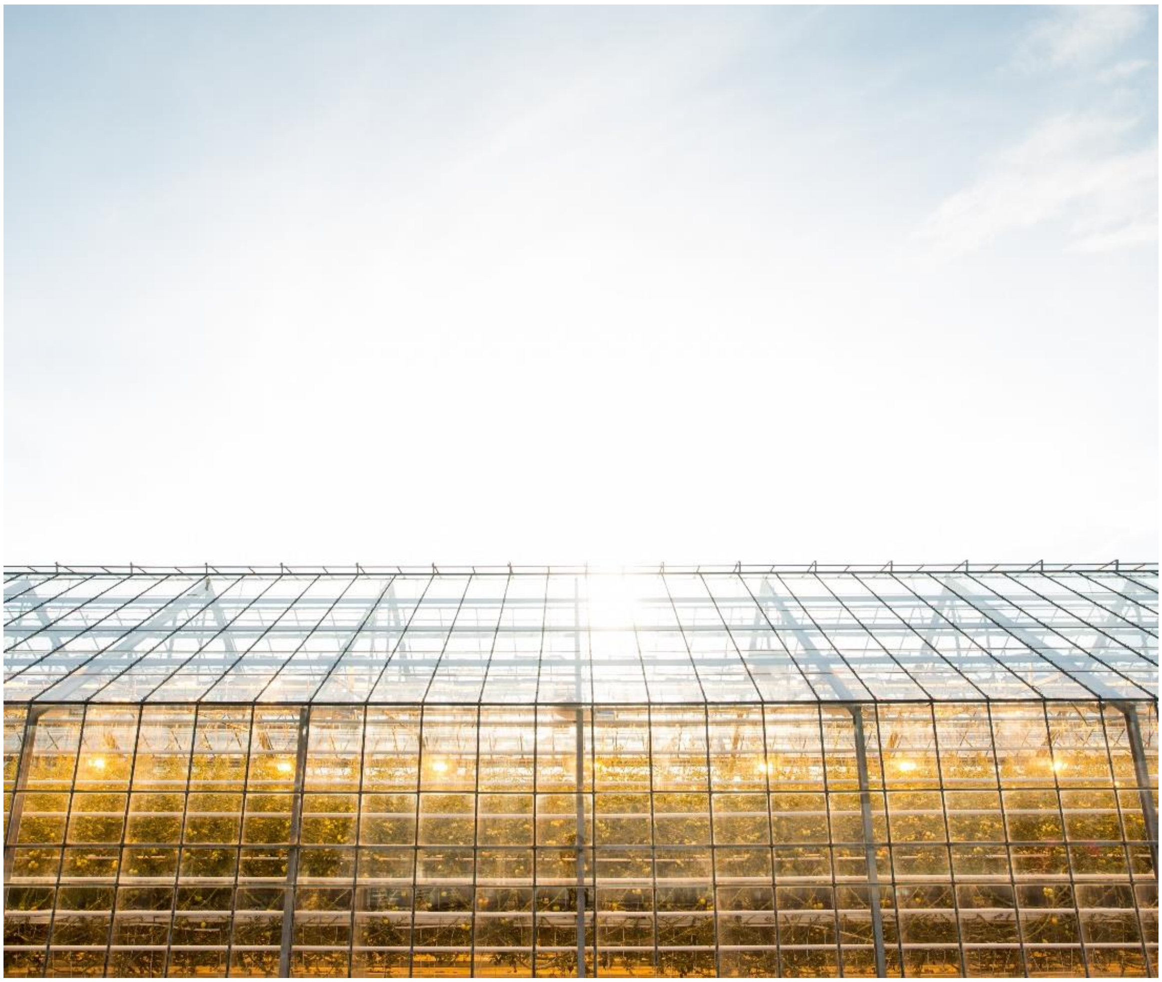
Greenhouse Lighting Controls

Final Report

ET22SWE0027



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March 17, 2023

Disclaimer

Executive Summary

The California Investor-Owned Utilities (IOU) are evaluating how they might encourage market adoption of adaptive lighting controls for greenhouses. In May 2021, Energy Solutions began a field study for Pacific Gas and Electric (PG&E) through its Emerging Technologies Program.[1] This was funded through the Fall of 2022. The main conclusion was that, for IOUs to evaluate offering a deemed measure package for the technology, a larger study would be needed. The report made specific recommendations for how that study should be designed.

This project through CalNEXT was a continuation of the work that was begun for PG&E and completed by the same core Project Team. The tasks were to gather more user experience from the grower, estimate energy savings potential, record the grower's observations of crop yield and quality, and conduct outreach to other growers and industry stakeholders. The objective was to recommend further steps for CalNEXT, if any, to encourage market adoption.

For reasons beyond the Project Team's control, it was not able to obtain savings data as hoped. Therefore, the Project Team created a model to identify the times that dimming might occur based on photoperiod parameters, published monthly average daily light integral (DLI), and estimates of glazing transmittance. With guidance from industry experts, it applied the model to cannabis and tomato crops and estimated 9 percent and 11 percent energy savings, respectively. For both crops, the simple payback was less than a year. This provided a more general understanding of savings potential than would have been obtained using the approach originally planned.

Through the findings of this project, it became clear that adaptive lighting controls are not suitable for a deemed measure. Implementation is highly dependent on user behavior, making it too difficult to guarantee the technology would be used correctly or consistently. The Project Team now recommends evaluating how effectively the technology could be incentivized through Normalized Metered Energy Consumption (NMEC) projects.

This report incorporates feedback about NMEC from more than ten industry stakeholders, all of whom agreed it would be the better approach. The main concern was that to be approved, NMEC projects must have projected savings of at least 10 percent of annual consumption. To reach this threshold, projects would likely include other measures as well, such as HVAC, dehumidification, or transmittance improvements. Whenever lighting changes are made, the effects on the other process inputs must be considered, making such an integrated approach highly desirable and a major reason to use NMEC. Another benefit of NMEC projects is they are normally implemented by a third party, who could help growers with additional savings opportunities they would not likely tap into themselves, such as load shifting, demand charge reduction, and demand response. Growers and implementers would only receive incentives for verified savings so would be motivated to save energy consistently. However, growers would still have the flexibility to change their processes at any time with no penalty.

The Project Team believes that a further study would best be led by industry. Therefore, it recommends encouraging lighting and controls manufacturers and other industry participants to

[1] The report can be found at the following link. https://www.etcc-ca.com/reports/controlled-environment-horticulture-ceh-field-study-adaptive-daylighting-controls

propose their own CalNEXT project(s). The goal of such projects would be to evaluate the potential of NMEC incentives to promote adaptive lighting controls and other energy efficiency measures in greenhouses. The Project Team has already begun discussions with specific parties and could help them submit their applications and provide guidance on meeting utility requirements.

Abbreviations and Acronyms

Acronym	Meaning
CASE	Codes and Standards Enhancement
CEH	Controlled Environmental Horticulture
CPUC	California Public Utilities Commission
DLI	Daily Light Integral
ET	Emerging Technology
GWh	Gigawatt hours
IOU	Investor-Owned Utility
kWh	Kilowatt-hours
LED	Light Emitting Diode
M&V	Measurement and Verification
NMEC	Normalized Metered Energy Consumption
PG&E	Pacific Gas & Electric
TRC	Total Resource Cost
μMo	Micromole

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Background

California is the largest producer of greenhouse vegetables and fresh-cut herbs in the United States, and greenhouse usage has been growing rapidly. From 2007 to 2017, the area in greenhouses increased at a 24.3 percent compound annual growth rate resulting in 35,200,900 sq ft. by 2017 (United States Department of Agriculture, 2017). When adult-use cannabis became legal in 2018, the use of greenhouses accelerated in California.

Although greenhouses are built to allow crops to receive natural light, many also use supplemental lighting to increase production. The 2022 Controlled Environment Horticulture (CEH) Codes and Standards Enhancement (CASE) Report estimated that 30 percent of supplementally illuminated greenhouses are now used for cannabis growing. Legal cannabis facilities are projected to consume over 380 gigawatt-hours by 2022, an increase of 162 percent from 2017 (Cale Microgrid Solutions and Resource Innovation Institute 2018).

The amount of light needed by a specific crop during distinct phases of growth is identified as the target daylight integral (DLI). This is the unit of measure of a plant's lighting needs, expressed as the number of photosynthetically active photons accumulated per square meter per day (mol/m^2/d). The DLI inside the greenhouse can be estimated by adjusting the outdoor DLI by the transmittance of the glazing. Excessive dust, pollen, and bird feces can reduce the light inside a greenhouse significantly.

Photoperiod is the amount of time a plant is exposed to light per day. It varies significantly by crop type and grower preference. The test site in this field study, which grows cannabis, exposed its crops to light for 24 hours per day during the vegetative phase, and then reduced the photoperiod to initiate the flowering phase. For other crops, such as tomatoes, changing the photoperiod does not affect when flowering occurs.

Supplemental lighting in greenhouses is typically controlled with an on/off switch and a timer. Adaptive controls work by using daylight sensors to measure the amount of natural light crops receive, and then dimming the supplemental light so they only receive the desired amount of light. Given photoperiod, DLI needs predicted natural light in the greenhouse, and the amount of lighting installed, it is possible to roughly estimate how often lights would be dimmed during a typical time of year to prevent exceeding the target DLI, and, therefore, to estimate the savings compared to simply using an on/off timer with no dimming.

In practice, adaptive lighting controls require the use of LED lighting because of its dimming capabilities. In the past, the prevalence of fixtures that were not LEDs would have been a barrier to adoption. However, market adoption of LED lighting is significantly increasing, so this is no longer the case.

Project Outcomes

User Experience from the Grower

Test Site

The Project Team continued the data collection that had begun with the PG&E project. The test site was a five-greenhouse cannabis growing facility operated by a large cannabis grower and retailer located south of San Jose, California. The test and control areas were both about 9,100 square feet. The Project Team certifies that permitting requirements did not apply to this project.

The lighting fixture used was the SolarSystem 550 from California Lightworks, as per Figure 1. Relevant specifications are given in Table 8.

Figure 1. Lighting fixtures used in test and control areas
Source: California Lightworks website

Methodology

The controls software vendor provided video conference training on how to set software parameters. The methodology for getting the grower's user experience was to use emails, phone calls, and text messages. The Project Team only had access to the Vice President of Cultivation, which was extremely limited.

Results

Staff turnover and a shift in business priorities prevented the test site from actively using the software and from being as engaged in the study as much as it had planned. However, the Project Team gained the following key general insights into user experience:

- In the software being used for the study, the photoperiod parameter must be manually updated in the software during each grow cycle. Therefore, changing the parameter must be made part of the photoperiod change procedure.
- Growers should have an independent means of verifying the lighting controls are delivering the desired DLI. This would create engagement with the system and build trust.
- If target DLI increases, but the lighting capacity does not, the utility of adaptive controls is reduced because there are fewer opportunities for dimming. For cannabis, most savings will occur during summer days when there is maximum natural light and therefore the most

opportunity for dimming. For details on why the test site dramatically increased its DLI target during the study, see the Discussion and Key Findings section of PG&E's CEH Adaptive Lighting Control Final Report.[2]

- The growers' primary objective was to maximize yield per square foot. One goal for the coming year was to install some new glazing, which the grower thought could make it possible to reach a DLI of up to 60 mols/m2/day during peak summer months. The grower speculated that under those conditions the main reason to turn off supplemental lighting would be to minimize excessive heat. During outreach, the Project Team received several comments that this was an extreme approach.

In September 2022, the Project Team lost the ability to access data remotely because of onsite IT issues. For future studies, the adaptive controls software should have a separate connection to the cloud that does not depend on local infrastructure.

Estimated Energy Savings Potential

Methodology

In the PG&E study, the methodology for estimating energy savings potential was to extrapolate from the savings from two test sites with different crops. This study continued with this methodology, even though there was only one test site.

The adaptive lighting controls software used a photosensor inside the greenhouse to monitor the amount of daylight entering through the glazing (shown below in Figure 3). If there was enough daylight, the software dimmed the LEDs to prevent the DLI from being exceeded and calculated how much energy this saved every month. The data was automatically logged and periodically uploaded to the cloud.

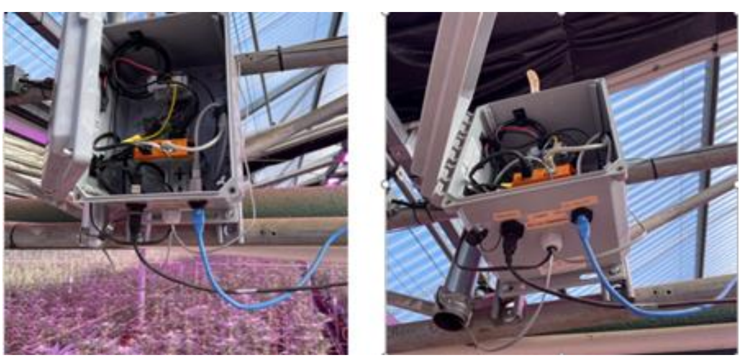

Figure 2. Lighting controls box installed above the test area
Source: Project Team

[2] https://www.etcc-ca.com/reports/controlled-environment-horticulture-ceh-field-study-adaptive-daylighting-controls

Figure 3. Apogee sq-420 photosensor for measuring available natural light

Source: Project Team

As it had done for PG&E, the Project Team also continued collecting load data at the electrical panels for the test and control areas. The Project Team visited the site on November 4, 2022, to download the logger data that had been recorded since October 2021.

Results

The Project Team compared the software's energy savings estimates from August 2022 and September 2022 with those of prior months. The key finding, confirmed after the December interview with the test site's Vice President of Cultivation, was that the savings estimates were incorrect because the photoperiod parameter had not been updated throughout the project. For each grow cycle, the photoperiod was 24 hours for two weeks and then 13 hours for approximately six weeks. Staff had set the photoperiod to 24 hours during initial training and left it unchanged. Although it would have been possible to manually correct the dataset and re-construct the analysis, this would have been too labor-intensive for the lighting controls vendor to accomplish during this project's time frame.

In October 2022, the site made changes to its IT infrastructure that prevented further data from being uploaded to the cloud. Therefore, the Project Team did not receive monthly savings analysis for October and November as planned. However, the site's DLI target of 50 mol/m^2/day was so high that during those months, no dimming occurred, so the data was not critical.

The reason to roughly estimate statewide savings potential in the PG&E study was to understand if the opportunity was large enough to consider developing a deemed measure. During this project, it became clear that adaptive lighting controls are not suitable for a deemed measure. Implementation is highly dependent on user behavior, making it too difficult to guarantee the technology will be used correctly or consistently. As detailed in the Modeling and Discussion sections, the Project Team decided to investigate how much could be saved at a single facility, to understand if adaptive controls could be incentivized through custom projects implemented by third parties.

Grower's Observations of Crop Yield and Quality

Methodology

The methodology was to collect qualitative data from site staff regarding any differences in quality and yield between the test and control areas.

Results

As detailed in the PG&E report, there were no times during that study when the test area lights were significantly dimmed. For this study, the Project Team had intended to collect yield and quality data for at least October 2022 and November 2022. However, due to the high DLI target, there was no significant dimming during these months either.

In theory, the only difference between the test and control areas should be that the target DLI in the test area would not be exceeded on days with high natural light. Therefore, crop and yield would only be harmed if the software worked incorrectly, or the settings were not input correctly.

In conversations with its lighting controls vendor, the Project Team realized many growers do not have a target DLI. Developing this requires also setting targets for other growing parameters. Therefore, one of the key benefits of lighting controls is to gain more control of the growing process.

Following are some suggestions for future studies:

- Rather than ask if yield and quality are affected if the target DLI is not exceeded, study how growers change their behavior to adopt a target DLI. Unlike warehouse operations, which use 100 percent artificial light, many greenhouse operations do not have experience using a target DLI, because they have not had the tools to do so.
- Study how to provide real-time, remote measurement and verification of actual dimming, so that growers can have confidence the proper dimming is taking place.
- Use smaller test areas so that growers are willing to allow significant differences in lighting levels compared to the control areas. The test area provided by the site in this study was over 9,000 square feet. However, a vendor contacted at the end of the study recommended using just 1,000 square feet. This would also greatly simplify data collection.
- Work with sites that are more able to engage in the study regarding the user experience of working with the adaptive controls, to understand how to build trust in the technology.

Modeling

As explained in the prior section, the Project Team was not able to collect actual energy savings data from the test site. Therefore, the Project Team created a model to identify the times that dimming might occur based on photoperiod parameters, published monthly average daily light integral (DLI), and estimates of glazing transmittance. It could then apply to other crops as well to provide a more general understanding of savings potential.

Methodology

Savings occur when the controls dim the lights so crops do not receive more light than the target DLI. Savings are calculated by comparing the energy used with dimming compared to the energy that would have been used if the lights had operated at full intensity during the entire photoperiod. The Project Team used the photosensor data from the test site, correct grow cycle parameters, and actual monthly energy costs to create a model of estimated savings and gain a clear understanding of savings potential at the site.

The types of crops for which controls would generate the most savings are those that have high DLI targets. Cannabis is the prime example, with a DLI of about 50 mol/m^2/day. However, other crops can have a target DLI of up to 30, as shown in Figure 4 and Table 1.

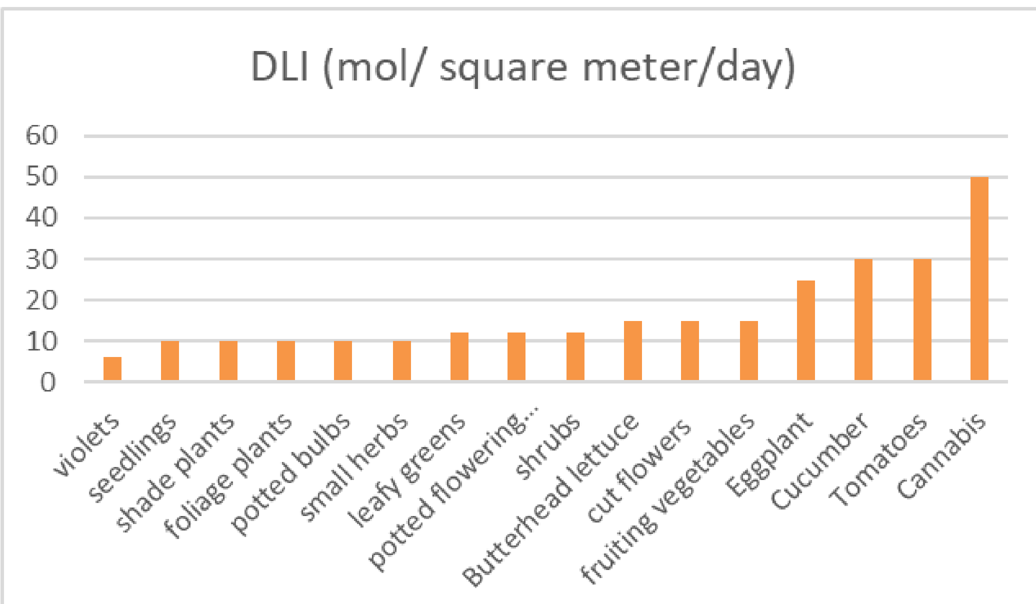

Figure 4. Comparison of Daily Light Integral (DLI) for Various Crops
Source: (LEDTonic 2021); (Hort Americas 2022); (Fluence 2022)

Table 1. Intensity of Horticultural Lighting Applications by Crop Type

Crop Type	DLI Target[24] (mol/(m2 day)	Horticultural Lighting Application
Cucumbers	15 - 30	Medium-High
Tomatoes	20 - 30	High
Peppers	20 - 30	High
Greens	12 - 17	Medium
Herbs & Microgreens	12	Low-Medium
Strawberries	17 - 20	Medium
Mushrooms	2 - 3	Low
Floriculture	2 - 30	Low-High

Source: Best Practices Guide, RII, Table 5

For modeling purposes, it is assumed the greenhouse has installed sufficient lighting to reach the DLI target during the longest photoperiod in December, which is the shortest month. As the days get longer, the lights can be dimmed to make a difference. See Table 2 for key modeling assumptions and Table 3 for average DLI values in the test site area (from monthly DLI maps for the grower's nearest city, which are based on solar radiation data 1998-2012).

Table 2. Key Modeling Assumptions

Item	Notes
Number of fixtures	Cannabis: 336 fixtures. No surplus light for most of year. Dimming only occurs during 8 weeks. Tomatoes: 200 fixtures. Dimming occurs during 17 weeks.
Week	Assumed actual growing four weeks per month (48 weeks/year)
Natural outdoors DLI	From monthly DLI maps for city nearest the site, which are based on solar radiation data 1998-2012.
Average percent entering greenhouse (transmittance)	Annual average calculated from outdoor DLI and site photosensor data
Natural DLI inside greenhouse (mol/m²/d)	Average of photosensor data installed by lighting controls vendor for PG&E field study
Supplemental DLI to reach target (mol/m²/d)	Target DLI - Natural DLI inside greenhouse
Percent of full power needed to reach target DLI during photoperiod	(Hours of LED at full power to reach DLI) / (photoperiod hours) It is assumed the lights would be on at the same intensity during the entire photoperiod, and the costs are calculated using the average monthly $/kWh. This is conservative because in practice, the lights could be on at higher intensity when electricity was less expensive.
Base case energy usage: LEDs on at 100 percent intensity during entire photoperiod (kWh/day)	Assume baseline is on/off switch and a timer. Some greenhouses may already use scheduled dimming, so their base case energy usage would be lower. However, adaptive controls can deliver much more precise DLIs than scheduled dimming because the amount of natural light inside the greenhouse can change considerably from day to day. See discussion of Table 5.
Avg cost of electricity ($/kWh)	Average monthly cost from test site

Source: Project Team, test site

Table 3. Average Outdoor Daily Lighting Integral (DLI) values for city nearest to the test site

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Avg Outdoor DLI	19	23	34	43	49	51	48	43	38	30	21	17

Source: https://myutk.maps.arcgis.com/home/webmap/viewer.html?useExisting=1

Results

Modeled savings for test site growing cannabis

Most of the test site's excess lighting occurred when the photoperiod was 24 hours, and the days were long. As shown in the highlighted columns of Table 4, there were savings for two weeks in March, six weeks in May-June, two weeks in July, and two weeks in September. During other times there was not enough light to reach the DLI target and so there was no dimming. The most dimming occurred in July when savings were $2,913 per week. Total savings for the year were 9 percent.

Table 4: Model Results for Cannabis

Wattage of one fixture	400
PPF of one fixture (µMo/s)	1005
Canopy area of test bay (m2)	851
Number of fixtures in test bay	336
kW at full power in test bay	134.4
Canopy area of test bay (ft2)	9152
Photon flux capacity of all lamps (mol/hr)	1216
Glazing transmittance	63%
Target DLI (mol/m²/d)	50

Table 4: Model Results for Cannabis Continued

Get Max LED PPFD (mol/m2/hr)

PPF of one fixture (µMo/s)	1005
Number of fixtures in test bay	336
Canopy area of test bay (m2)	851
Max LED PPFD (µMo/m2/s)	397
Max LED PPFD (mol/m2/hr)	1.43

Table 4: Model Results for Cannabis Continued

Annual Savings Estimate (48 weeks)

Month	Jan	Jan	Feb	Mar	Mar	April	May	May	June	July	July	Aug	Sept	Sept	Oct	Nov	Nov	Dec
Weeks of grow cycle	1-2	3-4	5-8	1-2	3-4	5-8	1-2	3-4	5-8	1-2	3-4	5-8	1-2	3-4	5-8	1-2	3-4	5-8
Week of grow cycle (1-8)	1	3	5	1	3	5	1	3	5	1	3	5	1	3	5	1	3	5
Week	1	3	1	1	3	1	1	3	1	1	3	1	1	3	1	1	3	1
Photoperiod (hrs)	13	24	13	13	24	13	13	24	13	13	24	13	13	24	13	13	24	13
Target DLI (mol/m²/d)	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Outdoor Sun DLI	19	19	23	35	35	43	49	49	51	48	48	44	38	38	30	21	21	17
Average % entering greenhouse (transmittance)	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%
Sun DLI inside greenhouse (mol/m²/d)	11.7	11.7	14.7	22.0	22.0	27.3	31.0	31.0	32.2	30.0	30.0	27.6	24.0	24.0	18.9	13.5	13.5	10.6
Supplemental DLI to reach target (mol/m²/d)	38.3	38.3	35.3	28.0	28.0	22.7	19.0	19.0	17.8	20.0	20.0	22.4	26.0	26.0	31.1	36.5	36.5	39.4
Hrs/day of LEDs at full power to reach target DLI	26.8	26.8	24.7	19.6	19.6	15.9	13.3	13.3	12.4	14.0	14.0	15.7	18.2	18.2	21.8	25.5	25.5	27.5
% of full power needed to reach target DLI during photoperiod	206%	112%	190%	151%	82%	122%	102%	55%	96%	108%	58%	120%	140%	76%	168%	196%	106%	212%
Base case energy usage: LEDs on at 100% intensity during entire photoperiod (kWh/day)	1747	3226	1747	1747	3226	1747	1747	3226	1747	1747	3226	1747	1747	3226	1747	1747	3226	1747
Base case energy usage: LEDs on at 100% intensity during entire photoperiod (kWh/week)	12230	22579	12230	12230	22579	12230	12230	22579	12230	12230	22579	12230	12230	22579	12230	12230	22579	12230
Energy usage with adaptive controls (kWh/day)	1747	3226	1747	1747	2635	1747	1747	1787	1671	1747	1883	1747	1747	2441	1747	1747	3226	1747
Energy usage with adaptive controls (kWh/week)	12230	22579	12230	12230	18447	12230	12230	12507	11694	12230	13183	12230	12230	17090	12230	12230	22579	12230
Estimated savings (kWh/week)	0	0	0	0	4133	0	0	10072	536	0	9396	0	0	5489	0	0	0	0
Avg cost of electricity ($/kWh)	$0.17	$0.17	$0.19	$0.19	$0.19	$0.20	$0.20	$0.20	$0.26	$0.31	$0.31	$0.32	$0.33	$0.33	$0.24	$0.20	$0.20	$0.19
Base case energy cost ($/week)	$2,079	$3,838	$2,324	$2,324	$4,290	$2,446	$2,446	$4,516	$3,180	$3,791	$7,000	$3,914	$4,036	$7,451	$2,935	$2,446	$4,516	$2,324
Savings ($/week)	$-	$-	$-	$-	$785	$	$	$2,014	$139	$	$2,913	$	$	$1,811	$	$	$	$
Base case usage (kWh/yr)	674,554																	
Estimated savings (kWh/yr)	60,324																	
Base case energy cost ($/yr)	$165,957																	
Estimated savings ($/yr)	$15,605																	
Estimated % savings	9%																	

Source: Project Team

For the base case energy usage, it was assumed the site would run its LEDs at 100 percent intensity during the entire photoperiod. Some greenhouses may already use scheduled dimming, so their base case energy usage would be lower. However, adaptive controls can deliver much more precise DLIs than scheduled dimming because the amount of natural light inside the greenhouse can change considerably from day to day. The grey bars in Table 5 show the daily amounts of natural light inside the test site greenhouse. July had fairly consistent light each day, but June and August did not. Therefore, even if the base case includes scheduled dimming, it would likely be conservatively programmed to ensure sufficient light for overcast days. Adaptive controls could still deliver significant saving.

Table 5: Variations in Natural DLI Inside the Test Site Greenhouse

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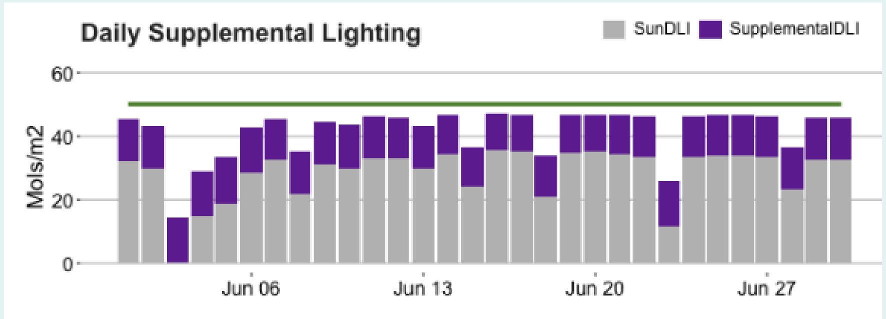

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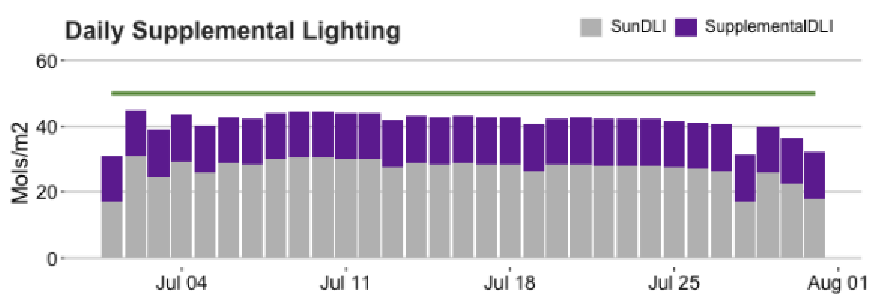

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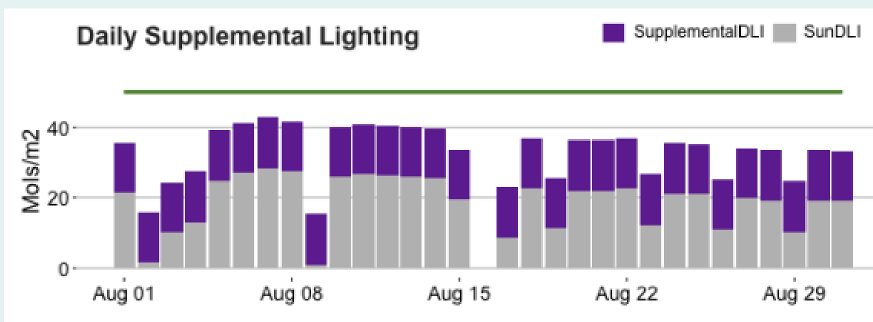

Source: Project Team

While the model may overestimate savings in kWh by not accounting for scheduled dimming, the $15,605 savings are underestimated because it assumed constant lighting intensity and an average monthly cost per kWh. In reality, the lights would be on at higher intensity when electricity was cheaper. The test site's equipment cost for the 9,100 sq ft test area was $5000, but assuming a total cost, including installation and training, of $10,000, the simple payback is under one year.

Transmittance is a major driver of how much energy can be saved from adaptive controls. The higher the transmittance for the same DLI, the more opportunity there will be for dimming. Table 6 shows that annual savings potential increases from 9 percent to 25 percent as transmittance values increase from 63 percent and 80 percent at a target DLI of 50. The test site shared with the Project Team that if it improved transmittance, it would probably raise its DLI target even higher- even though 50 is already high and raising it further would likely require supplemental CO_2 and other process changes. A higher DLI would reduce savings from adaptive controls since there would be less dimming, as shown in Table 6 for a DLI of 55.

Table 6. Modeled Effect of Glazing Transmittance on Savings Potential (Cannabis Test Site)

	DLI = 50			DLI = 55		
Glazing Transmittance	Modeled Annual Savings (%)	Annual savings, kWh	Annual utility bill savings ($)	Modeled Annual Savings (%)	Annual savings, kWh	Annual utility bill savings ($)
63%	9%	60,324	$15,605	5%	31,845	8,266
70%	14%	91,872	$23,661	7%	47,499	12,305
75%	19%	123,416	$31,830	10%	64,467	16,655
80%	25%	160,603	$41,357	22%	87,787	22,609

Source: PG&E Report, Table 3

Modeled savings if test site grew tomatoes

The Project Team also applied the model to tomatoes, using parameters found through an online search and confirmed by CABATech in January 2023. The DLIs for tomatoes vary throughout the grow cycle but the photoperiod does not, as seen in Table 7. Per Table 8, if the test site grew tomatoes instead of cannabis, it would only need about 200 lights to meet the target DLI for the same test area.

Table 7. Grow Cycle Assumptions for Cannabis and Tomatoes

	Cannabis		Tomatoes		
	Vegetation	Flowering	Propagation	Vegetation	Fruit/Flower
Photoperiod	24	13	16	16	16
DLI (mol/m²/d)	50	50	20	30	26
Weeks	2	6	3	4	9
Grow cycles/year	6		3		

Source: Test site, correspondence with CABATech on January 17, 2023.

Table 8. Modeling Parameters for Cannabis and Tomatoes

	CANNABIS	TOMATOES
Wattage of one fixture	400	400
PPF of one fixture (µMo/s)	1005	1005
Canopy area of test bay (m2)	851	851
Number of fixtures in test bay	**336**	**200**

Source: Project Team

As shown in Table 9 for tomatoes, full lighting capacity was needed in February and December, but dimming was needed in January, February, March, October, and November. From April to September, no supplemental lighting was needed. The most dimming occurred in March when savings were $1,200 per week because only 30 percent of lighting capacity was needed. Total savings for the year were 11 percent. As discussed above, they would not be as high if the grower had already used scheduled dimming. Assuming the same $10,000 cost for equipment and training as for cannabis, the simple payback is also under one year.

Table 9: Model Results for Tomatoes

Wattage of one fixture	400
PPF of one fixture (μMo/s)	1005
Canopy area of test bay (m2)	851
Number of fixtures in test bay	200
kW at full power in test bay	80
Canopy area of test bay (ft2)	9152
Photon flux capacity of all lamps (mol/hr)	1216

Glazing transmittance	63%
Target DLI (mol/m²/d)	20-30

Table 9: Model Results for Tomatoes Continued

Get Max LED PPFD (mol/m2/hr)

PPF of one fixture (μMo/s)	1005
Number of fixtures in test bay	200
Canopy area of test bay (m2)	851
Max LED PPFD (μMo/m2/s)	236
Max LED PPFD (mol/m2/hr)	0.85

Table 9: Model Results for Tomatoes Continued

Annual Savings Estimate (48 Weeks)

Month	Jan	Feb	Feb	Mar	April	May	June	June	July	Aug	Sept	Oct	Oct	Nov	Dec
Weeks of grow cycle	1-4	5-7	8	9-12	13-16	1-4	5-7	8	9-12	13-16	1-4	5-7	8	9-12	13-16
Photoperiod (hrs)	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Target DLI (mol/m²/d)	20	30	26	26	26	20	30	26	26	26	20	30	26	26	26
Outdoor Sun DLI	19	23	23	35	43	49	51	51	48	44	38	30	30	21	17
Average % entering greenhouse (transmittance)	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%	63%
Sun DLI inside greenhouse (mol/m²/d)	11.7	14.7	14.7	22.0	27.3	31.0	32.2	32.2	30.0	27.6	24.0	18.9	18.9	13.5	10.6
Supplemental DLI to reach target (mol/m²/d)	8.3	15.3	11.3	4.0	-1.3	-11.0	-2.2	-6.2	-4.0	-1.6	-4.0	11.1	7.1	12.5	15.4
Hrs/day of LEDs at full power to reach target DLI	9.8	17.9	13.2	4.7	N/A	N/A	N/A	N/A	N/A	N/A	N/A	13.1	8.4	14.6	18.1
% of full power needed to reach target DLI during photoperiod	61%	112%	83%	30%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	82%	52%	92%	113%
Base case energy usage: LEDs on at 100% intensity during entire photoperiod (kWh/week)	8960	8960	8960	8960	8960	8960	8960	8960	8960	8960	8960	8960	8960	8960	8960
Energy usage with adaptive controls (kWh/week)	5490	8960	7416	2646	8960	8960	8960	8960	8960	8960	8960	7333	4699	8204	8960
Estimated savings (kWh/week)	3470	0	1544	6314	0	0	0	0	0	0	0	1627	4261	756	0
Avg cost of electricity ($/kWh)	$0.17	$0.19	$0.19	$0.19	$0.20	$0.20	$0.26	$0.26	$0.31	$0.32	$0.33	$0.24	$0.24	$0.20	$0.19
Base case energy cost ($/week)	$1,523	$1,702	$1,702	$1,702	$1,792	$1,792	$2,330	$2,330	$2,778	$2,867	$2,957	$2,150	$2,150	$1,792	$1,702
Savings ($/week)	$590	$-	$293	$1,200	$-	$-	$-	$-	$-	$-	$-	$391	$1,023	$151	$-
Base case usage (kWh/yr)	403,200														
Estimated savings (kWh/yr)	54,414														
Base case energy cost ($/yr)	$100,352														
Estimated savings ($/yr)	$11,323														
Estimated % savings	11%														

Source: Project Team

Outreach to Other Growers and Industry Stakeholders

The Project Team did outreach for this project from November 2022 through January 2023. The objectives were to collect reactions to the PG&E report, connect with potential participants for an expanded study, and assess the required resources. The PG&E report was not released until January 17, and by then the Project Team had modified its recommendations. When the Project Team asked for feedback on the PG&E report, the main objective was to get opinions on changing the approach for future studies from a deemed measure package to NMEC (see Table 13).

Initial Outreach

As part of Energy Solutions' code advocacy work for the 2025 Title 24 code cycle, a member of the Project Team attended the Resilient Harvests conference November 1-3, 2022. This activity was not funded by CalNEXT. However, it allowed the Project Team to make many connections that it could later use for stakeholder feedback (see Table 13). The Project Team conducted outreach to lighting control vendors as in Table 10 and began connecting with potential other study sites as in Table 11. At the time of this outreach, the Project Team was still envisioning a study to support a deemed measure package, but emails did not mention specific incentives for participation or timing.

Table 10. Sample of Outreach Emails to Vendors

Email Recipient Group	Email Text
To potential lighting controls vendors:	We are planning a study for the California investor-owned utilities to see if they should incentivize adaptive daylighting controls for greenhouses. These controls measure how much light a greenhouse receives each day and adjust the amount of supplemental light, so crops get the exact amount growers specify, and growers don't waste any money by over lighting. Does (insert vendor name) have a product that could provide this control, and if yes would you like to learn more about this study proposal? Please let us know your level of interest as **High**, **Moderate**, or **Low.** The level of interest we receive will help determine if the study should be designed and funded. We have run one site so far (cannabis greenhouse), but we're looking to expand to other locations and crops.

Source: Project Team

Table 11. Sample of Outreach Emails to Identify Potential Other Study Sites

Email Recipient Group	Email Text
Request for introductions to potential sites:	We are planning a study for the California investor-owned utilities to see if they should incentivize adaptive daylighting controls for greenhouses. These controls measure how much light a greenhouse receives each day and adjust the amount of supplemental light, so crops get the exact amount growers specify, and growers don't waste any money by over lighting. Do you have any customers who might be interested in participating in a study like this? The level of interest we receive will help determine if the study should be designed and funded. We have run one site so far (cannabis greenhouse), but we're looking to expand to other locations and crops. Let me know if you can think of anyone interested in participating.

Source: Project Team

The Project Team contacted nine vendors, as listed in Table 12. Six of these reported a high level of interest in adaptive controls. These vendors could have connections with potential sites for future study. The Project Team also presented a summary of its work at the 2022 CalNEXT Projects 2022 Summit on November 29, 2022, which led to introductions to Agxano and CABATech through a member of the audience.

Table 12. Summary of Outreach Results

Vendor	Interest Level and Notes	
Agnetix	High	Mentioned a trend towards higher DLI's to boost yield.
Current Lighting	High	Proposed a follow-up call to discuss.
Fluence	High	Although they don't have a controls product that meets the project's requirements, they are highly interested in the progress of future studies.
Hawthorne	No response	
Kubo Greenhouses	High	Offered to connect us with Acrobat Projects and Anchor Hydro, two firms that he works with on greenhouse construction and design.
Ultra Yield Solutions	Moderate	Proposed a follow-up call to discuss.
Netafim	High	Interested in exploring an NMEC pilot.
Agxano	High	Provides machine learning solutions for CEH.
CABATech	High	Developed of spectral lighting technology to increase yields while lowering overall energy consumption. In strategic partnership with Agxano.
TRC	High	The engineering firm that occasionally works on projects with Energy Solutions and is interested in collaborating with Energy Solutions to help Agxano propose a project through CalNEXT.

Source: Project Team

Sample Outreach Conversation: Agnetix

Agnetix alluded to research showing that cannabis growth has a linear correlation with DLI up to 80 mol/m2/day. This is very high, which the Project Team had not encountered previously. Such an increase in yield would also require other process changes, such as supplemental CO_2, and it is not clear how many greenhouse growers currently use this. Agnetix also suggested that other crops have also been bred to use more fertilizer, water, and light to grow more quickly. This is the perspective of a lighting manufacturer, so may be biased towards more lighting capacity. However, it could be a trend that makes horticulture even more energy-intensive, which would increase the need for adaptive controls.

In addition, Agnetix reported measuring light levels inside greenhouses up to 50 percent lower than outside levels. This is consistent with the 63 percent average transmittance the Project Team estimated at the PG&E test site. As shown through modeling, the transmittance is a key factor. The Project Team has had conversations with growers that use single-pane glass and obtain a summer DLI of up to 50. Glazing upgrades could be a significant source of savings as well. Since it increases the amount of light entering the greenhouse, it could also increase the need for adaptive controls.

Outreach for Feedback on Draft CalNEXT Report

Once the PG&E report was published, the Project Team launched a second wave of outreach to get feedback on the draft of this report, especially on the use of NMEC strategies instead of a deemed measure package. Table 13 shows the parties that were contacted, and a sample outreach email.

Table 13: Feedback Requests for Draft CalNEXT Report

Outreach Destination (Marked with an asterisk * if a response was received)	Sample Email
2050 Partners	We recently published a report for PG&E, CEH Adaptive Lighting Control Final Report, that was posted to the Emerging Technologies Coordinating Council (ETCC) Site on January 17. Also, we submitted the attached draft report to CalNEXT on January 20. We were able to sharpen our conclusions between the first and second reports- please see the yellow highlights below from the CalNext report's Executive Summary. Should you have any time to provide feedback on the summary below or the CalNEXT report itself, we would very much appreciate it.
Agnetix	
Agxano	
CABA Tech*	
CLTC, UC Davis*	
Current lighting*	
DemeGrow	
Fluence	
Harborside / Statehouse	
Hawthorne Gardening Company	
Kubo Greenhouses*	
Netafim	
PG&E	
RII*	
Seinergy*	
TRC*	
Ultra Yield Solutions	

Source: Project Team

Table 14 provides the key feedback received, and the most important learnings are presented below:

- There was widespread agreement that NMEC approaches would be better than a deemed measure package.
- Projected savings for NMEC project applications are likely to require assumptions for scheduled dimming as standard practice. The Project Team, therefore, clarified that NMEC projects should integrate several other measures as well to ensure projected savings over 10 percent of annual consumption.
- The results produced by the Project Team's model appear consistent with the model that CABA TECH developed.
- There is a lack of consensus on how to set DLI targets for cannabis, reflecting a wide range of growing practices.
- Glazing improvements could be a significant source of energy savings for greenhouses as well.
- Project teams should be aware that growing processes and attitudes may differ significantly between growers of cannabis and of other crops.

Table 14. Summary of Stakeholder Feedback on Draft CalNEXT Report

Stakeholder	Key Feedback
2050 Partners	The idea to focus on NMEC rather than a deemed measure makes a lot of sense. I understand what you are saying about the difficulty and limitations of developing savings estimates to support a deemed measure package, as well as the potential behavioral factors that could undermine the actual savings if the facility manager didn't have a vested interest in demonstrating those savings after the technology was installed and rebate check cashed. This seems like a good candidate for the NMEC approach, especially if vendors and/or growers are willing to stomach some of the financial risks of waiting to verify savings.
CABA Tech	I think the model is very good, I would have a "target DLI" for the customer to provide if they have one, then populate the savings via that. Very similar to the analysis we perform for our clients. It's funny that they pushed to 50DLI, as there was no mention of C02 supplementation and PPM concentrations. I have run 50DLI rooms before and we had to push the C02 to >1500PPM before we saw increased bioactivity in the cultivars. I had to evacuate the C02 before we could allow gardeners into the room for safety reasons. We did not see an increase in yield commensurate with the added expense.

Stakeholder	Key Feedback
CLTC, UC Davis	Would be interested in seeing a cost estimate for this site specifically for updating glazing compared to the energy savings for LCA analysis to understand if it should be added to the list of recommended next steps for further evaluation. If there is an overlap on CalNEXT where CLTC would be useful, let us know.
DemeGrow	On behalf of the team over here I can share that we do generally support the conclusions you have presented. I know we each could feel the pain your team experienced as you had to work around the complexities of remote location connectivity, new technology introduction, staff training, and turnover, etc. I'm sure you gained some appreciation—in defense of the growers out there—that the task of wrestling a fickle mother nature over the delivery of a good crop rivals the complexity of many industrial operations, even indoors! These growers have a lot on their hands and stepping into the heart of this process is a little different than putting a daylight harvesting sensor in a window office. I think our perspective, having worked with growers in many circumstances and environments, is that with the proper attention and support, they can quickly master a new protocol.
Current Lighting	The reports are very well written, the author draws logical conclusions based on data and application reality, they are open-minded to grower's practice, explored energy saving potential from adaptive lighting control, and correctly pointed out the potential benefits of adaptive lighting control for load shedding and demand response. I have three comments: 1. There are clear marketing demand for dimming capability, majority of LED fixtures (~90 percent?) in horticulture segment do offer dimming. 2. Even though LED lighting has significantly increased its market share in the past several years, HPS and other traditional lighting technologies are still dominant. There is still a long runway to go for LED lighting to reach 50 percent of horticulture lighting market share. Promote greenhouse adaptive lighting control and LED lighting technology will accelerate the adoption of this energy-saving technology. 3. Many greenhouses have their own electricity generation capability built on-site to deal with electricity fluctuations or utility demand response. One of the largest greenhouse in the Cleveland area - Green Circle Growers – has such capability. I have no question that adaptive lighting control can facilitate demand response, it has to be managed so that doing so won't hurt plant growth and production yield.

Stakeholder	Key Feedback
Kubo Greenhouses	I have reviewed your report and discussed it with some colleagues that are major players in the produce industry. In general – we share the same thoughts – that this program appears to be driven by cannabis, and perhaps indoor (vertical) farming. The lights that have been trialed would never be used in floriculture or vegetable production, which will heavily skew (if not invalidate) the conclusions that have been drawn. For this reason - I would recommend splitting this into two pieces (separate cannabis). Traditional growers will not take this document seriously.
Resource Innovation Institute (RII)	I agree with their findings that by simply having access to light data, growers can realize a practical benefit, even without a full comprehension of the smart programming. At Purdue, when we switched from using on/off timers for lighting to Priva-controlled relays that operated off PAR intensity, we immediately saved 33 percent energy and became more aware of seasonal light than we had been before--particularly how much light we were receiving in early spring, though the air temperature made it still feel like winter to our senses. I also agree with their findings that they may need to find a more suitable partner who will dedicate more time and, frankly, demonstrate more curiosity and commitment. If commercial yield is no longer going to be measured, there is no reason why a university or community college couldn't be a partner, and they typically have small, independent growing zones, each with identical equipment
Seinergy	Good write-up; well organized and explained. Overall, I don't have much to comment on. I think this is validating that savings from daylighting controls are definitely not a sure bet (and should be rejected in any code proposal), but that they probably present some promise in low DLI crops and the summertime.
TRC	Based on our program experience and market assessment efforts, which may be biased toward cannabis growers, we are under the impression that basic dimming controls (i.e., scheduled dimming) for new LEDs may be standard practice (SP). Your report assumes "LEDs on at 100 percent intensity during the entire photoperiod" for the baseline. Since programs only pay for savings above SP, the Ag program would be forced to compare adaptive dimming controls to a standard dimming baseline. Assuming scheduled dimming for the baseline could reduce the savings impacts below the typical >=10 percent savings requirement for the site-specific NMEC approach.

Source: Project Team

From its outreach, the Project Team has high confidence there are vendors in the market that would be interested in further study. One such vendor would be Agxano. The Project Team had conversations with Agxano and its strategic partner CABATech on December 16 and 20, 2022, and on January 17, 2023. TRC, an engineering firm that occasionally works on projects with Energy Solutions and is a CalNEXT partner, also joined the January 17 call and expressed interest in collaborating with Energy Solutions to help Agxano propose a project through CalNEXT.

Discussion

The model the Project Team created provides a high-level understanding of when savings could be achieved and illustrates the most important variables: length and frequency of photoperiods for the vegetative and flowering phases, DLI target, outdoors DLI (subject to daily weather), indoor DLI (subject to glazing transmittance), and the cost of electricity at different times of the day. The Project Team hopes these results could be relevant to many greenhouse operators. Per conversations with a lighting controls vendor, many greenhouse operators may not currently use a target DLI at all, especially if they do have the tools to hit one.

Adaptive lighting controls could be a gateway to much more data-driven growing processes. For example, with lighting controls, it would be possible to schedule when flowers would bloom, based on when they were going to be shipped. As another example, Agxano's software compares the light inside the greenhouse with outside light and can alert growers when the glazing should be cleaned. In addition, some control systems allow the growers to change the lighting spectrum as crops grow, which could increase yield and/or quality.

In the past, fixtures that were not LEDs may have been a barrier because adaptive lighting controls require full dimming capability, which only LEDs provide. However, LED lighting is now becoming the baseline, so fixture type is no longer a significant barrier.

One goal of this study was to quantify the savings potential for adaptive lighting controls in greenhouses for the State of California. As the Project Team's model illustrates, the range of variables to describe the savings from reducing consumption is large – especially when behavioral variables are considered. In addition, there are three other sources of potential energy savings related to this technology, which could all be enabled by the same hardware:

1. Shifting energy usage away from peak times to reduce average energy cost
2. Shifting energy usage away from peak times to reduce demand charges
3. Participating in demand response programs and being paid to use less light during periods of critical grid load

Given this complexity, the Project Team did not attempt statewide savings potential calculations. However, they are not needed for the site-specific NMEC approach being recommended.

Recommendations

The recommendation in the PG&E report was to consider a larger study that would include two sites each for cannabis, food, and ornamentals to support a deemed measure package. To generate enough data for a measure package, the report suggested recruiting at least eight sites. However, this project for CalNEXT, by continuing the work started for the PG&E field study, allowed the Project Team to greatly increase its understanding, especially from its modeling work and outreach.

Rather than recommending a deemed approach, the Project Team recommends that further study concentrates on Normalized Metered Energy Consumption (NMEC) incentive models and that future projects be proposed and executed by the industry. Their goal would be to evaluate the potential of NMEC incentives to promote adaptive lighting controls and other energy efficiency measures in greenhouses.

This approach provides several advantages over a deemed measure package. First, with NMEC approaches, growers would only get incentives for actual savings measured at their meters, so they would be incentivized to use the technology. Growers would not be penalized for not using the technology; they just would not earn savings. Supplemental lighting, glazing transmittance, and environmental controls are highly connected. For example, if growers improved glazing transmittance, the daylighting controls might dim the lights more often. NMEC approaches would capture them all.

Second, NMEC approaches would only require projections showing that savings would be at least 10 percent of annual energy consumption. Estimates of deemed savings or of statewide savings potential would not be required.

Third, NMEC approaches would not be as dependent as a deemed measure on customers being sophisticated or proactive. They would leverage third parties and equipment vendors to influence growers' purchasing decisions and operational behaviors to use less energy.

The Project Team identified two firms interested in collaborating on a CalNEXT project to evaluate the potential of NMEC incentives to promote adaptive lighting controls. In addition, there are engineering firms, including Energy Solutions and TRC, who would be well-positioned to help them complete the CalNEXT application and advise on measurement and verification (M&V). Should this work result in projects that use NMEC successfully, it could help create a valuable source of energy savings for utilities as well as benefits to greenhouse operators and the electric grid.

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