Performance Assessment of Integrated Core Daylighting Technology

Final Report

ET23SWE0051

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Acknowledgements

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Abbreviations and Acronyms

Acronym	Meaning
CCT	Correlated Color Temperature
CLTC	California Lighting Technology Center
CRI	Color rendering index
fc	Foot-candle
Hz	Hertz
K	Kelvin
kW	Kilowatt
LED	Light-emitting diode
M&V	Measurement and verification
nm	Nanometer
PIR	Passive infrared
STF	Solar-tracking fiber optic lighting system
W	Watt
LM	Lighting manufacturer
PID	Proportional-integral-derivative
V	Volt

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Executive Summary

This report presents the findings from the Performance Assessment of Integrated Core Daylighting Technology project, which evaluates the performance of a solar-tracking fiber optic daylighting system. This system, which will be referred to in this report as the solar-tracking fiber optic lighting system (STF)—uses 40 optical light points and fiber optic cables to deliver natural daylight deep into a building's core. The project also explores the feasibility of integrating this solar-tracking lighting system with a commercially available electric lighting system, creating an efficient hybrid solution that combines both natural and artificial light. The study's primary goals are to assess the energy savings, demand reduction, and cost-effectiveness of this hybrid lighting approach.

Using the manufacturer's specifications for the STF system, the research team applied AGI32 lighting design software to model the spatial requirements of a demonstration room. The modeling was based on interior lighting power densities and target illumination levels for office spaces, allowing the team to estimate the room size needed to accommodate the fiber optic daylighting system. From this analysis, the team constructed a 20-by-24-foot demonstration room within the California Lighting Technology Center. The space included a drop ceiling with a T-bar configuration, designed specifically for integrating fixtures supplied by the STF system.

The research team then identified a 2-by-2-foot, 26-watt light-emitting diode (LED) luminaire, with a dimmable driver that could provide a comparable amount of light to four STF fibers. This ensured that the electric lighting alone would be capable of fully illuminating the room in the absence of daylight, such as during overcast conditions or in the evening. The team then fabricated several variations of hybrid fiber optic/LED luminaires, adjusting the fiber placement and internal optics to create uniform light distribution. Each luminaire was retrofitted to integrate four fiber optic cables, ensuring proper mixing of LED light and daylight within the fixture.

Once the luminaire designs were finalized, the team specified and tested commercially available lighting controls, including photo sensors and a room controller capable of processing sensor readings to switch or dim the LEDs. The control systems were configured in such a way that the LEDs would provide 30 foot-candles at the work plane without any daylight contribution. When daylight was present, the lighting controller would proportionally reduce the electric lighting, optimize energy use while maintaining ideal lighting conditions.

Measurement and verification sensors were also set up to measure the work-plane illuminance, daylight contribution from the fiber optics, and energy consumption of both the LED lights and the STF system. The research team observed energy savings of up to 40 percent compared to the installed LED baseline. Under less favorable conditions, such as overcast days, energy use increased by an average of 5 watts due to the added energy consumption of the STF motor system. Overall, the system achieved total savings of 40 percent in the controlled area. Given the current cost of STF technology, this represents a relatively high installation cost per watt saved. However, the hybrid system reduced fluctuations in work plane light levels and maintained a color rendering index above 85. A summary of best-case metrics is available below in Table 1.

Table 1: Metric summary.

Power Savings	Lighting Quality	Probability an occupant notices dimming	Light output
40%	85 CRI	10%-16%	22,300 lumens (lm)

Introduction

Core daylighting technologies, particularly fiber optic systems like the solar-tracking fiber optic lighting system (STF), shown below in Figure 1, present an innovative solution for enhancing natural light access within buildings, especially in areas unreachable by conventional daylighting methods. These systems are crucial in regions like California, where energy efficiency and sustainable building practices are increasingly prioritized due to the state's environmental goals and its unique weather conditions. California's sunny climate makes it an ideal environment for maximizing the use of daylighting technologies to reduce dependency on electric lighting, thus lowering energy costs and carbon footprints. Furthermore, fiber optic core daylighting systems typically incorporate infrared filters that negate the solar heat gain typically associated with other daylighting methods, further improving energy efficiency.

Figure 1: STF fiber optic daylighting system, fully installed.

Source: California Lighting Technology Center (CLTC).

A previous study (California Lighting Technology Center 2020) on a 12-light-point fiber optic daylighting system revealed both its strengths and limitations. The system provided consistent and efficient illumination on sunny days, which are common in California's climate. However, on cloudy days, the performance declined significantly, with noticeable fluctuations in light intensity, making it less effective as a standalone solution. This variability emphasizes the need for hybrid systems that can supplement natural daylight with artificial lighting to maintain a steady and reliable light output, regardless of seasonal or weather conditions. In response to these challenges, this project focuses on the latest generation of fiber optic daylighting systems, which promise greater energy efficacy by using 40 light collectors while maintaining the same electronic configuration as earlier versions. This increase in light points allows the system to deliver more daylight to the interior of a building while utilizing the same electrical energy as previous versions.

To improve the performance of the core daylighting system during cloudy days, the research team developed a hybrid fiber optic/light-emitting diode (LED) luminaire design by modifying commercially available luminaires and lighting controls. This system aims to seamlessly integrate natural daylight with energy-efficient LED lighting to maintain target illumination levels, regardless of external lighting conditions.

Objectives

The objectives for this project are:

Evaluate Performance of the Daylighting System

- **Light Output**: Measure the STF's maximum, minimum, and average light output under diverse operational conditions to understand the system's capacity and consistency.
- **Spectral Quality**: Assess the spectral quality of the delivered light to ensure compliance with standards for commercial building interiors, focusing on occupant comfort and productivity.
- **System Efficacy**: Quantify the STF's efficacy under varying weather conditions, including sunny and cloudy days, to evaluate its overall performance and energy-saving potential.

Design and Build a Hybrid Luminaire

Develop and build a hybrid lighting fixture that integrates fiber optic daylighting with commercially available LED technology and controls. The goal is to create a luminaire capable of dynamically balancing natural daylight with artificial LED light, optimizing efficiency and maintaining consistent indoor lighting levels while ensuring all components are commercially available.

Evaluate the Efficacy of Hybrid Luminaire

Assess the overall performance of the hybrid luminaire system, focusing on maintaining target lighting levels, reducing energy consumption, and enhancing occupant comfort across different environmental conditions. This includes evaluating the integration of control systems and their effectiveness in adjusting lighting levels based on daylight availability

Fiber Optic Solar Tracker

The STF system represents the latest advancement in daylighting technology, designed to bring natural sunlight deep into the interior spaces of buildings, as shown in Figure 2. The system comprises 40 individual solar collectors, each equipped with precision optics that capture sunlight and transmit it via glass fiber optic cables, providing high-quality natural illumination without the need for fenestration.

Figure 2: Solar tracking fiber optic system.

Source: STF manufacturer.

The STF is equipped with a motorized base and an electronic control system, which uses geographical positioning and time data to accurately follow the sun's path throughout the day. A central photosensor further optimizes alignment, ensuring that the maximum amount of sunlight is captured. The system's ability to track the sun ensures continuous and consistent natural lighting, even as the sun's position changes with the seasons.

According to the manufacturer's product documentation, each of the 40 fiber optic cables can output a maximum of 729 lumens, resulting in a total light output of 28,000 lumens, depending on the cable length and external conditions. This makes the STF particularly well-suited for spaces were bringing in daylight through traditional windows or skylights is impractical. The fiber optic cables are made from high-quality glass, ensuring minimal spectral shift and maintaining the natural quality of sunlight.

The STF system also offers flexible installation options. The fiber optic cables can be up to 100 meters long, allowing for optimal placement of the collectors on a roof or other sunny location while delivering sunlight precisely where it is needed indoors. With minimal infrared or ultraviolet radiation included in the transmitted light, the system provides cool, comfortable illumination that enhances occupants' well-being.

Methodology

System Design and Installation

The team installed the STF system on the south side of the research building, positioned adjacent to a previous installation of an older version of the system. This new installation aimed to leverage the lessons learned from the previous deployment while improving overall system performance and scalability.

The installation site was chosen to maximize exposure to sunlight throughout the day, ensuring minimal shading from surrounding structures, as shown in Figure 3. To achieve this, the team constructed a metal platform approximately 5 feet in height and 16 feet in length, providing adequate elevation for the solar tracking system to avoid shadows from nearby obstacles. The solar tracker itself was mounted on a 2-foot-tall riser on top of the platform to further reduce the risk of shading and optimize the sunlight capture throughout the day, across different seasons.

Figure 3: STF installation shown with optics covered.

Source: CLTC.

Each of the 40 fiber optics cables connects to two of the 80 solar collectors; they are routed into corrugated piping through a 6-inch building pass-through and directed through conduit into the laboratory space. The team installed the control panel for the STF system next to the existing one for the previous model, in the room just inside the wall where the fibers are routed through, although the panel is weatherproof and could be located outside if necessary, as shown in Figure 4. Inside the building, each fiber optic cable was terminated at hybrid luminaires designed to combine both natural daylight from the fiber optics and artificial light from LED sources, providing a balanced and consistent lighting experience.

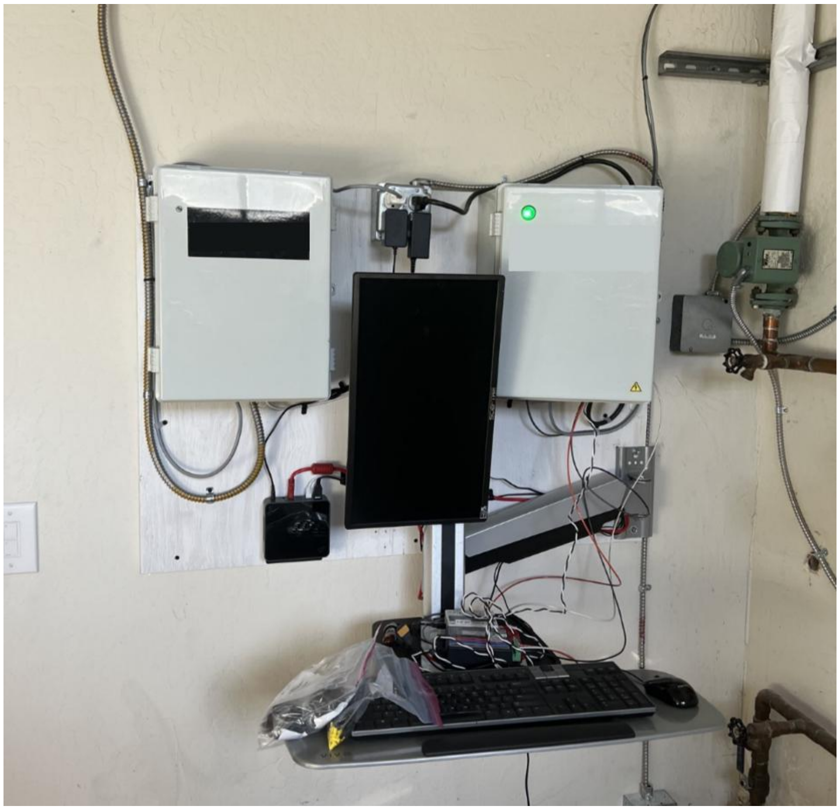

Figure 4: STF control board with power monitoring equipment.

Source: CLTC.

The installation process also involved setting up the motorized tracking base, which uses geographical positioning and time data to precisely follow the sun's movement. A photosensor located on the solar collector assembly further finetunes the alignment to ensure the highest possible efficiency in sunlight capture.

Demonstration Space Design and Construction

The demonstration space was constructed to evaluate the performance of the integrated daylighting and electric lighting system in a controlled, realistic environment. The team consulted the specification sheet for the fiber optic daylighting system to determine the light throughput for each of the 40 optical units—a critical step in understanding the potential light output and for planning the subsequent installation. AGI lighting analysis software was used to model the light throughput, simulating it as if it were coming from commercially available 2-by-2-foot LED luminaires. The primary goal was to determine an optimal room size and geometry that could be effectively illuminated by the integrated system.

Another goal was to achieve a light level of 30 foot-candle (fc) at a 2.5-foot work plane, which aligns with typical commercial interior lighting standards. We used black cloth for the room walls to block external light from the building that could interfere with the results; however, the black cloth did not represent the reflective properties of standard room walls. To adjust for this, the room was first modeled in AGI software (Figure 5) with a normal wall reflectance to achieve the target light level of

30 fc at the work plane. Then, the team changed the walls to black in the model—keeping all other parameters constant—and recorded the resulting light level, which demonstrated what would be achievable with black walls while maintaining the same target of 30 fc if the walls were white.

Through this process, we determined the functional target light level to be 21 fc for the room with black walls. After multiple iterations in the AGI software, experimenting with different room sizes and ceiling geometries, the team selected a 20-by-24-foot ceiling area with luminaires mounted at a height of 8 feet above the floor. This configuration provided the optimal balance of light distribution, meeting or exceeding the adjusted target for work-plane illuminance. The results in Figure 5 below are for the lighting fixtures at 100 percent power.

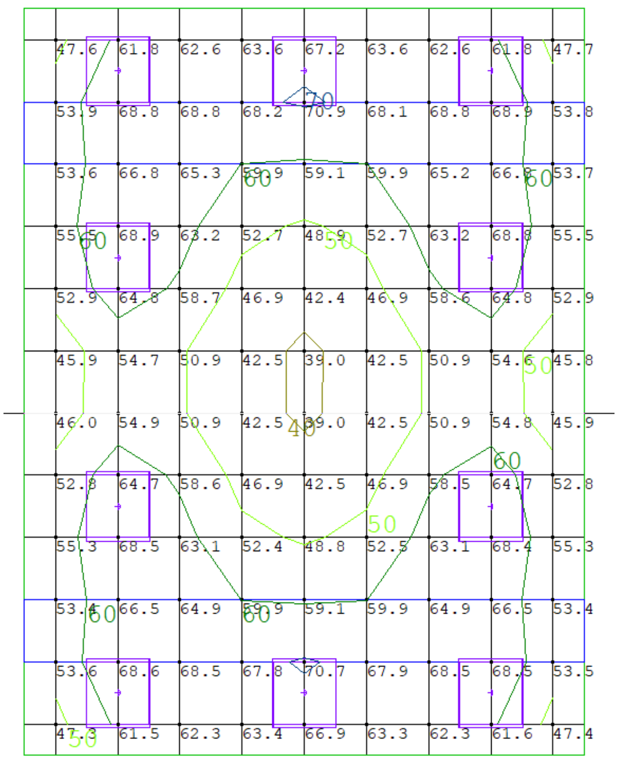

Figure 5: Lighting modeling for the hybrid luminaire system.

With the design finalized, the team identified a suitable lab space—shown in Figure 6—to accommodate the setup. The ceiling structure was constructed using dimensional lumber to provide a sturdy frame capable of supporting the weight of the ceiling grid and the luminaires. The ceiling itself was designed with a T-bar grid system with standard tiles that allowed for easy installation and adjustment of the 2-by-2 foot LED luminaires the team selected, which were spaced evenly to ensure consistent lighting throughout the lab. These luminaires were later integrated with the fiber optic daylighting system, using hybrid fixtures designed to combine both sources seamlessly.

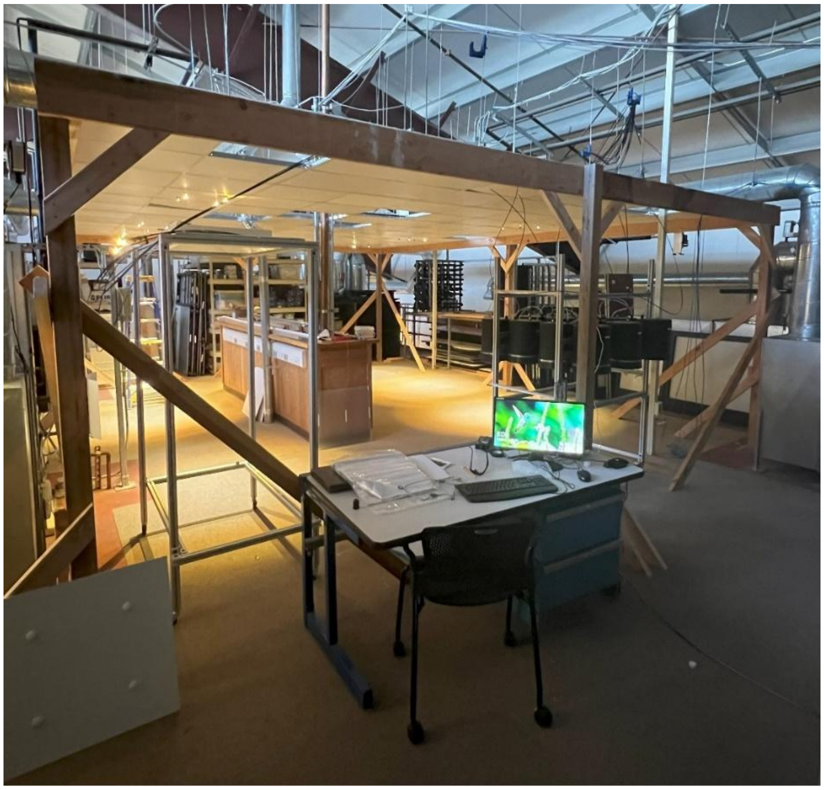

Figure 6: STF demonstration space under construction.

Source: CLTC.

After construction was complete, the team conducted an initial calibration of the lighting system using handheld light meters and data logging equipment to verify that the luminaires—in combination with the fiber optic daylighting—provided uniform coverage and achieved the desired illuminance at the work plane. We also performed a calibration of the control system to ensure smooth transitions between natural and artificial lighting, optimizing the balance to reduce energy consumption without compromising light quality.

Hybrid Fixture Development

Light emitted from a fiber optic cable follows a conical distribution, with the properties of the light cone determined by the refractive indices of the materials that make up the fiber. The STF fiber optics have a numerical aperture of 0.37 ± 0.02, resulting in a light cone angle between 41° and

46°. This conical distribution is narrow compared to typical cosine distribution that is commonly used for office area lighting, as shown in Figure 7.

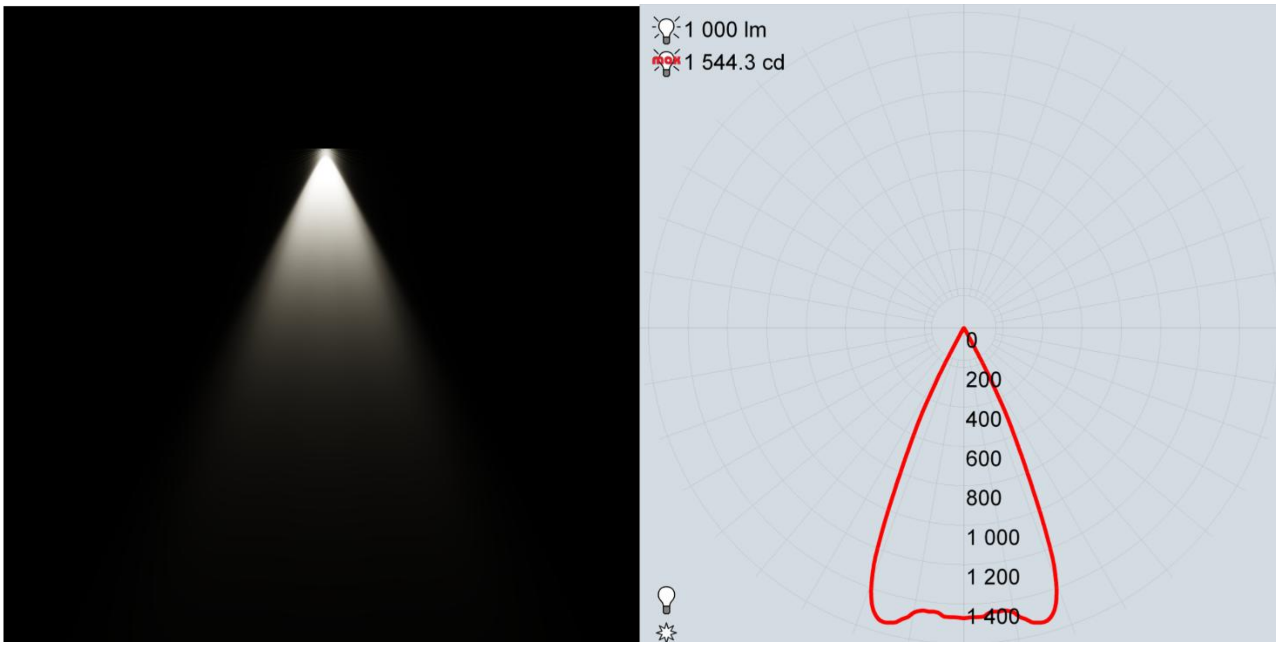

Figure 7: Photometric plot and rendering of fiber emission.

Source: CLTC, generated with data from STF.

Version 1: Baffled Design

The research team designed optics to reflect and distribute the light inside the fixture, creating a more uniform distribution that better matches the light pattern emitted by the LED components. We opted to use a fixture with a large volume behind the lens—allowing enough space to incorporate a refractive structure to better scatter the light—and selected a 26-watt, 2-by-2-foot LED luminaire before testing various types of optics.

The first solution involved attaching two plates of painted aluminum-polycarbonate laminate at an angle inside the fixture, which effectively reflected light that would otherwise escape through the sides, redirecting it back into the fixture for more even light distribution. The team sprayed the reflectors with a high-reflectance matte white paint, as the LED printed circuit board within the fixture—which featured a glossy white finish—was identified as a point of efficiency loss due to its relatively low reflectance compared to the powder-coated aluminum housing of the rest of the fixture.

To mitigate this issue, the fibers were positioned as far to the sides as possible, reducing the amount of light reflecting off the printed circuit board and improving overall efficiency. Figure 8 shows a modified fixture with one of the reflectors highlighted in red, and with the fiber locations behind the reflector highlighted in blue.

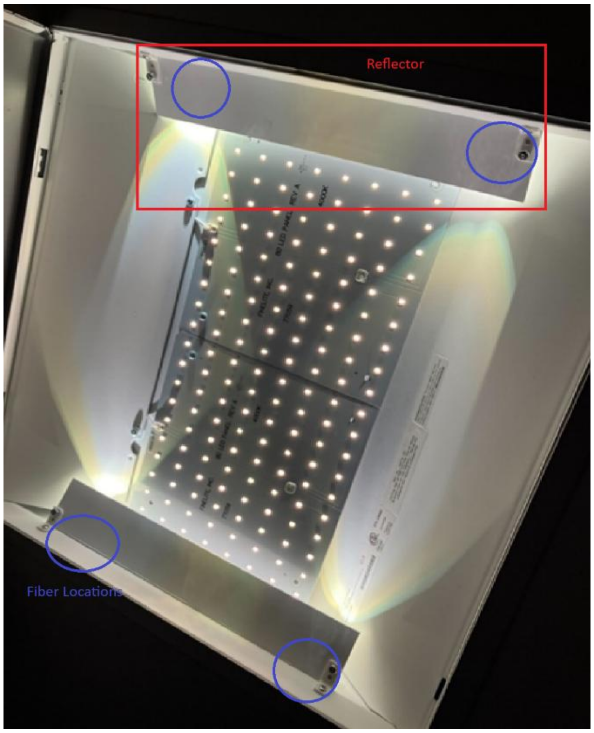

Figure 8: Hybrid fixture without lens.

Source CLTC.

Version 2: Maximum Throughput Design (Direct Fiber)

After the preliminary testing, the research team changed the configuration of the fixtures to minimize loss of illuminance from the fibers due to internal reflections. The fibers were repositioned to the top of the fixture, facing directly down and allowing the optics to distribute the light further. Light from the fibers is no longer reflected light through the baffles to attempt to scatter light but instead relied on the lens to distribute it further. The team made these modifications to the redesigned fixture—which is shown in Figure 9—to quantify the best-case scenario for energy savings.

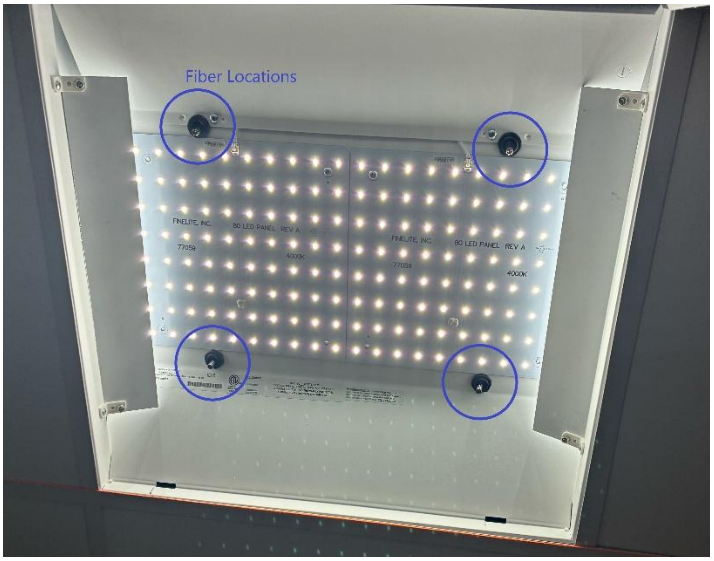

Figure 9: Redesigned fixture with straight-down fiber mounting.

Source: CLTC.

Control System Selection

The research team evaluated several commercial daylighting control solutions, with response time being a key consideration. In this report, the control systems are designated as LM1, LM2, and LM3, where “LM” denotes “lighting manufacturer.” A key consideration in control system selection was rapid response time, as clouds frequently move between the sun and the STF solar collectors, causing quick and noticeable fluctuations in the delivered light levels, described in Table 2 below. A previous study demonstrated that, on a cloudy day, the STF system alone would not be suitable as a reliable lighting solution, as the dips in light intensity were too rapid and pronounced for consistent indoor illumination (California Lighting Technology Center 2020). Therefore, it was crucial to select a system that could compensate for these fluctuations in real time.

Table 2: Performance of lighting controllers.

Manufacturer	Photosensor Type	Photosensor Dynamic Range	Photosensor Response Time	Controller Dimming Signal
LM1	Indoor	0-400 fc	5 seconds	0-10V
LM2	Indoor	0-90 fc	5-10 minutes	0-10V
Custom Controller	Indoor	0-100 fc	2 seconds	0-10V

For each control system evaluation, the team mounted the photosensor 2 feet below a hybrid luminaire, aimed upward at the fixture lens to measure both electric and daylight contributions, as shown in Figure 10. This configuration enabled real-time feedback on total light levels so the room controller could adjust luminaire output accordingly. The team calibrated the photosensor to maintain 21 fc at the work plane, verified through measurement and verification (M&V) procedures using light meters. The calibration ensured that as daylight varied throughout the day, the control system dynamically dimmed or brightened the electric lighting to sustain the target illuminance level.

Each of the three lighting control systems operated the hybrid lighting setup for a two-week period, rotating between each control system, which was done three times per system between March and August of 2025.

Figure 10: Control system illuminance sensor.

Source CLTC.

The team first evaluated a lighting control system from Lighting Manufacturer 1 (LM1), which consisted of a photosensor and a room controller. The LM1 uses a closed-loop photosensor with a 0–10-volt (V) dimming output. It responds rapidly, reaching 90 percent of its target level in about 5 seconds. The controller has a relatively high activation threshold, beginning to adjust only when light level changes exceed roughly 2 fc at the work plane.

The sensor from Lighting Manufacturer 2 (LM2) is a closed-loop controller—configured through an app—that has a downward facing sensor with a 0–10-V control output. The system exhibits a very slow response time, on the order of 2 minutes for a 90 percent rise time, and will respond to small changes in brightness on the order of 0.5 fc changes at the work plane.

After identifying performance limitations in the two commercially available lighting controllers—specifically, large deadbands around the setpoint and slow response times—the research team developed and tested a custom control system that integrated the best features of both. The controller used a proportional-integral-derivative (PID) algorithm tuned in Simulink, with data collected from the isolated fiber optic system to simulate real operating conditions. The control system was implemented using a National Instruments analog input/output device and a PLC Sensors MASS/IO photosensor, which provided an analog voltage signal. The PID loop was optimized to minimize rise time and overshoot and included a ±0.2 fc deadband around the work plane setpoint. This prototype served as proof of concept for how a purpose-built hybrid daylighting controller could achieve more responsive and stable operation than currently available commercial systems.

To highlight the response characteristics, the team monitored the 0–10-V control signals of the controllers while the lights in the space were switched from full off to full on, as shown in Figure 11.

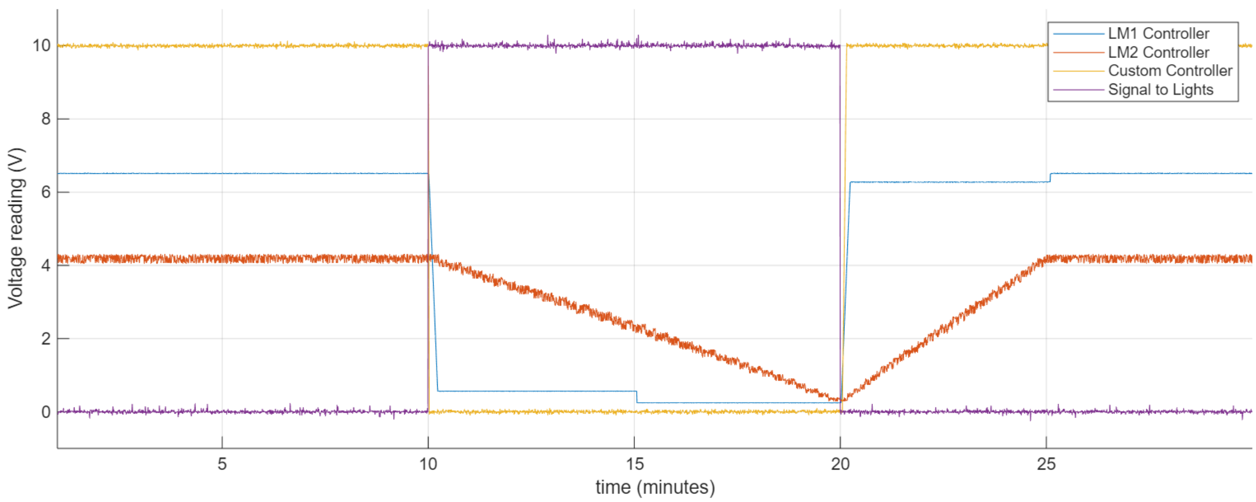

Figure 11: Control system responses to lights being turned on and off in the test space.

The control configuration allowed the system to either dim or increase the electric lighting, depending on the availability of daylight. When clouds obstructed the sunlight, causing a sudden dip in daylight contribution, the room controller would send a signal to increase the electric lighting output to compensate. Conversely, when sunlight became available again, the electric lighting gradually dimmed down to prioritize daylight. The team manually fine-tuned the parameters, such as “ramp rate,” to ensure that the transition between electric and natural light was smooth, preventing noticeable flickering or abrupt changes that could be distracting to occupants.

Measurement and Verification

Illuminance Sensors

To assess the stability of the hybrid luminaires, the team positioned a series of precision Konica Minolta T-10A () photometric sensors—shown in Figure 12—throughout the demonstration space. These sensors can be connected and sampled at set intervals, allowing for consistent monitoring of the lighting conditions across the space.

Figure 12: Konica Minolta illuminance sensors T-10A.

Source: Konica Minolta.

We positioned these sensors horizontally—2.5 feet from the floor (Figure 13) and pointing toward the ceiling—to capture data representative of work plane lighting conditions. The sensors were evenly spaced throughout the demonstration space to ensure consistent coverage and to identify any variance in light output from different fibers. One sensor head was placed in an isolated test chamber, as shown in Figure 19, to capture only the magnitude of daylight contribution from the STF system, synchronizing the time data from the other sensors. The Konica Minolta T-10A sensors were sampled at a rate of 2 hertz (Hz), or twice per second, with an accuracy of ±0.01 lux, and logged directly to a PC.

Figure 13: Work plane illuminance sensor.

Source: CLTC

Handheld Spectral Meter

To capture the spectral power distribution of the hybrid fixture under different conditions, the team used a Konica Minolta CL-70F, shown in Figure 14. The CL-70F was mounted on the sensor pole used for the control system photosensor, enabling consistent readings of the hybrid fixture spectrum from a fixed distance. The sensor has an accuracy of ±5 percent for spectral power, and its data can be uploaded to a computer for plotting and further analysis.

Figure 14: Konica Minolta Spectral Distribution sensor CL-70F.

Source: Konica Minolta.

Integrating Sphere

To measure the luminance and spectral distribution of individual fibers, the team positioned a 1-meter integrating sphere—shown in Figure 15—outside of the test space, close to the final installation point of the fibers. We conducted measurements on a sunny day, with 8 fibers tested over a 15-minute period to evaluate their performance against the specifications provided by STF.

Figure 15: Unilluminated fiber in 1-meter integrating sphere.

Source: CLTC

Electric Lighting Power Meter

To measure the energy consumption of the electric lighting system, the team installed current transformers and voltage sensors from Emporia on the power circuit supplying the hybrid lighting fixtures. The Emporia Vue monitoring system logged power consumption at a rate of 1 Hz, which was uploaded to a remote server hourly. This approach ensured that finer details of power usage were not lost and allowed for an accurate interpretation of the lighting system's power consumption and its response to control signals.

Figure 16: Emporia power monitor.

Source: Emporia.

Solar Tracker Power Monitor

To measure the energy consumption of the STF system itself, we installed WattNode energy meters on the circuitry providing power to the motorized base, which enables the system to track the sun; additionally, we used current transformers and voltage sensors to monitor this dedicated power circuit. The WattNode provided a continuous log of energy consumption, allowing the research team to evaluate the overall efficiency and operational power demand of the daylight tracking and control system.

Figure 17: WattNode energy monitor.

Source: Continental Control Systems.

Occupancy Sensor

The team installed an OPTEX passive infrared (PIR) occupancy sensor in the demonstration space to detect when someone was present in the room. The presence of individuals could impact the measurement data, for example by shading or casting shadows on the illuminance sensors. The occupancy sensor provided timestamped data of when it was triggered, allowing the research team to filter out potentially erroneous data collected during periods of human activity in the space. To ensure accuracy, all data recorded within 10 minutes of a sensor trigger were flagged and reviewed to avoid misleading conclusions.

Figure 18: OPTEX PIR occupancy sensor.

Source: OPTEX.

Illuminance Test Chamber

Finally, to measure the daylight contribution through the fiber optic cables, the team constructed an illuminance testing chamber, which was calibrated using the fiber optic illuminator shown in Figure 20. The chamber was made from 12-inch PVC material, fitted with two end caps (Figure 19). The exterior was painted black to prevent any external light interference, while the interior was painted matte white to maximize internal reflectance. Each fiber was fitted into the top cap of the chamber, along with a baffled reference meter—the Konica Minolta T-10 Illuminance Meter—to precisely measure the light output. To calibrate the testing chamber, the team used a fiber optic illuminator with a broadband halogen light source to provide consistent illumination. This light source was first characterized using an integrating sphere to establish a known output, which was then used to calibrate the chamber. By following this process, the team effectively calibrated the chamber to provide accurate measurements of the light output from the fiber optic cable.

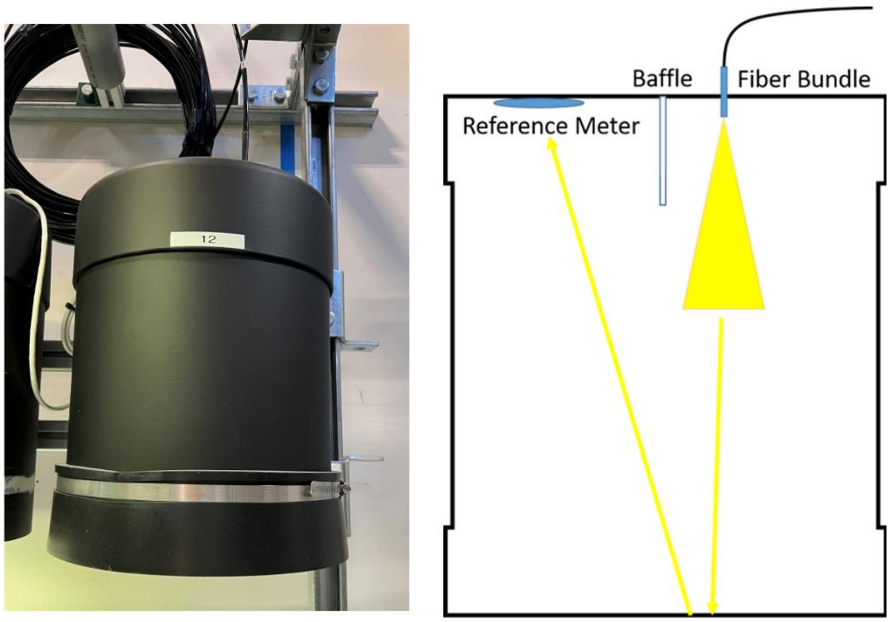

Figure 19: Illuminance test chamber.

Source: CLTC

Figure 20: Fiber optic illuminator with a 100W halogen light source.

Source: Thor Labs

Measurement and Verification Equipment Summary

Table 3 provides a summary of the measurement and verification (M&V) equipment used throughout the study. Each piece of equipment was selected for its specific role in monitoring the performance of the hybrid lighting system, from measuring illuminance levels to assessing power consumption and occupancy impacts.

Table 3: Use of metrology equipment in the test space.

Equipment	Use
Konica Minolta T-10As	To measure the work plane illuminance and the relative fiber contribution in the illuminance test chamber.
Konica Minolta CL-70F	To measure the relative spectral distribution of the hybrid lighting fixtures.
1-meter integrating sphere	To measure the spectral distribution and luminance of the fiber optic cables.
WattNode power meter	To measure the power to the STF solar tracking system.
Emporia power meter	To measure the power to the hybrid lighting system.
OPTEX PIR occupancy sensor	Occupancy of the test chamber to exclude data associated with troubleshooting and potential exclusion of work plane T-10A sensors.
Illuminance test chamber	Measure the relative fiber contribution and periods of sunlight on the system.
Fiber optic illuminator	Standard candle to calibrate illuminance test chamber.

Results

Spectral Quality and Luminous Flux

The research team also measured the spectral power distribution of the fibers when illuminated by daylight collected through the STF solar tracking optics. This was done by placing several fibers, one at a time, into the integrating sphere in 15-minute intervals on a clear day, starting at solar noon, as shown in Figure 21.

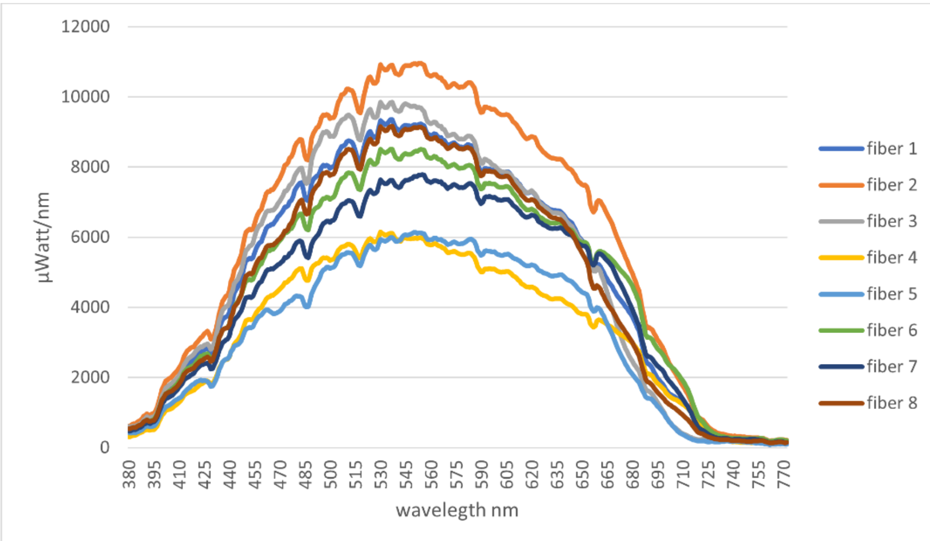

Figure 21: Spectral power distribution of 8 fibers taken within 15 minutes of solar noon on the same sunny day.

The measurements revealed that while there were significant differences in total light output from fiber to fiber, the spectral distributions were largely consistent (Table 4), resulting in a similar color quality across the fibers. The color variation between the fibers was within three MacAdam ellipses, indicating that the fibers maintained a stable color output. The observed differences in illuminance across fibers likely stem from variations in the construction of individual solar collector's lenses and their precise alignment with the fiber optic cables.

Table 4: Color and performance of individual fibers.

Fiber	Measured fiber output (lumens)	Measured Corrected Color Temperature [CCT] (° K)	Measured CRI
1	609.4	4965	85
2	729.2	4831	86

Fiber	Measured fiber output (lumens)	Measured Corrected Color Temperature [CCT] (°K)	Measured CRI
3	635.7	5158	84
4	396.5	5097	86
5	406.5	4637	87
6	562.3	4806	86
7	518.4	4623	88
8	597.4	4886	83

On average, the measured output of the fiber optic system was below the manufacturer's specified output of 700. The measured lumen outputs for individual fibers ranged from 396.5 to 729.2 lumens, indicating significant variation and an overall shortfall compared to the expected performance. This discrepancy suggests that the installation conditions, fiber alignment, or potential losses within the system may be affecting the efficiency of the daylight collection and transmission.

The measured correlated color temperature (CCT) ranged from 4623°K to 5158°K, with a relatively consistent color rendering index (CRI) between 83 and 88, as described in Table 5. While the CCT and CRI measurements fall within acceptable ranges for general interior lighting, the variations in output across different fibers highlight potential inconsistencies in the performance of the daylighting system. This inconsistency could result in uneven lighting distribution within the demonstration space, particularly if the lower-output fibers are installed in critical locations.

The spectral distribution of the installed hybrid fixtures was measured with the CL-70F handheld spectral power meter. The fixtures maintain a CRI between 85 and 85 during operation, depending on the mixing of the LED and sunlight contributions, and the color temperature can vary by ±500°K, centering near 4,000°K.

Table 5: Hybrid fixture color metrics

Configuration	Color Rendering Index (CRI)	Correlated Color Temperature (CCT)
Fiber Only	89	3,857°K
LED only at setpoint	85	4,120°K
Hybrid at setpoint	88	4,350°K

Figure 22 shows the color rendering results of the hybrid fixture, with both LED and fiber illuminance contribution at solar noon during the summer. 88 CRI from the hybrid configuration is a higher CRI than the LED fixture alone (85 CRI). The spectral power distributions are shown in Figure 23, highlighting the difference between fiber-only, LED-only, and hybrid operation. The spectrums—mostly in the green and yellow ranges of the spectrum—are additive.

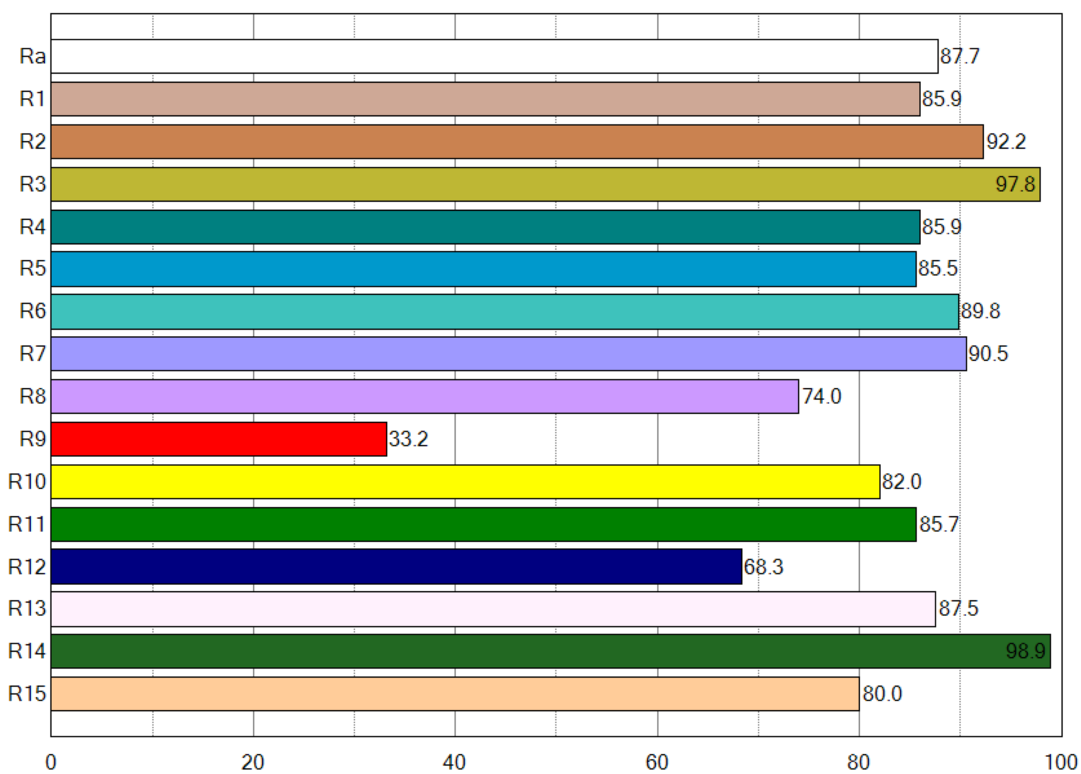

Figure 22: Color rendering results of the hybrid fixture in hybrid configuration at noon on a sunny day (88

CRI).

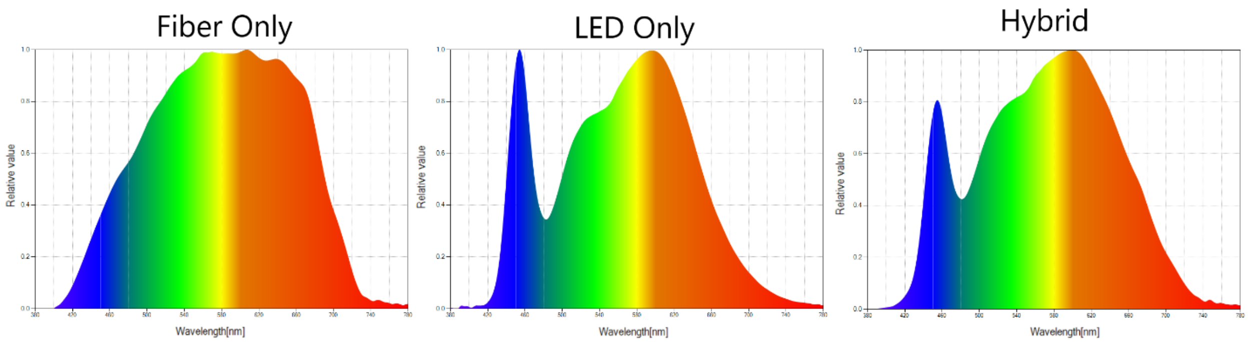

Figure 23: Relative spectral power distribution of the hybrid fixture.

Effects of Dust on STF Performance

The team monitored the isolated fiber throughout the year to assess the effects of dust accumulation on solar collection performance. We took measurements by averaging the illuminance recorded within the illuminance test chamber over a five-minute interval centered on solar noon each day. A gradual decline in illuminance was observed over time, corresponding to the buildup of dust and debris on the collector lenses. Following rainfall events, the measured illuminance increased sharply, indicating partial natural cleaning of the optical surfaces. Due to the predominantly dry and sunny climate at the test location, prolonged periods of dust accumulation were common, leading to sustained reductions in transmitted light. When the team manually cleaned the collector lenses, illuminance in the illuminance test chamber increased by up to 85.5 percent, confirming a substantial impact of surface contamination on optical efficiency.

Solar Tracker Energy Consumption

The energy consumption of the STF unit and its controller were monitored continuously for a week using a WattNode energy meter with revenue-grade accuracy (±0.5%) at the same level as American National Standards Institute C12.20 energy meters. The data collected revealed that the daily power draw of the unit remained consistent from day to day.

Figure 24 illustrates the small variations in average power consumption during the same time periods across different days, with the largest observed variation occurring at 2:00 p.m., where the power draw fluctuated by only 0.75 W from the mean. Given this consistency, the team calculated an average daily energy consumption that can be reasonably extrapolated to estimate energy usage on other days. The STF unit draws 10.37 W while idle and 19.44 W while actively tracking the sun, resulting in an average energy consumption of 337.2 watt-hours per day.

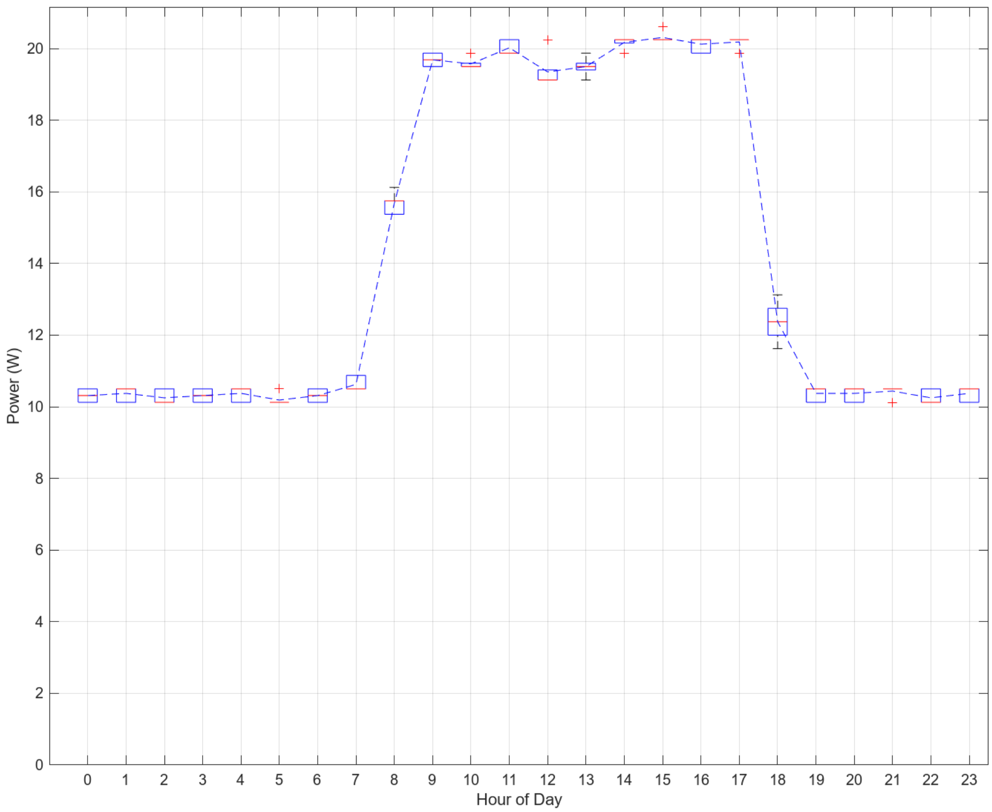

Figure 24: Power draw of STF solar tracker system over the day, with variability at each hour shown.

Hybrid Luminaire Control Performance

The control system was designed to maintain a consistent work plane illuminance by adjusting electric lighting to compensate for fluctuations in daylight provided by the fiber optic system. To assess the effectiveness of this control system, the research team analyzed instances of brightening and dimming in the work plane's illuminance data due to cloud coverage. These instances were then compared to existing studies on human sensitivity to temporal changes in light intensity, with a specific focus on contrast sensitivity and the threshold at which dimming becomes perceptible.

To detect changes in illuminance that are noticeable to the human eye, the research team processed the collected illuminance data through several steps:

1. **Data Smoothing**: The raw illuminance data often contains low-amplitude noise that can obscure significant changes. To reduce this noise, the team filtered out minor fluctuations that were significantly less than 1 fc. This allowed the more meaningful changes in illuminance to be clearly distinguished.
2. **Calculating the Rate of Change:** After smoothing the data, the team calculated the derivative of the illuminance with respect to time. This step highlights how quickly the illuminance is changing at any given moment. Rapid changes in the derivative indicate significant variations in light levels.

3. **Identifying Significant Events**: To determine when notable changes in illuminance occurred, the team monitored the rate of change in illuminance over time. When the rate of change exceeded a defined level that was determined to be perceivable by an occupant, the team flagged the corresponding time period as a significant event, indicating either dimming or brightening. These events were then logged into a database for further analysis.

The identified events were characterized based on two factors: event duration and the magnitude of change in illuminance. Figure 25 provides an example of the algorithm's detection of these events, highlighting flagged periods within a sample dataset collected on a cloudy day. Both plots are zoomed in to emphasize the shape differences between the two conditions. Although both conditions maintain work plane illuminance levels between 20 fc and 23 fc, the overcast day shows less stability than the clear day, frequently oscillating around a steady state at a much higher amplitude than the clear day.

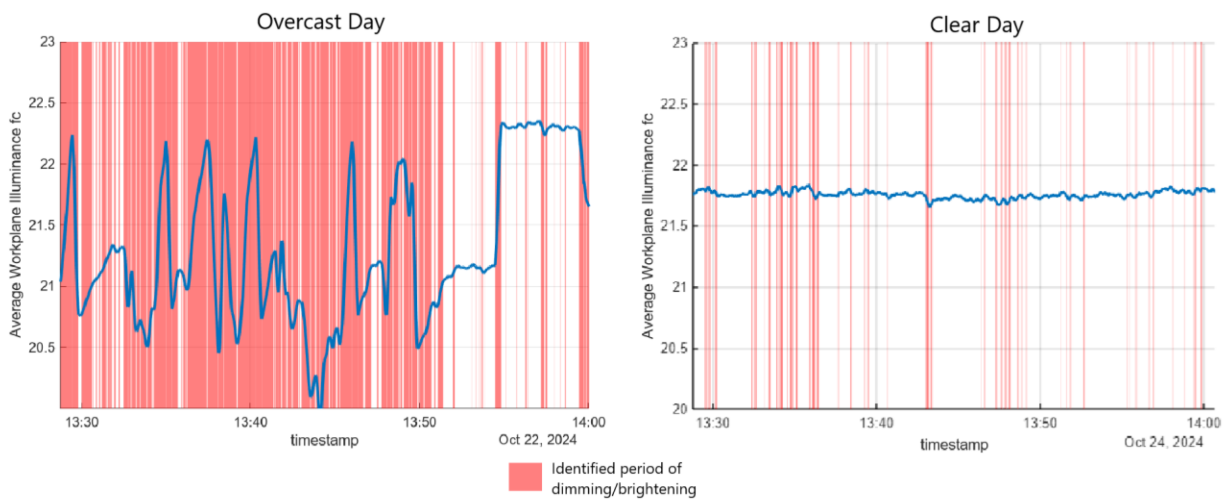

Figure 25: Algorithm output showing dimming and brightening events in work plane illuminance data under overcast conditions.

Note: Red regions indicate events at similar times on both clear and overcast days

To ensure the accuracy of the analysis, the research team excluded any events that occurred while the space was occupied. This exclusion was necessary because occupants could unintentionally affect the lighting conditions—such as by casting shadows or moving objects—which could interfere with the illuminance data. Most of the observed events involved changes of less than 1.5 fc in workplace illuminance, which represented about 99 percent of all events detected.

Studies on human perception of light level changes (Valeria et al., 2023) suggest that such minor changes are unlikely to be noticeable to more than 90 percent of occupants. After this filtering, the team analyzed 124 events and assigned them each a probability of being noticed. Figure 26 illustrates the probability that an individual notices dimming of lighting on a white plane directly in their central vision. Based on this experimental data, it is assumed that as the duration of the change increases, the probability of an event being noticed approaches zero percent. Consequently, events lasting longer than 60 seconds were excluded. To adopt a worst-case scenario, events lasting between 20 and 60 seconds were evaluated using the 20-second curve.

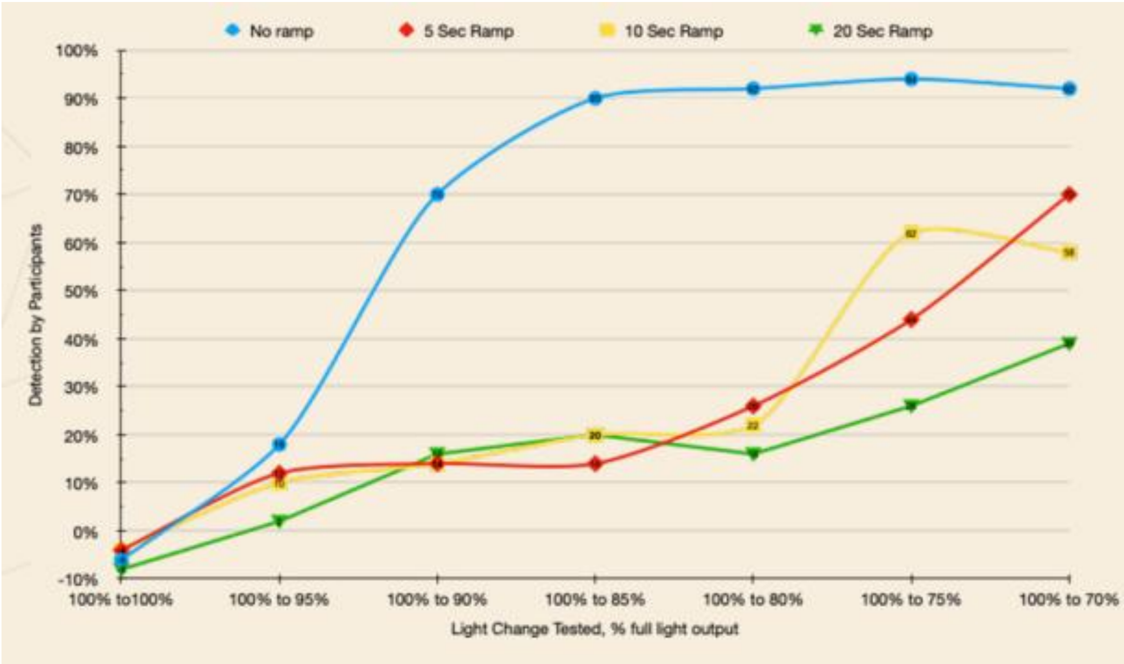

Figure 26: Probability that fluctuations are noticeable in the central vision.

Source: (Valeria 2023)

After filtering the data as described and interpolating the probability of detection, results were separated by weather conditions. This separation was implemented based on the research team's hypothesis that the type and density of cloud cover could influence the number of potentially detectable events in the test space. During the test period from August to November 2024, most daylight hours were classified as partly cloudy, followed by overcast as the next most common condition.

The time of day and distribution of potentially noticeable events can be seen in Figure 27.

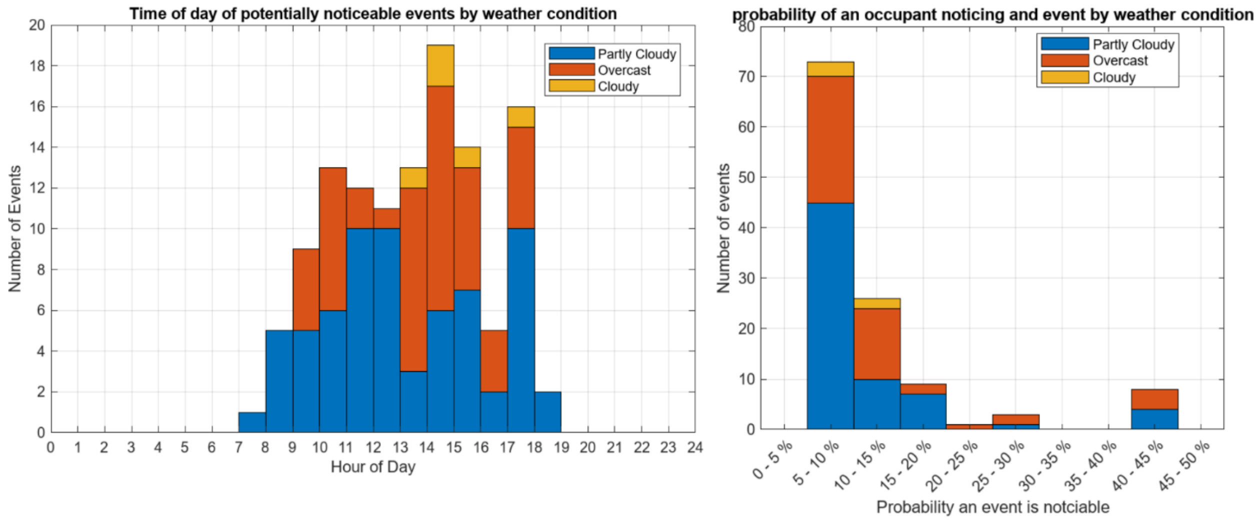

Figure 27: Time of day and detection probability of significant dimming/brightening events in the test space.

To assess the risk of occupant discomfort, the team developed a metric to quantify the probability of an occupant experiencing noticeable dimming or brightening of the space over a given period. The dataset analyzed for work plane illuminance spanned from August 5, 2024 to November 1, 2024. The team calculated an average number of events per hour by examining the number of potentially noticeable events, the weather conditions during these events, and the duration of similar weather conditions throughout the dataset. This calculation included only hours with sunlight contribution to the hybrid fixtures. A Poisson distribution was then applied to calculate the probability of observing at least one event in an hour, as shown in Equation 1.

- $P_{noticed}$: The average probability that an event is noticeable (Valeria 2023).
- T: The cumulative duration, in hours, that similar weather conditions were present during times when the STF system was actively tracking the sun.
- λ: The number of potentially noticeable events that occurred during the test period with specific weather conditions.
- P(t): probability of observing at least one change in illumination over a period of t in hours.

Equation 1: Probability of noticing any dimming and brightening in the test space over a period of one hour.

$$P(t) = 1 - e^{-\frac{\lambda}{T} * t * P_{noticed}}$$

The team generated Table 6 by using Equation 1. The low probability of an event being noticed during cloudy weather can be attributed to the limited duration of cloudy conditions within the test period, which totaled only 71 hours with 5 events. In comparison, partly-cloudy conditions spanned 791 hours with 67 events, and overcast conditions covered 195 hours with 48 events. The probabilities of events being noticeable are not significantly different across conditions, with a maximum difference of 4 percent in noticeability. The lowest probability was observed in the cloudy data, which is also the least statistically significant due to limited sample size.

Table 6: Probability of seeing dimming or brightening in the test space during a one-hour interval.

Weather Condition	The expected number of noticeable events per hour λ/T	Average probability that an event is noticed $P_{noticed}$
Partly cloudy	0.085	12.0%
Cloudy	0.070	9.7%
Overcast	0.246	13.7%

The control system demonstrates effective performance in maintaining stable illuminance levels on the work plane, as indicated by the probability metrics associated with noticeable dimming or brightening events. The system minimizes fluctuations in illuminance, keeping the probability of an event being noticeable below 14 percent. During partly cloudy conditions, the probability of detecting an event within any given hour is only 1 percent, with similarly low probabilities for cloudy and overcast conditions at 0.7 percent and 3.4 percent, respectively. These values suggest that the system effectively compensates for changes in daylight, preserving consistent lighting levels and minimizing potential occupant discomfort due to sudden changes in brightness.

Control System Response During Partly Cloudy Conditions

The overall goal of the hybrid system was to seamlessly integrate daylight and electric lighting to maintain consistent work plane illuminance regardless of outdoor weather conditions. The research team tested multiple control strategies to determine which approach could best maintain consistent lighting conditions in the test space, particularly during periods of rapidly changing daylight.

Although the originally installed LM1 system achieved some improvements, its limited ability to adjust control parameters without incurring noticeable light level changes posed challenges. As a result, the research team evaluated other commercially available lighting control solutions to determine whether they offered greater flexibility, improved stability, and a more precise response to daylight fluctuations. These control systems were primarily tested during spring and summer 2025, when outdoor conditions were predominantly clear or partly cloudy, allowing direct comparison of system performance under dynamic daylight conditions with the goal of enhancing occupant comfort and energy efficiency.

- **LM1 controller:** Quick response time, but a high threshold to begin responding to changing light conditions.
- **LM2 controller**: Slow response time, but low threshold to begin responding.
- **Custom control solution**: Quick response time with a low threshold to respond.

The higher luminous contribution of daylight to the test space resulted in more dimming events detected in the test space. Both commercial control systems exhibited similar performance, with the lower-threshold system decreasing the number of noticeable events. For the best occupant comfort results, a control strategy that minimizes the response time—as well as the threshold of response—lowers the odds of occupants noticing changes in daylight contribution. Results are shown in Table 7 below.

Table 7: Lighting controller performance comparison.

System	The expected number of noticeable events per hour λ/T	Average probability that an event is noticed $P_{noticed}$
LM1 controller	1.84	14.5%
LM2 controller	1.21	16.2%
Custom controller	1.09	16.2%

Total System Energy Consumption

To calculate the total system energy consumption, both the STF unit energy consumption and the electric lighting energy consumption must be considered. The STF unit's energy consumption was previously measured to be 19.5 W while tracking the sun and 10 W while stationary, or zero W when turned off at night. The team compared the power draw of the STF unit, along with the energy consumption of the electric lighting, to the electric lighting consumption without daylight, which was measured at 110 W. The installed lighting system is oversized to accommodate the number of fibers into the space with a narrow distribution; these fixtures are rated for 26 W per fixture at 100 percent output but are dimmed by 58 percent to achieve the uniform setpoint.

The team modified the system to reduce loss due to internal reflections and gathered data from this configuration during the spring and summer months.

The measured average power consumption of the lighting systems under the new configuration is available in Table 8, which shows that the average power consumption of these systems varies slightly due to quantization in their setpoints and deadbands in setpoint maintenance. All systems held the setpoint to within 1 fc of the setpoint for most of their running time. The measured savings and reduction account for the 19.4 W used by the STF system.

The hybrid daylighting-electric lighting system maintained required task illuminance while operating at a measured lighting power density of 0.115 W per square foot. This performance is approximately 81 percent below the Title 24, Part 6 allowance for office spaces larger than 250 square feet (0.60 W per square foot). Therefore, the system demonstrated that code-compliant lighting quality can be achieved while using only 19 percent of the electrical power permitted under California's current prescriptive lighting power budget.

Table 8: Lighting power saving analysis by controller used.

System	Avg Power (kW)	% Savings	Reduction (kW)	Reduction vs. Title 24
LM1 Controller	0.0458	40.8	0.045	82%
LM2 Controller	0.0497	37.3	0.041	81%
Custom Controller	0.0502	36.8	0.041	81%

Source: CLTC

Cost Effectiveness

During occupied daytime hours (9:00 a.m. to 5:00 p.m.), when most office lighting energy use occurs, the system achieves a 40 percent reduction compared to the installed LED baseline. This results in annual savings of 75 kilowatt-hours, assuming that the system is operated during business hours Monday through Friday, with 10 days of holidays hours. This results in a payback period function, as shown in Equation 2:

Equation 2: Payback period.

$$payback\ period\ (years) = \frac{\$48{,}872}{savings(kW)\ \times\ 0.21\left(\frac{\$}{kWh}\right)\times\ 8\left(\frac{hour}{day}\right)\times\ 250(days/year)}$$

A historical cost comparison indicates that the STF system evaluated in this study delivered light at approximately 35 percent of the cost per lumen of an STF system purchased by the research team in 2019 (excluding fiber optic cables). If this cost trajectory continues, a system that cost $16,872 in 2023 would decline to roughly $5,000 by 2028. The total cost of the system at time of purchase in 2023 was $48,872, meaning that if the system were able to offset 100 percent of the lighting energy use while not consuming any power, the payback would be 1,050 years.

The continued decrease in glass fiber costs—which would follow similar trends seen in data-transfer fiber—could further accelerate STF cost competitiveness. Based on cost trends observed over the past five years, STF systems may become viable core daylighting solutions in the next decade. Projected cost trends (excluding fiber optics) through 2035 are illustrated in Figure 28 and Figure 29, where the dotted lines indicate projected costs using an exponential decay rate observed between 2019 and 2025.

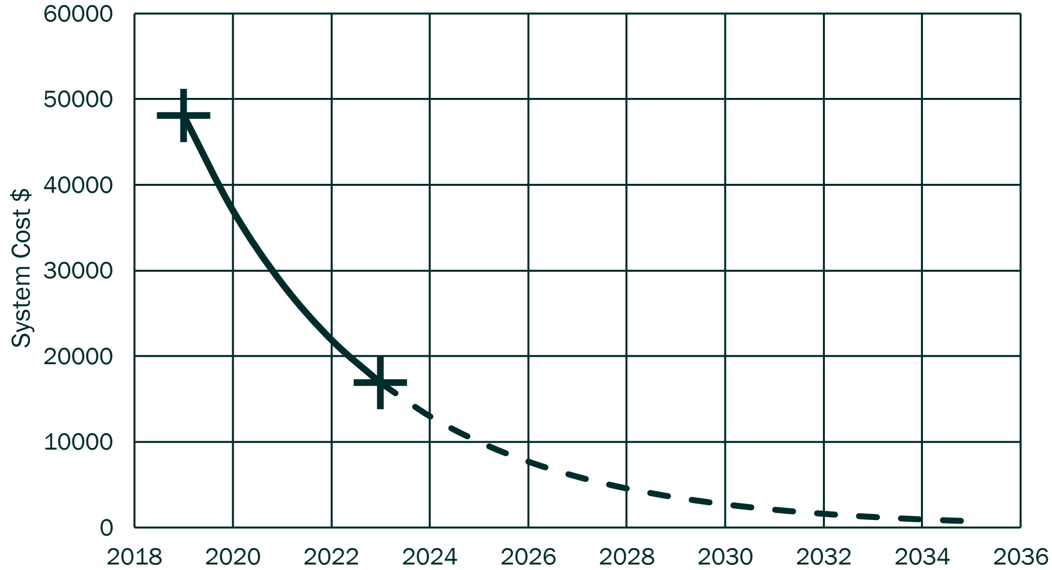

Figure 28: Projections for STF system cost (excluding fiber optics) with current trends.

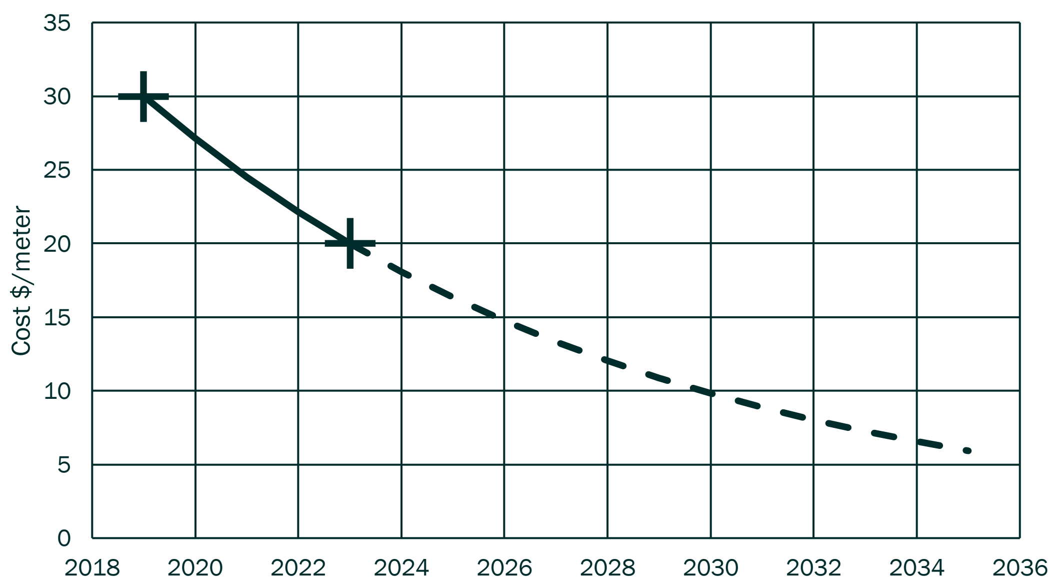

Figure 29: Projections for fiber cost per meter with current trends.

The STF system tested included 40 glass fiber cables, each 40 meters in length, to illuminate the test space. These cables represented most of the cost to install the system: approximately $32,000 in total, or $20 per meter, which is two-thirds the cost of the fiber in 2019. In most buildings, a minimum run length of 10 meters is required to reach an interior space from an exterior mounting location, assuming only one floor or room separation. Longer run lengths significantly increase total system cost due to the high price of fiber.

The team projected payback periods assuming fiber cost decreases at the current rate, and tracking system costs continue to follow current trends, as shown in Table 9. All projections assume stable electricity rates at 0.24 dollars per kilowatt-hour (EIA 2025). The annual savings over the installed LED system were 75 kilowatt-hours, which equates to $18.00 in annual savings.

Table 9: Current and projected payback periods.

Fiber optic Length	Total System Cost 2023	Payback 2023 (years)	Projected Total Cost 2035	Projected Payback 2035 (years)
40	$48,900	2,710	$10,200	567
30	$40,900	2,220	$7,800	426
20	$32,900	1,750	$5,500	590
10	$24,900	1,290	$3,100	161

During the testing period, several technological advancements emerged in the STF market. New systems with hexagonally arranged collection lenses reduced material requirements and manufacturing costs. Plastic fiber optic cables designed specifically for STF applications have also become available, offering significant cost reductions. These advancements indicate active innovation in the STF sector, aimed at lowering costs and improving long-term feasibility.

Peak Demand Reduction Potential

Lighting power reduction from the hybrid system remains at a consistent level through the 9:00 a.m. to 5:00 p.m. period. For commercial use cases of a hybrid daylighting system, the light fixtures remain at full power reduction through standard business operation hours. Based on calculations, the system achieves an energy reduction of approximately 45 W in the 432-square-foot test space during the peak period of 4:00 p.m. to 5:00 p.m. This equates to peak period reduction of 1 kilowatt-hour for every 9,600 square feet illuminated with an STF.

California has approximately 2.1 billion square feet of office floor space (CBECS). If an STF lit 1 percent of commercial floor space, 2.1 megawatt-hours statewide (California Energy Commission 2022) could be reduced during the 4:00 p.m. to 9:00 p.m. peak daily; this was calculated using 45 W of savings per 384 square feet.

Summary of Results

The STF system delivered high-quality daylight with stable spectral characteristics, with a CCT of 4,623 to 5,158 Kelvin and a CRI of 88; however, luminous output varied substantially across fibers (396 lumens to 729 lumens), falling below the manufacturer's stated maximum of approximately 700 lumens per fiber. Dust accumulation measurably reduced delivered light and required either rain or manual cleaning to restore performance. The hybrid fixtures achieved CRI values of 85 to 88 across operating modes, with color temperature shifting predictably as the LED to daylight ratio changed.

The STF tracker consumed an average of 337 watt-hours per day—idle i10.37 W and tracking 19.44 W. When integrated with LED luminaires and commercial control systems, total lighting energy fell by approximately 40 percent relative to the LED-only baseline, while maintaining a 30-fc work plane setpoint. The resulting lighting power density was 0.115 W per square foot, approximately 81 percent below the Title 24 prescriptive allowance for office spaces.

Temporal stability analysis showed that fluctuations in daylight produced by cloud transients rarely created perceptible dimming events when the STF system was integrated with electric lighting. After filtering for human perception thresholds, the probability of an occupant noticing any event within a one-hour period remained low: 1.0 percent (partly cloudy), 0.7 percent (cloudy), and 3.4 percent (overcast). Among controllers tested, faster response and smaller deadbands reduced event frequency.

Cost effectiveness remains the primary barrier to deployment. The 2023 STF system cost $48,900, of which approximately $32,000 was fiber. Annual savings under office-hour operation were about 75 kilowatt-hours, or $18 per year. Payback exceeded 1,000 years across all current configurations. Market trends—e.g., reduced glass fiber cost, emerging plastic fibers, and improved collector fabrication—indicate costs may fall by about 2035, but even projected 2035 paybacks remain in the range of several hundred years.

Conclusion and Recommendations

The hybrid STF–LED system demonstrated that core daylighting can reliably maintain acceptable illuminance, color quality, and occupant comfort while reducing electric lighting demand by roughly 40 percent and achieving a lighting power density far below Title 24 allowances. The control strategies—particularly those with fast response and minimal deadband—kept perceptible dimming events rare, and the spectral stability of daylight through the fibers was consistently high. These results confirm the technical viability of hybrid daylighting in deep-core spaces.

However, system economics remains the limiting factor. Current hardware costs—which are driven primarily by fiber and collector fabrication—produce payback periods that exceed hundreds to thousands of years, even under optimistic assumptions. Light output variability among fibers, sensitivity to dust accumulation, and installation complexity further highlight that while the system is technically mature, it is economically premature for widespread deployment.

To move the technology toward viability, we recommend several pathways. At the hardware level, improving collector uniformity, lens alignment, and fixture optics would increase delivered lumens and reduce variability. Dust mitigation measures—such as coatings, improved housings, or automated rinsing—should be pursued to stabilize long-term performance. On the controls side, manufacturers should prioritize fast-response daylighting algorithms with narrow deadbands to suppress perceivable fluctuations, ideally integrating fiber-specific daylight signals directly into the control loop.

Cost reductions are essential, with the continued development of low-cost plastic fiber, simplified collector geometries, and modularized tracker assemblies representing the most impactful levers. Field demonstrations in occupied buildings should be expanded to quantify real-world maintenance intervals, validate occupant comfort across seasons, and evaluate performance across varying fiber run-lengths.

References

California Energy Commission. 2022. *2018 - 2022 California Commercial End-Use Survey (CEUS).* CEUS, California Energy Commission.

California Lighting Technology Center. 2020. *Commercial Daylighting Retrofits Report.* Commision Report, California Energy Commision.

EIA. 2025. *Average Price of Electricity to Ultimate Customers by End-Use Sector.* July. Accessed October 10, 2025. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a.

Valeria, Soto, Young Suk, Siminovitch, Hathaway. 2023. "Maximizing Energy Savings with Optimized Dimming Ramp Rates in Retail and Museaum Buildings." *LD+A* 34-37.