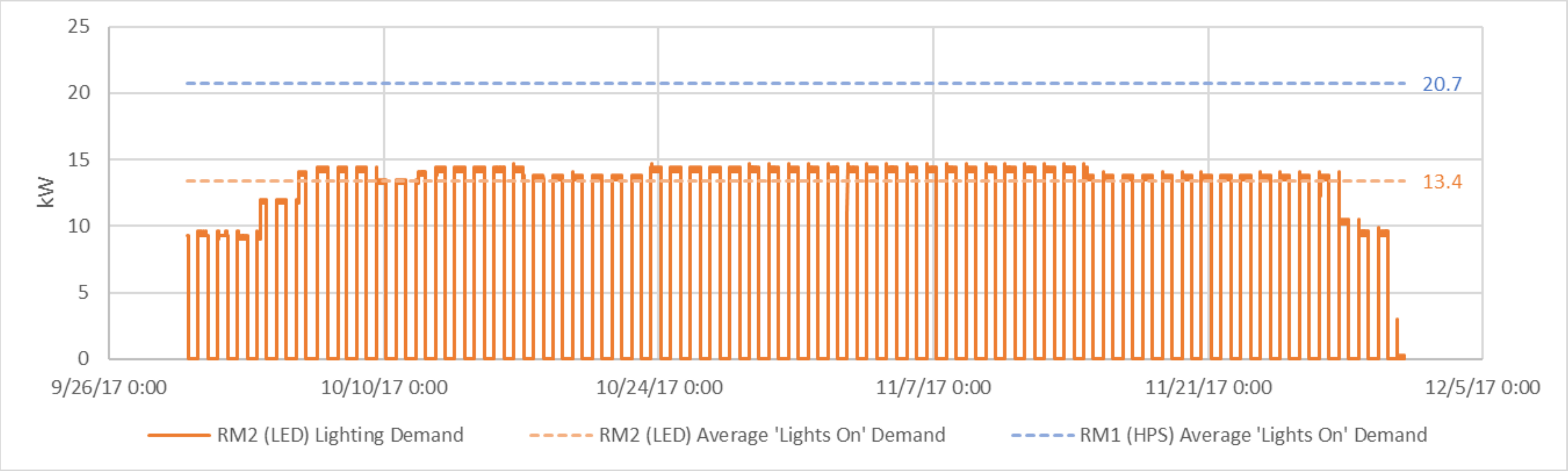

Figure 22: Room 2 (LED) lighting power demand throughout monitoring period 2**.**

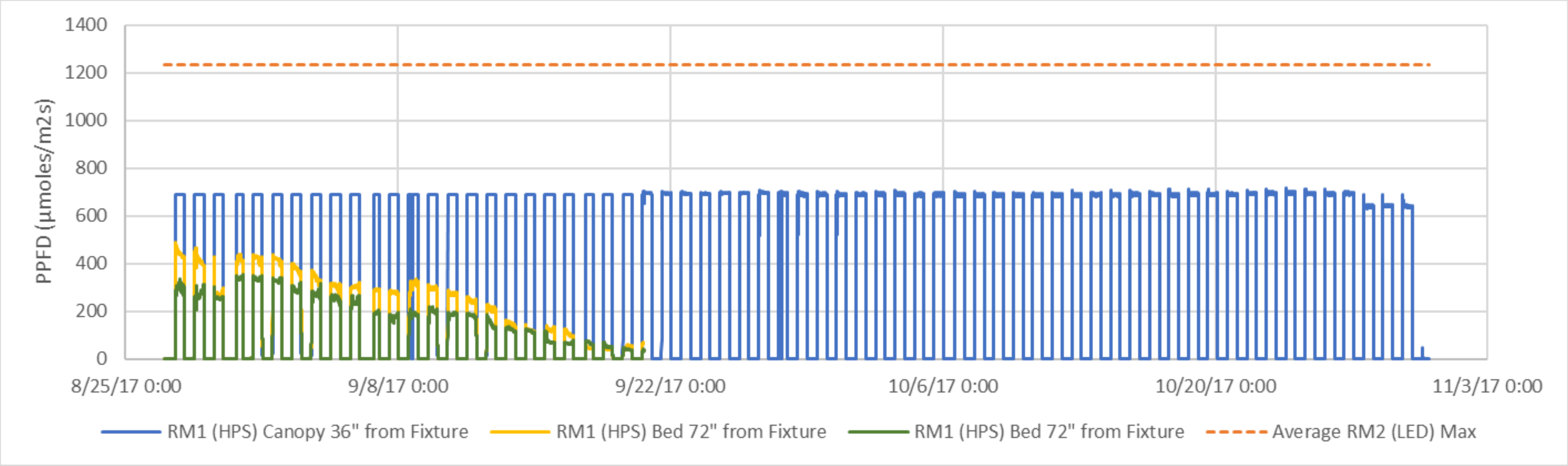

Figure 23: Room 1 (HPS) PPFD throughout the monitoring period.

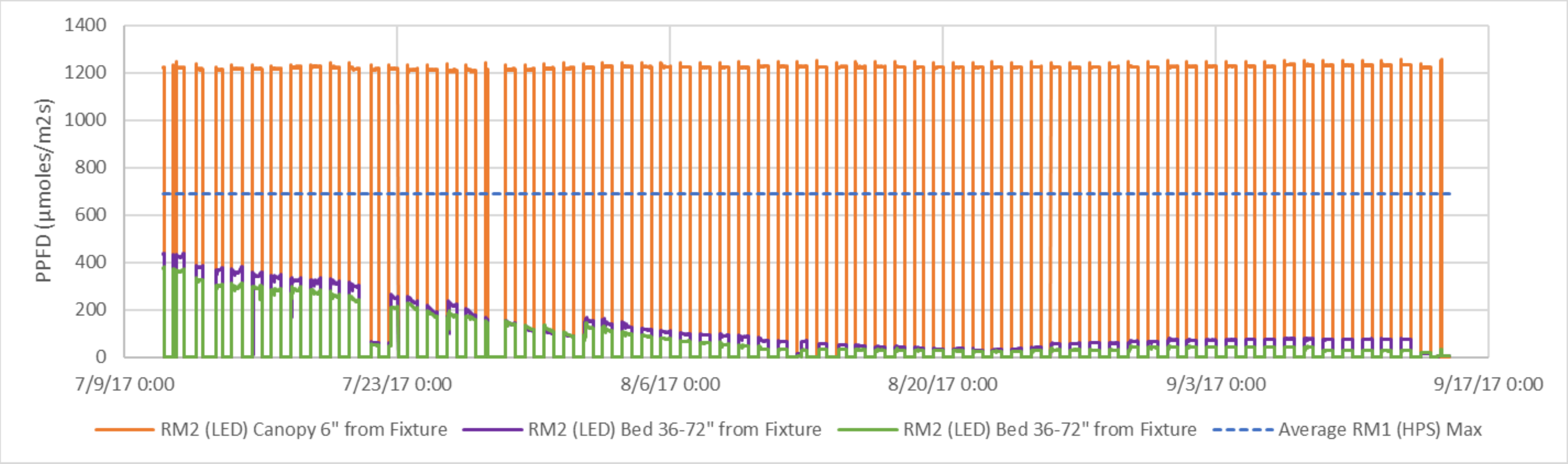

Figure 24: Room 2 (LED) PPFD throughout monitoring period 1.

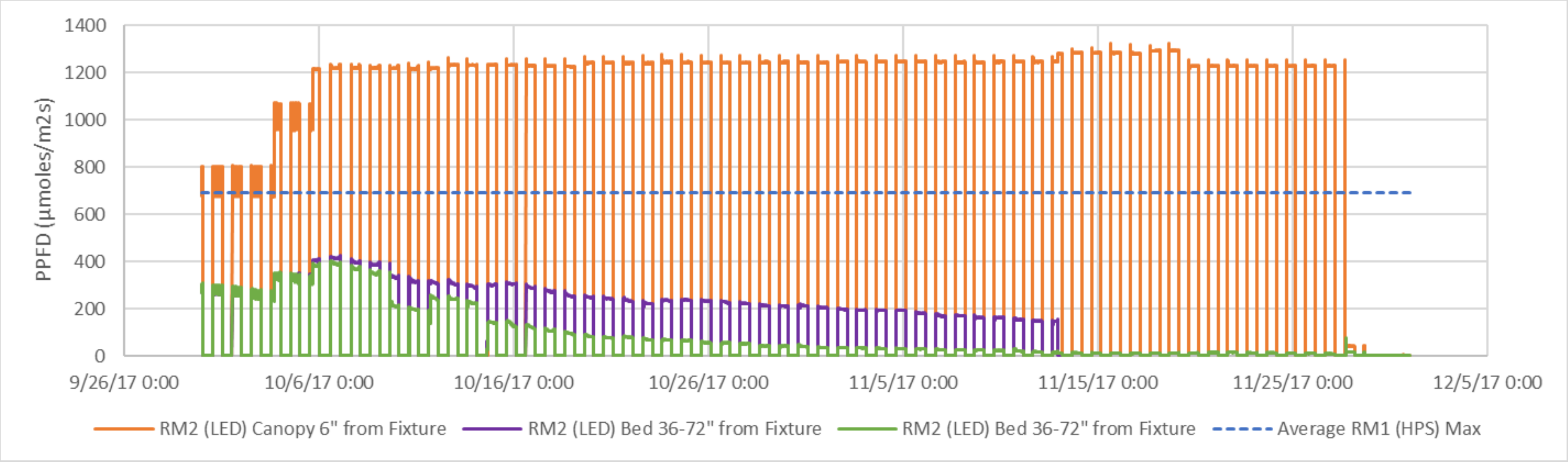

Figure 25: Room 2 (LED) PPFD throughout monitoring period 2.

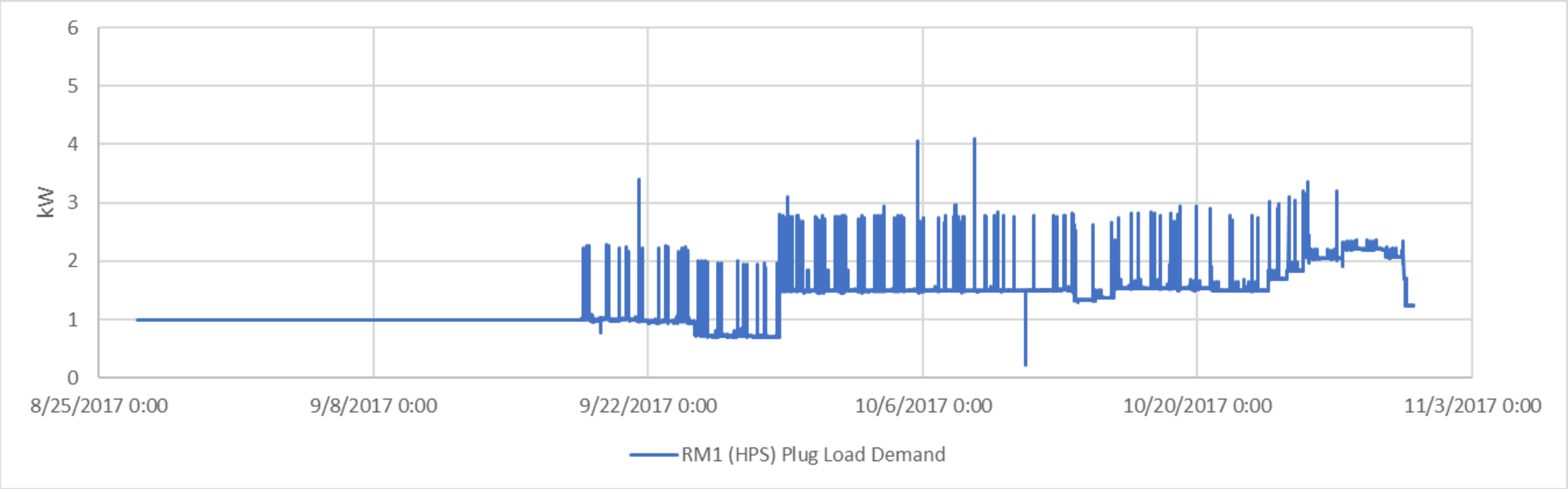

Figure 26: Room 1 (HPS) plug loads power demand throughout the monitoring period. The average demand for 9/18/17 - 9/24/17 was extrapolated to estimate the demand before 9/18/17.

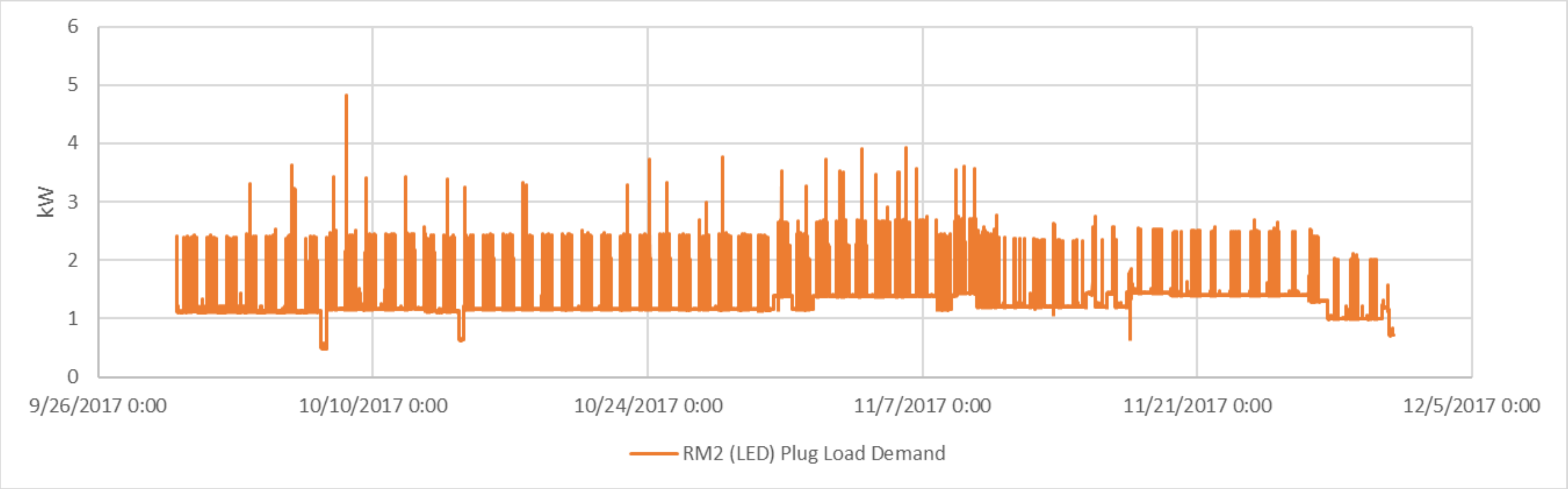

Figure 27: Room 2 (LED) plug loads power demand throughout the monitoring period.