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Energy Savings Potential of SSL in Horticultural Applications

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Disclaimer

This report was prepared for:

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Executive Summary

This 2017 report presents the findings for horticultural lighting applications where light-emitting diode (LED) products are now competing with traditional light sources. The categories of indoor horticulture employing electric grow lighting included in this report are supplemented greenhouses, non-stacked indoor farms, and vertical farms:

Supplemented Greenhouses Structures enclosed by glass, rigid plastic, or a plastic film that is used for the cultivation or protection of plants. Supplemented greenhouses employ electric lighting to extend the hours of light provided to plants, to supplement low levels of sunlight on days with inclement weather, and/or to disrupt periods of darkness for purposes of altering plant growth. Because of the cost and environmental sensitivity of supplemental lighting technologies, **we assume that supplemental lighting is only used in permanent rigid glass greenhouse structures that operate year-round, and not in semi-permanent or plastic film covered structures.**

Non-stacked Indoor Farms Used for simple growing operations and/or tall plants, and represents an application where plants are grown in a single layer on the floor under ceiling-mounted electric lighting.

Vertical Farms In more sophisticated indoor farming operations, 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 indoor non-stacked farms or supplemented greenhouses.

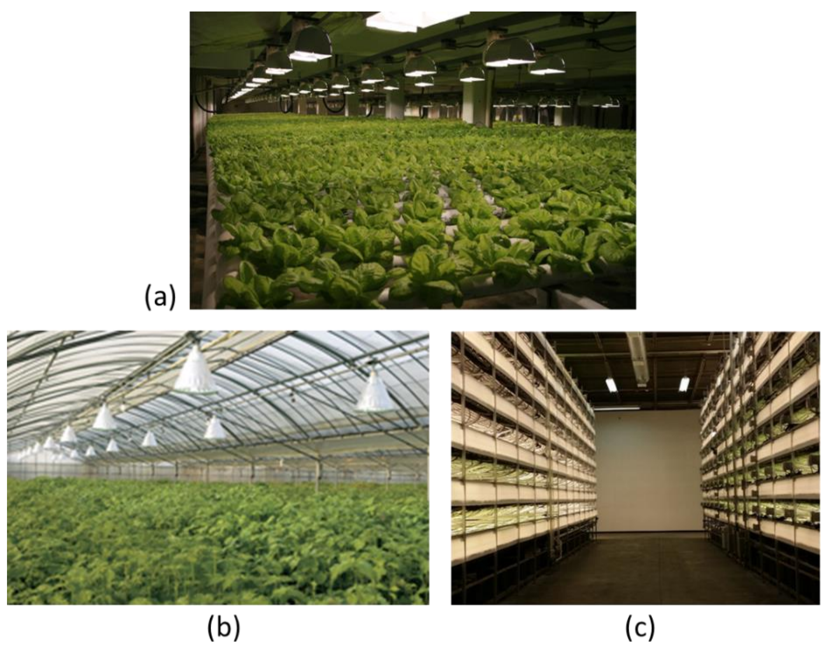

Figure E.1 Examples of: (a) Non-Stacked Indoor Lettuce Farm [1], (b) Greenhouse with Supplemental Lighting [2], and (c) Vertical Farm [3]

To estimate energy consumption of horticultural lighting, the following resources were utilized:

- Interviews with 19 growers, horticultural lighting manufacturers, horticultural lighting retailers, utilities, and other industry experts;
- Catalog and product specification databases for horticultural lighting products;
- U.S. Agriculture and Horticulture Censuses.

Each of these resources helped in determining total grow area, typical lighting configuration and power consumption (for both LED and incumbent technology), operating hours, and installed lighting technology mix for each of the three categories of indoor horticulture. Additionally, a theoretical "All LED" scenario was also calculated in which all existing horticultural lighting was assumed to switch to today's best performing LED lighting products. The "All LED" scenario represents the technical potential of LED lighting in horticulture applications based on 2017 performance levels.

The summary results for the 2017 LED Adoption and 2017 Energy Savings Potential are provided below in Table E.1. It is important to note that the findings of this study are current industry estimates as of the second quarter of 2017. The horticultural lighting market is changing and requires careful consideration of rapid improvements to LED technology, as well as market growth.

Table E.1 Summary of Horticultural Lighting Analysis

Analysis Outputs	Units	Vertical Farming	Supplemented Greenhouse	Non-Stacked Indoor	Total[1]
Estimated Total Lit Grow Area	**Million ft²**	0.5	26.8	18.7	46.0
Annual Operating Hours	**Hours/year**	6278	2120	5475	–
Average Electricity Consumption					
LED	**W/ft²**	17.4	7.3	41.8	–
HPS/MH	**W/ft²**	N/A	10.4	60.8	–
Fluorescent	**W/ft²**	22.8	N/A	60.0	–
2017 Technology Mix					
LED	**%**	66%	2%	4%	–
HPS/MH	**%**	<1%	98%	89%	–
Fluorescent	**%**	34%	–[2]	7%	–
2017 Annual Energy Consumption					
Current	**GWh/year (tBtu/year)**	60 (0.62)	588 (6.1)	5300 (55)	5940 61
Theoretical "All LED"	**GWh/year (tBtu/year)**	55 (0.57)	416 (4.3)	3100 (32)	3570 37
Theoretical % Energy Savings[3]	**%**	10%	29%	41%	40%

1. Values may not add due to rounding.
2. Supplemented greenhouses may sometimes use a small number of fluorescent fixtures in a separate room or facility for the purpose of cultivating seedlings and grafted plants. However, these lights were not included as part of the study.
3. 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.)

The major findings of the analysis include the following:

- In terms of grow area, supplemented greenhouses have the largest total area, at 26.8 million square feet (ft^2), followed by non-stacked indoor farms at 18.7 million ft^2, and lastly 0.5 million ft^2 for vertical farms. These vertical farms represent a new market entrant and best practices are still being developed.
- Based on current performance, for each category of indoor horticulture, LED lighting offers 24% to 30% reduction in electricity consumption per ft^2 of grow area.
    - Non-stacked indoor farms employ the most energy intensive lighting, with incumbent technology using about 60 Watts (W) per ft^2 (W/ft^2) of electricity and LED lighting consuming 41.8 W/ft^2.
    - Fluorescent lighting in vertical farms consumes 22.8 W/ft^2 compared to 17.4 W/ft^2 for LED lighting.
    - Supplemented greenhouses, which use sunlight as the primary light source, have the lowest electricity consumption per ft^2 of electric lighting with high-intensity discharge (HID) lighting consuming 10.4 W/ft^2 and LED lighting consuming 7.3 W/ft^2.
- In 2017, vertical farms have seen the highest adoption of LED lighting, at 66%, while LED products make up only 2% of lighting supplemented greenhouses and 4% of lighting in non-stacked indoor farms.
- Both vertical and non-stacked indoor farms rely solely on electric lighting and, as a result, require long operating hours, averaging 6,278 and 5,475 hours per year, respectively. Electric lighting used to supplement sunlight in greenhouses is operated an average of 2,120 hours per year.
- In 2017, horticultural lighting installations in the U.S. consume 5.9 terawatt hours (TWh) of electricity per year, which is equivalent to 61 trillion Btu (tBtu) of source energy consumption.[1] Of this 5.9 TWh, 89% comes from lighting in non-stacked indoor farms, 10% from supplemental lighting in greenhouses, and 1% from lighting in vertical farms.
- If all horticultural lighting today was converted to LED technology, annual horticultural lighting consumption would be reduced to 3.6 TWh, or 37 tBtu, which represents energy savings of 40% or $240 million.

[1] Source energy consumption is calculated by multiplying electricity consumption by a source-to-site conversion factor of 3.03 [15].

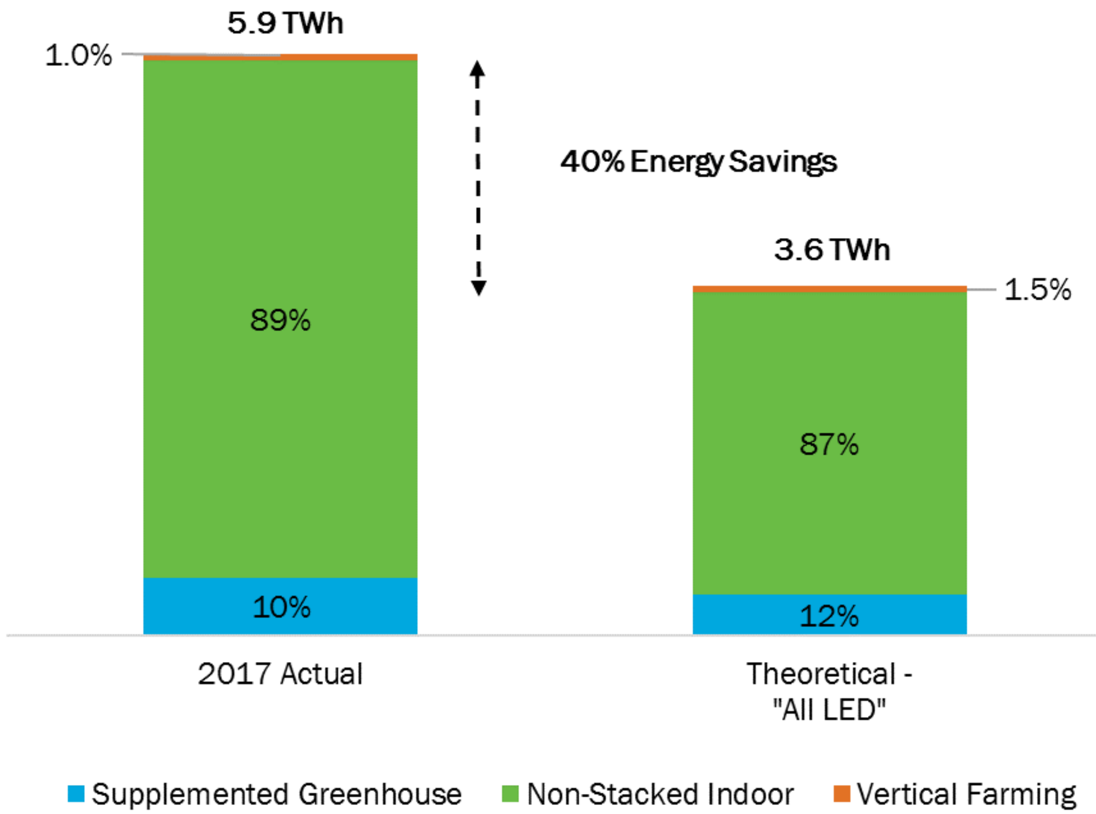

Figure E.2 2017 Annual Energy Consumption (TWh) of U.S. Horticultural Lighting

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1 Introduction

Light-emitting diode (LED) based lighting, the primary type of solid-state lighting (SSL), is revolutionizing the lighting market. LED lighting has surpassed all conventional lighting technologies in terms of energy efficiency, lifetime, versatility, and color quality, and, due to their increasing cost competitiveness, LED products are successfully competing in a variety of lighting applications. The Department of Energy (DOE) 2016 study, Energy Savings Forecast of Solid-State Lighting in General Illumination Applications, forecasts that LED lighting will represent 86% of all lighting sales by 2035, resulting in an annual primary energy savings of 3.7 quadrillion British thermal units (Btu) [4].

Since 2003, the DOE has evaluated the lighting applications where LED technologies are having the greatest energy savings impact. This assessment represents the first report investigating the adoption and resulting energy savings of LED lighting in horticulture applications.

This report aims to estimate the use of electric lighting in U.S. horticulture 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 horticulture 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 horticulture applications?

Growing food is an energy and resource intensive process. In traditional field agriculture, 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. Alternative horticulture approaches include controlled environment agriculture (CEA), the production of plants and their products inside structures, such as greenhouses, to produce high value crops at maximum productivity in an efficient and environmentally friendly way [5]. By employing CEA, also referred to as "indoor horticulture", growers can carefully and securely control plants to maximize their productivity and consistency without the negative impacts of inclement weather and climate, pests, or other unpredictable factors. While indoor horticulture is not a new practice, electric lighting has enabled a new era of food and crop production by supplementing sunlight in greenhouses or providing 100% of light to plants grown in indoor farms.

The increased use of electric lighting in CEA systems has been driven by advancements in horticulture science and lighting technology. 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 [6]. LED lighting technology offers the unique ability to spectrally tune light sources to engage specific plant 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 crops to a level of control that was previously impossible. However, the energy implications of such systems can be significant, with the top two end-uses 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 can be up to 50% of the total electricity consumption. However, the total electricity consumption from lighting depends on the source technology that is employed. The following sections briefly describe three categories of indoor horticulture as defined for use in this study: supplemented greenhouses, non-stacked indoor farms, and vertical farms. It also describes four horticultural lighting technologies most commonly used: high intensity discharge (HID), fluorescent, incandescent, and LED.

2 Indoor Horticulture Grow Architectures

For the purposes of this analysis, indoor horticulture using electric lighting is separated into three categories, because each has their own unique lighting requirements and grow architecture. In this report, the three types of indoor horticulture operations are supplemented greenhouses, non-stacked indoor farms, and vertical farms.

Supplemented Greenhouses Structures enclosed by glass, rigid plastic, or a plastic film that is used for the cultivation or protection of plants. Supplemented greenhouses employ electric lighting to extend the hours of light provided to plants, to supplement low levels of sunlight on days with inclement weather, and/or to disrupt periods of darkness for purposes of altering plant growth. Because of the cost and environmental sensitivity of supplemental lighting technologies, **we assume that supplemental lighting is only used in permanent rigid glass greenhouse structures that operate year-round, and not in semi-permanent or plastic film covered structures.**

Non-stacked Indoor Farms Used for simple growing operations and/or tall plants, and represents an application where plants are grown in a single layer on the floor under ceiling-mounted electric lighting.

Vertical Farms In more sophisticated indoor farming operations, 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 indoor non-stacked farms or supplemented greenhouses.

2.1 Supplemented Greenhouses

Greenhouses have been employed since the times of the ancient Romans covered cucumber beds with a frame glazed with transparent stone (mica) for sunny winter days. Greenhouse use evolved again in the late 1500's where lantern covers were placed over small areas of ground and used to force vegetable production [7]. Modern greenhouses have evolved to 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 in shown below in Figure 2.1.

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 [2]

In some cases, other additional features are installed, such as temperature regulation, humidity 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 during months with long periods of daylight.

The majority of light for plants grown in supplemental greenhouses is provided by natural sunlight, with supplemental lighting being 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, whether or not a greenhouse has 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 virtually nonexistent.

2.2 Non-Stacked Indoor Farms

Non-stacked indoor farms are the next evolution in indoor horticulture from greenhouses, in that by bringing growth operations indoors, operators have complete control over all parameters affecting plant growth, such as light exposure, ambient 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. Warehouses are typically used for indoor growth operations, due to high ceilings and large floor space.

As shown in Figure 2.2, non-stacked indoor farms employ ceiling mounted lighting fixtures to provide 100% of light to plants grown in a single layer on pallets, tables, or the floor. Non-stacked indoor farms are simpler than stacked (vertical) indoor farms (discussed in the next section), and are preferred where space is not necessarily a premium or where plants are too large to be stacked on top of each other.

Figure 2.2 Non-Stacked Indoor Lettuce Farm, The Lettuce Farm [1]

2.3 Vertical Farms

Vertical farms, also known as stacked indoor farms, are the newest and most advanced form of indoor agriculture. They differ from non-stacked 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. 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 important metric is total lit grow area, the shelves on which plants are grown, rather than the building area.

Figure 2.3 A Vertical Farm Growth Configuration; AeroFarms in Newark, NJ [3]

Unlike non-stacked indoor 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 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.

2.4 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 per second (μmol/s) [8]. Table 2.1 compares the best in class photosynthetic photon efficacy (PPE), which is defined as the PPF divided by input electrical power. The units of PPE are measured in micro-moles per joule (μmol/J) [8]. Each technology will be discussed in more detail in the following sections; however, we see that LED lighting products already offer higher PPE over incumbent technologies, and that 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 [9]
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 [10]
LED (2017)**	2.5	DOE SSL Program, “2017 Suggested Research Topics Supplement: Technology and Market Context”, 2017 [11]
Future LED	> 4	

*Does not account for ballast losses
**Efficiency values are provided for 2014 and 2017 for double-ended HPS and LED because they are relatively new innovations that have been the subject of continued work.

2.4.1 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 non-stacked indoor farms. HPS and MH technologies utilize a gas-discharge lamp with mixture 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 for higher efficacies (up to 69%) than traditional mogul-based HPS lamps, allowing growers to increase their PPF and/or reduce electricity costs [9]. 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 [10].

HPS and MH fixtures are the most common type of horticultural lighting found in greenhouses and non-stacked indoor farms. They provide for a wide, uniform distribution of light. Typical fixtures range from 400 Watts (W) to 1000W 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) infeasible with this technology type.

2.4.2 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 [9]. 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 been the predominant incumbent technology used in vertical farming.

2.4.3 Incandescent

Incandescent lights consist of tungsten filament lamps that emit a yellowish 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 since the energy consumption impact of this type of horticultural lighting is very small in relation to HID, fluorescent, and LED lighting.

2.4.4 LED

While still and emerging application, 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, as their PPE is generally higher. Some recent integrated horticultural LED products claim PPE levels as high as 2.5 μmol/J. 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. 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 [11]. 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].

In addition to energy savings, the use of LED lighting in horticulture applications can enable spectral tailoring, dynamic spectral tuning, instantaneous intensity control, and light distribution control required for effective indoor horticulture systems. However, stakeholders in the industry express caution that independent third-party research is needed to substantiate claims that tailored spectra can offer improvements over a broad spectrum source (i.e., those that mimic sunlight). For example, LED lighting products often lack UV radiation necessary for proper plant growth, which is not a significant issue for greenhouse operations, where natural, broad spectrum sunlight provides the bulk of the light requirement. However, for completely indoor operations, LED products may require additional engineering to ensure the fixtures provide UV light needed for plant growth. An additional barrier to LED adoption is high cost relative to incumbent technologies. As with LED lighting for general illumination, costs are expected to decline; however, as LED products enable new value for horticultural applications higher first cost will become less of a deterrent.

LED technology can support a greater understanding of the specific lighting needs for horticultural crops, and 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].

3 Methodology

For the purposes of this analysis, indoor horticulture using electric lighting is separated into three categories, because as discussed in Section 2, each has their own unique lighting requirements and grow architecture. In this report, the three types of indoor horticulture operations are supplemented greenhouses, non-stacked indoor farms, and vertical farms.

It is important to note that growing requirements, including lighting requirements, differ for various plant species. Therefore, lighting intensity, duration, and configuration will differ from one supplemented greenhouse to another based on crop choice and business goals. This same principle applies to non-stacked and vertical indoor farms. This report presents an average of growth conditions for each category of indoor horticulture as opposed to the conditions for specific plants.

To characterize the U.S. indoor horticulture market, including the total size of grow area, typical lighting configuration used, and current LED lighting adoption in each of these categories, the team conducted interviews with 19 growers, horticultural lighting manufacturers, horticultural lighting retailers, utilities, and other industry experts. Individual input provided by the contributing parties is kept confidential, and was used in conjunction with various publications to create estimates for the U.S. indoor horticulture market. A list of contributing stakeholders is provided in the Acknowledgements Section of this report. In addition to stakeholder inputs, the U.S. Agricultural Census, the Census of Horticultural Specialties, U.S. Naval Observatory data on daylight hours, and research on available horticultural lighting products were used as inputs for the analysis, as shown in Figure 3.1.

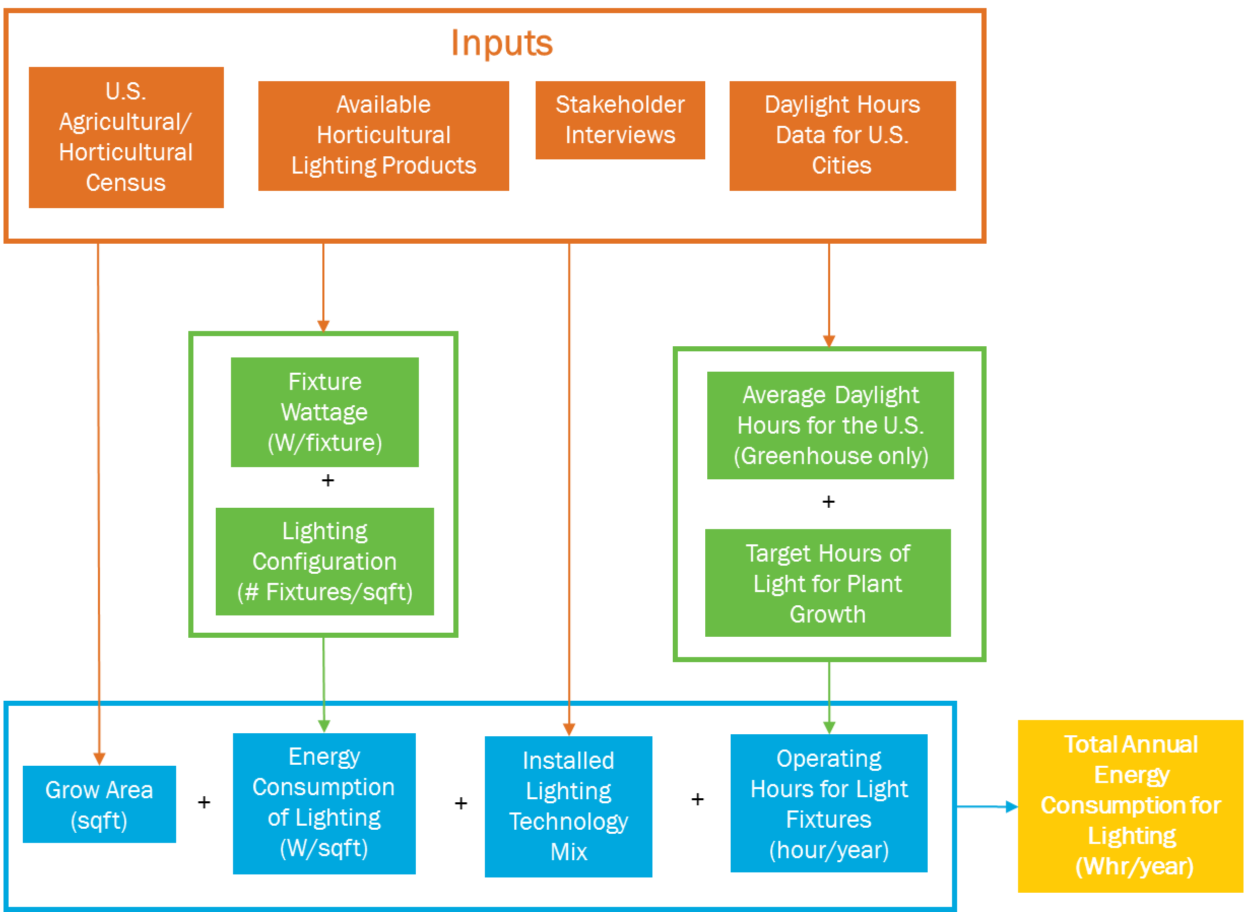

Figure 3.1 Horticulture Analysis Methodology

Figure 3.1 describes the methodology used to determine the total annual energy consumption for lighting for each category of indoor horticulture. The four main variables used to calculate total annual energy consumption: grow area (ft^2), energy consumption of lighting (W/ft^2), installed lighting technology mix, and operating hours for light fixtures (hour/year) are shown in blue, while intermediate variables are shown in green. The method for determining each of these variables is explained below:

3.1 Grow Area

The total grow area (in ft^2) for each category of indoor horticulture was determined using the following methods:

1. **Stakeholder interviews and industry information**: Stakeholders provided estimates on the total lit grow area of vertical farming.

2. **USDA Census data**: Data from the 2012 Census of Agriculture was used to determine total U.S. grow area for greenhouses. For the purpose of this study, U.S. greenhouse area was included for the following plant types: floriculture, fruits, berries, vegetables, and fresh cut herbs. Certain crop types were excluded from the calculation of the total applicable greenhouse area, such as aquatic plants and mushrooms, as these crops are not expected to require any horticultural lights. Input from stakeholder interviews and data from the 2014 Census of Horticultural Specialties were used to determine the percentage of total U.S. greenhouse area that is estimated to supplement with horticultural lighting. The results are discussed in Section 4.1.

3. **Back-calculation of grow area via total electricity consumption estimates**: Utility companies provided estimate values regarding the total electricity draw associated with non-stacked indoor farming in their state or region. This electricity consumption was used to back-calculate the estimated total grow area for the industry based on typical lighting configurations and the typical energy consumption characteristics of those configurations.

3.2 Energy Consumption

First, a list of available horticultural lighting products was compiled and reviewed to determine typical performance characteristics such as wattage and dimensions. 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 lighting configurations they have typically used and/or seen. Average watts per fixture and the typical grow area covered by one lighting fixture was used to estimate the electricity consumption normalized by grow area (W/ft^2) for both LED and incumbent lighting in each of the three categories of indoor horticulture.

3.3 Installed Lighting Technology Mix

Stakeholder interviews were used to estimate the percentage of lighting installed in 2017 that is LED vs. incumbent technology (i.e., linear fluorescent, HPS, or MH) in each category of indoor horticulture.

3.4 Operating Hours for Light Fixtures

Stakeholder interviews were used to determine an average target amount of light in hours for all indoor horticultural categories. However, for supplemental greenhouse lighting, the monthly average hours of daylight for 6 different regions in the U.S., was subtracted from the target amount of light to determine the average hours of supplemental lighting required by month for each region. An annual total of operating hours for supplemental lighting was calculated from the monthly average for each region, and then these were averaged to determine the typical annual operating hour estimate for supplemental lighting greenhouses across the U.S. Because the annual average daylight hours across all six regions was within +/- 0.3%, all regions were weighted equally. However, within these regions there can be different requirements based on typical weather patterns that require greater usage of supplemental lighting. These regional variations were not accounted for in this analysis.

Table 3.1 Average Annual Hours of Operation for Supplemental Lighting

Location	Annual Average
Seattle, WA	2,105
New York, NY	2,116
Salinas, CA	2,126
Charleston, SC	2,130
Pierre, SD	2,112
Dallas, TX	2,129
Total	**2,120**

Source: Calculated from U.S. Naval Observatory Daylight Duration Data for 2016

3.5 Potential Energy Savings Estimate

The typical energy consumption per ft^2 was determined for each of the three categories of indoor horticulture for both conventional and LED lighting products. This characteristic energy consumption, in conjunction with estimates of annual operating hours, current LED adoption, and the total market size enabled the estimation of total energy use for each of the three indoor horticulture 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 horticultural lighting installed in 2017 was converted to LED lamps and luminaires "overnight", given current PPE levels. This estimate likely underestimates the potential for energy savings because, according to the stakeholders interviewed, the indoor lighting-supplemented horticultural market is expected to grow, and LED horticultural product PPE is still below technical limits.

4 Results

As of 2017[2], in the U.S., a total of 46 million ft^2 of grow area was lit by electric horticultural lighting, 58% of which was in supplemental greenhouses, 41% in non-stacked indoor farms, and only 1% in vertical farms, as shown in Figure 4.1.

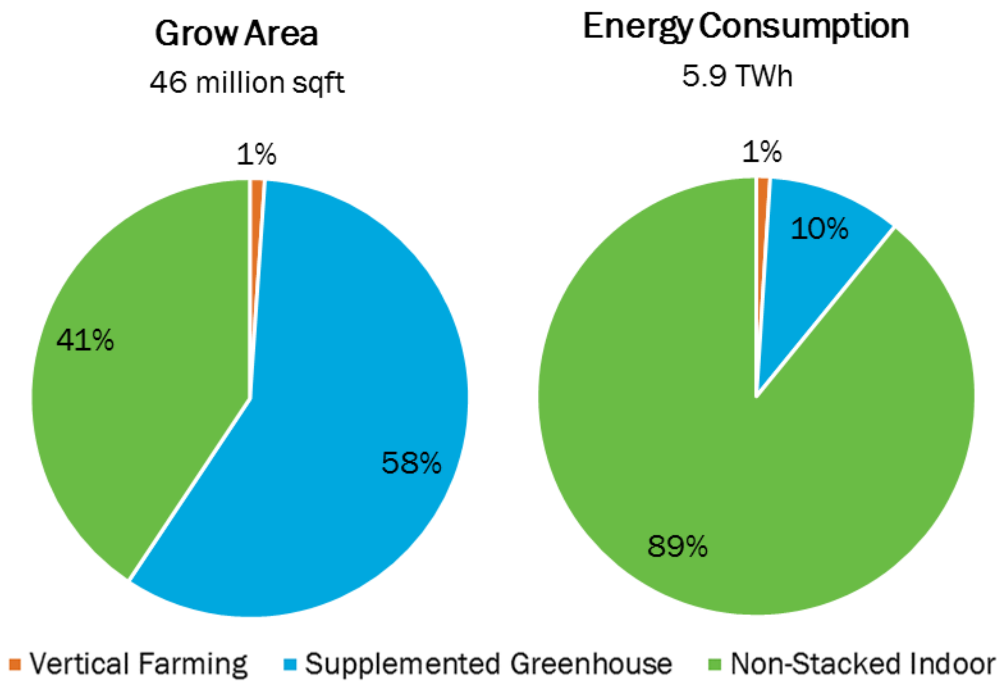

Figure 4.1 Total U.S. Grow Area and Annual Energy Consumption

These horticultural lighting installations consumed 5.9 terawatt hours (TWh) of electricity per year, equivalent to 61 trillion British thermal units (tBtu) of source energy consumption.[3] Of this 5.9 TWh, 89% come from lighting in non-stacked indoor farms, 10% from supplemental lighting in greenhouses, and 1% from lighting in vertical farms. By comparison, in 2016, DOE estimated that white lighting for general illumination consumed 5,500 tBtus in 2016 [12].[4] To estimate the potential 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 3.6 TWh, or 37 tBtu annually, which represents energy savings of 40% or $240 million annually. The annual energy consumption in 2017 and the theoretical energy consumption of switching to the "All LED" scenario is shown in Figure 4.2 below.

[2] Interviews and data collection were conducted from May through July of 2017. All figures, calculations, and estimates are reflective of this date.
[3] Source energy consumption is calculated by multiplying electricity consumption by a source-to-site conversion factor of 3.03 [15].
[4] In the 2017 Report "Adoption of Light-Emitting Diodes in Common Lighting Applications", DOE estimated that in 2016, there were 6.9 billion lighting systems installed in the U.S. and that they consumed approximately 5.5 quads of energy annually.

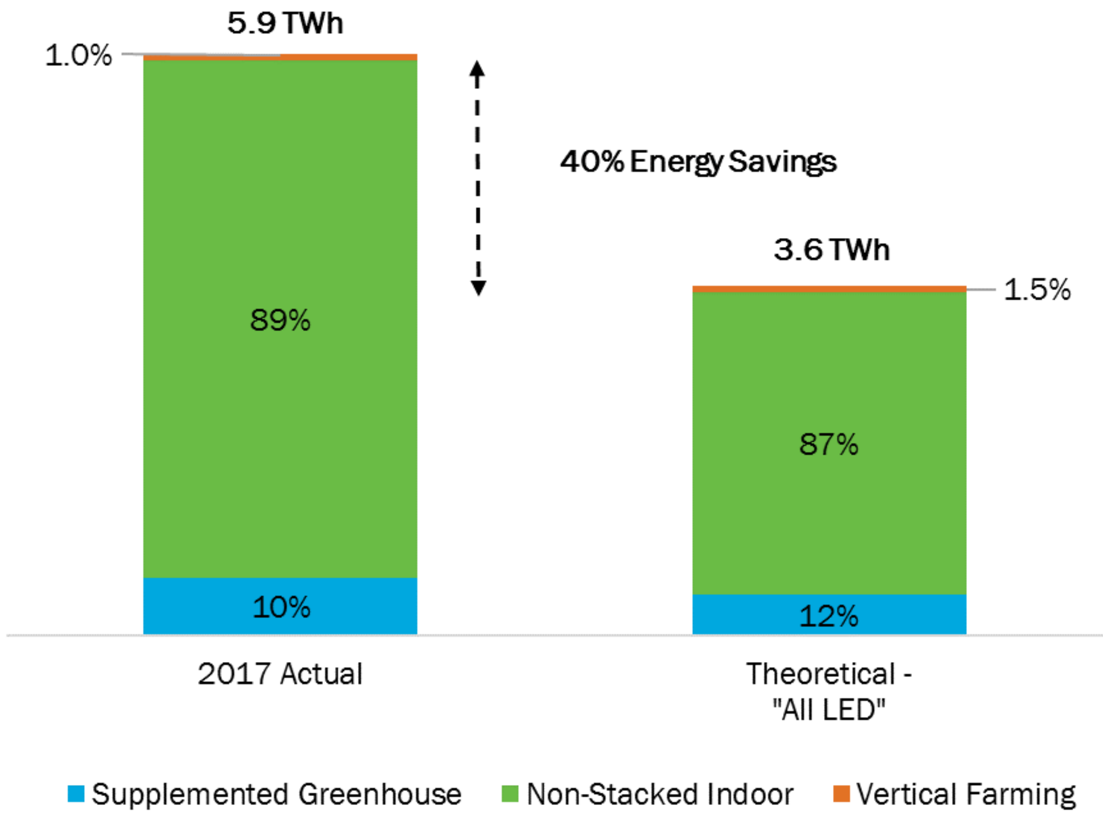

Figure 4.2 2017 Actual and Theoretical "All LED" Annual Energy Consumption

A summary of the results is shown in Table 4.1 below. Horticultural lighting in each of these indoor horticulture market segments will be discussed in more detail in the following sections of this report.

Table 4.1 Summary of Horticultural Lighting Analysis

Analysis Outputs	Units	Vertical Farming	Supplemented Greenhouse	Non-Stacked Indoor	Total[1]
Estimated Total Lit Grow Area	**Million ft²**	0.5	26.8	18.7	46.0
Annual Operating Hours	**Hours/year**	6278	2120	5475	–
Average Electricity Consumption					
LED	**W/ft²**	17.4	7.3	41.8	–
HPS/MH		N/A	10.4	60.8	–
Fluorescent		22.8	N/A	60.0	–
2017 Technology Mix					
LED	**%**	66%	2%	4%	–
HPS/MH		<1%	98%	89%	–
Fluorescent		34%	–[2]	7%	–
2017 Annual Energy Consumption					
Current	**GWh/year (tBtu/year)**	60 (0.62)	588 (6.1)	5300 (55)	5940 61
Theoretical "All LED"		55 (0.57)	416 (4.3)	3100 (32)	3570 37
Theoretical % Energy Savings[3]	**%**	10%	29%	41%	40%

1. Values may not add due to rounding.
2. Supplemented greenhouses may sometimes use a small number of fluorescent fixtures in a separate room or facility for the purpose of cultivating seedlings and grafted plants. However, these lights were not included as part of the study.
3. 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.)

4.1 Supplemented Greenhouses

According to the 2012 Census of Agriculture, greenhouses for floriculture, fruits, berries, vegetables, and fresh cut herbs in the U.S. covered nearly 980 million ft^2 [13]. 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) [14]. Based on data provided during stakeholder interviews, we estimate that 20% of permanent glass greenhouses across the U.S. employ supplemental lighting, which is equal to roughly 27 million ft^2 of grow area. Of the three types of indoor horticulture, supplemented greenhouses represent the largest by grow area, with supplemented greenhouses housing 58% of grow area under electric lighting. Despite the large grow area, supplemented greenhouses consumed just 10% of electricity dedicated to horticultural lighting because of shorter operating hours and sparse fixture density relative to all indoor applications.

The majority of supplemental greenhouse lighting is used to stretch the duration of light for plants to 18 hours to counteract shorter daylight hours or cloudy days, and therefore the amount of supplemental lighting required, and hence daily operating hours, vary over the course of one calendar year. For example, in Seattle, Washington the average daylight hours in 2016 ranged from 8 hours 29 minutes in December to 15 hours and 55 minutes in June. Therefore, to meet the target of 18 hours of incident light on the plants per day, supplemental lighting would operate for about 9.5 hours in December, but only 2 hours in June. The average hours of daylight each month for six locations across the U.S. were used to approximate the daylight hours for the major regions in the US: Northeast, Southeast, Midwest, Northwest, and West. The average daylight hours were then subtracted from 18 hours, our estimated average daily light dose target for plants in greenhouses, to determine how long supplemental lighting would be used each month. From this estimate we determined that, on average, U.S. greenhouse supplemental lighting operates 2,120 hr/year.

Because operating hours of electric lights in supplemented greenhouses are low relative to fully indoor operations, high first cost is the primary impediment, and the long-term energy savings offered by LED lighting products are less attractive. In 2017, LED lighting adoption in supplemented greenhouses was estimated to be 2%, with the remaining 98% of light being provided from high pressure sodium (HPS) and metal halide (MH) fixtures.

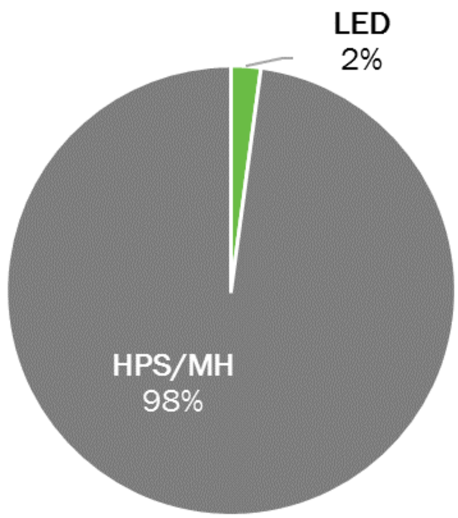

Figure 4.3 2017 Technology Mix for U.S. Supplemental Greenhouse Lighting

Light fixtures for supplemental lighting in greenhouses are typically ceiling 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 1000W or 400W HPS or MH lamps.[5] A single lamp is installed per fixture and 1000W HPS lamps are typically used over a grow area of about 100 ft^2, while the 400W HPS lamps are typically used over about 50 ft^2. The estimated energy consumption of incumbent supplemented greenhouse lighting is 10.4 W/ft^2.

For this report, it is assumed that LED lighting products used in greenhouses can function as 1 to 1 replacements for existing HID fixtures, i.e., the configuration and PPF remains unchanged, but due to higher PPE, the overall energy consumption is reduced. 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. However, it is assumed that the majority of growers have already optimized the amount of electric light incident on their plants, and would be installing direct replacement LED lighting configurations that produce the same light for less energy. Therefore, the estimated energy consumption of supplemented greenhouses utilizing LED lighting is estimated at 7.3 W/ft^2, a 30% reduction in electricity consumption per square feet of grow area.

[5] HPS and MH lamp wattages provided do not include ballast efficiency losses.

In 2017, the supplemental lighting installed in U.S. greenhouses has an annual consumption of 588 gigawatt-hours (GWh) of electricity, equivalent to 6.1 tBtu of 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 416 GWh or 4.3 tBtu annually. This represents a 29% energy savings potential, and a savings of $18 million, offered by current best-of performing LED lighting products.

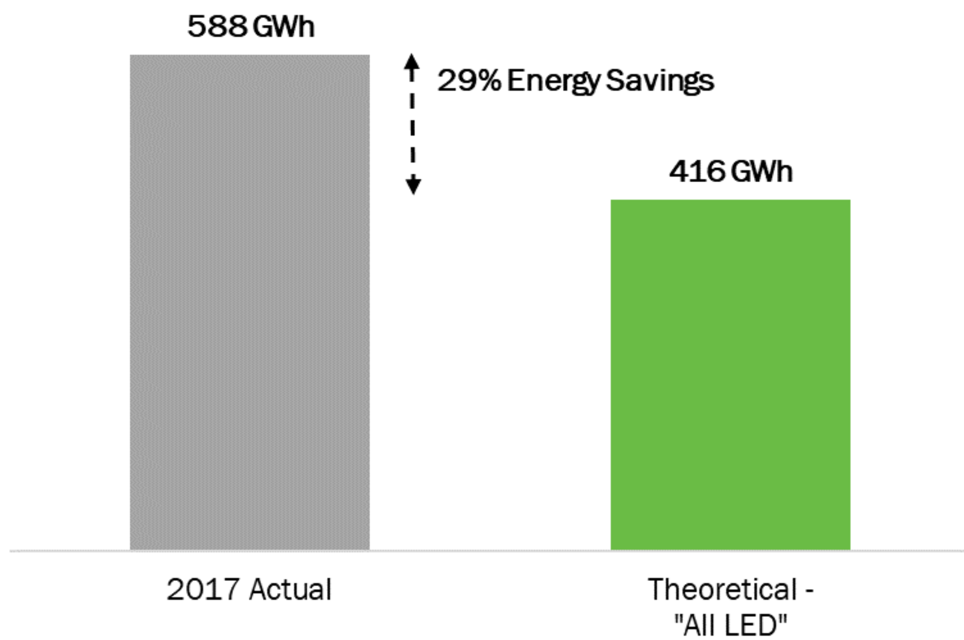

Figure 4.4 2017 Annual Energy Consumption of Supplemental Lighting in U.S. Greenhouses and Savings Comparison with a Theoretical “All LED” Scenario

4.2 Non-Stacked Indoor Farms

In 2017, a total of 18.7 million ft^2 of grow area within the U.S. falls into the category of non-stacked indoor farms. Non-stacked indoor farms have a single growth plane, like greenhouses; however, as they are completely indoor, electric lighting provides 100% of light to the plants which results in much higher electricity consumption.

Light fixtures for non-stacked indoor farms are ceiling mounted to maintain uniformity across plant canopies, with the number of fixtures depending on how much light is required, which varies by plant type. Like supplemented greenhouses, the typical HID grow light consists of a 1000W HPS lamp or a 600W MH lamp (does not include ballast losses), which is typically used over a grow area of about 20 ft^2. Linear fluorescents while used, are much less common, and may be preferred in buildings with low ceiling heights, in smaller “research and development” areas of the farm, or exclusively for seedlings or grafted plant cycles. The estimated energy consumption of incumbent non-stacked indoor lighting is 60.8 W/ft^2, which 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 high efficiency linear fluorescents are installed close to the plants, minimizing wasted light). LED products used in non-stacked indoor farms are also mounted on the ceiling, but due to higher PPE, the overall energy consumption is reduced. The estimated energy consumption of LED supplemented greenhouse lighting is 41.8 W/ft^2, a 31% reduction in energy consumption per square feet of grow area.

Unlike in supplemented greenhouses, all light in non-stacked indoor farms is provided by electric lighting, and therefore non-stacked indoor farm lighting is characterized by long operating hours from 12 hr/day up to 18 hr/day. On average, U.S. non-stacked indoor farms operate their lights for 15.0 hr/day, 365 days a year for total annual operating hours of 5,475 hr/year. First cost remains a significant barrier to the adoption of LED lighting products in non-stacked indoor applications. Also, interviewed stakeholders indicated that growers who are more familiar with HID sources may be hesitant to try relatively unproven LED technology for fear it may alter the growth and yield of their crop. In 2017, LED adoption in non-stacked indoor farms was estimated to be 4%, while 89% of fixtures were HID (i.e., metal halide or HPS) and 7% were linear fluorescent.

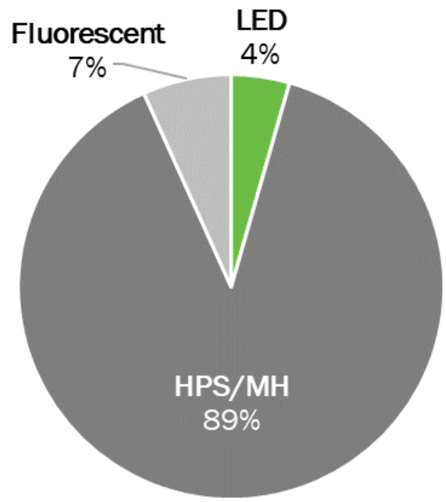

Figure 4.5 2017 Lighting Technology Mix for U.S. Indoor Non-stacked Farms

In 2017, electric lighting installed in non-stacked indoor farms consumed 5,300 GWh of electricity, equivalent to 55 tBtu of source energy. If the remaining 96% of lighting fixtures that are HID and linear fluorescent were to convert to LED “overnight”, electric lighting installed in U.S. non-stacked indoor farms would consume 3,100 GWh of electricity, or 32 tBtu of source energy annually. This represents over 41% energy savings and a savings of $226 million per year.

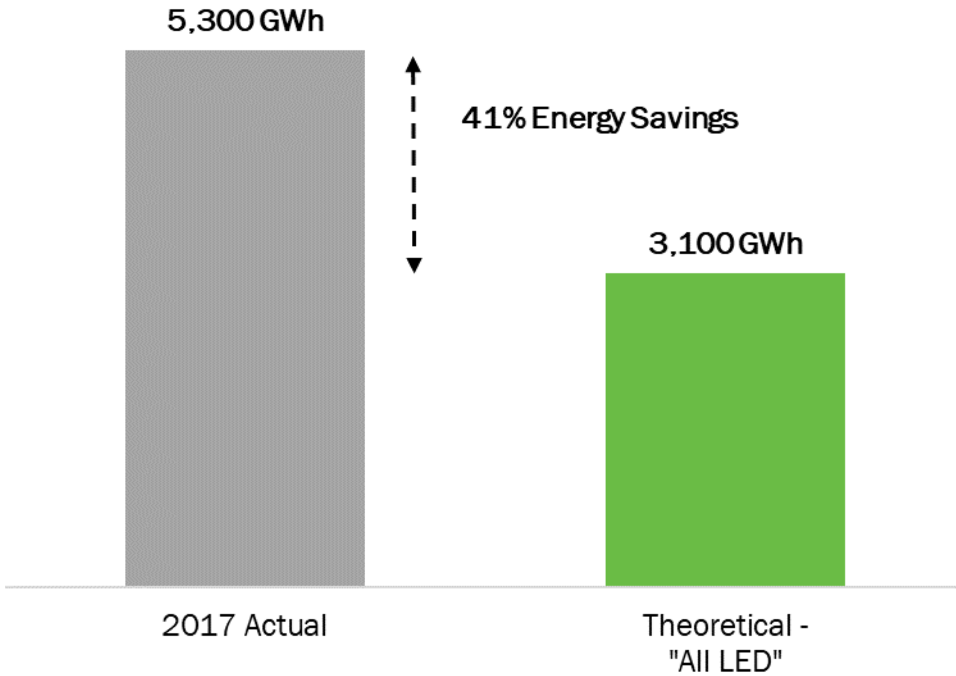

Figure 4.6 2017 Annual Energy Consumption (GWh) of Lighting in U.S. Non-stacked Indoor Farms and Savings Comparison with a Theoretical "All LED" Scenario

4.3 Vertical Farms

Vertical farming is the newest of the indoor horticulture operations described in this report, and as such, the market is small, but growing rapidly. The industry consists of both large, commercial scale businesses as well as small, local operations, and there are many vertical farming operations in the U.S., including AeroFarms based in Newark, NJ, Green Sense Farms in Portage, Indiana, and Green Spirit Farms in Detroit and New Buffalo, Michigan. For vertical farms, the important metric is total grow area, the shelves on which plants are grown, rather than the building area. Using the estimates provided in stakeholder interviews, the current estimate for total grow area in U.S. vertical farms is 500,000 ft^2.

Due to their unique grow architecture that requires intracanopy lighting and close proximity to plants, LED and linear fluorescent fixtures are the only viable technology options for vertical farms. Typical linear fluorescent lamps may be mounted within the stack above each row of plants, where they consume an estimated 22.8 W/ft^2 of grow area. LED products used in vertical farming can function as 1 to 1 replacements for existing linear fluorescent fixtures, i.e., the configuration and PPF remains unchanged, but due to higher PPE, the overall energy consumption is reduced. However, because vertical farms are a new endeavor, the majority are installing LED fixtures outright which enables them to adopt new LED architectures rather than being confined to a linear tube as they would be when serving as direct replacements for linear fluorescent lamps. LED lighting enables a host of other functionalities including tailored spectral output and dynamic controls. Both LED linear replacement lamps and integrated LED luminaires offer energy savings. The estimated energy consumption of LED lighting for vertical farms is 17.4 W/ft^2, a 24% reduction in energy consumption per square feet of grow area.

Similar to non-stacked indoor farms, all light is provided by electric lighting. Therefore, vertical farm lighting is characterized by long operating hours from 15 hr/day up to continuously at 24 hr/day. On average, we estimate U.S. vertical farms operate lighting for 17.2 hr/day, 365 days a year for total annual operating hours of 6,278 hr/year. With long operating hours, the energy savings offered by LED lighting products often offsets 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, many stakeholders believe LED technology is enabling the growth of vertical farms because LED products enable flexible lighting solutions for various, compact, and unique grow architectures. In 2017, LED adoption in vertical farms was estimated to be 66%, with the remaining 34% of light being provided from linear fluorescent fixtures.

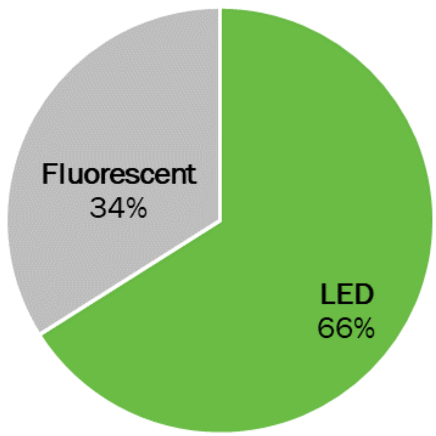

Figure 4.7 2017 Lighting Technology Mix in U.S. Vertical Farms

In 2017, the electric lighting installed in U.S. vertical farms has an annual consumption of 60 GWh of electricity, equivalent to 0.62 tBtu. If the remaining 34% of fixtures installed in U.S. vertical farms that are fluorescent were to convert to LED "overnight", lighting in U.S. vertical farms would consume 55 GWh of electricity annually, a savings of 10%. This savings is small in comparison to non-stacked indoor farms and supplemented greenhouses where LED products currently make up less than 5% of the fixtures.

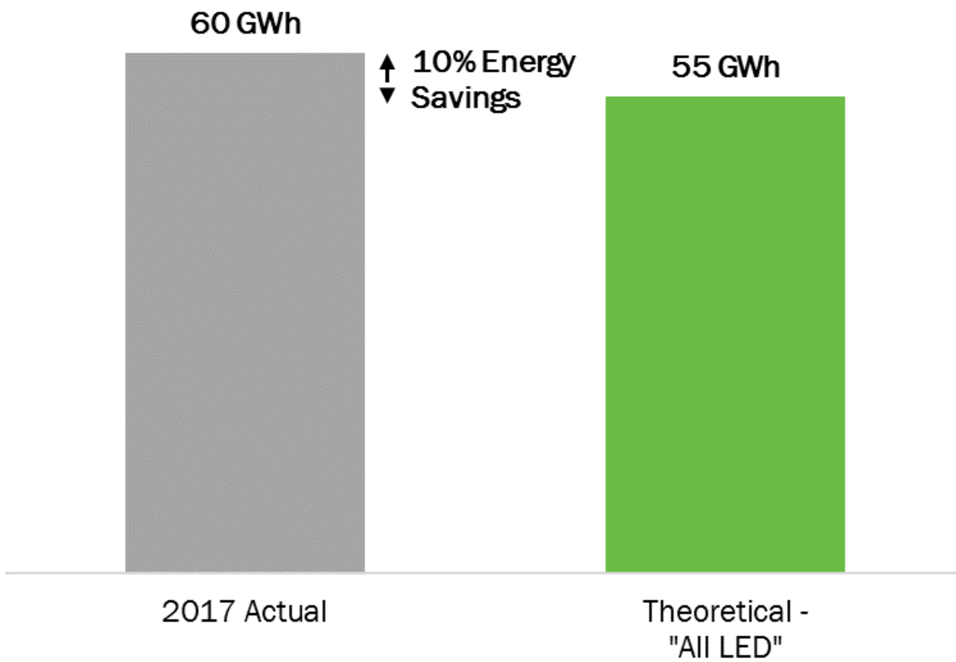

Figure 4.8 2017 Annual Energy Consumption (GWh) of Lighting in U.S. Vertical Farms and Savings Comparison with a Theoretical "All LED" Scenario

5 Conclusion

In 2017[6], the total annual energy consumption of horticultural lighting is estimated to be 5.9 TWh per year, which is about 1% of the energy consumed by general illumination and equal to the annual electricity consumption of approximately 550,000 U.S. households [12].[7] Horticultural lighting electricity consumption is expected to rise as the total number of indoor and supplemental greenhouse operations increase. Although there is no established industry reference on lit grow area projections, stakeholders indicated that assumptions between 15% and 25% growth each year are reasonable. In Figure 5.1, the dark green demonstrates total energy consumption of horticultural lighting from 2017 to 2025 assuming the total lit horticultural grow area in the U.S. increases at 19% per year[8], given the current mix of lighting technologies employed remains constant. This is then compared to a theoretical "all LED" scenario to illustrate potential energy savings offered by LED lighting products. As the total lit area for US horticultural applications increases, the potential energy savings of the "all LED" scenario also increases. The 2017 potential annual energy savings from LED horticultural lighting is estimated at 2.3 TWh, but that could grow to as much as 13.7 TWh by 2025.

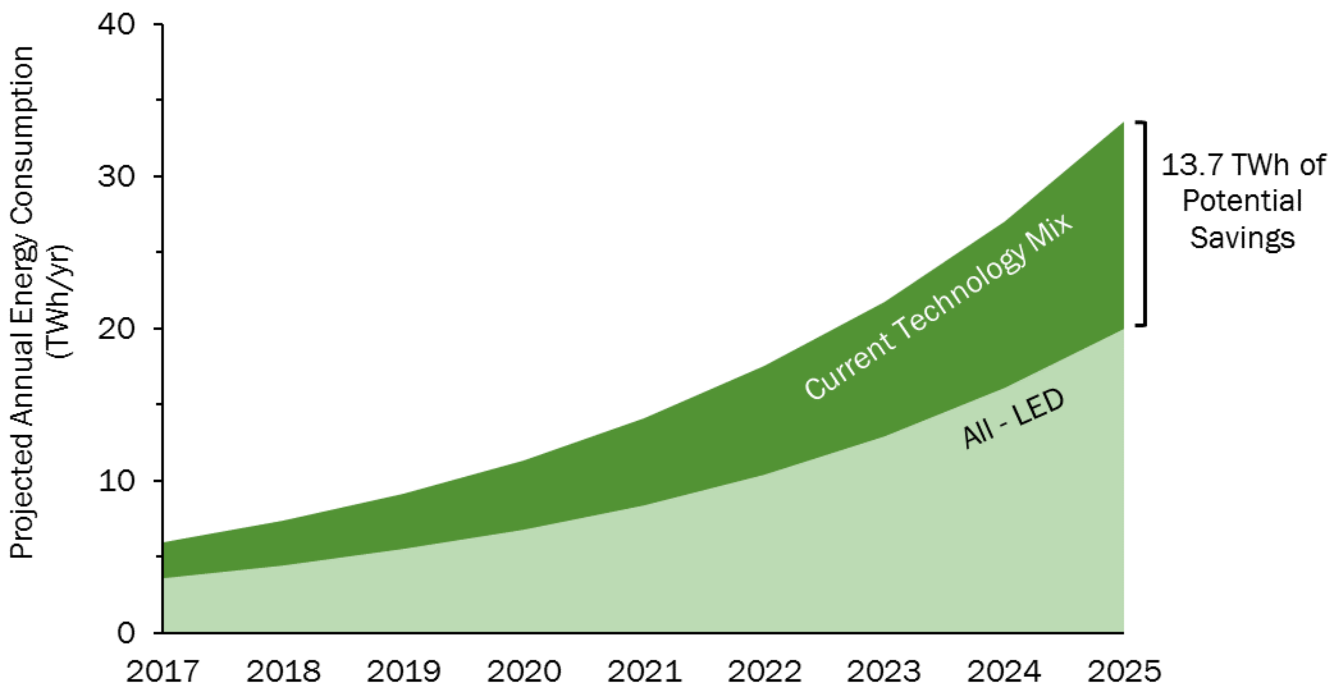

Figure 5.1 Estimated Growth Horticultural Lighting Energy Consumption

Just as with general illumination, LED lighting is ultimately expected to dominate in horticultural applications, thereby providing significant energy and cost savings. However, there are currently numerous barriers to widespread LED adoption in horticultural applications. High first cost is still a significant deterrent to the adoption of more efficient LED technology. Additionally, there are no established testing standards by which horticultural lighting products can be evaluated, and therefore users are wary of unsubstantiated claims regarding performance, reliability, and impact on plant growth. Horticulture lighting performance and

[6] Interviews and data collection were conducted from May through July of 2017. All figures, calculations, and estimates are reflective of this date.
[7] Based on EIA 2015 estimate that average annual electricity consumption for a U.S. residential utility customer was 10,812 kWh. https://www.eia.gov/tools/faqs/faq.php?id=97&t=3
[8] The 19% represents an assumption of future market growth based on stakeholder input, as opposed to a quantitative forecast of actual growth, and is included to illustrate the increasing potential for future energy savings.

reliability has a direct relationship to plant growth and total yield and, therefore, the bottom line for the growing operation. As a result, commercial growers may be hesitant to adopt new, unproven technology. For example, greater understanding of the light output depreciation and reliability of the LED horticultural lighting products may be required before growers gain confidence, since catastrophic failures and reduced PPF would directly impact yield.

The findings of this study are based on current industry estimates collected between May 1st and July 31st, 2017. LED lighting products are an emerging technology option within horticulture applications, and electric lighting use in horticultural operations is itself a recent practice. Therefore, it is important to acknowledge that the horticultural lighting market is evolving rapidly, and its future is uncertain. Due to this mounting uncertainty, continuing analysis to monitor U.S. indoor horticulture operations and the progress of LED horticultural lighting is advised. This will help to ensure that the energy savings potential of LED technology is realized now and in the future.

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