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Energy Savings Potential of SSL in Agricultural Applications

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This report was prepared by:
Guidehouse, Inc.
1200 19th Street NW, Suite 700
Washington, DC 20036

Authors:
Kyung Lee, Guidehouse, Inc.
Clay Elliott, Guidehouse, Inc.
Morgan Pattison, SSLS, Inc.

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Patrick Rutan	Acreage Holdings
Roger Buelow	AeroFarms
Neil Yorio	BIOS Lighting
Gretchen Schimelpfenig	Burlington Electric Department
J.C. McCann	Burlington Electric Department
Jim Faust	Clemson University
Jake Martin	Dairy Design Engineers
Bryan Jungers	E Source
Jasmine Rivest	Efficiency Vermont
Lauren Morlino	Efficiency Vermont
Craig Metz	EnSave
Kyle Clark	EnSave
Steve Oster	Farm Ecology
Dung Duong	Fluence (Osram)
Steve Graves	Fluence (Osram)
Melissa Rickert	Focus on Energy
Steve Craker	Focus on Energy
Kathleen Sullivan Garman	Forever Green Indoors
Kevin Sullivan	Forever Green Indoors
Ricardo Campos	Fred C. Gloeckner & Company, Inc.
Erico Mattos	Greenhouse Lighting and Systems Engineering
Chris Higgins	Hort Americas
Zdenko Grajcar	Once (Signifiy)
Ian Burnside	PG&E
Derek Smith	Resource Innovation Institute
Dominic Chen	Sananbio
Jennifer Boldt	U.S. Department of Agriculture
Brian Fairchild	University of Georgia
John Bernard	University of Georgia
Michael Czarick	University of Georgia

Comments

The Energy Department is interested in feedback or comments on the materials presented in this document. Please write to Brian Walker, Lighting R&D Program Manager:

Brian J. Walker, Ph.D.
Lighting R&D Program Manager
U.S. Department of Energy
1000 Independence Avenue SW
Washington, D.C. 20585-0121

Executive Summary

This 2020 report presents the findings for agricultural lighting applications where light-emitting diode (LED) products are now competing with traditional light sources. The analysis broadly divided agricultural lighting into horticultural lighting and animal lighting. Indoor horticultural grow architectures can be further divided into three categories: lighting supplemented greenhouses, high intensity sole-source farms, and sole-source indoor vertical farms typically growing leafy greens. This report also analyzed, for the first time, animal lighting and its corresponding LED adoption and potential energy savings. To characterize animal lighting, the analysis investigated the three largest markets of livestock in the U.S. that use lighting – poultry, swine, and dairy farming.

To estimate energy consumption of agricultural lighting, the analysis utilized resources ranging from interviews with lighting manufacturers, growers, utility companies, academic professionals, and industry consultants, as well as various data sources. Each of these resources enabled the determination of total market size and illuminated area, typical lighting configuration, lighting power density (LPD) for LEDs and incumbent technologies, operating hours, and the installed lighting technology mix. Additionally, a theoretical "All LED" scenario was calculated in which all existing agricultural lighting was assumed to switch to LED lighting products at current performance levels as of 2019. The "All LED" scenario represents the technical potential of LED lighting in agricultural applications based on 2019 performance levels.

The summary results for the 2019 LED adoption and energy savings potential are provided below in Table E - 1 and Table E - 2. It is important to note that the findings of this study are current industry estimates as of the second quarter of 2019. The agricultural lighting market is changing and requires careful consideration of rapid improvements to LED performance and adoption, as well as overall market growth.

Table E - 1 Summary of Horticultural Lighting Analysis

Analysis Outputs	Units	Vertical Farming	Supplemented Greenhouse	High Intensity Sole-Source	Total[1]
Estimated Total Lit Grow Area	**Million ft²**	0.8	56.6	31.9	89.3
Annual Operating Hours	**Hours/year**	6,570	2,000	5,200	--
Average Electricity Consumption					
LED	**W/ft²**	15	7	35	--
HPS/MH		N/A	11	56	--
Fluorescent		23	N/A	5	--
2019 Technology Mix					
LED	**%**	100%	2%	11%	--
HPS/MH		0%	98%	86%	--
Fluorescent		0%	0%	3%	--
2019 Annual Energy Consumption					
Current	**GWh/year**	81	1,202	8,307	9,591
	(tBtu/year)[3]	(1)	(11)	(79)	(92)
Theoretical "All LED"		81	832	5,395	6,307
		(1)	(8)	(52)	(60)
Theoretical % Lighting Energy Savings[2]	**%**	0%	31%	35%	34%

1. Values may not add due to rounding.
2. The theoretical percent energy savings given current technologies were all converted to LEDs, which is the percent difference in energy consumption of the Current and the Theoretical “All LED” scenarios. (Note percent energy savings are calculated from raw data, as opposed to rounded values presented in the table and, therefore, may not match.)
3. tBtu values given in this table are representative of source energy. Source energy consumption is calculated by multiplying site electricity consumption by a source-to-site conversion factor of 2.80 [34].

The major findings for indoor horticultural lighting include the following:

- If all horticultural lighting today was converted to LED technology, annual horticultural lighting consumption would be reduced to 6.3 TWh of site electricity, or 60 tBtu of source energy, which represents lighting energy savings of 34% or $350 million annually.
- In terms of grow area, supplemented greenhouses have the largest total area, at 56.6 million square feet (ft^2), followed by high intensity sole-source farms at 31.9 million ft^2, and lastly 0.8 million ft^2 for vertical farms.
- Based on current performance, for supplemented greenhouse and high intensity sole-source farms, LED lighting offers a 31% to 35% reduction in site electricity consumption per ft^2 of grow area compared to conventional lighting technologies.
  - High intensity sole-source farms employ the most energy intensive lighting, with incumbent technology using about 56 Watts (W) per ft^2 (W/ft^2) of site electricity and LED lighting consuming 35 W/ft^2.
  - LED lighting in vertical farms consumes an estimated 15 W/ft^2.
  - Supplemented greenhouses, which use sunlight as the primary light source, have the lowest site electricity consumption per ft^2 of electric lighting with high-intensity discharge (HID) lighting consuming 11 W/ft^2 and LED lighting consuming 7 W/ft^2.
- In 2019, vertical farms have the highest adoption of LED lighting, with virtually 100% LED adoption in commercial vertical farms, while LED products make up only 2% of lighting supplemented greenhouses and 11% of lighting in high intensity sole-source farms.

- Both vertical and high intensity sole-source farms rely solely on electric lighting and, as a result, require long operating hours, averaging 6,570 and 5,200 hours per year, respectively. Electric lighting used to supplement sunlight in greenhouses is operated an average of 2,000 hours per year.
- In 2019, horticultural lighting installations in the U.S. consumed 9.6 terawatt hours (TWh) of site electricity, which is equivalent to 92 trillion Btu (tBtu) of source energy consumption.[1] Of this 9.6 TWh, 87% comes from lighting in high intensity sole-source farms, 13% from supplemental lighting in greenhouses, and less than 1% from lighting in vertical farms.

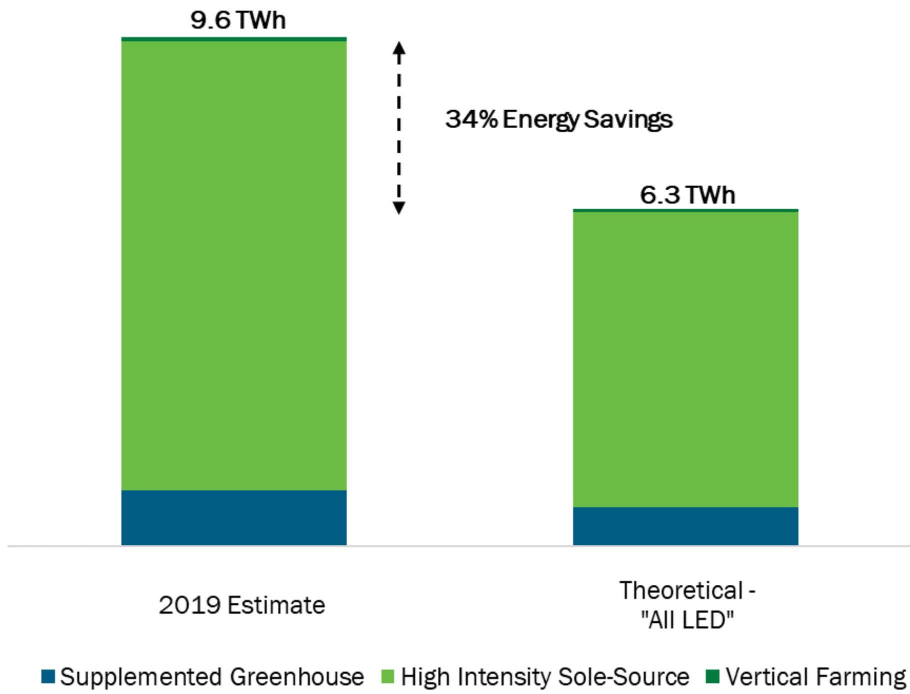

Figure E - 1 Annual Electricity Consumption of U.S. Horticultural Lighting. In 2019, it is estimated that horticultural lighting consumed 9.6 TWh of site electricity. If LED penetration were to reach 100%, this consumption is estimated to decrease to 6.3 TWh based on current market size and efficacy levels, representing potential lighting energy savings of 34%.

[1] Source energy consumption is calculated by multiplying site electricity consumption by a source-to-site conversion factor of 2.80. [34]

Table E - 2 Summary of Animal Lighting Analysis

Analysis Outputs	Units	Poultry - Broiler	Poultry - Layer	Dairy	Hog	Total[1]
Estimated Total Animal Count (million)	**Million**	8,890	368	10	235	9,503
Estimated Total Illuminated Area	**Million ft²**	2,387	1,105	715	835	5,042
Average Electricity Consumption						
LED	W/ft²	0.026	0.021	0.459	0.092	--
HPS/MH		0.029	0.024	0.693	0.139	--
Fluorescent		0.030	0.025	0.533	0.107	--
Incandescent		0.139	0.112	N/A	N/A	--
2019 Technology Mix						
LED	%	58%	26%	36%	47%	--
HPS/MH		0%	25%	22%	19%	--
Fluorescent		25%	23%	42%	34%	--
Incandescent		17%	25%	0%	0%	--
2019 Annual Energy Consumption						
Current	GWh/year	884	263	2,263	258	3,667
	(tBtu/year)[3]	(8)	(3)	(22)	(2)	(35)
Theoretical "All LED"		503	122	1,918	224	2,766
		(5)	(1)	(18)	(2)	(26)
Theoretical % Lighting Energy Savings[2]	%	43%	54%	15%	13%	25%

1. Values may not add due to rounding.
2. The theoretical percent energy savings given current technologies were all converted to LEDs, which is the percent difference in energy consumption of the Current and the Theoretical "All LED" scenarios. (Note percent energy savings are calculated from raw data, as opposed to rounded values presented in the table and, therefore, may not match.)
3. tBtu values given in this table are representative of source energy. Source energy consumption is calculated by multiplying site electricity consumption by a source-to-site conversion factor of 2.80 [34].

The major findings for indoor animal lighting include the following:

- If all animal lighting today was converted to LED technology, annual lighting energy consumption for animal production would be reduced to 2.8 TWh site electricity, or 26 tBtu of source energy, which represents lighting energy savings of 25% or $96 million.
- The poultry industry has the largest total illuminated area, with 2.4 billion ft² for broilers and 1.1 billion ft² for layers. The hog industry has an estimated 835 million ft² and the dairy industry has an estimated 715 million ft².
- As of 2019, broiler farms have seen the highest adoption of LED lighting, at 58%. LED products make up 47% of lights in hog production, 36% of the lights in dairy farms, and only 26% of the lights for layers.
- As of 2019, lighting installations for animal production in the U.S. consume 3.7 TWh of site electricity per year, which is equivalent to 35 tBtu of source energy consumption.[2] Of this 3.7 TWh, 60% comes from lighting in dairy farms, 24% from broilers, and 7% each from lighting in layers and hog facilities.

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[2] Source energy consumption is calculated by multiplying site electricity consumption by a source-to-site conversion factor of 2.80 [34].

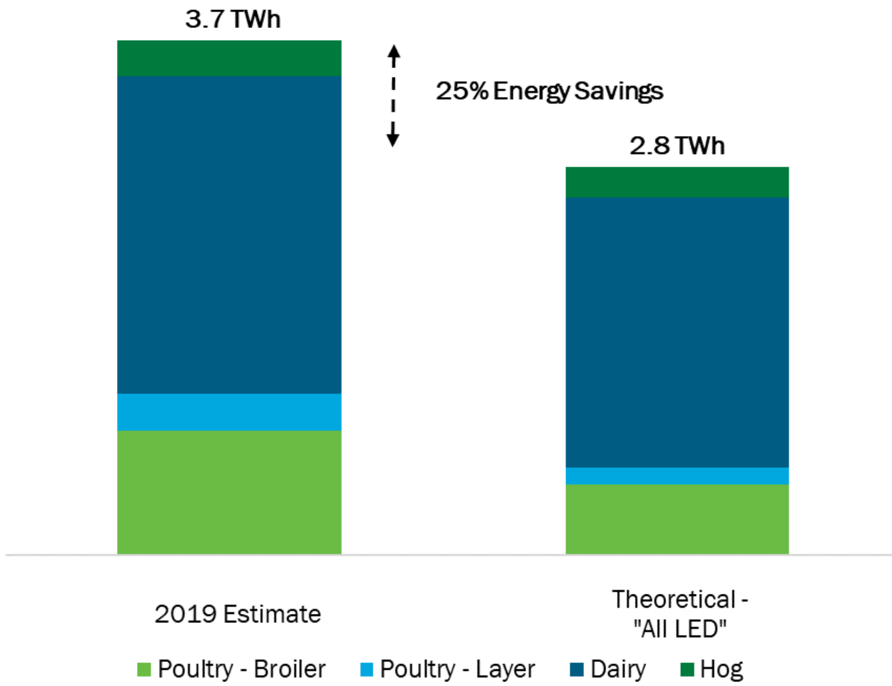

Figure E - 2 Annual Electricity Consumption of U.S. Animal Lighting. In 2019, it is estimated that animal lighting consumed 3.7 TWh of site electricity. If LED penetration were to reach 100%, this estimated consumption would decrease to 2.8 TWh based on current market size and efficacy levels, representing a 25% potential lighting energy savings.

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1 Introduction

Adoption of light-emitting diode (LED) lighting has continued to increase across all lighting applications since its commercial introduction. LED lighting has surpassed all conventional lighting technologies in terms of energy efficiency, lifetime, versatility, and color quality. Furthermore, due to improvements in manufacturing and increases in volume, LED products are cost competitive in most lighting applications. The Department of Energy (DOE) 2019 study, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications, forecasts that LED lighting will represent 84% of all lighting sales by 2035, resulting in annual primary energy savings of 4.8 quadrillion British thermal units (Btu). [1]

Since 2003, the DOE has evaluated the lighting applications where LED technologies are having the greatest energy savings impact. This study is an update to the 2017 report investigating the adoption and resulting energy savings of LED lighting in indoor horticulture applications. This updated report also investigated the characteristics of lighting for indoor animal agriculture in the United States.

This report aims to estimate the use of electric lighting in U.S. agricultural applications as well as the potential energy savings from LED lighting products by addressing the following three research questions:

1. What is the total area of controlled environment agriculture employing electric lighting in the U.S.?
2. What is the current installed stock and energy consumption of lighting technologies installed in indoor agricultural applications in the U.S.?
3. What is the theoretical energy savings potential if LED lighting achieved 100% penetration in the existing U.S. indoor agricultural applications?

Growing food is an energy and resource intensive process. In traditional field agriculture for crops, irrigation systems deliver water, various tools are used for applying pesticides, planting and harvesting, and finally transportation delivers produce from farm to store to table. Controlled environment agriculture (CEA), the production of plants and animals indoors can produce high value food at maximum productivity in an efficient and environmentally friendly way. [2] By employing CEA, also referred to as "indoor horticulture", growers can carefully and securely control plants to maximize their productivity and consistency in locations and at times when outdoor growth would be impractical and without the negative impacts of inclement weather and climate, pests, or other unpredictable factors. While indoor agriculture itself is not a new practice, electric lighting enabled a new method of food and crop production by supplementing sunlight in greenhouses or providing 100% of light to plants or animals grown in indoor farms. In the past decade, adoption of LED lighting for general illumination grew significantly, and the usage of LED lighting for indoor agriculture has followed.

Similar to field agriculture for crops, in traditional field agriculture for animals and livestock, animals are grown outdoors in large open areas and sometimes provided indoor shelter as necessary. Alternatively, most commercial production of animal protein in the U.S. now involves an indoor component. For example, broiler chicken farming is carried out in fully indoor production houses that mimic a free-range space that allow the animals to move around, feed, and interact. These facilities allow farmers to precisely control all aspects of the growing environment including photoperiod (the amount of light received per day), light spectrum, light intensity, humidity, temperature, bedding material, feed, and ventilation. Even for free range dairy farming, there is often an indoor shelter used to house them throughout certain parts of the day or during different times of the year.

The increased use of electric lighting in CEA systems has been driven by advancements in lighting technology that result in reduced lighting cost, as well as new understanding in plant and animal physiology. Discoveries have revealed that light regulates several plant attributes, including flowering, branching, plant height, biomass accumulation, plant immunity and defense, stress tolerance, and phytoceutical production. This can then influence various aspects of plant growth, such as the size of the plant, germination process, flowering, vegetation, and even nutritional value. [3] Similarly, light has a significant effect on animal welfare, animal lifecycle and development, and productivity. The full understanding of physiological responses to light for both plants and animals continues to be developed. Although adoption of LED lighting has been primarily driven by electricity savings, LEDs provide other benefits as well. LED lighting technology offers the unique ability to spectrally tune light sources to engage specific plant and animal light responses. In addition, LED lighting technology is more efficient and can be designed with a vast array of light output levels, optical distributions, and controls, which were not possible with previous lighting technologies.

Indoor horticulture enables cultivation of plants and animals to a level of control that was previously impossible. However, the energy implications of such systems can be significant, with the top two energy consuming aspects of indoor farming being heating, ventilation, and air conditioning (HVAC) and lighting electric loads. Stakeholder interviews indicated that on average, the electricity required for lighting in indoor farms for plants can be up to 50% of the total electricity consumption. In indoor animal production, electricity required for lighting constitutes up to 10% of the total energy required. The total electricity consumption from lighting depends on the source technology that is employed. This report explores the various modes of indoor agriculture for both plants and animals, including grow architectures for the plant cultivation and the various parts of the animal industry that involve a significant indoor component. It also describes four lighting technologies most commonly used in agricultural lighting: high intensity discharge (HID), fluorescent, incandescent, and LED.

2 Indoor Horticultural Lighting

2.1 Indoor Horticulture Grow Architectures

For the purposes of this analysis, indoor horticulture using electric lighting was separated into three categories, because each has their own unique lighting requirements and grow architecture. The three types of indoor horticulture operations are lighting supplemented greenhouses, high intensity sole-source farms[3], and sole-source vertical farms (hereafter referred to as "vertical farms"). The three architectures also require different lighting photosynthetic photon flux densities (PPFD), which results in different lighting power densities. These applications are described below and in terms of power density if LED lighting is used. Although there are different growing practices that do not readily fall into these categories, these categories describe the vast majority of growing applications.

Supplemented Greenhouses Structures enclosed by glass, rigid plastic, or a plastic film that are used for the cultivation or protection of plants. Supplemented greenhouses employ electric lighting to extend the hours of light provided to plants, supplement low levels of sunlight on days with inclement weather, and/or disrupt periods of darkness for purposes of altering plant growth. Because of the cost and environmental sensitivity of supplemental lighting technologies, **it is assumed that supplemental lighting is only used in permanent rigid plastic and glass greenhouse structures that operate year-round, and not in plastic film covered structures.** Typical crops grown are fruits, vegetables, and ornamental crops. Supplemental lighting is typically configured to provide about 200 μmol/m^2/s of PPFD using lights near the ceiling of the greenhouse that are designed to minimize blocking of natural sunlight. LED lighting power density is estimated to be 7 W/ft^2.

High Intensity Sole-Source Farms A fully indoor facility that represents an application where plants are typically grown in a single layer on the floor under high intensity electric lighting with no sunlight. Typical crops, such as hemp, that require high amounts of light are grown in high intensity sole-source farms. Crops grown in high intensity sole situations typically require PPFD up to 1100 μmol/m^2/s or more. LED lighting power density is estimated to be 35 W/ft^2.

Vertical Farms In vertical farms, small plants are stacked along vertical shelving from floor to ceiling such that grow area can be increased in the same building floorspace. Due to vertical farms' unique grow architectures, lighting is typically mounted within the vertical shelving units and much closer to the plants themselves than in either high intensity sole-source farms or supplemented greenhouses. Typical crops grown are leafy greens. Crops grown in vertical farms typically require PPFD up to 300 μmol/m^2/s. LED lighting power density is estimated to be 15 W/ft^2.

2.1.1 Supplemented Greenhouses

Modern greenhouses are structures enclosed entirely by glass, rigid plastic, or a thin plastic (polyethylene film) that is used for various levels of cultivation and protection of plants. Some are large permanent structures, and more sophisticated operations use electric lighting to maintain ideal growth conditions year-round, such as a greenhouse as shown below in Figure 2-1.

[3] High intensity sole-source farm refers to the 2017 report category "non-stacked indoor farms" and represents a name change from the previous report.

Figure 2-1 Greenhouse Miyazaki uses EYE Metal Halide and EYE HPS lamps to maintain optimum growing conditions throughout the year in their growing facilities. [4]

In some cases, other additional features are installed, such as temperature regulation, humidity regulation, CO_2 regulation, and monitoring and control systems. Greenhouses with permanent structures and more advanced technology, such as supplemental lighting, tend to operate all year round, whereas simple greenhouse operations, such as those covered in polyethylene, generally operate seasonally.

The majority of light for plants grown in supplemental greenhouses is provided by natural sunlight, with supplemental lighting used to extend daylight hours during winter seasons with short periods of sunlight or on inclement weather days when sunlight levels are suboptimal. Since sunlight is the primary source of light in a greenhouse, the use of supplemental lighting and the hours of operation varies largely based on location within the U.S. In northern states where daylight hours shorten significantly for winter months, or in the Pacific Northwest where it is often rainy, supplemental lighting in greenhouses is more common. In the sunny southeastern and southwestern states, supplemental lighting in greenhouses is less common.

Supplemental greenhouses, for the purposes of this report, only refer to farms and operations for floriculture, fruit, and vegetable production.

2.1.2 High Intensity Sole-source Farms

High intensity sole-source indoor farms rely on electric lamps and luminaires as their only source of light. By bringing growth operations indoors, operators have complete control over all parameters affecting plant growth, such as total light exposure, ambient and leaf temperature, delivery of nutrients and water, and regulation of CO_2 in the atmosphere, and therefore they offer better environmental control and protection for high value crops. As shown in Figure 2-2, high intensity sole-source farms employ ceiling-mounted lighting fixtures to provide 100% of the light to plants grown, typically in a single layer, on pallets, tables, or the floor.

Figure 2-2 High Intensity Sole-Source Farm for Hemp. The grow area is fully indoors with no natural sunlight, and all light is provided by fixtures above the grow plane. [5]

2.1.3 Vertical Farms

Vertical farms are the newest form of indoor agriculture. They differ from regular sole-source indoor farms because plants are stacked along vertical shelving from floor to ceiling such that grow area can be increased (as shown in Figure 2-3) and have much lower lighting power density (per shelf area). Vertical farms enable large-scale commercial grow operations to be brought into densely packed urban centers, where the demand for fresh, local produce is high. For vertical farms, the total lit grow area is multiplied by the number of stacks (shelves) on which plants are grown.

Figure 2-3 A Vertical Farm Growth Configuration; AeroFarms in Newark, NJ. Vertical stacking the grow areas of leafy greens and herbs enable the total grow area of a facility to be increased in the same building footprint. [6]

Unlike high intensity sole-source farms and supplemental greenhouses, light fixtures for vertical farms cannot be mounted on the ceiling. To ensure even light reaches all plants within the vertical stack, light fixtures must be embedded inside each level of the shelf system directly over the plants. Incandescent, halogen, and HID lamps produce too much heat to be installed in such close proximity to the plants, so linear fluorescent or LED lighting products are the most suitable options for vertical farming. In addition, LEDs offer more granular control of the light intensity through both dimming and optical distribution engineering, so that the light sources can be placed close to the plants, minimizing shelf height and maximizing light delivery efficiency to the plants. Vertical farm operations in the United States generally focus on the production of leafy greens and herbs that require a high level of quality control, as well as localized supply and demand. The vertical farms reflected in this analysis typically grow leafy greens and culinary herbs.

2.1.4 Horticultural Lighting

Usable light output in horticultural lighting products is measured in photosynthetic photon flux (PPF), which is defined as the rate of flow of photons within the photosynthetically active radiation (PAR) waveband from a radiation source and is measured in micro-moles of photons per second (µmol/s). [7] Table 2-1 compares the best in class photosynthetic photon efficacy (PPE), which is defined as the PFF divided by input electrical power. The units of PPE are measured in micro-moles per joule (µmol/J). [7] Each technology will be discussed in more detail in the following sections; however, LED lighting products already offer higher PPE over incumbent technologies, and there is more room for improvement.

Table 2-1 Best-in-Class Photosynthetic Photon Efficacy for Horticultural Lighting Products

Lighting Product Type	Best-in-Class PPE (µ-moles/joule)*	Source(s)
Mogul Base HPS	1.02	Table 3 from Nelson & Bugbee, "Economic analysis of greenhouse lighting: light emitting diodes vs. high intensity discharge fixtures", 2014 [8]
Double-Ended HPS (2014)	1.70	
Ceramic Metal Halide	1.46	
Fluorescent Induction	0.95	
T8 Fluorescent	0.84	
LED (2014)	1.70	
Double-ended HPS (2017)	2.1	Philips Lighting, MASTER GreenPower Plus Specification Sheet [9]
LED (2019)	3.2	Philips Lighting, GreenPower LED Toplighting Specification Sheet [10]
Future LED	> 4	DOE SSL Program, "2017 Suggested Research Topics Supplement: Technology and Market Context", 2017 [11]

*Does not account for ballast losses

2.1.4.1 High Intensity Discharge

HID fixtures, including high-pressure sodium (HPS) and ceramic metal halide (MH), are the primary incumbent technology used in supplemented greenhouses and high intensity sole-source farms. HPS and MH technologies utilize a gas-discharge lamp with mixtures of different vaporized metals and are known by their distinct color ranges. Whereas MH fixtures often provide a blue-white color of light, HPS fixtures provide a somewhat monochromatic yellow-orange light. Depending on the crop type, plant cycle, PPF requirement, and cost, growers may choose to use these two different types of HID lighting. Historically, mogul-base HPS fixtures were most commonly used in greenhouses and indoor farms alike, however, recent implementation of double-ended HPS lamps provide higher efficacies (up to a 69% efficacy increase) than traditional mogul-based HPS lamps, allowing growers to increase their PPF and/or reduce electricity costs. [8] Some of the newer double-ended HPS products claim PPE levels as high as 2.1 µmol/J, although in practice this number may be lower due to ballast losses. [9]

HPS and MH fixtures are the most common type of horticultural lighting found in greenhouses and high intensity sole-source farms. They provide a wide, uniform distribution of light. Typical fixtures range from 400

Watts (W) to 1000 W in order to provide large amounts of PPF output to large canopy areas. While HPS and MH lights are highly utilized in greenhouses and indoor farms, the high concentration of light and heat from these fixtures makes intracanopy and close proximity lighting (such as those found in vertical farming) impractical with this technology type.

2.1.4.2 Fluorescent

Fluorescent technology consists of a glass tube filled with mercury or argon vapor, through which flows an electric current. In many cases, fluorescent light sources are often used for cultivating seedlings and grafted plants in the early stages of the growth cycle. These plants are then moved to a different light source upon reaching maturity. In general, fluorescent fixtures, including induction fluorescent, have a large form factor relative to their low photon output and are not favorable in greenhouse lighting because they block natural sunlight and cast shadows on the plant canopy [8]. Fluorescent technology is relatively efficient, and therefore does not produce a lot of waste heat. Because linear fluorescent lamps have a slim form factor and produce little waste heat, they have previously been the predominant incumbent technology used in vertical farming. However, due to decreasing prices of LED fixtures specifically designed for vertical farming, as well as high efficacy, fluorescent products have been replaced by LED lighting in vertical farms.

2.1.4.3 Incandescent

Incandescent lights consist of tungsten filament lamps that emit a 'warm' white light. They have short operating lifetimes, high heat output, and low PPE, which make incandescent lights disadvantageous for horticultural lighting applications compared to other technology options. According to interviews with stakeholders, incandescent lights make up a negligible fraction of the horticultural lighting market and are generally only used for specific growth cycle purposes, such as interrupting a dark cycle to manipulate growth phases. Therefore, incandescent lamps were excluded from this analysis considering the energy consumption impact of this type of horticultural lighting is very small in relation to HID, fluorescent, and LED lighting.

2.1.4.4 LED

LED lamps and luminaires are increasingly used for horticultural applications. Currently, LED lighting products offer the opportunity for energy savings over HID, fluorescent, and incandescent light sources, since their PPE is generally higher. Some recent integrated horticultural LED products claim PPE levels as high as 3.2 µmol/J. [10] However, LED product PPE varies widely. It is dependent on color mix, LED quality, drive current, and thermal management. In the report, *2017 Suggested Research Topics Supplement: Technology and Market Context*, projections show that horticultural LED lighting PPE may ultimately exceed 4 µmol/J, based on performance projections for the underlying LED technology used for general illumination LED performance projections. Figure 2-4 shows the historical and projected LED PPE levels. [12] While there would be some efficiency losses when integrated into a luminaire, this would represent a significant improvement over today's LED and incumbent technology. LED technology can also enable energy savings due to improved optical distributions that more efficiently deliver light to the plant canopy. This impact is currently difficult to quantify, but similar improvements have been seen with LEDs for general illumination where prescribed light levels can be achieved with less total light. [11]

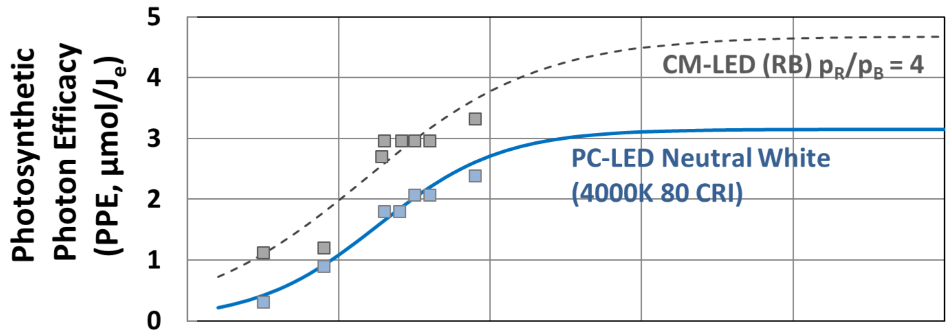

Figure 2-4 Historical and projected LED photosynthetic photon efficacy for good caliber white LED (blue line) and red-blue LED combination with red to blue output power ratio of 4:1 (gray dashed line) from DOE Lighting R&D Program Research and Development Opportunities (RDO). Efficacy is for bare LEDs (not fixtures) at 25C and 350mA/mm² operation. Practical performance of LEDs will be different at different operating temperatures and current densities. Further discussion can be found in the 2019 RDO. [12]

LED horticultural lighting typical uses white + red or blue + red or white spectral power distributions. Figure 2-4 shows the progression and projection of photosynthetic photon efficacy (PPE) for two spectra in units of µmoles of photosynthetic photons per joule. The red + blue spectrum exhibits superior efficacy but can make it difficult for humans to inspect plants and work in the lighted space. With LED technology it is possible to further optimize the light spectrum for plant growth and even include active spectral tuning to adjust the spectrum as plants mature. However, the full benefits and trade-offs of highly optimized spectra and spectral tuning are not yet fully understood and may be quite different for different crops.

A barrier to LED adoption is a high first-cost relative to incumbent technologies, although LED products will have reduced energy and maintenance costs, resulting in lower total cost of ownership. As with LED lighting for general illumination, costs are expected to decline, and as LED products more clearly demonstrate lower total cost of ownership and enable new value for horticultural applications, the higher first-cost will become less of a factor.

As a research tool, LED technology can support a greater understanding of the specific lighting needs for horticultural crops, which can enable more efficient and effective growth and control of the ultimate product. This understanding, along with continued advancements in LED efficiency and reductions in cost of LED lighting products, can improve the economics for indoor horticulture. [11]

2.2 Analytical Approach

To estimate the current energy consumption and potential energy savings of LEDs in indoor horticulture, the analysis was separated into three categories, as discussed in Section 2, since each has their own unique lighting requirements and grow architecture. In this report, the three types of indoor horticulture operations are supplemented greenhouses, high intensity sole-source farms, and vertical farms.

2.2.1 Current State Estimate

As part of this analysis, the team conducted interviews with growers, horticultural lighting manufacturers, horticultural lighting retailers, utility companies, academic professionals, and other industry experts. Individual input provided by the contributing parties was kept confidential and was used in combination with various publications to create estimates for the U.S. indoor horticulture market, as shown in Figure 2-5.

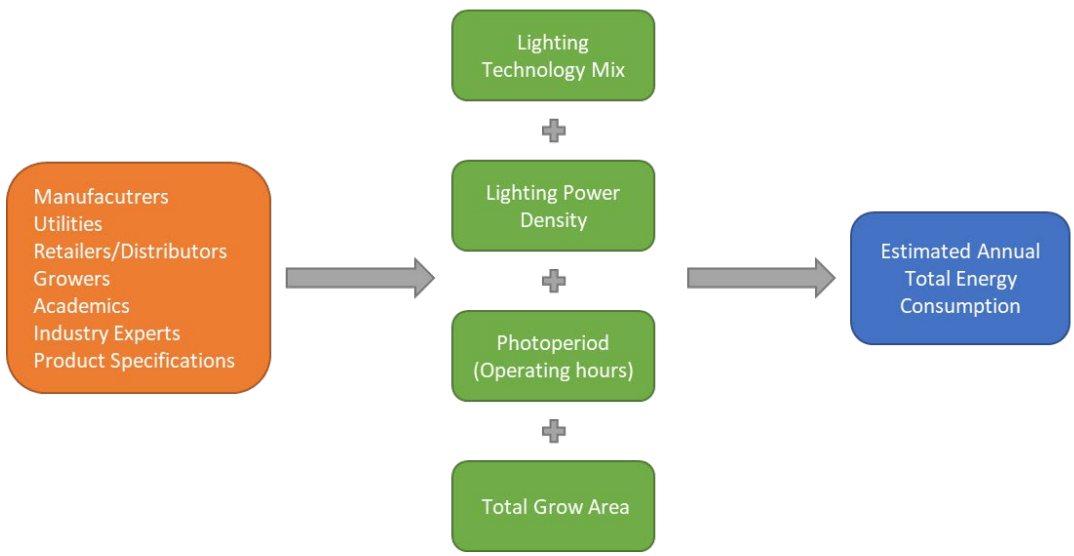

Figure 2-5 Horticulture Analysis Methodology. Stakeholder interviews, research, and primary data enabled the calculation of intermediate variables such as lighting technology mix, lighting power density, photoperiod, and grow area. These intermediate variables were then used to estimate the annual total energy consumption of horticultural lighting in the United States.

Figure 2-5 describes the methodology used to estimate total annual energy consumption of lighting for each category of indoor horticulture. The four main intermediate variables used to calculate total annual energy consumption are installed lighting technology mix, lighting power density (LPD) (W/ft^2), photoperiod (hours of light per day), and grow area (ft^2).

The lighting technology mix, LPD, and typical operating hours were readily determined from industry reports, stakeholder interviews, and the data collection process. Available horticultural lighting products were compiled and reviewed to determine typical performance characteristics. In addition, stakeholder interviews with lighting product manufacturers yielded information about the intended lighting configuration and area of coverage for their products. Growers and other industry experts provided information on the most common lighting configurations and practices. Average watts per fixture and the typical grow area covered by one lighting fixture were used to estimate the electricity consumption normalized by grow area, yielding an estimated power density (W/ft2) for both LED and incumbent lighting. Similarly, average photoperiods, or operating hours, were determined based on industry practices.

Lighting intensity and duration for growing plants can vary widely depending on the selected crop, business goals, and other growing environment conditions. This study presents the typical LPD as determined from industry and does not take into account individual differences in plant species, strain, or growing process used by a specific grower.

The following sections describe the methods used to determine 2019 estimates for total applicable grow area in the United States.

2.2.1.1 Grow Area for Vertical Farms

The analysis for vertical farming in the U.S. consisted of collecting data through interviews with vertical farms, manufacturers, and other industry stakeholders to determine estimates for total canopy area of vertical farms in the United States.

2.2.1.2 Grow area for Supplemented Greenhouses

Data from the 2017 Census of Agriculture were used to determine total U.S. grow area for greenhouses.[4] To determine the amount of total greenhouse area that is supplemented by electric lighting, only those greenhouse areas with certain specifications indicative of potential supplementation were considered. These steps are outlined below:

<u>Step 1: Determine the percentage of greenhouses in the U.S. that are constructed of glass or rigid plastic material.</u> Only greenhouses constructed of glass and rigid plastic material were considered to have supplemental lighting.[5] Polyethylene greenhouses (often informally called "hoop houses") were excluded. Polyethylene greenhouses are not as capital intensive as their glass or rigid plastic counterparts and therefore unlikely to offer environmental controls or supplemental lighting. Data from the 2014 Census of Horticultural Specialties were used to determine the percentage of greenhouses that are constructed from glass and rigid plastic. [13]

<u>Step 2: Determine the applicable grow area of greenhouses in the U.S. that are used for growing crops that potentially utilize supplemental lighting.</u> Only greenhouses used for the USDA designated categories of *floriculture and bedding crops*, *total greenhouse vegetables and fresh cut herbs*, and *greenhouse fruits and berries* were considered to potentially have supplemental lighting. [14] Other crop choices in the USDA greenhouse data, such as aquatic plants, mushrooms, and sod, were determined to be unlikely candidates for light supplementation in a greenhouse setting and therefore excluded.

<u>Step 3: Multiply the percentage of greenhouses constructed with glass or rigid plastic with the applicable grow area.</u> The result of multiplying these two values provided an estimate on the total greenhouse grow area in the United States that are constructed of glass or rigid plastic and are used for growing floriculture crops, vegetables, and fruits (crops for which growers will typically use supplemental lighting).

<u>Step 4: Apply percentage estimate regarding the proportion of these greenhouses that use supplemental lighting.</u> Various stakeholders indicated that the proportion of these greenhouses that use supplemental lighting fixtures as between 5-25% of these "high capital cost" greenhouses.

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[4] The report analysis for greenhouses was based on the USDA 2017 Census of Agriculture data. Therefore, the calculated grow area is reflective of the total U.S. greenhouse area as of 2017, though there were likely some minor market size changes between 2017 and 2019.

[5] In the previous 2017 report, only glass greenhouses were considered to have supplemental lighting fixtures. Based on industry feedback on the previous report, this updated analysis considers both glass and rigid plastic greenhouses to use supplemental lighting.

2.2.1.3 Grow Area for High Intensity Sole-Source Farms

High intensity sole-source indoor farming market in the United States is focused in several key states. In order to get an accurate assessment of the estimated grow area for high intensity sole-source farms, publicly available commercial license data was used to estimate the total licensed area in the United States.

2.2.2 Potential Energy Savings Estimate

A combination of typical LPD, annual operating hours, current LED adoption and market technology mix, and the total market size enabled the estimation of total annual energy consumption for each of the three indoor horticulture applications in the U.S. As a measure of potential lighting energy savings offered by LED technology, the energy consumption of a theoretical "All LED" scenario was also determined. This scenario assumes that all horticultural lighting installed in 2019 was converted to LED lamps and luminaires "overnight", given current PPE levels. Current LED horticultural product PPE is still below technical limits and is expected to improve.

2.3 Results

As of 2019,[6] in the U.S., a total of 89 million ft^2 of grow area was lit by electric horticultural lighting, 63% of which was in supplemented greenhouses, 36% in high intensity sole-source farms, and only 1% in vertical farms, as shown in Figure 2-6.

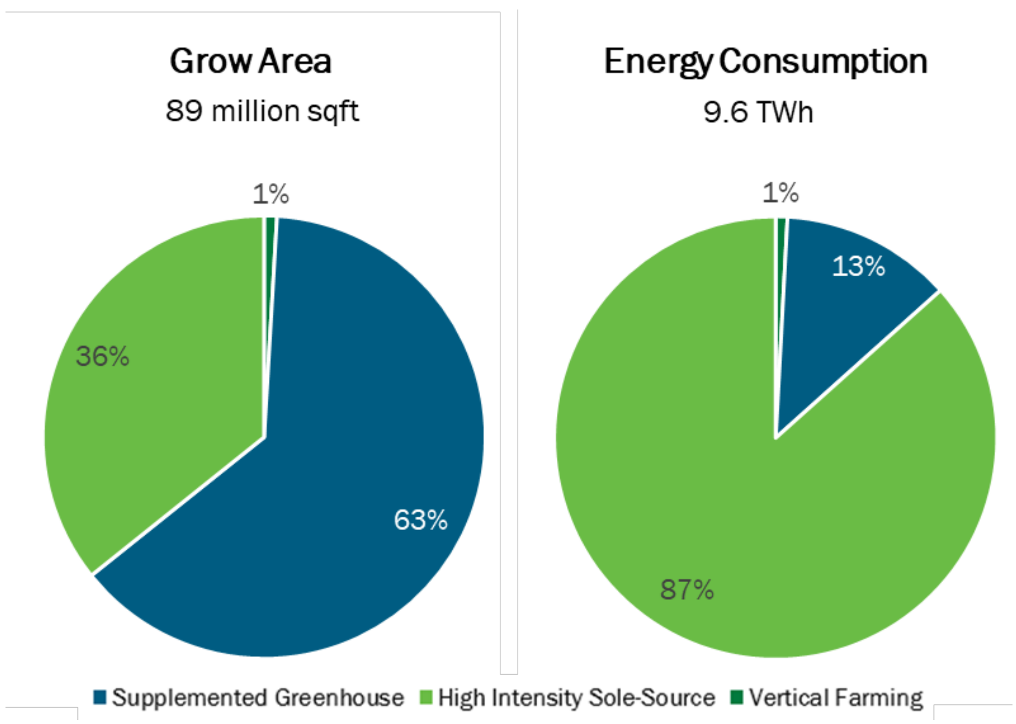

Figure 2-6 2019 Total U.S. Grow Area and Annual Electricity Consumption. In 2019, a total of 89 million ft^2 of grow area was lit by horticultural lighting, which consumed an estimated 9.6 TWh of site electricity. Although supplemented greenhouses are the largest by total illuminated area (63%), high intensity sole-source farms consume the largest share of lighting energy (87%).

[6] Interviews and data collection were conducted from May through August of 2019. All figures, calculations, and estimates are reflective of this date.

These horticultural lighting installations consumed 9.6 terawatt hours (TWh) of site electricity per year, equivalent to 103 trillion British thermal units (tBtu) of source energy consumption.[7] Of this 9.6 TWh, 87% comes from lighting in high intensity sole-source farms, 12% from supplemental lighting in greenhouses, and 1% from lighting in vertical farms. By comparison, DOE estimated that in 2017, white lighting for general illumination consumed approximately 6,000 tBtu annually.[8] [1] In another comparison, as discussed later, animal lighting installations consumed 3.7 TWh of site electricity per year, equivalent to 35 tBtu of source energy consumption. To estimate the potential lighting energy savings opportunity offered by LED horticultural lighting, it was determined that if all horticultural lighting today was converted to LED technology, horticultural lighting consumption would be reduced to 6.3 TWh, or 68 tBtu annually, which represents lighting energy savings of 34% or $350 million annually.[9] The annual electricity consumption in 2019 and the theoretical electricity consumption of switching to the "All LED" scenario are shown in Figure 2-7 below.

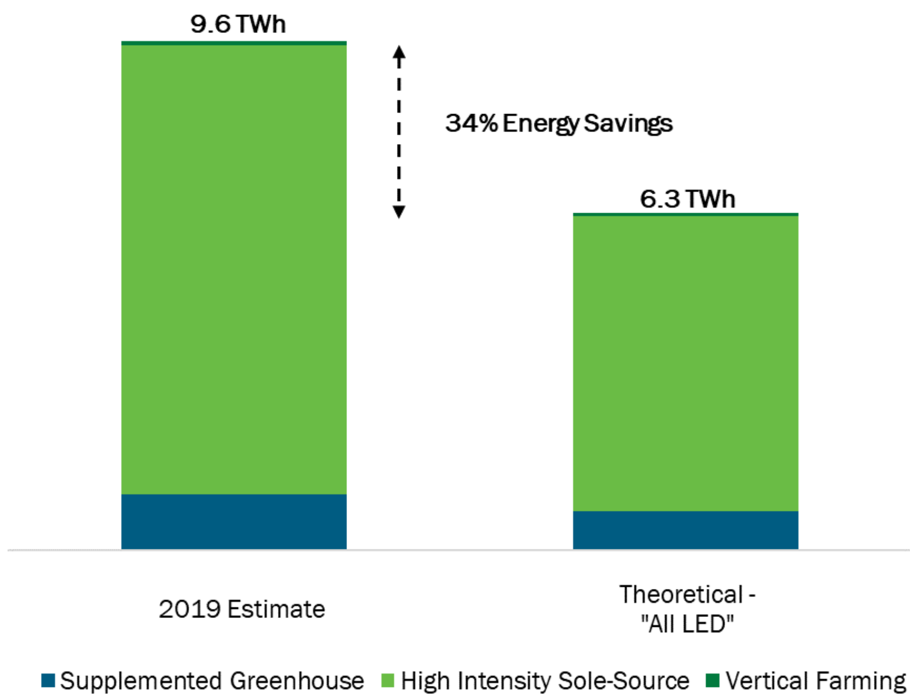

Figure 2-7 Annual Electricity Consumption of U.S. Horticultural Lighting. In 2019, it is estimated that horticultural lighting consumed 9.6 TWh of site electricity. If LED penetration were to reach 100%, this consumption is estimated to decrease to 6.3 TWh based on current market size and efficacy levels, representing potential lighting energy savings of 34%.

A summary of the results is shown in Table 2-2 below. Horticultural lighting in each of these indoor horticulture market segments will be discussed in more detail in the following sections of this report.

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[7] Source energy consumption is calculated by multiplying site electricity consumption by a source-to-site conversion factor of 2.80 [34].

[8] In the 2019 Report "Energy Savings Forecast of Solid-State Lighting in General Illumination Applications", DOE estimated that in 2017, there were 7.6 billion lighting systems installed in the U.S. and that they consumed approximately 6 quads of energy annually.

[9] The average cost of electricity in 2019 was 10.67¢ per KWh. [35]

Table 2-2 Summary of Horticultural Lighting Analysis

Analysis Outputs		Units	Vertical Farming	Supplemented Greenhouse	High Intensity Sole-Source	Total[1]
Estimated Total Lit Grow Area		**Million ft²**	0.8	56.6	31.9	89.3
Annual Operating Hours		**Hours/year**	6,570	2,000	5,200	--
Average Electricity Consumption						
	LED	W/ft²	15	7	35	--
	HPS/MH	W/ft²	N/A	11	56	--
	Fluorescent	W/ft²	23	N/A	5	--
2019 Technology Mix						
	LED	%	100%	2%	11%	--
	HPS/MH	%	0%	98%	86%	--
	Fluorescent	%	0%	0%	3%	--
2019 Annual Energy Consumption						
	Current	GWh/year (tBtu/year)[3]	81 (1)	1,202 (13)	8,307 (89)	9,591 (103)
	Theoretical "All LED"	GWh/year (tBtu/year)[3]	81 (1)	832 (9)	5,395 (58)	6,307 (68)
Theoretical % Lighting Energy Savings[2]		%	0%	31%	35%	34%

1. Values may not add due to rounding.
2. The theoretical percent energy savings given current technologies were all converted to LEDs, which is the percent difference in energy consumption of the Current and the Theoretical "All LED" scenarios. (Note percent energy savings are calculated from raw data, as opposed to rounded values presented in the table and, therefore, may not match.)
3. tBtu values given in this table are representative of source energy. Source energy consumption is calculated by multiplying site electricity consumption by a source-to-site conversion factor of 2.80 [34].

2.3.1 Supplemented Greenhouses

According to the 2017 Census of Agriculture, greenhouses for floriculture, fruits, berries, vegetables, and fresh cut herbs in the U.S. covered approximately 994 million ft^2. [14] The 2014 Census of Horticultural Specialties determined that of U.S. land covered by greenhouses, 14% was covered by glass, 15% by rigid plastic, and 72% by plastic film (polyethylene). [13] Based on data provided during stakeholder interviews, it was estimated that 20% of permanent glass and rigid plastic greenhouses across the U.S. employ supplemental lighting, which is equal to roughly 56.6 million ft^2 of grow area.[10] Of the three types of indoor horticulture, supplemented greenhouses represent the largest market by grow area, comprising 63% of the indoor horticulture market analyzed in this study. Despite the large grow area, supplemented greenhouses consumed just 13% of the total annual energy consumed by horticultural lighting because of the lower LPD, sparse fixture density, and reduced usage time relative to other indoor applications.

Supplemental greenhouse lighting is used to supplement sunlight and increase the size, quality, or yield of the plants. Due to the capital costs of installing supplemental light fixtures, stakeholders indicated that most supplemented greenhouse operators do not use their light fixtures to meet the minimum daily light integral (DLI) requirements, but rather utilize their lights as long as it is economically beneficial (i.e., the benefits in quality or yield are greater than the cost of keeping the lights on). In most cases, this operating hour range is an

[10] In the previous 2017 report, only glass greenhouses were considered to have supplemental lighting fixtures. Based on industry feedback on the previous report, this updated analysis considers both glass and rigid plastic greenhouses to use supplemental lighting, thereby increasing the applicable grow area from 26.8 million ft^2 to 56.6 million ft^2.

annual total of 2,000 to 2,500 hours per year. It is important to note that in many cases, supplemental lighting is used primarily in the winter months from October to March when the total DLI from sunlight is the lowest. Therefore, depending on the crop choice, time of year, and geographical location, the daily operating hours of the supplemental light fixtures can range from a few hours up to 12 hours or more.

Because LPD and intensity in supplemented greenhouses are low relative to fully indoor operations, high first cost is the primary impediment to installing LED products. Furthermore, due to the majority of light being provided by sunlight, the long-term energy savings (and associated cost savings) offered by LED lighting products are less attractive. In 2019, LED lighting adoption in supplemented greenhouses was estimated to be 2%, with the remaining 98% of light provided from HPS and MH fixtures.

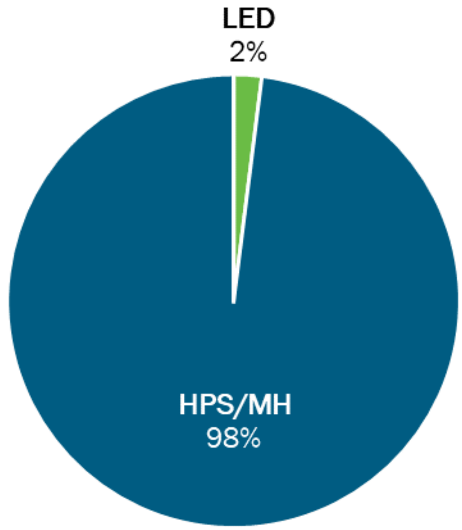

Figure 2-8 2019 Technology Mix for U.S. Supplemental Greenhouse Lighting. In 2019, 98% of supplemented greenhouse grow area was installed with HPS and MH fixtures. The remaining 2% of grow area was installed with LED lighting.

Light fixtures for supplemental lighting in greenhouses are typically ceiling- or support-mounted, with the number of fixtures depending on total PPF and how much light is required, which varies by plant type. Typical HID grow lights used in supplemented greenhouses are either 1000 W or 400 W HPS or MH lamps.[11] A single lamp is installed per fixture and 1000 W HPS lamps are typically used over a grow area of about 100 ft^2, while the 400 W HPS lamps are typically used over a smaller area. The estimated LPD of incumbent HID supplemented greenhouse lighting is 10.7 W/ft^2.

For this report, it is assumed that LED lighting products used in greenhouses can function as one to one replacements for existing HID fixtures (i.e., the configuration and PPF remains unchanged, but due to higher PPE, the overall LPD is reduced). The estimated LPD of supplemented greenhouses utilizing LED lighting is estimated at 7.4 W/ft^2, a 31% reduction in electricity consumption per square feet of grow area. Interviews with industry stakeholders suggest that because crop yield is the primary goal, growers previously limited by electricity capacity may instead switch to LED product configurations that consume the same amount of electricity as incumbent technology but give greater PPF in hopes of increasing yield by increasing the light for plants. Therefore, in practice, the LPD of installed LED fixtures may be the same or higher but with resulting increases in productivity.

[11] HPS and MH lamp wattages provided do not include ballasts.

In 2019, the supplemental lighting installed in U.S. greenhouses has an estimated annual consumption of 1,202 gigawatt-hours (GWh) of site electricity, equivalent to 11.5 tBtu of source energy. If the remaining 98% of U.S. greenhouse supplemental lighting fixtures that are currently HID were to convert to LED lighting systems "overnight", consumption would drop to 832 GWh or 7.9 tBtu of source energy annually. This represents a 31% lighting energy savings potential, and savings of $39 million, offered by current top performing LED lighting products.

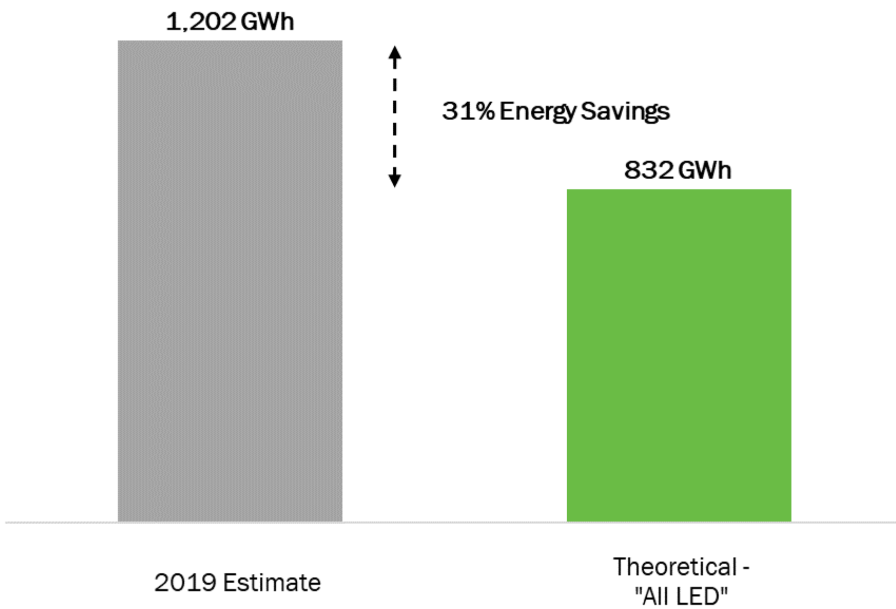

Figure 2-9 Annual Electricity Consumption of Supplemental Lighting in U.S. Greenhouses and Savings Comparison with a Theoretical "All LED" Scenario. In 2019, it is estimated that horticultural lighting in supplemented greenhouses consumed 1,202 GWh of site electricity. If LED penetration were to reach 100%, this consumption is estimated to decrease to 832 GWh based on current market size and efficacy levels, representing potential lighting energy savings of 31%.

2.3.2 High intensity Sole-source Farms

In 2019, a total of 31.9 million ft^2 of grow area within the U.S falls into the category of high intensity sole-source farms. The vast majority of this grow area is accounted for by the commercially licensed grow area estimate in states with both recreational marijuana programs and medical marijuana programs. Grow area in medical-only states account for a small proportion of the total domestic grow area. This study does not take into account any non-commercial or unlicensed growing facilities. Therefore, the results of this analysis should be considered as a conservative estimate of lighting energy use.

The estimated LPD of incumbent high intensity sole-source farms is significantly higher than that of incumbent lighting in either supplemental greenhouse (where the bulk of light is provided by natural sunlight) or vertical farming (where low intensity lights are installed close to the plants).

First cost remains a significant barrier to the adoption of LED lighting products in these operations. Furthermore, growers who are more familiar with MH or HPS sources may be hesitant to try LED technology over the concern that it may alter the growth and yield of their crop. Due to the high costs of licensure, facility maintenance, operating costs, and high value of the crops, growers are hesitant to change pre-established norms of lighting practices. In 2019, LED adoption in high intensity sole-source farms was estimated to be 11%, while 86% were HID (i.e., metal halide or HPS) and 3% were fluorescent.

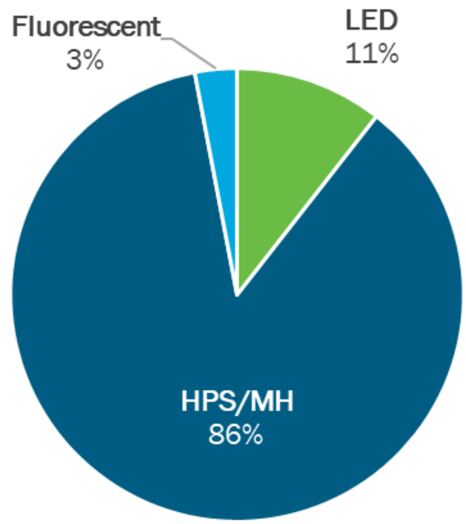

Figure 2-10 2019 Lighting Technology Mix for U.S. High Intensity Sole-Source Farms. In 2019, 86% of high intensity sole-source grow area was installed with HPS and MH fixtures, and an additional 3% was installed with fluorescent lighting. The remaining 11% of grow area was installed with LED lighting.

In 2019, electric lighting used in high intensity sole-source farms consumed an estimated 8,307 GWh of site electricity, equivalent to 79.4 tBtu of source energy. If the remaining 89% of lighting fixtures that are HID and fluorescent were to convert to LED "overnight," electric lighting installed in U.S. high intensity sole-source farms would consume 5,395 GWh of site electricity, or 51.5 tBtu of source energy annually. This represents 35% lighting energy savings and $310 million per year in annual electricity costs.

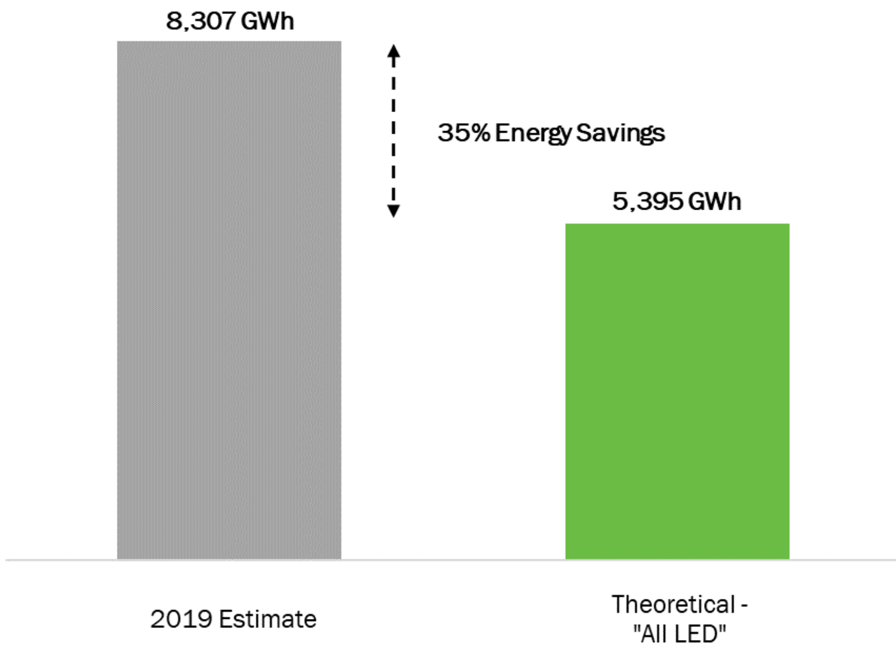

Figure 2-11 Annual Electricity Consumption (GWh) of Lighting in U.S. High Intensity Sole-source Farms and Savings Comparison with a Theoretical "All LED" Scenario. In 2019, it is estimated that horticultural lighting in high intensity sole-source farms consumed 8,307 GWh of site electricity. If LED penetration were to reach 100%, this consumption is estimated to decrease to 5,395 GWh based on current market size and efficacy levels, representing potential lighting energy savings of 35%.

2.3.3 Vertical Farms

Vertical farming is the newest entrant in the market described in this report. The market is the smallest by grow area and total energy consumption. The industry consists of both large, commercial scale businesses as well as small, local operations. The size of the grow area is much greater in proportion to the building footprint, as many commercial scale vertical farms have grow towers with more than 10 levels of stacked grow planes. Using the estimates provided in stakeholder interviews, the current estimate for total grow area in U.S. vertical farms is approximately 800,000 ft^2.

Due to their unique grow architecture that benefits from lighting with close proximity to plants and the typically small plant types (i.e., leafy greens), LED and linear fluorescent fixtures are the only viable technology options for vertical farms. Other traditional light sources, such as HID lights, produce too much heat and are too bright to be used in proximity to the plants for use in vertical farming. In older generation vertical farms, linear fluorescent lamps were mounted within the stack above each row of plants, where they were operated with an estimated power density of 22.8 W/ft^2. However, due to the continual decrease in LED capital costs, as well as improved efficacy, quality, and reliability of LED fixtures, linear fluorescent lighting has been phased out in this application.

LED products used in vertical farming can function as one to one replacements for existing linear fluorescent fixtures (i.e., the configuration and PPF remains unchanged, but due to higher PPE, the overall LPD is reduced). LED lighting enables a host of other benefits and functionalities, including increased product lifetime, tailored spectral output, tailored optical distribution, and dynamic controls. The estimated LPD of LED lighting for vertical farms is approximately 15 W/ft^2, a 34% reduction in LPD.

In vertical farms, generally all light is provided by electric lighting. Vertical farms typically focus on the cultivation and production of leafy greens (e.g., lettuce) or herbs (e.g., basil). The most common lighting schedules operate lighting for 18 hours per day, 365 days a year, for total annual operating hours of 6,570 hours per year. With long operating hours, the energy savings offered by LED lighting products often offset the higher first cost when driving purchasing decisions. Additionally, because lights must be placed within the stacks of plants and plants are sensitive to heat, LED lamps and luminaires are well suited for use in vertical farms. In fact, stakeholders believe LED technology is enabling the growth of vertical farms because LED products offer flexible lighting solutions for various, compact, and unique grow architectures. In 2019, LED adoption in vertical farms was estimated to be 100%.[12]

In 2019, the electric lighting installed in U.S. vertical farms has an annual consumption of 81 GWh of site electricity, equivalent to 0.78 tBtu of source energy. Because vertical farming has fully adopted usage of LED lighting for commercial scale production, there is no theoretical potential savings by “switching” to LED lights – savings from replacing incumbent lighting solutions with LED lighting has been realized. However, there is the possibility for more energy savings from future increases in PPE of LED fixtures, improvements to optics, more effective lighting distribution patterns, and tailoring spectrum for improved aspects of plant growth.

[12] Stakeholders indicated that some vertical farms may still use other forms of lighting such as fluorescent or induction lighting systems in an “experimental” area of the farm not intended for commercial scale production.

3 Indoor Animal Lighting

In the United States, there many types of agricultural facilities for the purpose of raising livestock. With few exceptions, most aspects of animal farming involve exposure to indoor lighting during some phase of their growth and development. In this first analysis of animal lighting, a few of the largest animal agricultural markets are examined: poultry farming, hog farming, and the dairy farming industry. These three markets constitute the most intensive indoor farming markets, and therefore represent the largest portion of energy consumed by indoor lighting for livestock agriculture. Similar to horticulture, the fundamental drivers for controlled environment production of animals are improved control of the environment, reduced weather impacts, more consistent production, reduced risk of contamination, and controlled access to production. These factors can make production more consistent, independent of geographical and weather constraints, and enable production that may be more local to the ultimate consumer. All of these factors contribute to more resilient food production systems – in which lighting plays an important, and possibly enabling role.

3.1 Types of Livestock Analyzed

3.1.1 Poultry

The poultry industry is one of the largest segments of animal production in the United States, with a market value of $46.3 billion in 2018. The largest segments of the poultry industry are comprised of broilers (chickens for meat production) and layers (for egg production), constituting a combined 92% of the poultry market by value. [15]

In the United States, chicken consumption surpassed pork consumption in 1985 and beef consumption in 1992, making poultry the largest segment of domestic animal production by consumption. In general, broiler chickens have the best feed conversion ratio among domesticated land animals, which may have potentially contributed to the success of this industry. Although historically, poultry production was based in small-scale farms with meat merely as a byproduct of egg production, current farming methods for poultry production are largely consolidated and consist of large vertically integrated farm businesses. [16]

Large modernized commercial broiler and layer farms are often completely indoor operations consisting of long houses, ranging from 40 to 50 feet wide and 400 to 600 feet long, equipped with HVAC and lighting systems to provide the proper growing environment. As shown in Figure 3-1(a), in broiler houses, chickens are grown in large flocks in open indoor spaces lined with bedding material, with spaces for feeders and drinkers. Often, in layer houses, the chickens are grown in individual cages, although some farms will have open, free range housing spaces. An example of a layer operation is shown in Figure 3-1(b). Because of the chicken's completely indoor environment, ventilation is critical (as sudden changes to temperature and air quality requirements can lead to negative effects on the health of the animals, and even death) and HVAC is the largest energy consuming element in a poultry farm's operation. However, lighting also has significant physiological and behavioral impacts on the animals, and therefore is often controlled for proper intensity and photoperiod during different stages of the growth cycle. In most modern commercial broiler and layer farms, all lighting requirements are met with electric lighting from incandescent, fluorescent, HID, and LED sources, with little to no natural sunlight.

(a) (b)

Figure 3-1 (a) Indoor Poultry Broiler Farm [17] (b) Indoor Poultry Layer Farm [18] Lighting has significant physiological and behavioral impact on growing and laying chickens. In most cases of commercial poultry farming, all lighting requirements are met with electric lighting with little to no natural sunlight.

3.1.2 Dairy

The cattle segment of livestock agriculture can be broadly separated into two groups consisting of raising cattle for beef and dairy. Much of the beef cattle industry in the United States is based on outdoor feedlot systems with the beef cattle primarily receiving their lighting through natural sunlight. Unlike the production of beef, the dairy industry involves considerable electric lighting requirements with indoor housing barns for dairy cows. The importance of lighting and its effects on lactating cows and milk production has been well documented. [19] Although the total number of milk cows has declined from over 25 million in 1944 to less than 10 million in 2019, the average product per cow has improved by an approximate factor of 4. [20]

Whereas the broiler and layer industries are very standardized in their production, the dairy industry has more variation in barn and housing design. A large segment of the dairy industry in the United States are made up of dairy cooperatives, or co-ops, in which individual farm owners have a membership and stake within the co-op. Because membership in co-ops vary and there is not a strong push for standardization from a vertically integrated business, many different designs are used. Freestalls are typically used to house dairy cows, as it is an effective, permanent design that includes a bedding area for rest, and the cows are provided their feed and water needs. An example of a freestall barn is shown in Figure 3-2. Freestall barns may be open air, partially open, or completely enclosed operations depending primarily on the geographical location and climate. Southern regions of the United States are more likely to have open freestall barns. In northern regions with colder winter climates, most barns will require some level of enclosure in order to provide a comfortable environment for the animals.

Figure 3-2 Freestall Barn for Dairy Cows [21] [22] Freestall barn designs can be open air, partially open, or completely enclosed. Lighting has significant impacts on lactating cows and milk production. Therefore, with any barn design, electric lighting plays an important role in dairy farms.

Regardless of the type of enclosure, freestalls will require lighting in order to maintain the most effective environment for milk production. Lighting has been shown to be an essential external factor to optimize milk production during the lactating cycle of cows, with direct influence on milk production. [23] In most cases, metal halide, fluorescent, or LED lighting fixtures are used to provide the proper lighting regimen based on the specific needs of the cows. HPS lighting is not typically used to provide lighting for dairy cattle.

3.1.3 Hog

The United States is the world's third-largest producer and consumer of pork and pork products, with the majority of hog production focused in the Midwest. In the last three decades, the individual number of farms with hogs has declined by over 70 percent, whereas the size of hog farms has increased. In hog farming, there are three types of facilities: 1) farrow-to-finish farms that raise hogs from birth until market ready weight, 2) feeder farms that raise hogs from birth then sell to finishing facilities to grow until market weight, and 3) finisher facilities that buy feeder pigs and grow them to market weight. Indoor farm facilities for hogs allow year-round production by protecting the animals from outside factors, such as weather, and mitigate exposure to disease. [24]

Figure 3-3 Typical Indoor Hog Farm. Hog farms are often a combination of stalls and open housing areas. In fully enclosed facilities, all light is provided by electric lighting. In open air facilities, lighting requirements are met by both electric lighting and natural sunlight.

Depending on the type of facility, hog farms can be a combination of stalls and open housing areas, with feed and water dispensed in specific compartments. Similar to the poultry industry, hog farms are typically fully indoor operations and have strict environmental controls to prevent disease and cross-contamination. In most cases, metal halide, fluorescent, or LED lighting fixtures are used to provide the proper lighting regimen based on the specific needs of the hogs and their life stage.

3.2 Analytical Approach

To estimate the current energy consumption and potential energy savings of LEDs in animal lighting, the analysis examines the three largest segments of the animal production industry: poultry, hog, and dairy. Because each has their own unique lighting requirements, the different animal segments are analyzed separately with their own characteristics.

3.2.1 Current State Estimate

As part of this analysis, the team conducted interviews with agricultural engineers and scientists, lighting manufacturers, utility companies, academic professionals, and other industry experts. As shown in Figure 3-4, the intermediate variables necessary for calculating annual energy consumption of the industry is similar to horticulture.

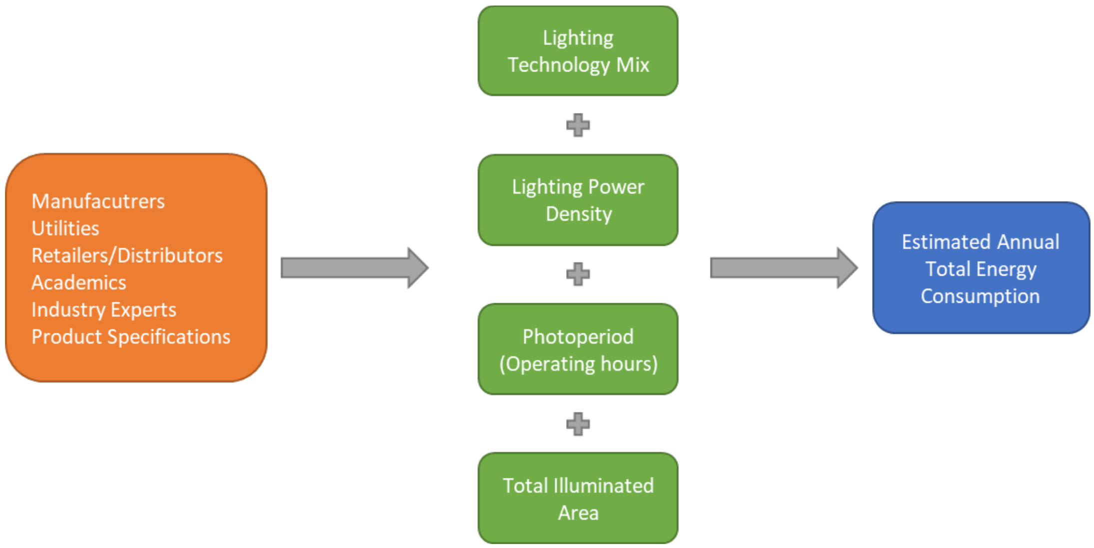

Figure 3-4 Animal Analysis Methodology. Stakeholder interviews, research, and primary data enabled the calculation of intermediate variables such as lighting technology mix, lighting power density, photoperiod, and total illuminated area. These intermediate variables were then used to estimate the annual total energy consumption of animal lighting in the United States.

Figure 3-4 describes the methodology used to estimate the total annual energy consumption of lighting for each category of indoor animal production. The four main intermediate variables used to calculate total annual energy consumption were installed lighting technology mix, LPD (W/ft^2), photoperiod (operating hours), and grow area (ft^2).

Usage of specific, tailored lighting regimens for the production of animals is still a developing field. Unlike plant production and indoor horticulture, the quality, intensity, and photoperiod of lighting systems do not have as direct of an influence on yield, and therefore the adoption of animal centric lighting is not as widespread. The intermediate variables in Figure 3-4 required various additional calculations and analyses to develop. The following sections describe the steps used to determine the intermediate variables needed for calculating total annual energy consumption for animal lighting.

3.2.1.1 Animal Count and Illuminated Area

The analysis utilized data from the 2017 Census of Agriculture to determine total U.S. industry size for each of the animal groups.[13] The analysis estimated total illuminated area from the total number of animals in the industry. These steps are outlined below:

Step 1: Determine the total number of animals grown or maintained per year. For the broiler and hog industry, the annual number of animals grown was determined from the USDA designated categories *Broilers and other meat-type chickens sold* and *Hogs and pigs sold*. For the layer and dairy industry, the annual number of animals being maintained was determined from the USDA designated categories *Layers inventory* and *Milk cows*.

Step 2: Calculate the number of animals being grown at any given time during the year. For the broiler and hog industry, the total annual number of animals determined in Step 1 was then divided by the average number of

[13] The report analysis for total number of animals was based on the USDA 2017 Census of Agriculture data. Therefore, the calculated animal numbers and illuminated area is reflective of U.S. totals as of 2017, though there were likely some minor market size changes between 2017 and 2019.

flocks or herds produced per year, based on the life cycle and grow-out time typically required. For the layer and dairy industries, this number was the same as Step 1.

Step 3: Determine minimum housing or growing floorspace requirements for each of the animal groups. Minimum floor space per animal was determined from various sources, such as university extension publications.

Step 4: Multiply the minimum floorspace requirement per animal by the total number of animals being grown at any given time during the year. By multiplying the minimum floorspace requirement per animal by the number of animals for each group, the total illuminated area can be estimated. Note that this estimates the total illuminated space of the housing area in which the animals spend most of their time and does not account for additional spaces within a facility used for other purposes.

3.2.1.2 Illuminance Requirements and Lighting Power Density

Step 1: Determine minimum illuminance requirements for each animal group and lifecycle stage. The minimum illuminance requirements were determined from standard practice guidelines and minimums defined in the American Society of Agricultural and Biological Engineers (ASABE) document *Lighting Systems for Agricultural Facilities* EP344.4. [25] For broilers, the minimum illuminance requirements were grouped by lifecycle stage from 0 to 1.5 weeks and 1.5 weeks to market (7 weeks). For layers, the minimum illuminance requirements were grouped by lifecycle stage from 0 to 6 weeks, 6 to 18 weeks, and 18 to 80 weeks. For hogs, the grower-finisher illuminance requirements were used. For dairy, the minimum illuminance for housing and feeding area was used.

Step 2: Divide minimum illuminance requirements by typical efficacy for each possible technology. The general performance characteristics of commercial and industrial light sources were derived from representative data collected in the DOE 2019 SSL Forecast. [1]

Step 3: Apply a coefficient of utilization. Because the lighting distribution, optics, and reflectance of the ambient environment for each individual farm is unknown, a coefficient of utilization of 50% was applied to every light source expected to operate in animal agricultural facilities. [26] Dividing the minimum illuminance requirement by the efficacy of the light source, then applying a coefficient of utilization provides a rough estimate of LPD corresponding to that application.

3.2.1.3 Photoperiod

The photoperiod requirements for each animal group was derived from ASABE EP344.4, as well as stakeholder interviews. Similar to illuminance requirements, for broilers, the photoperiod requirements were grouped by lifecycle stage from 0 to 1.5 weeks and 1.5 weeks to market (7 weeks). For layers, the photoperiod requirements were grouped by lifecycle stage from 0 to 6 weeks, 6 to 18 weeks, and 18 to 80 weeks. A single photoperiod requirement was used for hog and dairy calculations.

3.2.1.4 Lighting Technology Mix

To determine the lighting technology mix of installed lighting in animal agriculture facilities, data collected by the energy audit and consulting firm EnSave were used to estimate the share of installed lighting attributable to each technology group. The sample size (in fixtures analyzed) was 79,800 for the broiler segment, 1,900 for the layer segment and 1,800 for the dairy segment. Data from both 2018 and 2019 were used in the analysis. Due to a lack of data regarding installed lighting technology mix for hog farming, the technology mix for hog facilities was estimated by normalizing the technology mix across all other animal segments to exclude incandescent (which is generally not used in hog production) and then averaging these values.

3.2.2 Potential Energy Savings Estimate

A combination of typical LPD, annual operating hours, current LED adoption and market technology mix, and total market size enabled the estimation of total annual energy consumption for each of the three indoor animal agriculture applications in the U.S. As a measure of potential energy savings offered by LED technology, the energy consumption of a theoretical "All LED" scenario was also determined. This scenario assumes that all animal lighting installed stock for broilers, layers, hog, and dairy production in 2019 was converted to LED lamps and luminaires "overnight", given current luminous efficacy levels. This estimate likely underestimates the potential for energy savings because a large portion of the installed stock of LED lighting in animal agriculture is not specifically designed for animal housing and welfare. As animal-centric lighting continues to develop and be adopted, LED products may be better tailored to provide light to animals in an efficient manner, while maximizing any physiological or behavioral benefits.

3.3 Results

In 2019, the United States grew or maintained 9.5 billion animals in the poultry, dairy, and hog industries. This accounted for an estimated 5 billion ft^2 of illuminated area. Figure 3-5 shows the breakdown of illuminated area and energy consumption of lighting in the animal agriculture industry. The poultry industry accounted for 69% of all illuminated space, with broilers and layers constituting 47% and 22% respectively. The hog industry comprised 17% of illuminated space, and the dairy industry, the smallest by illuminated area, accounted for 14%.

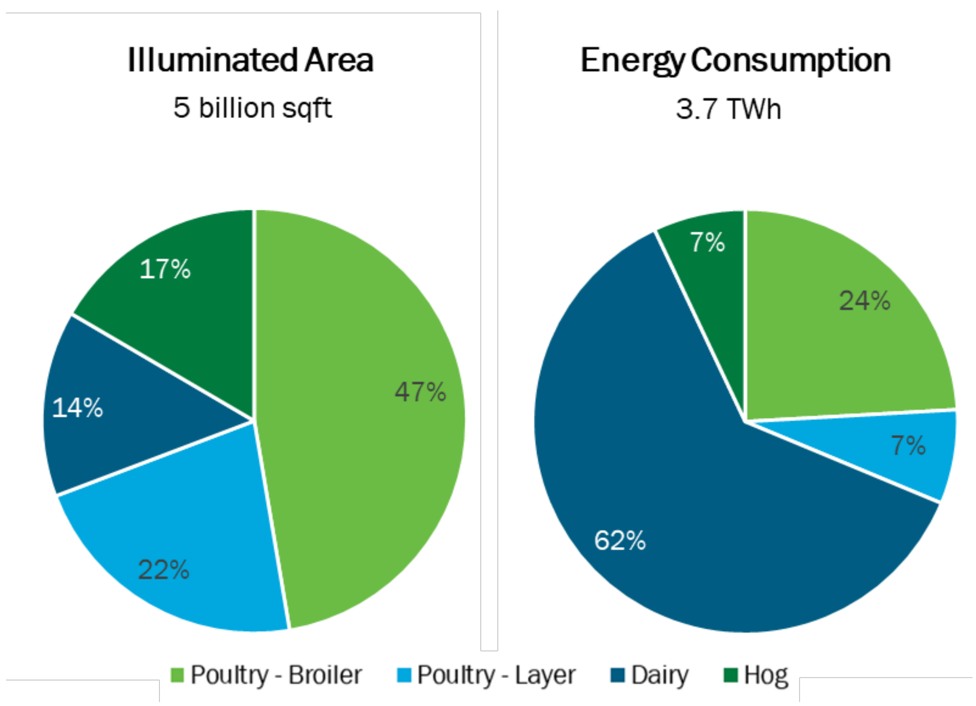

Figure 3-5 2019 Total U.S. Animal Production Illuminated Area and Annual Electricity Consumption of Lighting. In 2019, a total of 5 billion ft^2 of illuminated area was lit by animal lighting, which consumed an estimated 3.7 TWh of site electricity. The broiler industry is the largest by total illuminated area (47%), while the dairy industry has the largest share of energy consumption of lighting (62%).

Combined together, these animal production industries consumed 3.7 TWh per year of site electricity for lighting, equivalent to 35 tBtu of source energy consumption. [14] Although it was the smallest industry (by animal count and illuminated area), the dairy industry consumed the largest share of the energy due to high lighting intensity requirements, with 62% of lighting energy consumption attributable to dairy cattle housing. The broiler industry, the largest by both animal count and illuminated area, consumed 24% of total lighting energy consumption. The layer and hog groups each consumed 7% of total lighting energy consumption. By comparison, for 2017, DOE estimated that white lighting for general illumination consumed approximately 6,000 tBtus annually.[15] [1] In another comparison, as discussed earlier, horticultural lighting installations consumed 9.6 TWh of site electricity per year, equivalent to 103 trillion British thermal units (tBtu) of source energy consumption.

To estimate the potential energy savings opportunity offered by LED lighting for animal agriculture, it was determined that if all lighting used for animal production today was converted to LED technology, the total lighting energy consumption would be reduced to 2.8 TWh of site electricity, or 26 tBtu of source energy annually, which represents lighting energy savings of 25% or $96 million annually. The annual electricity consumption in 2019 and the theoretical electricity consumption of switching to the "All LED" scenario is shown in Figure 3-6 below.

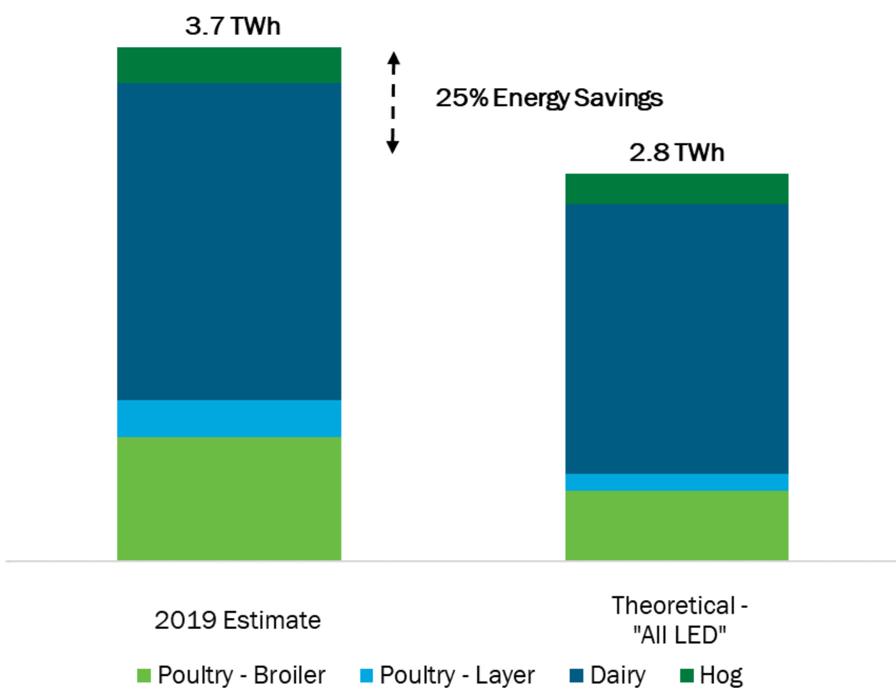

Figure 3-6 Annual Electricity Consumption of U.S. Animal Lighting. In 2019, it is estimated that animal lighting consumed 3.7 TWh of site electricity. If LED penetration were to reach 100%, this estimated consumption would decrease to 2.8 TWh based on current market size and efficacy levels, representing a 25% potential lighting energy savings.

A summary of the results is shown in

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[14] Source energy consumption is calculated by multiplying site electricity consumption by a source-to-site conversion factor of 2.80 [34].

[15] In the 2019 Report "Energy Savings Forecast of Solid-State Lighting in General Illumination Applications", DOE estimated that in 2017, there were 7.6 billion lighting systems installed in the U.S. and that they consumed approximately 6 quads of energy annually.

Table 3-1 below. Lighting in each of these indoor animal agriculture market segments will be discussed in more detail in the following sections of this report.

Table 3-1 Summary of Animal Lighting Analysis

Analysis Outputs	Units	Poultry - Broiler	Poultry - Layer	Dairy	Hog	Total[1]
Estimated Total Animal Count	**Million**	8,890	368	10	235	9,503
Estimated Total Illuminated Area	**Million ft²**	2,387	1,105	715	835	5,042
Average Electricity Consumption						
LED	W/ft²	0.026	0.021	0.459	0.092	--
HPS/MH	W/ft²	0.029	0.024	0.693	0.139	--
Fluorescent	W/ft²	0.030	0.025	0.533	0.107	--
Incandescent	W/ft²	0.139	0.112	N/A	N/A	--
2019 Technology Mix						
LED	%	58%	26%	36%	47%	--
HPS/MH	%	0%	25%	22%	19%	--
Fluorescent	%	25%	23%	42%	34%	--
Incandescent	%	17%	25%	0%	0%	--
2019 Annual Energy Consumption						
Current	GWh/year (tBtu/year)[3]	884 (8)	263 (3)	2,263 (22)	258 (2)	3,667 (35)
Theoretical "All LED"	GWh/year (tBtu/year)[3]	503 (5)	122 (1)	1,918 (18)	224 (2)	2,766 (26)
Theoretical % Lighting Energy Savings[2]	%	43%	54%	15%	13%	25%

1. Values may not add due to rounding.
2. The theoretical percent energy savings given current technologies were all converted to LEDs, which is the percent difference in energy consumption of the Current and the Theoretical "All LED" scenarios. (Note percent energy savings are calculated from raw data, as opposed to rounded values presented in the table and, therefore, may not match.)
3. tBtu values given in this table are representative of source energy. Source energy consumption is calculated by multiplying site electricity consumption by a source-to-site conversion factor of 2.80 [34].

3.3.1 Poultry - Broilers

The U.S. poultry industry produces an estimated 8.9 billion broiler chickens annually. [14] Using an average 7 week lifecycle per flock, this equates to an estimated 1.2 billion broiler chickens being grown at any given time during the year.

The Food and Agriculture Organization of the United Nations (FAO) recommends floor spacing of 2.1 to 2.7 ft² per bird for housing broiler chickens. [27] The National Chicken Council recommends approximately 0.8 ft² per bird as the absolute minimum. [28] For the purpose of this analysis, a floorspace requirement of 2 ft² per bird was used for broiler production, as recommended in *Management Requirements for Meat Bird Flocks* by the Virginia Tech Cooperative Extension. [29] In practice, the actual utilized floorspace may fall above or below this estimate.

Given the 1.2 billion broiler chickens being grown at any given time during the year, a floorspace requirement of 2 ft² per bird equates to 2.4 billion ft² of illuminated area for broiler production. Of the different animal groups analyzed, broilers represent the largest segment by illuminated area, consisting of 47% of the illuminated space analyzed in this study. However, because broilers have the lowest illuminance requirements among the animal groups, the broiler segment consumes 28% of the total lighting energy consumption.

Broiler houses have relatively low illuminance requirements, and many farms have traditionally operated relying on incandescent screw-in light sources, which provided sufficient light to meet their needs. Many of these were then replaced by CFLs as they were a cheap alternative to incandescent. In recent years, as the prices of LED screw-in lamps have come down, most broiler houses have transitioned to energy efficient LEDs, which offer benefits ranging from energy savings to minimizing overhead required to constantly change incandescent lamps as they burn out. In 2019, the LED lighting adoption in broiler houses was estimated to be 58%. Fluorescent and incandescent light sources accounted for an estimated 25% and 17% of broiler light sources, respectively, as shown in Figure 3-7. Due to the low illuminance requirements of broiler production, HPS and MH light sources are not typically used.

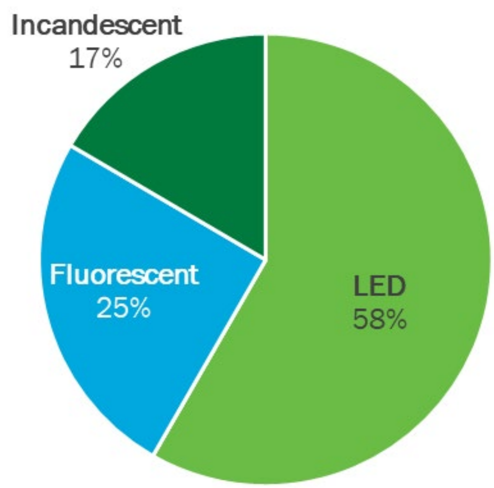

Figure 3-7 Technology Mix for U.S. Broiler House Lighting. In 2019, LED lighting adoption in broiler houses was estimated to be 58%. Fluorescent light sources accounted for 25% of the installed base. The remaining 17% was made up of incandescent lights.

The typical recommended lighting regimen for broilers is 50 lux for 23 hours per day in the first 1.5 weeks of the lifecycle and a minimum of 5 lux for 20 hours per day from 1.5 weeks until market (assumed to be 7 weeks in this study). At 50 lux, this equates to approximately 0.489 W/ft^2 for incandescent lights, 0.107 W/ft^2 for fluorescent lights, and 0.092 W/ft^2 for LED lights. At 5 lux, this equates to approximately 0.049 W/ft^2 for incandescent lights, 0.011 W/ft^2 for fluorescent lights, and 0.009 W/ft^2 for LED lights. The weighted lifecycle average LPD is approximately 0.139 W/ft^2 for incandescent lights, 0.030 W/ft^2 for fluorescent lights, and 0.026 W/ft^2 for LED lights.

In 2019, the lighting installed in U.S. broiler houses has an annual consumption of 884 GWh, equivalent to 8.4 tBtu of source energy. If the remaining fluorescent and incandescent light sources were to convert to LED lighting "overnight," the annual site electricity consumption would drop to 503 GWh or 4.8 tBtu of source energy annually. This represents a 43% lighting energy savings potential and savings of $41 million annually.

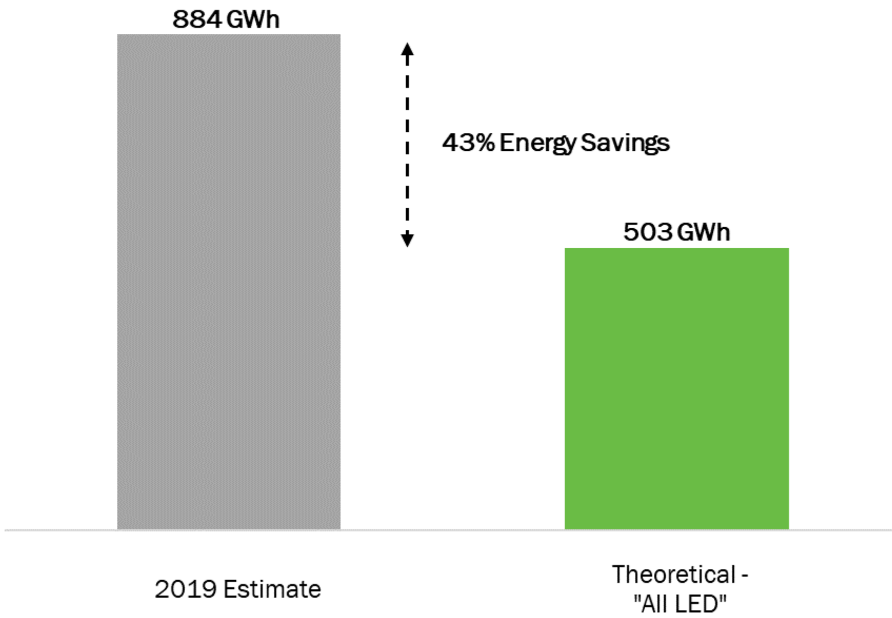

Figure 3-8 Annual Electricity Consumption of Lighting in U.S. Broiler Houses and Savings Comparison with a Theoretical "All LED" Scenario. In 2019, it is estimated that lighting in broiler farms consumed 884 GWh of site electricity. If LED penetration were to reach 100%, this consumption is estimated to decrease to 503 GWh based on current market size and efficacy levels, representing potential lighting energy savings of 43%.

3.3.2 Poultry – Layers

The U.S. poultry industry maintains an estimated inventory of 368 million layer chickens. [14] General industry guidelines recommend 1.5 to 3.5 ft^2 per bird for housing layer chickens. [30] [31] For the purpose of this analysis, a floorspace requirement of 3 ft^2 per bird was used for layers. In practice, the actual utilized floorspace may fall above or below this estimate.

Given the 368 million inventory, a floorspace requirement of 3 ft^2 per bird equates to 1.1 billion ft^2 of illuminated area for layers. Of the different animal groups analyzed, layers represent the second largest segment by illuminated area, consisting of 22% of the illuminated space for animal agriculture, and consume 7% of the total lighting energy consumption for the animal agriculture segments analyzed in this study.

The layer segment represented a large diversity of installed lighting mix. In 2019, the LED lighting adoption in layer houses was estimated to be 26%. Fluorescent lights represented 23% of installed lighting. Incandescent and HPS light sources each accounted for 25% of the installed lighting mix.[16] Figure 3-9 shows the market breakdown by each technology type.

[16] The technology mix does not add to 100% due to rounding.

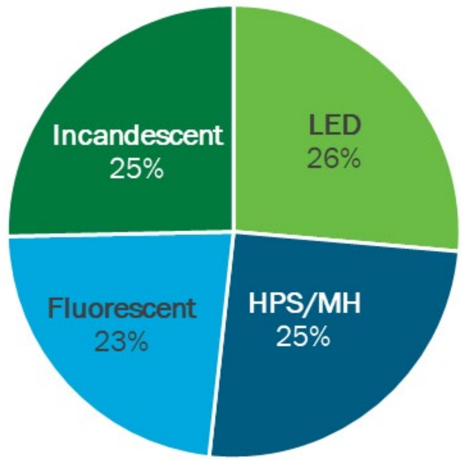

Figure 3-9 Technology Mix for U.S. Layer House Lighting. In 2019, LED lighting adoption in layers was estimated to be 26%. Incandescent and HPS light sources each made up 25% of the installed base. The remaining 23% was made up of fluorescent lights.

Layers require relatively more light than broilers in order to optimize sexual maturity and egg laying. Furthermore, a reduction in photoperiod during the laying period can have significant effects on the egg production of the bird. The recommended lighting regimen for layers is as follows: a minimum 30 lux for 16 hours per day in the first 6 weeks of the lifecycle; 10 lux for 8 hours per day from weeks 6 to 18; and 10 lux for up to 15 hours per day from weeks 18 to 80. [25] At 30 lux, this equates to 0.293 W/ft^2 for incandescent lights, 0.064 W/ft^2 for fluorescent lights, 0.062 for HPS lights, and 0.037 W/ft^2 for LED lights. At 10 lux, this equates to 0.098 W/ft^2 for incandescent lights, 0.021 W/ft^2 for fluorescent lights, 0.021 for HPS lights, and 0.018 W/ft^2 for LED lights. The lifecycle weighted average LPD is approximately 0.112 W/ft^2 for incandescent lights, 0.025 W/ft^2 for fluorescent lights, 0.024 for HPS lights, and 0.021 W/ft^2 for LED lights. However, the market data provided by EnSave showed that in practice, the LPD can often be up to 10 times higher in the range of 0.2 to 0.3 W/ft^2. For the purpose of this study, the illuminance and LPD levels were kept consistent with the recommendations provided in ASABE EP344.4.

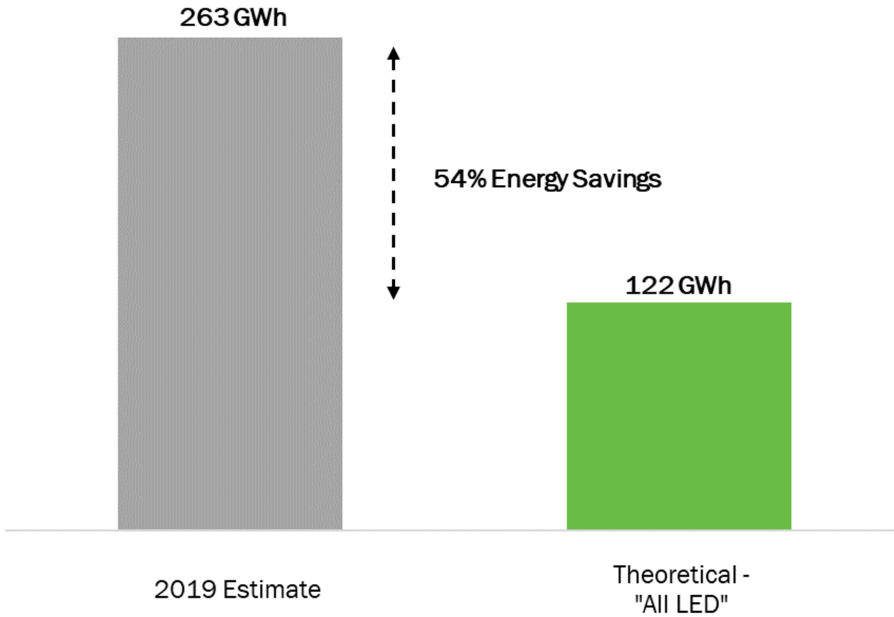

Figure 3-10 Annual Electricity Consumption of Lighting in U.S. Layer Houses and Savings Comparison with a Theoretical "All LED" Scenario. In 2019, it is estimated that lighting in layers consumed 263 GWh of site electricity. If LED penetration were to reach 100%, this consumption is estimated to decrease to 122 GWh based on current market size and efficacy levels, representing potential lighting energy savings of 54%.

In 2019, the lighting installed in U.S. layer houses was estimated to have an annual consumption of 263 GWh, equivalent to 2.5 tBtu of source energy. If the remaining fluorescent, incandescent, and HPS light sources were to convert to LED lighting "overnight," the annual site electricity consumption would drop to 122 GWh or 1.2 tBtu of source energy annually. This represents a 54% lighting energy savings potential and savings of $15 million annually.

3.3.3 Dairy

The U.S. dairy industry maintains an estimated inventory of 9.5 million milk cows. [14] General industry guidelines recommend 75 ft^2 per cow for housing in stalls or barns. [32] In practice, the actual utilized floorspace may fall above or below this estimate.

Given the 9.5 million inventory, a floorspace requirement of 75 ft^2 per cow equates to 715 million ft^2 of illuminated area for milk cows. Of the different animal groups analyzed, the dairy segment represents the smallest segment by illuminated area. It consists of only 14% of the illuminated space but consumes 58% of the total lighting energy consumption for the animal agriculture segments analyzed in this study.

In 2019, the LED lighting adoption in the dairy industry was estimated to be 36%. Fluorescent lights represented the most common technology installed at 42%, and MH light sources accounted for 22% of the installed lighting mix. Figure 3-11 shows the market breakdown by each technology type.

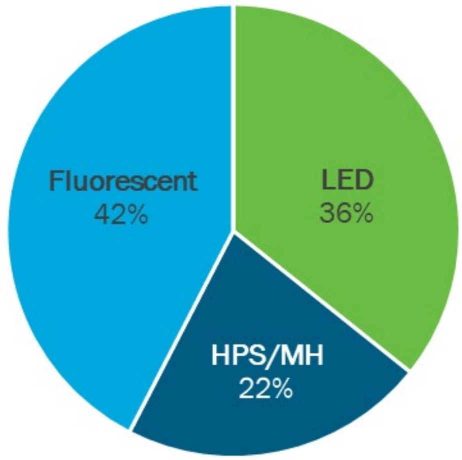

Figure 3-11 Technology Mix for U.S. Dairy Lighting. In 2019, LED lighting adoption in dairy production was estimated to be 36%. Fluorescent light sources made up 42% of the installed base. The remaining 22% was made up of MH lights.

Dairy housing requires the highest amounts of light of all the animal groups analyzed in this study. The recommended lighting regimen for dairy housing is a minimum 250 lux for 16 hours per day. [25] At 250 lux, this equates to approximately 0.53 W/ft^2 for fluorescent lights, 0.69 W/ft^2 for MH lights, and 0.46 W/ft^2 for LED light sources.

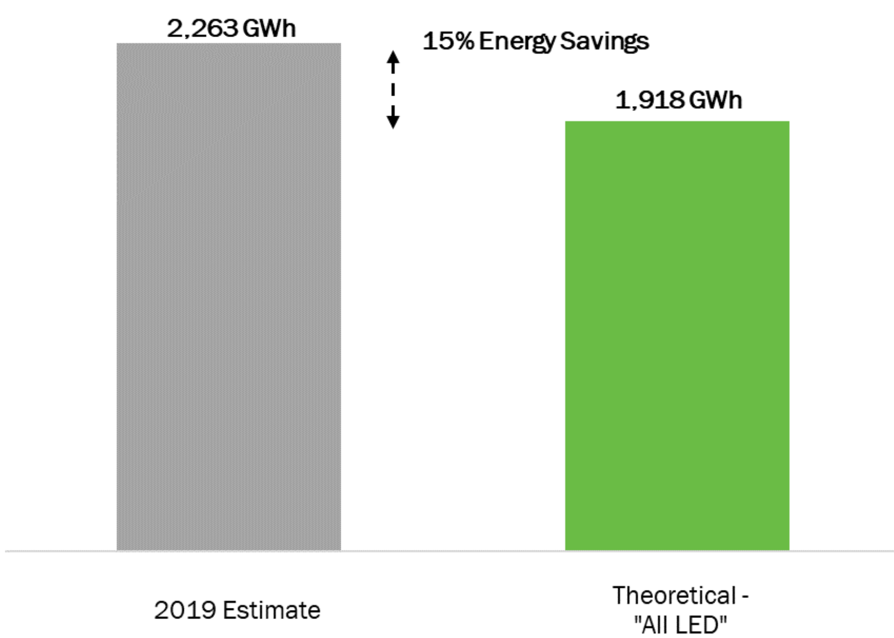

Figure 3-12 Annual Electricity Consumption of Lighting in U.S. Dairy Cow Housing and Savings Comparison with a Theoretical "All LED" Scenario. In 2019, it is estimated that lighting in dairy cow housing consumed 2,263 GWh of site electricity. If LED penetration were to reach 100%, this consumption is estimated to decrease to 1,918 GWh based on current market size and efficacy levels, representing potential lighting energy savings of 15%.

In 2019, the lighting installed in U.S. dairy cow houses was estimated to have an annual consumption of 2,263 GWh, equivalent to 21.6 tBtu of source energy. If the remaining fluorescent and MH light sources were to convert to LED lighting "overnight," the annual site electricity consumption would drop to 1,918 GWh or 18.3 tBtu of source energy annually. This represents a 15% lighting energy savings potential and savings of $37 million annually.

3.3.4 Hog

The U.S. hog industry produces an estimated 235 million hogs annually. [14] Using an average 26 week lifecycle per group, this equates to an estimated 116 million hogs being grown at any given time during the year. General industry guidelines range from 7 to 12 ft^2 per hog for housing hogs indoors. [33] For the purpose of this analysis, an average floorspace of 7.2 ft^2 per hog, as defined in *Space Allocation Decisions for Nursery and Grow-Finish Facilities*, was used for hog facilities. [34] In practice, the actual utilized floorspace may fall above or below this estimate.

Given the 116 million hogs being grown at any given time during the year, a floorspace requirement of 7.2 ft^2 per hog equates to 835 million ft^2 of illuminated area for hogs. The hog segment consists of 17% of the total illuminated space and consumes 7% of the total lighting energy consumption for the animal agriculture segments analyzed in this study.

In 2019, the LED lighting adoption in the hog industry was estimated to be 47%. Fluorescent lights were estimated to be 34%. MH light sources accounted for 19% of the installed lighting mix. Figure 3-13 shows the market breakdown by each technology type.

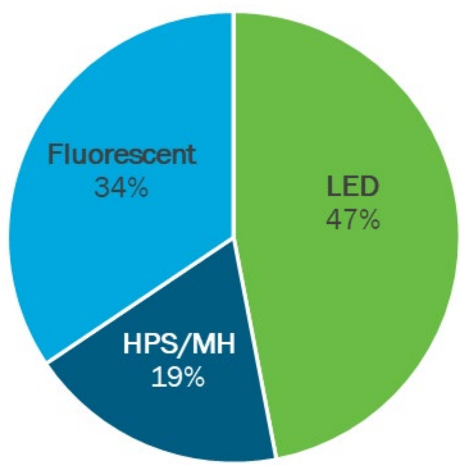

Figure 3-13 Technology Mix for U.S. Hog Lighting. In 2019, LED lighting adoption in layers was estimated to be 47%. Fluorscent light sources made up 34% of the installed base. The remaining 19% was made up of HPS or MH lights.

The recommended lighting regimen for hog nursery and growing facilities is a minimum 50 lux for 8 hours per day. [25] At 50 lux, this equates to approximately 0.11 W/ft^2 for fluorescent light sources, 0.14 W/ft^2 for MH light sources, and 0.09 W/ft^2 for LED light sources.

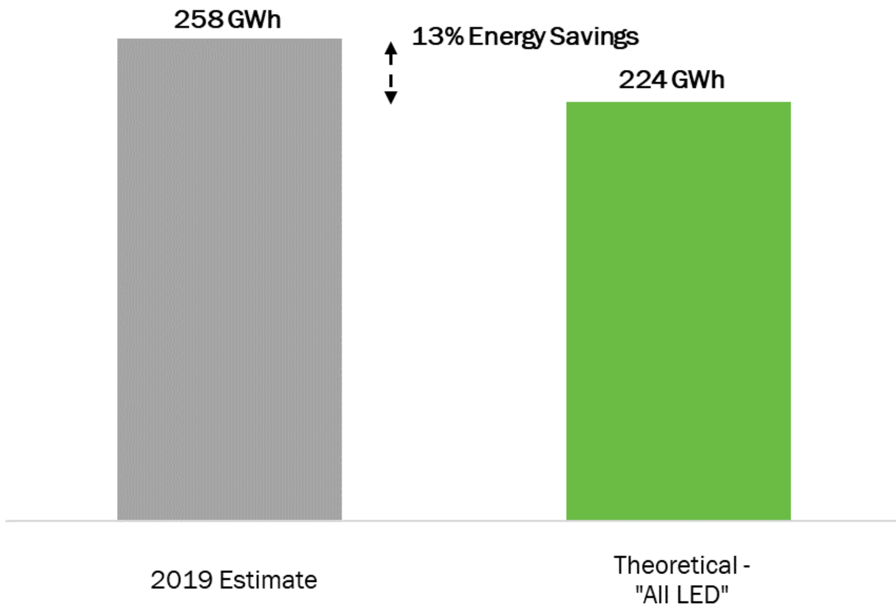

Figure 3-14 Annual Electricity Consumption of Lighting in U.S. Hog Facilities and Savings Comparison with a Theoretical "All LED" Scenario. In 2019, it is estimated that lighting in hog farms consumed 258 GWh of site electricity. If LED penetration were to reach 100%, this consumption is estimated to decrease to 224 GWh based on current market size and efficacy levels, representing potential lighting energy savings of 13%.

In 2019, the lighting installed in U.S. hog facilities was estimated to have consumed 258 GWh, equivalent to 2.5 tBtu of source energy. If the remaining fluorescent and MH light sources were to convert to LED lighting "overnight," the annual site electricity consumption would drop to 224 GWh or 2.1 tBtu of source energy annually. This represents a 13% lighting energy savings potential and savings of $4 million annually.

4 Outlook

Usage of CEA, for both plants and animals, is increasing. CEA can provide numerous benefits including extended growing period, reduced water and chemical consumption, more localized production, year-round production, reduced impacts from weather, and increased food security. In general, CEA can be more resilient and productive than field agriculture but requires electric lighting and HVAC, thus resulting in significant energy loads. The trade-offs between energy cost and consumption versus the various productivity benefits will become clearer as growing practices evolve. However, with LED lighting technology, the energy consumption can still currently be reduced.

In 2019, the total annual electricity consumption of agricultural lighting as discussed in this report is estimated to be 13.3 TWh of site electricity per year, or 127 tBtu of source energy per year, which is about 2% of the energy consumed by general illumination. [1] Agricultural lighting electricity consumption is expected to rise as the total number of indoor operations increase. Furthermore, there are several markets within indoor agriculture that the scope of this analysis did not cover. Cultivators are growing industrial hemp in indoor settings, such as supplemental greenhouses. Although traditionally grown outdoors, increasing indoor growth of industrial hemp may constitute a substantial amount of energy-intensive lighting. Furthermore, an increasing number of high intensity sole-source farm growers are opting for growing their crops in supplemented greenhouses, which was not addressed in this study, but it could eventually represent a significant segment of the industry.

This report analyzed the current energy consumption for the described applications and the energy impact of switching lighting to LED technology. However, similar to the use of LED lighting technology for general illumination, there will be health and productivity impacts enabled by the new technology. LED lighting technology offers the ability to efficiently generate a wide range of spectral power distributions, optical distributions, and intensity levels for plant or animal production. Optimizing these lighting attributes for the various agricultural applications can improve plant growth and animal well-being, resulting in increased productivity. These benefits can be achieved, in addition to the energy savings offered by LED technology, once there is a clear understanding of the optimal lighting conditions for all of the various agricultural lighting applications. Plant growth can be greatly affected by different spectrums, optical distributions, and intensities, and the effects can be very different for different plant species or cultivars. Ongoing research in plant responses to light is elucidating the relationships between lighting attributes and the resulting plant growth. Optimizing lighting will enable improvements to plant growth and resulting productivity, while also reducing the required energy. Similar to human general illumination, lighting for animals can have a significant impact on animal health and well-being through stimulus of non-visual receptors that influence hormone production and circadian timing, and these impacts have a range of resulting health implications. Further research in this field will enable optimized lighting for animals in controlled environments that achieve significant energy savings and improve food productivity. Advancements to productivity need to be considered in parallel with energy savings to achieve the maximum effectiveness from lighting.

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