

SunGrown Indoor

Can Sunlight from Solatube® Daylight Harvesting System Support Indoor Cannabis Growth?

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ABSTRACT & RESEARCH OBJECTIVES

This agricultural research examined how Tubular Daylighting Devices (TDDs), manufactured by Solatube International, Inc., can support indoor cannabis cultivation. TDDs are daylight harvesting systems that use optics to capture outdoor sunlight and transfer it indoors via highly engineered and reflective internal mirrored films. While the economic incentives and human health benefits of bringing natural sunlight indoors have been thoroughly studied, very little empirical research has examined the suitability of TDDs for agricultural use. Is the light quality and quantity emitted from Solatube TDDs suitable for driving photosynthesis?

Using a spectroradiometer, we measured the spectral composition of light emitted from Solatube TDDs and found it closely resembled that of full-spectrum sunlight - rich in 400 to 700 nm wavelengths ideal for plant photosynthesis. Using handheld and mounted Apogee quantum PAR sensors, we quantified the intensity of TDD light as photosynthetic photon flux density (PPFD). We found two unexpected elements: a constant, room-filling ambient light averaging 300 to 600 µmol/m2/s and a dynamic "hot spot" averaging 900 to 1300 µmol/m2/s. This was not expected, as most artificial lights used in agricultural settings are engineered to deliver a constant light level across the 2D plane that is the plant canopy. The potential value of these elements for cannabis cultivation is discussed.

Our third-party validation of TDD light quality and quantity for plant growth then led to a novel hybrid-light grow facility design incorporating Solatube SkyVaults®, LEDs and advanced grow room intelligence. The cannabis industry suffers from a lack of credible, data-driven empirical research of cultivation techniques and maximizing resource efficiency. Throughout several grow cycles, our goal was to maximize resource efficiency as indicated by three primary key performance indicators: lighting power density (watts/square foot), electrical productivity (grams/kilowatt hour), and energy use intensity (kWh/ft2/year). We report cannabis flower production rates exceeding 30 g/ft2 with lighting power densities lower than typical indoor or greenhouse facilities. SGI electrical productivity levels exceeded 2 g/kWh, the highest reported to date, and our energy use intensity was 2-3x lower than indoor or greenhouse designs at 80 – 160 kWh/ft2/year. As such, this preliminary research established that SGI facilities can provide substantial cultivation cost savings while maintaining high-quality cannabis flower output. For large commercial cannabis operations (10,000 ft2 of plant canopy), an SGI hybrid cultivation approach could result in cultivation resource efficiency optimizations of 60-80% - with cost savings exceeding $500,000/year and admirable carbon-foot reductions.

The contribution presented by this proof of concept research is demonstrating that TDDs not only support plant growth but do so by delivering light spectrums better suited for photosynthesis with no energy use. Building from our preliminary studies, there are now several larger cultivation operations actively using Solatube TDDs for cannabis cultivation. We believe it's only a matter of time until legal cannabis market pressures drive operations with high cultivation costs and unsustainable methods out of business. We compare the SunGrown Indoor approach to that of modern hybrid light designs (greenhouses) and highlight unique advantages that make SunGrown Indoor the most resource efficient approach to indoor agricultural and horticultural grow operations presented to date. While the interest and value in cannabis allowed for this research, its implications go beyond as well into urban farming, vertical farming or even subterranean farming as the chaos faced by surface farmers expands.

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SUNGROWN INDOOR SYSTEMS & HYBRID-LIGHT CULTIVATION FACILITIES

The cultivation facility was a hybrid-light cultivation design – pairing natural sunlight with artificial LEDs as supplemental light similar to most modern greenhouses. However, the biggest weakness of commonplace greenhouse designs is the inherent trade-off between light transmission and insulation value. The only way to increase light intensity inside of a greenhouse is to reduce the opacity and thickness of the greenhouse exterior walls. More light = less insulation, more insulation = less light. The use of Solatube TDDs to bring in sunlight eliminates this design trade-off.

Our cultivation facility & grow techniques – SunGrown Indoor (SGI) – were designed to maximize internal climate stability and control, while minimizing electrical & water resource input requirements, and maintaining product quality. Artificial lighting & HVAC systems represent 75%+ of indoor cannabis cultivation energy use, and, after labor, are the largest contributor to cost-of-goods sold in any indoor agricultural operation. Consequently, improving the interplay & efficiency in these two facility components was our primary focus. SGI facilities are characterized by 1) Solatube TDDs as the primary light source, paired with supplemental LEDs used only as needed and to drive photomorphogenesis, 2) a smart grow room intelligence sensor network and 3) a programmable controller system that actively monitors internal and external environmental conditions to modulate the grow systems in real-time (Figure 1 & 2).

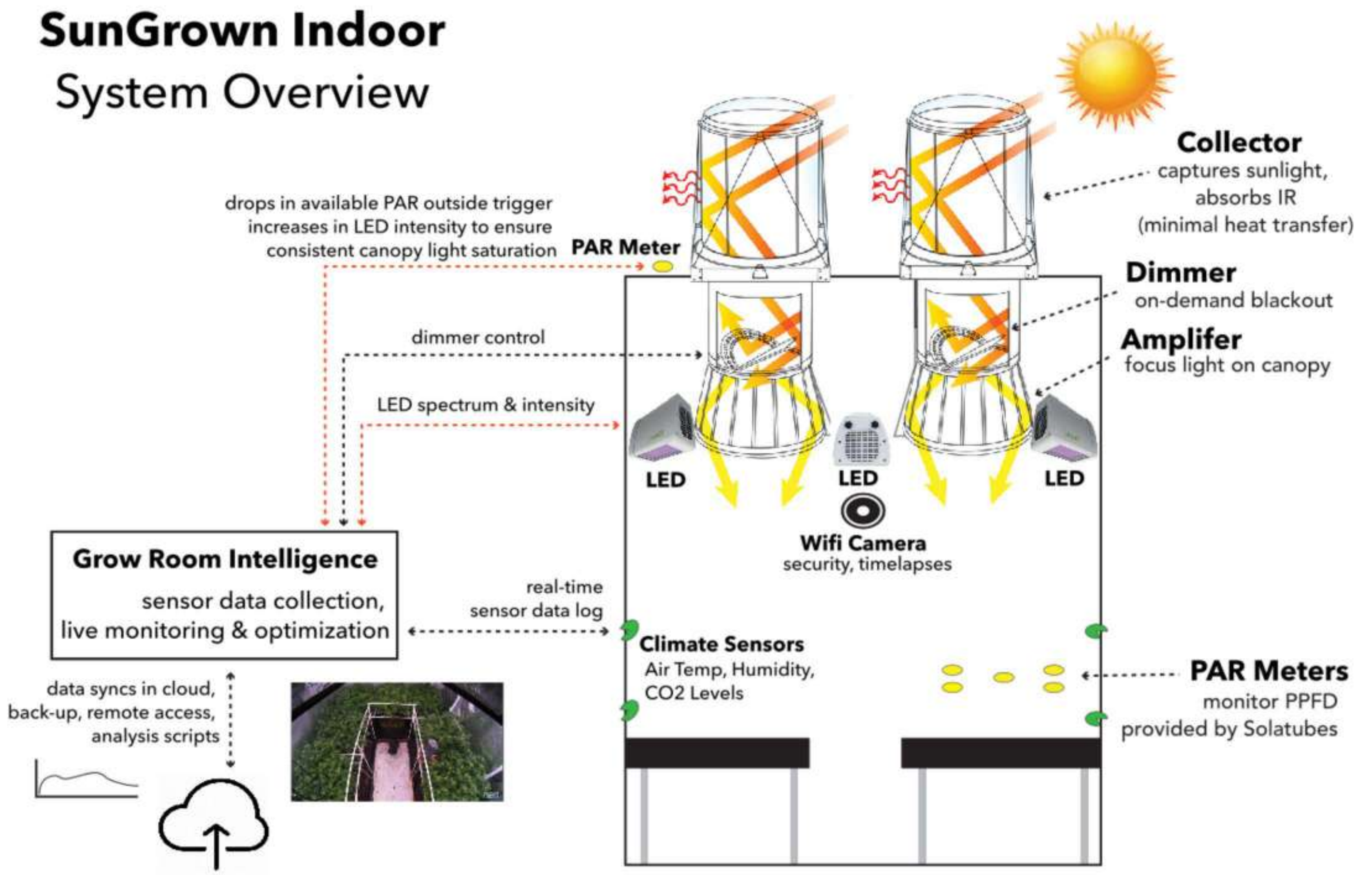

Figure 1 - SunGrown Indoor hybrid cultivation facility design and core system components.

Figure 2 - SunGrown Indoor Flower Grow Rooms (Exterior and Interior).

Building Envelope & Equipment

The research flower grow rooms were built in triplicate as research progressed. Vegetative growth was performed in a smaller unit (with a TDD) or hoop house. A 10′ x 12′ Tuff Shed barn shell was constructed per manufacturer plans with additional measures to aid in sealing off the internal environment (i.e. use of caulk on all wood joints), including 2″ foil backed foam board insulation on all exterior walls. With summer highs of 110°F (43°C) and nighttime lows into the 40s°F (4°C), we sought to keep the internal temperature swings less than 10°F with reasonable temporal lengths (i.e. daily, weekly). The critical goal was complete control of the temperature to our specifications based on the strain and phase. For high-THC or medical cannabis, this is the level of stress control necessary to maintain maximum end-product quality. For Hemp CBD and other plant produce (i.e. tomatoes, poinsettias), such tight control is not necessarily critical – consumers are not as meticulous or calibrated to such granular quality indicators.

Each building was meticulously insulated and did not contain any components that produced significant, distinctly measurable radiant heat (like High-Pressure Sodium (HPS) lamps). These design choices resulted in significant resilience to changes in outdoor weather. By contrast, most greenhouse facilities are seemingly in a constant battle to maintain internal conditions despite external weather. A full equipment list is provided in Appendix A.

Tubular Daylighting Devices (TDDs); Solatube SkyVault w Collector, Daylight Dimmer & Amplifier Prismatic Diffuser

Originally intended for large open spaces (warehouses, gymnasiums), the Solatube SkyVault Series (M74DS model) is the largest commercial TDD available (29″ diameter). It consists of an External Collector component that captures low-angle sunlight during sunrise and sunset, an Amplifier that focuses captured light directly below the unit and a dimmer (Figure 1). The Daylight Dimmer is a light modulating valve consisting of a butterfly baffle that can open or close to control the amount of sunlight coming through the tube. Only used on long summer days to control the photoperiod when going to "dark" when some available sunlight is still in the sky. Each of these components represents an "Add-on", selected in our research to maximize control. We did not experience any issues with sunlight leaking into the flower room, especially because the dark phase was at night.

Figure 3 - Grow Room Intelligence - Control Panel & Circuit Breaker (top left), Climate Sensors placed around grow room (top right), placement of LEDs among SkyVaults (bottom). Note, in top right photo Solatube SkyVaults are partially installed, without dimmer, amplifier or prismatic diffusers components.

In our research units, a SkyVault was positioned directly above industry standard 16 ft2 (4′ x 4′) hydroponic trays. The first research design included a single SkyVault centered within a 10′ x 10′ floor plan, and the second & third iteration included four SkyVault units within the same 10′ x 10′ floor plan (Figure 4). Ceiling height was 10′, with the dimmer and amplifier unit reaching 3′ below the ceiling. In other words, the SkyVault diffuser was 7′ above the floor and 3′ above the hydroponic trays. A prismatic diffuser lens was selected to maximize spatial light distribution across and penetrating the crop canopy.

Unlike competitors, sunlight harvested by Solatube TDDs maintains its intensity and specular quality while preventing heat-generating Infrared (IR) and approximately 90% of Ultraviolet (UV) waves from entering the room. They deliver "cool" sunlight indoors ideal for plant growth – hence the name "SunGrown Indoor". While there is significant interest in the precise role of UV in phytocannabinoid synthesis, there is a lack of empirical data and consensus among growers to precisely how UV modifies cannabis metabolites. The SGI design provides an ideal environment to probe for these details, but such research was outside the scope of these preliminary studies.

Heliospectra LX602c series LED lamps were selected as supplemental for their connectivity (WI-FI, CAT5 Ethernet) and ability to change spectral output and intensity on demand. The intensity of four wavelengths (blue @ 450nm, red @ 660nm and 735nm and white 5700k) could independently be controlled, allowing for custom spectral output. Each 10′ x 10′ grow room was outfitted with eight LX602 units near the SkyVaults and above the hydroponic trays.

This many LEDs is more than typically necessary (artificially increasing installed lighting power density) but ensured we could mitigate any unforeseen (sun)light loss albeit almost inconceivable. Future designs will be well served by modeling facility-specific light level projections which are now possible based on this research (See Appendix Images at end). We had some early harvests paired with a Gavita Plasma lamp but did not directly evaluate TDDs with HPS lamps. Lastly, the efficacy of horticulture LEDs has also increased over 50% since the Heliospectra 602 series was released. Thus, future installs will require fewer LEDs for supplemental lighting backup and in compliance with lighting power density regulations.

Grow Room Intelligence

SGI grow room climate sensors, current transducers (CT), and programmable logic controller (PLC) systems were custom designed and built by Grownetics (Boulder, Colorado). Based on our specifications, the Grownetics team deployed an integrated Air Temp (F/C), Relative Humidity (%) and CO2 sensor box that was placed in four locations in flower chambers, both high (above the canopy) and low (near root zone) in each SGI flower room (Figure 3 & Figure 4).

Each 100 ft2 SGI grow room was outfitted with:

- 8 Air Temp, RH and CO2 Sensor boxes (4 high, 4 low)
- 8 Apogee full-spectrum quantum PAR sensors (7 inside, 1 outside)
- 6 Water Temp & pH monitors (in each water reservoir, external)

Our target environmental conditions varied slightly based on the stage of growth. In general, a daytime temperature between 70 - 80°F and night temperature of 60 - 65°F were comfortable threshold ranges over 24 hours. Plant leaf temperatures were also monitored daily with an Infrared thermometer, during feeding and plant inspection runs. Daily set points for relative humidity levels also fluctuated based on strain and growth stage, remaining within 50%-60% RH. Keeping temp and humidity stable, within these ranges, supported ideal strong vapor pressure deficit (VPD) values from 0.8 kPA to 1.25 kPA. In flowering rooms, we kept CO2 levels above 900 ppm with CO2 tank regulated by the Grownetics system.

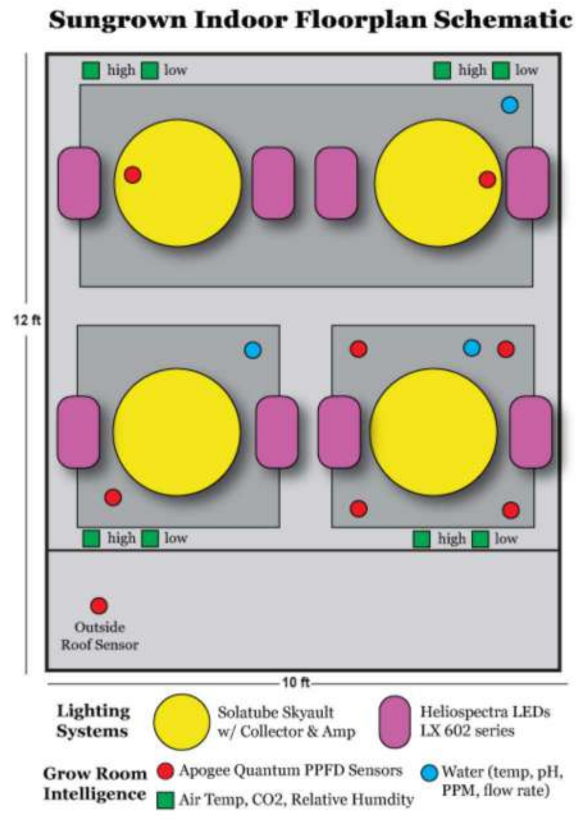

Figure 4 - Lighting & Climate Sensor Floor Plan Layout.

All sensors were calibrated to manufacturer specifications, programmed to set intervals and, report data as needed. Individual sensor data was monitored and validated with handheld units made by different companies throughout the project and during every harvest turn or flip. Particular attention was given to PAR sensor output in close collaboration with Apogee to ensure data integrity. PPFD levels were logged automatically and monitored daily with a handheld single sensor (Sun System), multi-sensor bars (Apogee). The light spectrum quality was assessed on-demand with a Stellar-RAD Handheld Spectroradiometer (StellarNet Inc., Florida) able to quantify the spectral composition of light sources.

In a similar manner, individual outlet energy use and total building energy use was monitored closely. Every electrical outlet was controlled and monitored with CT sensors (as part of the Grownetics system) and a separate CT system (Engage, Efergy, UK) was installed upstream on each flower room's main circuit breaker.

The degree of redundancy on light and energy monitoring systems was done intentionally and affectionately referred to as our "speedometer". Each day, we strove to optimize canopy light quantity (intensity) and quality (spectrum) without "speeding". Note, our goal was not simply to maximize canopy light levels for X hours of the day ("flooring it") but rather to ensure plants received optimal levels for biomass growth with minimal resource expenditures. Initially, this was a daily, manual balancing act that considered geographical location, local weather, genetics, growth stage, nutrient input and, available photosynthetic photon flux density (PPFD) at multiple points internally and externally to each flower room.

While more data is necessary, previous research has demonstrated that photosynthetic rates in flowering cannabis plants become saturated as PPFD levels exceed 550 µmol/m2/s (see References). In other words, minimum PPFD levels of at least 450-500 µmol/m2/s are needed to harvest commercially viable flower yields. By monitoring internal and external (outside) PAR levels, in real-time, we hypothesized that dynamically triggering the LEDs to come on and increase light intensity up to at least 550 PPFD would optimize energy use without sacrificing harvest yields. Initially, this was a manually set, stepwise protocol that initiated when canopy PPFD levels dipped below 350 µmol/m2/s for a set amount of time. The grow room controllers then brought ON the Heliospectra LEDs to preset % of full light intensity (ranging from 30% to 70%). External and Canopy (internal) PPFD trigger levels, duration till action, and LED light intensities were custom-developed based on growing location to achieve the optimal savings based on regional weather conditions. This is referred to as a closed-loop daylight harvesting system in illumination and lighting industries focused on human-occupied interiors.

Over the course of several flowering cycles, we were able to start using artificial intelligence and analysis techniques to automate optimization programming and rapidly assess the trade-offs of different PPFD trigger rangers. These techniques, developed during this research, can now be applied to any potential cultivation facility location beforehand and in real-time to continuously improve resource efficiency – optimizing end-product quality and resource use (costs) to a theoretical maximum based on geographic position, local weather and strain characteristics.

SKYVAULT LIGHT EVALUATION RESULTS

Light Spectral Quality Emitted from TDD

Plant growth is driven by light quality (spectral composition) and quantity (intensity, µmol/m2/s). The McCree Curve represents the wavelengths plant photosynthesis is primarily driven by – it is commonly referred to as photosynthetically active radiation (PAR) and spans 400 nm to 700 nm (Figure 5, top). Our measurements of light spectral composition emitting from the SkyVault diffusers (approx. 16" below diffuser) is shown in Figure 5, middle. It is an ideal match against the required PAR spectrum, high peaks within the blue 400-500 nm range as well as the reds in 600-700 nm wavelengths. It demonstrates how well the Solatube TDDs preserve the quality of natural sunlight – the light source photosynthesis evolved to capture in the plant. The spectrum shown in Figure 5 is representative of a clear day in Sonoma County, California. Overall, in the course of daily review, it became clear that any time-based or weather-based changes in our location's sunlight quality were mirrored inside of each grow room. Meaning, any changes or fluctuations in sunlight intensity or quality outside each room were paralleled inside and our control systems were adopted to compensate as such.

The recorded spectral composition also illustrates how Solatube TDDs filter out UV (< 400 nm) wavelengths. While opinions on the importance of UV rays in cannabis cultivation are strongly held, there are not yet been empirical tests performed to definitively determine a relationship. Anecdotally, we noticed a lack of browning and what seemed to be a longer shelf life of the SunGrown Indoor cannabis flower presumably due to the lack of UV exposure.

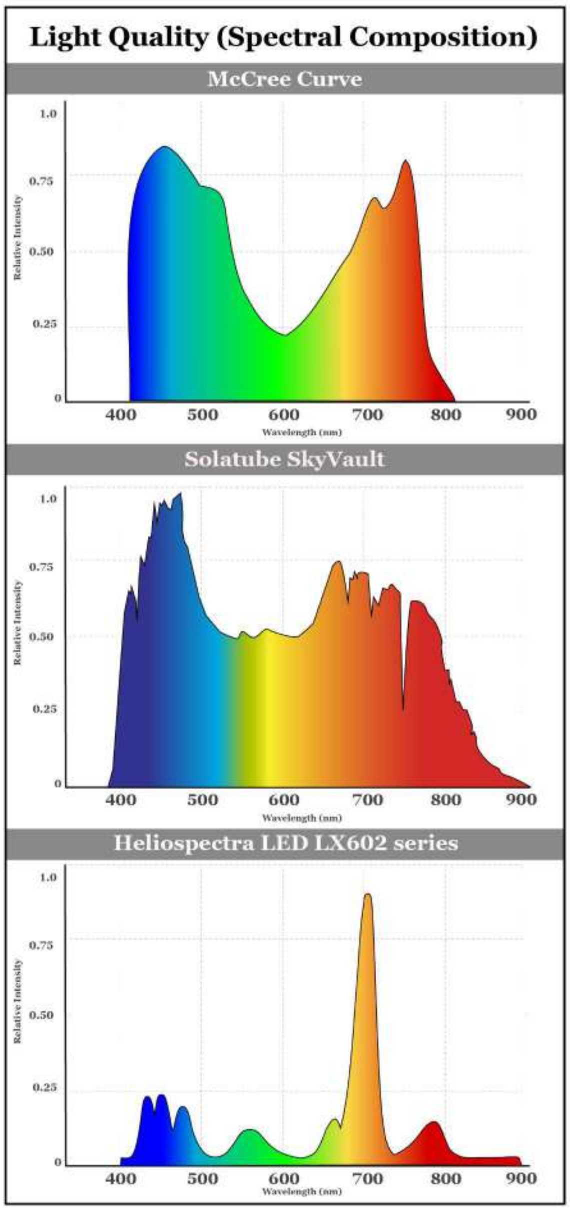

Figure 5 - Light Quality (Spectrum) from Solatube TDD - Spectral Composition of McCree Curve (PAR), Solatube SkyVault output and Heliospectra LX602 LEDs. Measurements taken approximately 16" below light. Solatube light spectrum was recorded on a clear, sunny day in Northern California (August 2016).

Light Intensity Emitted from SkyVault

Measuring PPFD emitted from Solatube TDDs proved interesting due to the dynamic nature of sunlight over the course of a day. As the sun moves across the sky, the pattern of harvested daylight changes due to varying reflection patterns through the TDD. As seen in the time-lapse videos (http://bit.ly/SGITimelapse) there is a noticeably brighter spot that changes positions throughout the day. This was unexpected.

Our handheld PAR meter measurements (recorded 16" to 2' below the diffuser) recorded 900 to 1300 μmol/m2/s in this brighter spot. Around and beside this spot, we logged between 300 – 600 ambient μmol/m2/s (16" to 7' below diffuser; Figure 6) overall. Over time, it was clear incidental or spot PPFD measurements fail to demonstrate the overall sunlight levels received by the plant canopy in the course of a day.

It was striking how differently the sunlight fills the space compared to artificial lights. Being inside these grow rooms, under the TDDs, there was a marked sensory difference – you could "feel" the room was being filled with sunlight. Whereas artificial lights are designed to emit a steady, constant, and even light intensity on a 2D plan approximately 3' to 6' below the lamp – sunlight fills up the entire space. This resulted in deeper canopy penetration compared to the LEDs alone & less light loss as we measured deeper into the canopy. This was observed in lower level fan leaf's "stretching" or "reaching" for the higher intensity sunlight as it moved throughout the day. As the SunGrown Indoor technique is further developed, delivering sunlight to "subcanopy" plant sections, perhaps even horizontally, it will be interesting to see how much yield can be gained. Moreover, clear plant adaptation was observed on days where LED light was acting as the primary light a few hours before sunlight entered. It was as if the plants developed a preference for the TDD delivered sunlight and were waiting for it to enter the space before waking. More research will be required to fully unpack these observed plant responses to TDD sunlight indoors. The PPFD data collected by installed Apogee PAR sensors also reveals this dynamic pattern.

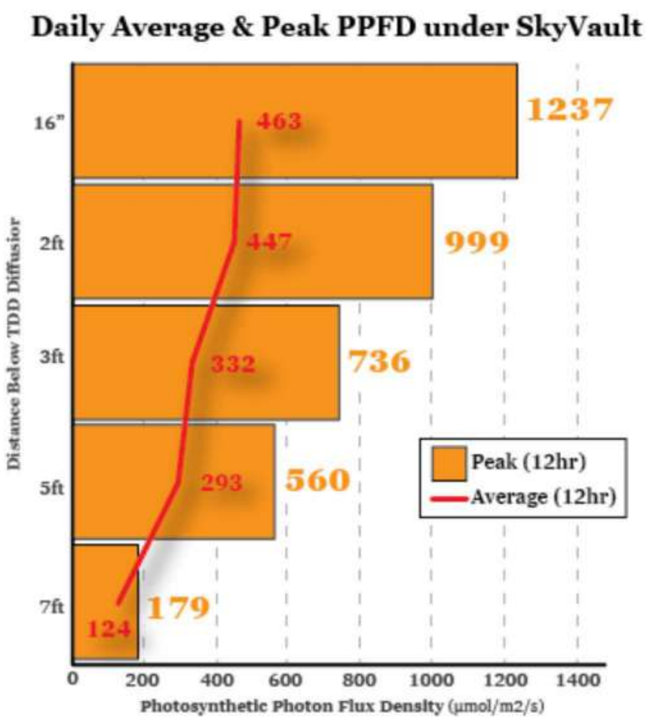

Figure 6 – Daily Average & Peak PPFD (μmol/m2/s) measurements under Solatube SkyVault. PPFD levels across entire 12hr "ON" light cycle were recorded with Apogee Quantum PAR sensors at different distances from TDD prismatic diffuser. Orange bars represent the maximum, or peak PPFD (averaged max from each day), red line represents the average, ambient PPFD (averaged average from each day). Data collected in August 2016 (Northern California).

This facility was designed to fuel plant photosynthesis with sunlight via TDDs (Solatube SkyVaults) and supplement or direct growth activity with LEDs. Using relatively well-documented research on light spectrum and photomorphogenesis, we increased the intensity of blue wavelengths (450nm) during vegetative growth and the first 10-20 days of flowering phases. Blue light has been shown to promote important aspects of vegetative growth – branch and node stretching, "cage" building – essentially, the structural foundation needed in a plant to support large, heavy cannabis flowers or buds. As the plants entered later weeks (Week 8+) of flowering growth, the focus shifted to increasing intensity of red and far-red (660nm, 735nm) wavelengths. At first, the intensity of reds was spiked intermittently in shorter bursts (Weeks 8, 9) and eventually for several hours each day in Week 10+. While not a primary focus of this research, we were able to perform this during two harvest cycles wherein genetically identical plants were treated differently only regarding these light changes. In these comparisons, the plants exposed to the driven blue/red light enhancements were harvested two weeks earlier than those that did not receive the LED-driven light treatment. However, in terms of overall cannabis flower yield and the cannabinoid/terpene profiles the plants were nearly identical. We were able to shave two weeks off total grow time, without reducing production rates or product quality – an epitome of resource efficiency optimization. In the truest sense, the SunGrown Indoor facility fueled plant growth with free, natural sunlight and supplemental LEDs with spectral controllability allowed us to intentionally drive morphology and metabolite synthesis towards the most desired endpoints.

Future research examining the very specific interplay between light spectrums and cannabis photomorphogenesis is greatly needed and will be crucial toward improving outcomes for medical cannabis patients.

Throughout this research, our relationship with cannabis analytical laboratories also led to the realization that "outdoor" grown cannabis flowers, by-in-large, have slightly higher cannabinoid content and more diverse terpene profiles. Until analytical labs demonstrated this finding, our working assumption was that flower grown indoors under HPS lights consistently produced higher cannabinoid buds with richer, crisper terpene profiles. As a lab director put it, "Nope – outdoor plants, no matter the strain, on average have more THC and more terpenes – there is something about the full sun, natural sunlight that brings this out."

We then wondered, if full sunlight does lead to increased cannabis quality (from cannabinoid and terpene perspective) do the plants grow in SunGrown Indoor facilities also show these benefits. Our initial experimental run suggests the answer is yes, but more data is needed for statistically significant proof. Briefly, genetically identical plants were grown with the same water, feeding and pruning schedules & techniques – the only difference being one lot was inside a SunGrown Indoor flower room and the other planted outdoors, let free to grow in Northern California. The outdoor plants grew larger, producing more flower biomass and used more water overall. However, our interest was in the cannabinoid and terpene content – and the analytical results proved they were essentially identical. The boosts in cannabinoid concentration and terpene diversity typically attributed to outdoor plants were found in our SunGrown Indoor plants. Such preliminary results, from this single A/B trial are hopeful and are a promising direction for future research.

Lastly, this research did not feel the need to perform an A/B comparison between a SunGrown Indoor facility and an identical grow room outfitted with double-ended HPS lamps. It is one of the most frequently asked questions, did you perform control trials in the same grow units just with HPS? As our research focus was on resource efficiency, minimizing artificial light use to reduce cultivation costs – it simply did not seem necessary to empirically prove HPS lights consume more energy. Essentially, it would be like performing a highway vehicle fuel efficiency study comparing a Tesla Roadster to a diesel semi-truck. Of-course the semi-truck consumes more fuel to travel the same distance or at the same speed, it wasn't purposely built to maximize fuel use like the Tesla. We thought the SGI to HPS comparison was unnecessary and already a foregone conclusion. In an indoor cannabis grow, every second the artificial grow lights can be turned off or down - the operation is more resource efficient and business more profitable. Our goal was not to completely eliminate the need or value in using artificial lights indoors, it was to design a facility that optimizes and automatically adjusts the use of artificial lights second-by-second to maximize overall savings both economically (profit-margins) and environmentally (carbon-footprint).

From a light quality and quantity perspective, the use of Solatube TDDs for cannabis cultivation represents an ideal approach for resource efficiency optimization. The spectral composition is rich across the entire PAR spectrum and particularly strong in the blue and red wavelengths necessary for photosynthesis. The realized sunlight PPFD levels in Northern California were high enough to not require any artificial, supplemental LED light for 5-8 hours of the day, on average (more detail in Energy Profiles, below, and Figure 7 & 8). Moreover, we anticipate that there is an added value to the dynamic nature of this sunlight. The plants are not constantly exposed to blaring light intensities beyond the point of diminishing returns. Many HPS grow facilities are targeting 800-1000 PPFD, constantly, 12 hours a day. In this regard, it seems that plants are not given any reprise from high intensity, spectrally poor HPS light. In our grows, it was noted that fan leaves exposed to the brighter sunlight spots moved along with that light source. They followed the higher intensity light until it moved out of their reach. This may be less stressful and beneficial for overall cannabis flower quality – but was beyond the scope of this research project.

CANNABIS CULTIVATION RESULTS

Overall, the use of Solatube TDDs dramatically reduced the electrical energy and water use while still producing high-quality cannabis flower. Compared to the industry standard of HPS indoor grow facilities, we were able to dramatically reduce inputs without negatively effecting quality or yields in these preliminary investigations (Table 1).

Cycles 1 and 2 were grown in a research grow room with one Solatube SkyVault centered over the 100 sq. ft floor-plan in Sacramento, CA. This initial one SkyVault design was built to determine how cannabis plants respond to TDD delivered sunlight, if at all. Cycles 3-6 were grown in Petaluma, CA using the 100 sq. ft, four SkyVault design shown in Figure 2. With four TDDs, 8 LEDs, and integrated grow room intelligence, the primary goal of this design and grow cycles was to optimize the system towards higher production rates (grams/ft2) while minimizing energy and water use as much as possible. Overall, approximately 12 cycles/harvests were completed in SunGrown Indoor research grow rooms during this research. The 6 cycles presented here were selected based on the overall completeness of research data across the plant's entire lifecycle from cloning to end-product analytical lab profiles.

	Strain	Flower Time	Yield & Rate	Chemical Profile
Cycle 1	Afghan, Auto Sweet Tooth Lavender	84 days	240 g, 6.00 g/ft2,	THC 18.16; Terp 1.04%
Cycle 2	Tangie, Girl Scout Cookies	80 days	383 g, 9.58 g/ft2	THC 20.35%, Terp 0.59%
Cycle 3	SkyWalker OG	77 days	869 g, 27.16 g/ft2	THC 18.78%, Terp 1.22%
Cycle 4	Birthday Cake	53 days	467 g, 29.19 g/ft2	THC 17.23%, Terp 1.64%
Cycle 5	Grape Ape	58 days	1509 g, 33.09 g/ft2	THC 15.33%; Terp 0.97%
Cycle 6	Silver Mango	60-75 days	1012 g, 31.63 g/ ft2	THC 22.70%, Terp 1.94%

Table 1 - SunGrown Indoor Research Cycle Cannabis Harvest Details. Cycles selected based on completeness and integrity of collected research data, from strain selection to analytical profile lab results and resources used during cultivation. Flower phase grow time length varied due to strain, environmental and vegetative phase variance. In cycle 6, two lots of genetically identical plants were harvested at different points to evaluate the effects of blue/red light LED emphasis. Production Rate is shown as grams of manicured cannabis flower (buds) collected, not total biomass, per square foot of canopy. Analytical testing results are listed as chemical profile and include total THC (THCA+Delta9THC) and total terpene concentrations (the average total concentration is provided for cycles that had multiple samples of cannabis flower tested.

Overall, the use of Solatube TDDs dramatically reduced the electrical energy and water use while still producing high quality cannabis flower. Compared to the industry standard of HPS indoor grow facilities, we were able to dramatically reduce inputs without negatively affecting quality or yields in these preliminary investigations (Table 1).

In Cycles 1 and 2, our goal was to determine if cannabis plants even respond to the light delivered by the Solatube TDDs. Reviewing time-lapse videos of these cycles demonstrates a positive plant response (available at http://bit.ly/SGITimelapse). As soon as sunlight entered the room, the plants clearly "woke-up" and started positioning fan leaves toward and within the TDD delivered sunlight. The initial harvest consisted of several cannabis strains, started from seed, and included several auto-flowering plants. Auto-flowering strains contain genetic changes originating from Cannabis ruderalis varieties that uncouple vegetative-flower transition from photoperiod length, making it more dependent on plant age. While observing the plants' most basic responses to TDD delivered sunlight, we had no issues flipping from veg to flower with standard light schedules (18:6 to 12:12) in typical cannabis or auto-flowering strains. If a light deficiency were present, we expected to detect differences based on this difference in photoperiod sensitivity – that was not the case. In the end, these first cycles provided significant evidence that cannabis plants can grow under TDD sunlight delivered indoors. The plants thrive, in fact, by demonstrating all expected plant morphology and growth phase responses to changes in the primary light source.

In Cycles 3 – 6, we sought to continually optimize the balance between production rates, harvest yields and energy/water use – maximize the amount and quality of cannabis flower, while minimizing resource of cultivation processes. Empirically sound production rates are unheard of in the cannabis industry. The amount of cannabis produced at your location is the single most incriminating piece of evidence in the illegal market. "X per light, X per tray, X per plant" claims are tossed around as powerful opinions regularly. In the legal cannabis industry, that data is no longer evidence of illicit activity, but critically important information for optimization. We chose a reasonable target production rate of at least 28 g/ft2, or one pound of cannabis flower per 4' x 4' tray (16 ft2). With the four SkyVault SunGrown Indoor designs, we began exceeding 28 g /ft2 by the second runs and continually improved up to 33 g/ft2. These initial production rates are just the beginning and with continued improvements to facility design, automation, strain selection, and cultivation techniques will increase significantly.

ENERGY USE PROFILES

Given the regulatory spotlight on horticultural lighting power density (watts/ft2) it was important to establish a comparative baseline for SunGrown Indoor facilities. However, there is growing frustration with energy efficiency regulations being formulated around lighting power density as it is not a true measure of efficiency (like energy use intensity or electricity productivity). SGI rooms exemplify the disconnect. Each flower room was equipped with eight Heliospectra LX602, each with 620 watts power rating as full power. Therefore, our installed lighting power density was 78 watts/ft2 (8*620/64) which is on par with the lighting power density of fully artificially lighted facilities. As discussed, the eight LED design was overkill but selected due to the very early, proof-of-concept stage of SunGrown Indoor. More importantly, the actual lighting power used (at any point) was far less dense – about 25% intensity when averaged over an entire grow cycle or less than 20 watts/ft2 in lighting power. Considering progress in LED technology and our understanding of projecting supplemental light in SGI facility based on local weather, SunGrown Indoor cultivation can certainly achieve compliance with lighting power density limits (i.e. 36 watts/ft2).

SunGrown Indoor daily energy use profiles display a characteristic pattern unique to hybrid-light cultivation facilities (Figure 7). Over a 24-hour day with 12:12 flowering light schedule (7 am to 7 pm ON), clear peaks during sunrise and sunset are logged.

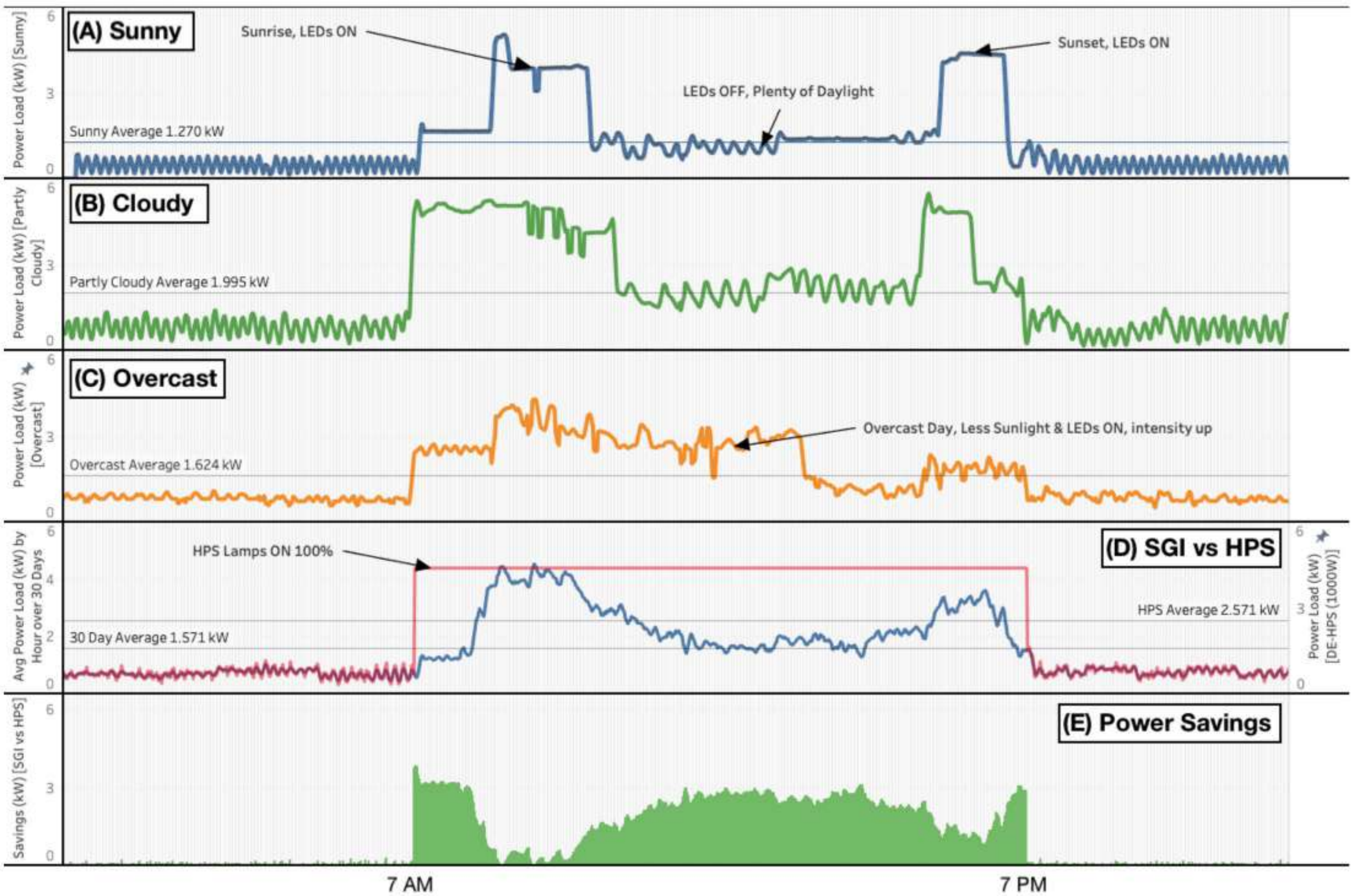

Figure 7 - SunGrown Indoor Energy Use Profiles - Charts actual electricity load (kW) over a 24hr day in flowering grow room. From the top-down, representative energy profiles for a sunny day (A), a partly cloudy day (B), and heavily overcast day (C) are shown. (D) SGI vs HPS shows the minute-by-minute daily average energy load (kW) for August 2016 (blue line) compared to hypothetical HPS light energy load in the same grow room (pink line). Lastly, overall power savings (the difference between HPS lamp energy use and average daily SGI energy use) is depicted below in Power Savings (E). Optimizing resource efficiency in SGI facilities is a function that maximizes the area under the pink line, above the blue line in (D).

On a typical sunny day (Fig 7A), total room energy use peaked in the early morning (7-11 am) and late afternoon (5-7 pm), while returning to baseline mid-day and at night. By parsing the CT data from individual outlets, we were able to attribute 90% of that energy use to increased LED intensities. On partly cloudy (Fig 7B) and heavily overcast days (Fig 7C), relatively less harvested daylight triggers a proportional increase in LED light intensity and thus energy use. On the representative sunny day, the average power load was 1.27 kW, a cloudy day was 1.996 kW and an overcast day was 1.624 kW.

Given the daily fluctuations in weather (daily cloud clover), we were concerned that too many overcast days would essentially washout the savings gained in the SGI system. In other words, not all days are clear & blue sky sunny. Over the flowering phase, do cloudy days (with additional LED use) negate the energy (cost) savings seen on full sun days? To evaluate the impact of cloudy days on overall energy savings, the average power load (kW) for each minute of the 24-hour day was calculated over 30 days (an entire month) (Fig 7D). The blue energy profile represents the average energy use at time X across every day of the month (average power load 1.571 kW). If additional energy use during cloudy or overcast days was greater than the energy saved, we would expect the energy profile to plateau similar to a 100% artificially lighted facility (Fig 7D). The red energy profile represents the power load for four double-ended HPS lamps (just the lights, no other components). The plateaued energy use profile of an HPS set-up represents a 12:12 light schedule at 100% intensity. Full energy use is static, locked in for the entire "ON" phase. Optimization of the SGI system, therefore, is directly tied to maximizing the "peak-and-value" profile over the "plateau." The final panel (E) of Figure 7 represents the total energy savings in SGI vs HPS – it is the difference between the HPS energy use profile (Fig 7D, red) from the average SGI energy use profile (Fig 7D, blue). Optimizing resource efficiency in SGI facilities is a function that maximizes the area under the pink line, above the blue line in (D).

The cyclical nature of energy use by climate control and HVAC components is also visible in these energy use profiles. Notice during periods of low energy use, rapidly fluctuating energy use patterns are repeated throughout the day – this was ON/OFF dance between mini-split (temp) and dehumidifier (RH) components. While the full details are beyond the scope of this report, our attention was drawn to energy use wave height (max and min kW range of single cycle) as an indicator of internal climate stability and energy wave interval length (time between ON/OFF cycles) as a relative influence gauge between air temperature and relative humidity driving changes.

We did not find a significant correlation between light intensity and air temperature changes. Meaning, activation of LED lights (themselves), or relatively higher TDD sunlight levels of bright days did not markedly or reliability cause room temperature increases. Indoor grows using 100% artificial lights, especially HPS bulbs, do show a clear correlation between light intensity and room temp/humidity patterns. This liability is the root cause of microclimate formation and eventual crop infections or pest infestations that can eliminate value if not properly balanced.

As a hybrid-light facility, the recorded energy profiles of the SGI grow rooms were markedly different, characterized by peaks in the morning and afternoon hours. On a 12:12 light cycle, this meant that for 5-8 hours of that day we did not need to use the LEDs at all – significantly reducing our overall consumption. There were several days when the entire 100 ft2 grow space was running on <50 watts of total energy load. Any second the artificial lights can be turned down; production costs are reduced. This unique and achievable optimization goal (peak and valley) is what sets hybrid light designs apart from 100% artificially lighted indoor grows.

On average, the SGI flower rooms consumed 10 to 21 kWh/day (lighting+HVAC+systems). If HPS lamps were the primary light source in these 100 ft2 grow rooms, at least 52.8 kWh/day would be drawn each day just from HPS lights (no other grow systems). As such, SGI operating loads are at least 50% more efficient each day. With commercial electricity rates of $0.12/kWh, these small 100 ft2 grow rooms cost $2.60 and $6.33/day. Extrapolated yearly, a 100 ft2 SGI facility will cost approximately $950 in electricity, while a 100 ft2 HPS facility will rack up around $2,300 in electricity – making SGI 50-60% more efficient at this scale.

SGI energy savings was upwards of 80% with a 65% reduction in peak demand loads. Using data collected in this research, we are now able to predict PPFD values of harvested daylight from Solatube TDDs. Using solar irradiance data, specific floor plans, locations, and calendar dates can be modeled and evaluated to inform final design decisions (see images in Appendix A). We have found total annual days of sunlight are highly correlated with projected energy savings in selecting a SunGrown Indoor design.

Cannabis Cultivation Efficiency Metrics - Electrical Productivity & Energy Use

The best key performance indicators for resource-efficient cannabis cultivation are Electricity Productivity (grams/kWh) and Energy Use Intensity (kWh/ft2/year). In other words, how well is the facility converting electricity to cannabis flower and what are the annual costs of that cultivation energy use? The Electrical Productivity of selected SGI cannabis grow cycles are provided in Table 2.

	Flower Yield	Total Energy	Electricity Productivity	Energy Use Intensity
Cycle 1 & 2	623 g	485 kWh	1.28 g/kWh	32.9 kWh/ft2/yr
Cycle 3 & 4	1336 g	977 kWh	1.36 g/kWh	46.4 kWh/ft2/yr
Cycle 5 & 6	2071 g	803 kWh	2.57 g/kWh	38.2 kWh/ft2/yr

Table 2 - SunGrown Indoor - Productivity Efficiency Metrics - Flower yield (grams) was calculated as the total cannabis flower/bud output of paired cultivation cycles. Total energy (kWh) represents the cumulative energy demand of each cycle, approximated across all growing phases.

Looking at the total harvested flower yield (grams) and the total kWh used during each grow phase, we were able to achieve Electricity Productivities of 1.28, 1.36 and 2.57 grams/kWh. These metrics represent an excellent preliminary SGI baseline compared to initial reports of 0.79 g/kWh for HPS indoor, 1.4 g/kWh for LED indoor and 1.07 g/kWh for greenhouse facilities. Holding energy use constant, our results suggest that SGI rooms can produce an additional 1-1.5 grams of cannabis flower per kWh consumed compared to indoor and greenhouse cultivation approaches. Practically, making more with less.

Energy Use Intensity (EUI) is a robust indicator of a cultivation operation's resource efficiency and is the sustainability metric preferred by most energy efficiency experts and is particularly valuable for utilities tasked with anticipating a proposed facility's energy consumption/reducing existing facility's energy consumption. Initial reports from Research Innovation Institute's Cannabis PowerScore tool established EUI of indoor HPS at 262.05 kWh/ft2/yr and of greenhouse grow at 133.72 kWh/ft2/yr (outdoor at 2.36 kWh/ft2/yr). Based on the grow cycles in Table 2, preliminary EUI of SunGrown Indoor Facilities ranges from 33 – 46 kWh/ft2/yr, or roughly 97% less than indoor, 73% less than greenhouse grows. While this does suggest massive energy efficiency improvements, more data is needed (for all grow types) to establish statistically significant baseline EUI ranges. Broadly speaking, looking across all SGI grow cycles (not just those selected for this report) the average daily energy use is ~10 to 20 kWh/day, which provides perhaps a more representative SGI EUI range of 55 – 115 kWh/ft2/year.

ECONOMICS AT 10,000 sq ft OF PLANT CANOPY

The range of options for configuring a cultivation operation is wide – geolocation, building shell, floor plan, technology, equipment, and so on. This makes direct 1:1 comparison between facilities challenging. The comparisons and budgetary ranges provided below are based on fairly standard, community-shared facility design choices. It is a basic, big picture approach to a process that requires granular, technical evaluation, and properly informed planning when doing it.

	Indoor (HPS)	Greenhouse	SunGrown Indoor
CAPEX	$15 – 30/ft2	$60 - 75/ft2	$60 - $100/ft2
OPEX	$75 – 150/ft2	$30 - 50/ft2	$20 - 40/ft2
Electricity Productivity (grams/kWh)	0.79 g/kWh	1.07 g/kWh	2.57 g/kWh
Energy Use Intensity (kWh/ft2/year)	280 – 360 kWh/ ft2/yr	100 – 150 kWh/ft2/yr	50 – 160 kWh/ ft2/yr
Cultivation COGs	$400-800/lb	$300-600/lb	$200-500/lb
Crop Loss Risk	Medium	High	Low

Table 3 - Comparison of costs and output of 10,000 ft2 HPS, GH, SGI cultivation facilities. 10,000 ft plant canopy (70% flower, 30% vegetative). CAPEX reflects lighting technology equipment costs, not the entire facility with all required systems. OPEX defined as energy load from lighting, HVAC, and cultivation consumables annually (labor, other business overhead not included). Cultivation COGs and Crop Loss Risk estimated based on available industry data and new reports.

The start-up capital expenses required for an HPS lighting is roughly half that needed for a technologically enabled greenhouse (LEDs) or SunGrown Indoor (TDD+LED). 1000W DE-HPS lamps estimated $170,000, greenhouse supplemental LEDs est. $325,000 and Solatube SkyVault TDDs + supplemental LEDs est. $645,000. Supply-side demand reduction incentives offered from forward-looking utility companies can equalize CAPEX costs by covering the incremental costs needed for the more resource-efficient facility.

Operating expenses (OPEX) was estimated with lighting and HVAC energy use (including peak demand charges), and consumable cultivation supplies. It does not include labor and other business overhead costs. Annually, indoor HPS grows will spend approx. $700,000 in cultivation OPEX, followed by GH at ~$330,000 and SGI estimated at $200,000/year.

With energy efficiency incentives, a 10,000 ft2 SGI facilities' CAPEX is like an HPS indoor warehouse or full-featured greenhouse (heating, sealed). No matter the cultivation approach, investments in high quality, cultivation purpose-built technology upfront will increase CAPEX but pay off several-fold as sustained viability. SGI facilities provide robust 1.5-2x reductions in cultivation OPEX annually. This accelerates ROI on the system within 12-16 months. Moreover, these metrics do not incorporate operational improvements, increased productivity, or sale volumes which can also result in transitioning to a resource-efficient philosophy.

In terms of efficient electricity use for agricultural purposes, SunGrown Indoor facilities are approximately 70% more productive (g/kWh) and consume half of the energy of indoor HPS grows. Compared to greenhouses, SunGrown Indoor grows could achieve double the cannabis flower output with 20-30% less electricity consumption. These gains in energy efficiency over standard greenhouse designs result primarily from a less drastic push-and-pull relationship between lighting and HVAC driven climate control. By keeping the internal climate more stable and resilient to influence from external weather conditions, SGI operations are not in a constant battle for homeostasis and become 20-30% more energy efficient. This key distinction between SGI and GH hybrid light grows is particularly important when considering crop loss risk.

Greenhouses, especially as they get larger, are notorious for crop failure. Crop failure most often results from a contamination (i.e., powdery mildew, bud rot, banned pesticide) or infestation (i.e., Russet mites, spider mites) that prevents a harvested crop from passing internal or state-mandated quality assurance testing. Cannabis is subjected to some of the most intense safety testing thresholds of any agricultural crop, especially regarding the use of first-line defense measures like pesticides or herbicides. Most basically, the root causes of crop failure are stresses like climate instability and microclimate formation.

In 2018, one of the largest Canadian Licensed Producers made headlines after losing over 200,000 cannabis plants (est. $45M revenue loss) in BC based, modern greenhouses (1M ft2) – for the second time. While not of such magnitude, there is a clear understanding amongst greenhouse operators that higher failure rates are par for the course. Two years later, in March 2020, this same Canadian producer has now announced they are abandoning 3 million square feet of licensed greenhouse production space (along with 500 jobs) in hopes to increase working capital and profitability. While technologically enabled, the biggest challenge with growing high-quality cannabis in large commercial greenhouses is maintaining a stable internal climate despite external weather conditions. Keeping internal conditions stable while fighting fluctuating outdoor conditions puts less stress on HVAC, heating, and dehumidification systems resulting in less energy use overall as well as much less crop failure.

CONCLUSION - THE GROWER'S DILEMMA, RESOURCE EFFICIENCY AND LONG-TERM COMMERCIAL SUCCESS

As the market pressures bear down on commercial cannabis cultivation operations, producing a high-quality flower at the lowest cost possible will determine long-term commercial success. The SunGrown Indoor system represents the best of both worlds – a hybrid grow facility that utilizes natural sunlight without having to sacrifice resilience to external weather conditions. This is the Grower's Dilemma – surviving decreases in market value from commodification with increasing costs of cultivation and compliance.

The SunGrown Indoor approach, presented here, was designed to support continual optimization with empirically sound, data-driven levers of control. The design provided notable benefits for overall cultivation operational management, beyond the economic factors. All cultivation systems are integrated and monitored in real-time. Our grow room intelligence was programmed and managed to begin to predict canopy illuminance, artificial light power reductions, and associated thermal load interactions. Data is reported to staff in empowering ways, revealing unexpected patterns in resource use that can be manually modified and eventually automated to site-specific nuances. Experienced growers recognize this as the "dialing in" or "stabilizing" of all cannabis grow sites.

By providing cultivation staff with an informed operational environment, they can manage issues proactively avoiding them altogether or at least more quickly than typically allotted. This is vastly different than the reactive, "firefighting" approach most growers are used to.

The natural sunlight also provided a "cushion of forgiveness," making plants less sensitive and exposed to unplanned grow room problems. Throughout this research, there were at least 3 days when power to the grow units was completely lost. While this would represent a major issue for an indoor grow, the SunGrown Indoor design was able to remain operational with only the sunlight delivered by the TDDs. Loss of light completely is a huge problem for cannabis grows, one that can lead to complete loss or viability of cannabis flower.

In our experience, most cannabis cultivation businesses do not collect production-line performance data. There are even fewer integrating and automating the analysis of data needed for process improvement and optimization. This is a direct result of prohibition during the formative years of cannabis industry growth. The operational pressures of illegal, unregulated grows are antithetical to a regulated, legal cannabis market. Written records and detailed production data is an enormous business risk when used as evidence of criminal activity. Data is no longer evidence, and it is no longer viable to operate on community consensus processes borne out of the black market. In the legal markets, profit or perish is determined by operational processes and cost of production – its resource efficiency.

The legalization of cannabis has made it past the tipping point, and the market will continue to expand. Current estimates put US cannabis cultivation energy use around 4 billion kWh/year, behind only data centers and medical operating rooms in terms of total energy use. There are several reasons cannabis companies need to strive for more resource-efficient operations – competitive advantages, brand differentiation, sustainability marketing, and emerging regulatory limits (see "5 Values of Resource Efficiency Cultivation Approach" breakout box). Energy and code regulations have already been established in Massachusetts (36 watts/ft2), Illinois (36 watts/ft2 or 2.2 μmol/J), Washington state (1.2 μmol/J) and are proposed in Denver, CO (1.6 - 1.9 μmol/J based on the light source). All indicators point to similar energy regulations expanding, especially once federal regulators tackle the industry nationwide. These legal mandates on energy use outlaw the prohibition era double-ended HPS cultivation style currently used as an "industry standard" and are forcing operators to look towards more efficient methods. Looking at the bigger picture, moving away from legacy models developed in a different market, is imperative for businesses seeking long-term viability and profitability.

The SunGrown Indoor technique was researched and developed as a proof of concept that it is possible to produce high-quality indoor cannabis with a low carbon footprint. As its use moves into commercial operations and controlled environment agricultural research, we expect it will be found useful beyond cannabis – in urban farming, vertical farming, and other alternative farming approaches as our ability for agriculture in traditional regions is shifted and challenged by a changing climate.

Top 5 Value-Adds of

RESOURCE EFFICIENT

CANNABIS CULTIVATION APPROACH

#1 REDUCE COST OF GOODS

increased operational efficiency minimizes waste & error, reducing COGs and increasing operations profit margins.

#2 HIGH QUALITY HARVESTS

consistently, year-round with less crop failure

#3 DROP CARBON FOOTPRINT

reduce carbon footprint to improve company image & positive brand differentiation

#4 PROACTIVE RISK MITIGATION

saved labor costs and reduced equipment/supply waste

#5 NO REMEDIATION COSTS

clean-up, environmental remediation costs avoided

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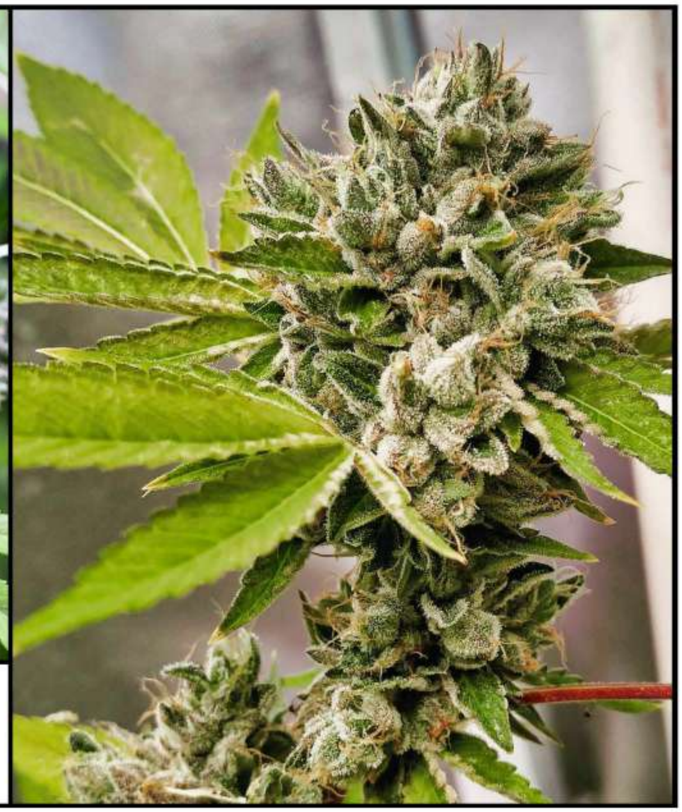
APPENDIX A - EQUIPMENT LIST

- Engage Current Transducers Sensors (Electrical Load) (Efergy, UK)
- Grownetics Grow Room Intelligence
    - Humidity Sensor
    - Air Temperature Sensor
    - Co2 Sensor pH Sensor
    - CT Sensor (Electrical Load)
    - PAR Sensors (Apogee Full-spectrum Quantum Sensor)
- Stellar-RAD Handheld Spectroradiometer (StellarNet Inc., Florida)
- Sun System PAR Meter w/ Remote Sensor
- Heliospectra LX602c
- Oscillating Fans, Clip Fans, 8" Exhaust Fan, 4" Exhaust Fan, MiniSplit, Dehumidifier
- Split System Air Handler, 17,000 BtuH, 208/230VAC, 18 SEER, Wall-Mount (FRIEDRICH, MW18Y3J)
- Airpots w/ local soil mixed with coco-fibers

SUNGROWN INDOOR CANNABIS FLOWERS GROWN DURING THIS RESEARCH

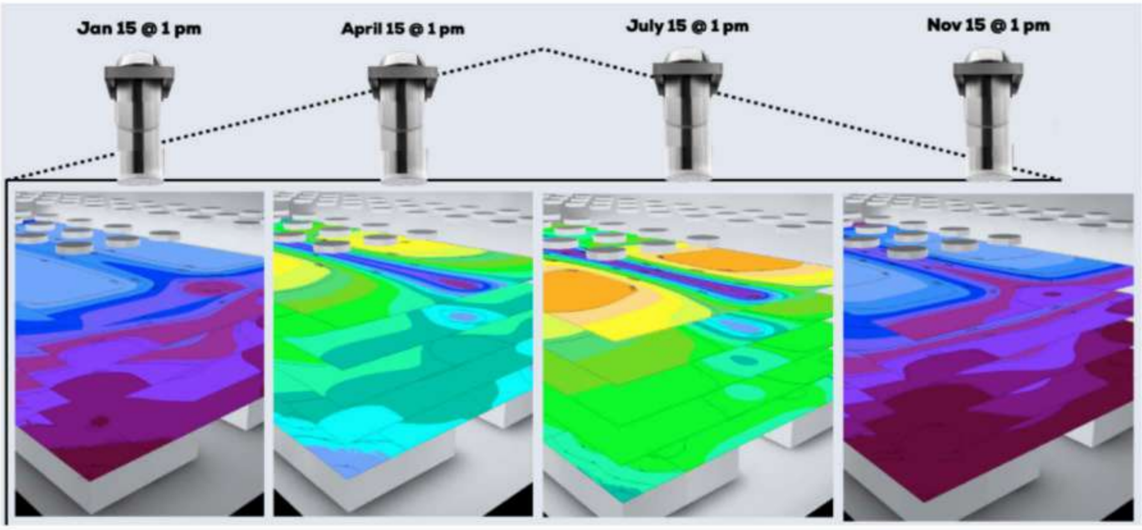
SunGrown Indoor
Skywalker OG - Week 9

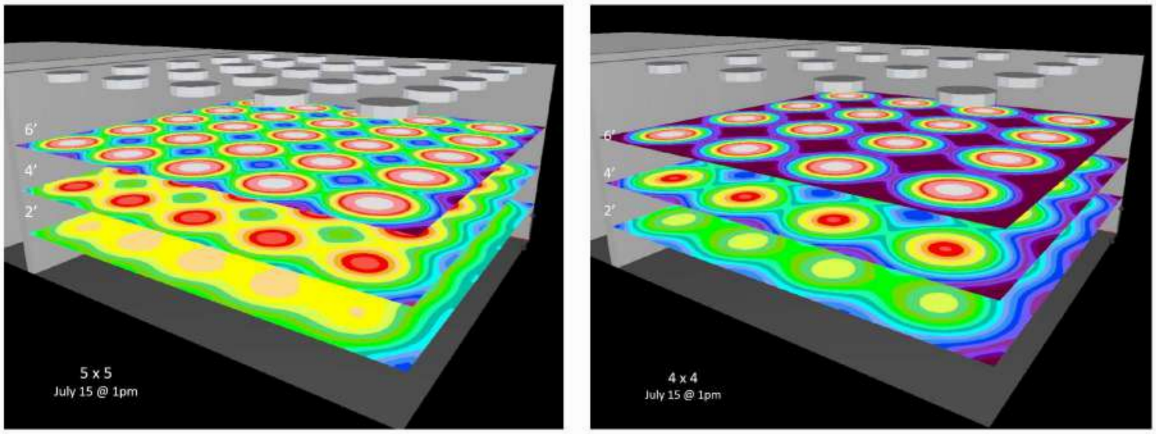


SUNGROWN INDOOR CANNABIS FLOWERS - RESEARCH CYCLES 1-6

SUNGROWN INDOOR GROWING FACILITY DESIGN & LIGHT PROJECTIONS

Examples of SunGrown Indoor light level modeling and intensity projections. Sunlight data collected during this research informed the development of a quantitative light projection modeling that can be applied to proposed facilities located across the globe. Before construction, these models permit an evaluation and optimization of SGI room design (placement of TDDs) including how many supplemental lights are needed. Each SGI preliminary analysis incorporates features specific to the proposed floor plan, location, and weather seasonality. As a result, we can confidently predict how well an SGI facility will perform at any given geolocation including its potential energy savings relative to other cannabis cultivation approaches being considered. Preliminary analyses can also be shared with utility companies to demonstrate energy efficiency gains and assist in obtaining energy efficiency incentives.





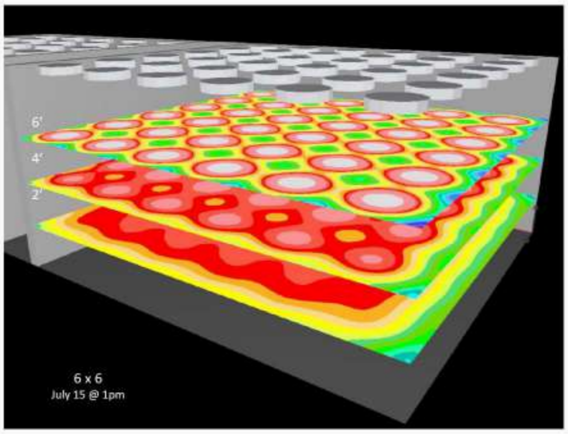


FIGURE / TABLE LIST

Figure 1 - SunGrown Indoor hybrid cultivation facility design and core system components.

Figure 2 - SunGrown Indoor Flower Grow Rooms (Exterior and Interior).

Figure 3 - Grow Room Intelligence - Control Panel & Circuit Breaker (top left), Climate Sensors placed around grow room (top right), placement of LEDs among SkyVaults (bottom). Note, in top right photo Solatube SkyVaults are partially installed, without a dimmer, amplifier, or prismatic diffuser component.

Figure 4 – Lighting & Climate Sensor Floor Plan Layout

Figure 5 – Light Quality (Spectrum) from Solatube TDD - Spectral Composition of McCree Curve (PAR), Solatube SkyVault output, and Heliospectra LX602 LEDs. Measurements were taken approximately 16" below the light. Solatube light spectrum was recorded on a clear, sunny day in Northern California (August 2016).

Figure 6 – Daily Average & Peak PPFD (μmol/m2/s) measurements under Solatube SkyVault. PPFD levels across the entire 12hr "ON" light cycle were recorded with Apogee Quantum PAR sensors at different distances from TDD prismatic diffuser. Orange bars represent the maximum, or peak PPFD (averaged max from each day), the red line represents the average, ambient PPFD (averaged average from each day). Data collected in August 2016 (Northern California).

Table 1 - SunGrown Indoor Research Cycle Cannabis Harvest Details. Cycles selected based on completeness and integrity of collected research data, from strain selection to analytical profile lab results and resources used during cultivation. Flower phase grows time length varied due to strain, environmental, and vegetative phase variance. In cycle 6, two lots of genetically identical plants were harvested at different points to evaluate the effects of blue/red light LED emphasis. Production Rate is shown as grams of manicured cannabis flower (buds) collected, not total biomass, per square foot of canopy. Analytical testing results are listed as chemical profile and include total THC (THCA+9THC) and total terpene concentrations (the average total concentration is provided for cycles that had multiple samples of cannabis flower tested.

Figure 7 - SunGrown Indoor Energy Use Profiles - Charts actual electricity load (kW) over a 24hr day in flowering grow room. From the top-down, representative energy profiles for a sunny day (A), a partly cloudy day (B), and heavily overcast day (C) are shown. (D) SGI vs HPS shows the minute-by-minute daily average energy load (kW) for August 2016 (blue line) compared to hypothetical HPS light energy load in the same grow room (pink line). Lastly, overall power savings (the difference between HPS lamp energy use and average daily SGI energy use) is depicted below in Power Savings (E). Optimizing resource efficiency in SGI facilities is a function that maximizes the area under the pink line, above the blue line in (D).

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