5-2019

Lighting and Economic Considerations for a Hydroponic S-Based Greenhouse at Tri Cycle Farms

Laura Gray

Recommended Citation

Gray, Laura, "Lighting and Economic Considerations for a Hydroponic S-Based Greenhouse at Tri Cycle Farms" (2019). *Biological and Agricultural Engineering Undergraduate Honors Theses*. 58.
https://scholarworks.uark.edu/baeguht/58

LIGHTING AND ECONOMIC CONSIDERATIONS FOR A HYDROPONICS-BASED GREENHOUSE AT TRI CYCLE FARMS

Laura Gray

Biological Engineering Program

Biological and Agricultural Engineering Department

College of Engineering

University of Arkansas

Undergraduate Honors Thesis

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

PROJECT SUMMARY

Hydroponics is an agricultural technology that involves growing plants without soil, instead using other growth media with added nutrients, typically inside a controlled facility such as a greenhouse. Hydroponics-based agriculture has a number of benefits, namely that it is more water efficient, requires less intensive labor, yields higher quality crops consistently in shorter time, and is easier to control. It also has the potential to be economically advantageous, due to its ability to grow certain crops in the off-season. In Fayetteville, Arkansas, a non-profit urban farm known as Tri Cycle Farms has been seeking a way to design, build, and implement a profitable hydroponics-based greenhouse in order to better offset their costs of operation. Tri Cycle Farms operates off of the motto of "Give a Third, Sell a Third, and Share a Third" of their produce, and currently does not have any paid staff. Tri Cycle tends to give and share more of its produce than they sell, and while admirable, makes it difficult to keep their doors open. After getting involved with Tri Cycle Farms as volunteers and consulting with Don Bennett, the owner, Sarah Gould and I decided to take on the initial stages of design for this hydroponics greenhouse, or "HydroHouse." The objectives of this project are to 1) size and design the lighting needs for a hydroponic subsystem of Dutch buckets in the house based on Ms. Gould's work, and 2) to produce a general set of engineering economics calculations and recommendations. This report includes the process of fulfilling these objectives, the justification behind various design decisions, and a discussion of the future work to be completed and the future impacts of the greenhouse for Tri Cycle Farms and the Northwest Arkansas community in general. As a conservative estimate, ten LED grow lights were determined to be needed for the Dutch bucket system based on the light requirements for tomatoes. Additionally, the simple payback period for the Dutch bucket system was calculated to be 0.43 years, or 5.1 months, with a Gross Annual Benefit of $20,000 for the first year, and $34,000 in following years.

INTRODUCTION

In the next forty years, it is expected that more food than farmers have harvested in the past 8,000 years will need to be produced in order to keep up with the exponential growth of the human population (Viviano, 2017). On the Global Scale, one in nine people are undernourished (United Nations, 2019) and on the local level, one in four people in Northwest Arkansas are food insecure (Nexstar Broadcasting, Inc., 2015). This is a serious issue, and has gained the attention of organizations like the United Nations, various NGOs, and local nonprofits. The United Nations has made food insecurity one of its 18 Sustainable Development Goals, and around the world, the agriculture industry is feeling the burden of advancing technology to produce more while using less resources.

However, new techniques and agricultural practices are being developed to advance production in novel ways. One such innovation is hydroponics, or the growing of plants without soil in a water-based, nutrient rich solution. Hydroponic farming has become a widespread practice in areas such as the Netherlands, as it reduces runoff, uses less land, and saves both water and money (Viviano, 2017; Barbosa et al., 2015). Additionally, hydroponics is a favorable alternative to traditional farming because it does not use pesticides and eliminates the risk of soil-borne diseases for plants. Plant spacing in hydroponics is also much more efficient than traditional soil-based agriculture, as it is only limited by light, instead of light and soil nutrition, thus increasing the number of plants to be grown per area and producing a higher yield. Hydroponics is very water efficient, and if managed correctly, the water loss in hydroponic systems should be equal to the loss due to transpiration (Resh, 2013). Overall, hydroponics is a much more efficient and better way to grow plants, and is a promising technology to use in many kinds of systems despite its high capital cost and supervision needs.

Tri Cycle Farms, a 501(c)(3) nonprofit, is an urban farm located in Fayetteville, Arkansas, with a mission to combat food insecurity in Northwest Arkansas. Tri Cycle Farms champions the vision of “Giving a Third, Sharing a Third, and Selling a Third" of their harvests to community members, with volunteers, and with local businesses, respectively. Founded in 2010, Tri Cycle has been giving back and making an impact on the community since its inception. However, due to the complexities in running a generous non-profit such as this one, Tri Cycle needed a way to consistently keep working in the community while making a profit in order to keep the operation running. Several years ago, Don Bennett heard about hydroponics technology from a horticultural engineer, Joseph Chidiac, and began to think of the impact such technology could have on Tri Cycle.

In the Fall 2017 semester, Sarah Gould and I decided to participate in the University of Arkansas' Social Innovations Challenge as an opportunity to work with a local nonprofit on a social-entrepreneurship based solution. We soon met with Don Bennett, who proposed to have us work on a project he had been thinking about for years: a hydroponics-based greenhouse, whose profits would be used entirely to offset the costs for the rest of the farm using reverse-seasonality growing and similar methods. Ms. Gould and I loved the idea of working with Mr. Bennett on a project that we felt had real importance, and decided to continue with the project and turn it into our honors theses. We decided to split up the project roughly into two parts: Ms. Gould would take on the water considerations within the system and the overall design of systems within the house, and I would adopt the economic and energy-related concerns within the house. The two design objectives for my part of the thesis then became as follows: LED lighting sizing for a specific hydroponic sub-system and engineering economic analysis based on the layout and projected produce yield for said sub-system.

LITERATURE REVIEW

Greenhouse agriculture often requires additional equipment to facilitate the growth process for various plant species, particularly with regards to hydroponics. The hydroponic equipment itself is necessary, but an additional important consideration is the lighting and what light sources are needed. Some greenhouses are designed to allow sunlight into the house, but depending on the plant species and seasonality of the greenhouse location, additional growing lights are typically needed to best stimulate yield (Cuce, Harjunowibowo, & Cuce, 2016).

There are a wide variety of grow lights that are available for use in greenhouses. Some of the most common types are Incandescent lights, Fluorescent lights, T-5 Fluorescent lights, High Intensity Discharge (HID) lights, and LED lights. In general, lights with the smallest initial capital cost often are the most expensive long-term, and are the least effective (Moore, 2016). Incandescent lights are the cheapest to buy, and work well for singular plants. However, there are several major disadvantages with incandescent light. Not only does it produce a significant amount of heat, increasing cooling costs, it does not have a long life, and thus need to be replaced more often (Moore, 2016). Fluorescent lights are somewhat better. They are typically more efficient, have an easy installation process, and will last up to 20,000 hours (Moore, 2016). Fluorescent lights are also ideal for starting out seeds, as they will tend towards the blue light spectrum which is known to be good for seed starting (Hemingway, 2014). T-5 Fluorescent lights are the newer generation of fluorescent bulbs, lasting even longer and providing more efficiency. Plants can work well with these lights when T-5's are placed very close to the vegetation itself (Moore, 2016). HID lights encompass several different categories of lights such as Metal Halide and High Pressure Sodium. These lights are often used commercially, as they can cover wide areas and have a higher output. However, these lights also produce a high amount of heat (Cuce, Harjunowibowo, & Cuce, 2016). Heat from lights is not ideal, as it causes an added source of stress for plants. Even if they are not placed close to the plants, the extra heat interferes with temperature control, adding additional energy costs. Metal

Halide lights mimic sunlight extremely well, but High Pressure Sodium lights have a better lifespan (Moore, 2016). Though these are all potential options and have some advantages, a newer kind of grow light seems to be the most promising.

Light-emitting diode (LED) lights have a number of advantages in their favor. For one, they can be operated to give high light output with little radiant heat (Morrow, 2008). LED lights are much safer for the user and for the environment they are placed in, as they pose no heat-related injuries due to high temperatures, do not have a glass envelope that can be broken, and do not contain hazardous elements such as mercury (Olle & Viršilė, 2013). With LED lights, it is also possible to maximize plant growth through control of the different wavelengths, and can allow growers to eliminate the use of certain wavelengths unused during photosynthesis, namely green and yellow, which decreases the amount of energy used (Yeh & Chung, 2009). This in turn reduces the amount of energy used, and greenhouse gases produced by a system. Compared with the lifespan of incandescent lights and fluorescent lights of 1000-h and 8000-h respectively, LED lights have a much longer life of 100,00 h (Yeh & Chung, 2009). LEDs are typically more expensive than the other types of lights, but this higher capital cost is projected to decrease in the future (Olle & Viršilė, 2013), and they also last longer and have a multitude of other benefits that make them worth the investment.

Being able to size grow lights is an important feature, and is done using several important concepts related to plants and their light receptivity. One of these concepts is photosynthetically active radiation, or PAR. PAR is a measure of the total energy covered within the visible light range of 400-700nm where organisms can use light energy for photosynthesis (Albright, Both, & Chiu, 2000). Plants most efficiently absorb wavelengths of mid-400s and mid-600s, or blues and reds respectively (Yeh & Chung, 2009). PPFD is the Photosynthetic photon flux density (Albright, Both, & Chiu, 2000). PPFD measures how many photons are hitting an area per second, and is given in micromoles per meter squared per second (Park & Runkle, 2018). There is an important rule when sizing grow lights regarding light intensity and

PPFD. Light intensity, or brightness, of a source of light is a function of the inverse square of its distance, otherwise known as the Inverse-Square Law (NASA STEM Engagement, 2011). When applied to horticultural purposes, the closer a light is to a plant, the more photons will reach the leaves, and vice versa. Moving the light by just a small amount can thus have a major impact on the light levels that will reach the plant, making it an important consideration in choosing lighting systems. PPFD is reported by light manufacturers on their equipment information, and is typically given as an average at a specific height.

One of the most important concepts to understand in plant lighting is the Daily Light Integral, or DLI. DLI is a measure of the daily accumulation of photosynthetically active photons delivered to a given area over the course of one day (Faust & Logan, 2018), or the amount of PAR received each day as a function of the light intensity and duration with units of moles of light per meter squared per day (Torres & Lopez, 2010). Minimum DLI is necessary for every plant's growth and flowering, but too much light exposure can become damaging and decrease growth or yield due to interruption of the dark period (Dorias, 2003). The DLI in the contiguous United States varies from 5-60 mol/m^2/day depending on the latitude, time of year, day length, as well as basic cloud cover. Greenhouse growers, particularly those in seasonal conditions, such as in Arkansas, must consider DLI for supplemental lighting calculations for periods of lower light, particularly since DLI inside greenhouses is often stunted due to greenhouse infrastructure itself and how much light infiltrates the walls (Faust & Logan, 2018). Additionally, some crops have higher light needs than others, and supplementary light is likely needed especially if grown in the off season. Fayetteville, Arkansas has an annual average DLI of 32.0 mol/m^2/day, but in the winter, has a DLI as low as 16.1 mol/m^2/day in December and in the summer, it has a high of 47.6 mol/m^2/day in July (Logan & Faust, 2018). When growing cash crops like tomatoes, which have high lighting needs sometimes higher than 30 mol/m^2/day (Lopez, 2012), in the winter, it is especially important to have supplemental lighting.

In addition to lighting, another important consideration in greenhouse planning is the type of crops that will be grown and their projected yield and profit. Based on a market survey conducted by University of Arkansas sustainability capstone students on local restaurants, co-ops, and grocery stores, tomatoes, basil, lettuce, and other leafy greens are very marketable crops in the Northwest Arkansas area. The selling price for basil can be from $2-$3 per ounce, and approximately $4 per pound for organic tomatoes and closer to $2 per pound for regular tomatoes. (Storey, 2016; Pillsbury, 2011). Strawberries sell for $6.99 per pound, and organic Romaine lettuce can sell for as much as $3.54 per head with regular produce selling at closer to $2 per head (Pillsbury, 2011). These numbers are important to recognize in completing any economic analysis related to the yields for a greenhouse, and particularly a hydroponic greenhouse that uses fewer inputs.

METHODS

System Design & Produce Considerations

The work I have completed relies heavily on what my project partner, Ms. Gould, initially completed for her part of the system design. Based on her own research, she chose to design the house using five different hydroponic technologies: Shallow Aggregate Ebb and Flow (SAEF), Deep Flow Technique (DFT), Nutrient Flow Technique (NFT), Dutch buckets, and a vertical wall dedicated to strawberry growth. As mentioned previously in the literature review, Ms. Gould and I also relied heavily on the marketing survey completed by the sustainability capstone course (SUST 4103) to choose what crops to grow and how best to use the space. In the survey, we made sure to include the following questions:

1. Would your store consider carrying hydroponic produce?
2. Would you market hydroponic crops to your customers?
3. If so, at what price would you sell these products?
4. Are there any other hydroponics crops or herbs that you would be interested in marketing toward your customers?
5. What produce does your company lack in each season?
6. Would you be interested in collaborating with a local non-profit such as Tri Cycle Farms?

Based on the results of this survey, Ms. Gould finalized the specific hydroponic systems to be used in the hydroponics house and their positioning within the house, shown below in Figure 1. Figure 2 shows the conceptual image of the “HydroHouse” itself. For the purposes of analysis, Ms. Gould and I decided to fully size the system equipment for the Dutch bucket system, which is planned to be used year-round to grow tomatoes, a water and light intensive crop.

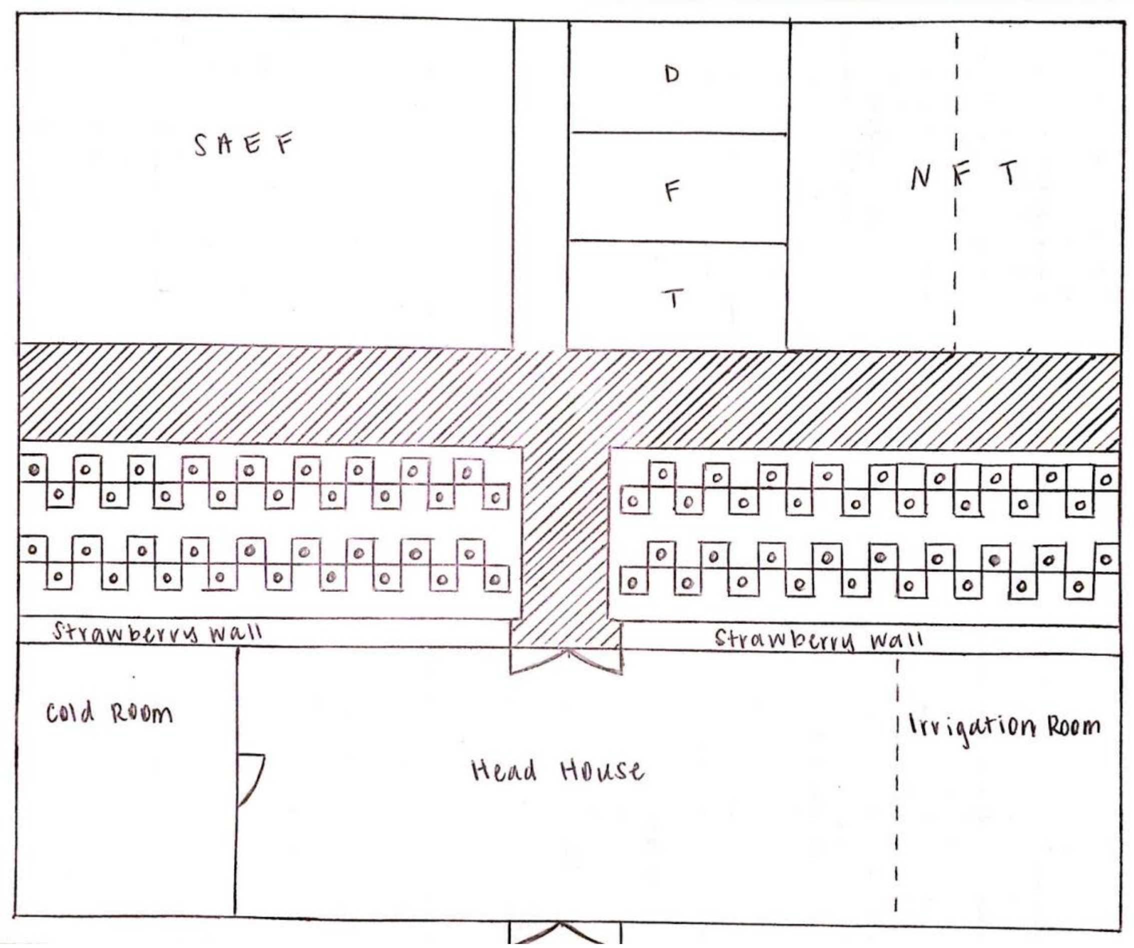


Figure 1. Final Internal Design of the "HydroHouse" for Tri Cycle Farms (Gould, 2019). SAEF corresponds to the Shallow Aggregate Ebb and Flow system, DFT refers to Deep Flow Technique system, and NFT refers to the Nutrient Flow Technique system. The system of boxes in between the strawberry wall and the walkway is the Dutch bucket system.

Figure 2. Computer-generated image of the general greenhouse structure of the CERES greenhouse chosen by Tri Cycle. The smaller grey attachment located behind the main greenhouse is the “head house,” or potential seeding space Don Bennett hopes to build in the secondary phase of this project.

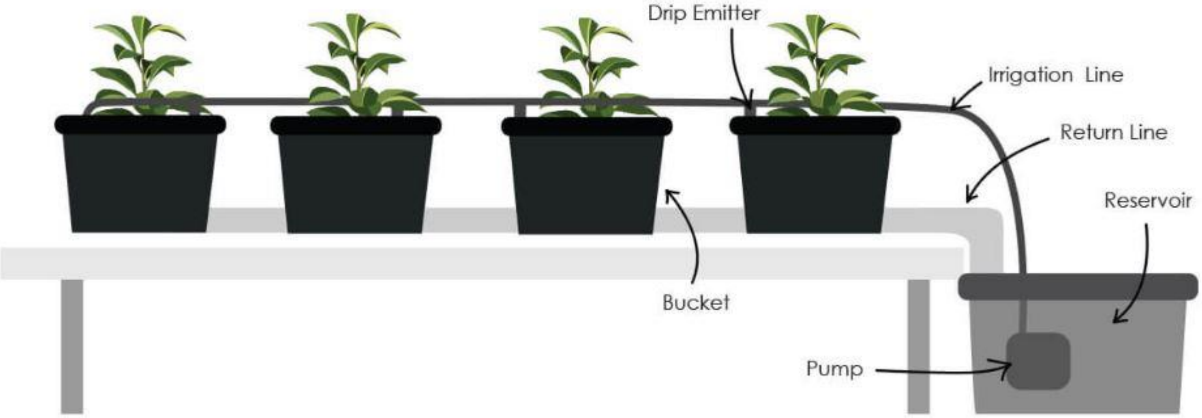


Figure 3. Generic Dutch bucket hydroponic system schematic.

Design Objective 1: Lighting Considerations

Tomatoes need more light than most plants. For their Daily Light Integral (DLI), a measurement of the total number of photosynthetically active photons they absorb each day, tomatoes need more than the average plant. Tomatoes can produce high yields with a DLI around 30 $mol/m^2/day$ (Torres & Lopez, 2010), but the overall range of vegetative tomato DLI can be anywhere from 20-40 moles per square meter per day (MechaTronix, 2019), whereas many other plant species typically have lower ranges. The available amount of sunlight that filters through a greenhouse rarely exceeds 25 $mol/m^2/day$ (Torres & Lopez, 2010), but can also be lower in the autumn or the winter. Because of this, and because tomatoes have a higher DLI range, supplemental lighting for tomatoes, used in the Dutch bucket system, was needed for certain times of the year. I chose to use LED lights based on the research completed and outlined in the literature review, as they are proven to be more efficient in addition to producing less heat. Less heat added is better for plant health, and allows for more consistent temperature control inside the greenhouse and thus will likely be more sustainable. A day length or photoperiod of 12 hours per day was chosen based on light sensitivity of tomatoes and in consideration of the other systems of plants projected to be in the greenhouse, which led me to choose lighting systems based on their PPFD, compatibility with plant species, and their initial cost.

I completed calculations about the lighting needs for the tomatoes within the greenhouse for two different scenarios, outlined in the results, calculated the total power needed for each lighting alternative based on the required number of lights to cover the system, calculated the annual electricity cost for each lighting alternative, and even did a Net Annual Cost analysis for each alternative, based on their power savings from other types of lights, capital cost, and warranty. For these calculations, an important factor was the commercial cost of electricity in Fayetteville, Arkansas, which is \$0.0674 per kilowatt hour. This is lower than the Arkansas and national average commercial electricity cost of \$0.0771 and \$0.1009, respectively (Electricity Local, 2019). When I looked at the Net Annual Cost associated with the purchase of the LED light fixtures, I used 5% for an interest rate to account for inflation over the warranty period for the LED lights, and used the warranty length for the ***n*** value. For the number of required hours that the LED light fixtures would need to run, I accounted for the worst case scenario, a very snowy winter where significant additional lighting was needed each day. I used 12 hours of lighting per day for 4 months, to account for winter as well as any other possible slight cloudy or rainy days when supplemental lighting was needed. This translates to 1344 hours needed annually.

To make a final decision on which lighting fixture to use for the Dutch bucket system, I created a weighted objectives table with five objectives: meeting Scenario 1's lighting requirement, meeting Scenario 2's lighting requirement, having a comparative reasonable capital cost, having a long warranty length, and having a low annual power cost. Scenario 1's lighting requirement involves the worst-case scenario for taxing tomato growth on a snowy day in the winter, and Scenario 2's lighting requirement involves taxing tomato growth assuming a high DLI inside the greenhouse. I chose each of these objectives for a reason, as I wanted the light fixture chosen able to account for the tomato lighting needs, even in the very-worst case scenario, wanted the system of lights chosen to last relatively long, especially considering LED lighting high capital costs, and wanted to have a lower power cost, which also translates to a low electricity usage and thus lower greenhouse gas emissions. I assigned a weight of 0.2 to the objectives of meeting each scenario's lighting requirements and having a lower power cost. I gave more weight, a 0.3, to the objective regarding warranty length and less weight, 0.1, to the reasonable capital cost, particularly since the capital costs were similar in my alternatives. It is important that the LED lights chosen have a long life because they are an investment, hence I weighted that objective heavier than the others and the reasonable capital cost lower.

Design Objective 2: Economic Analysis

To perform an economic analysis for solely the Dutch bucket system, a basis of comparison for the cost of municipal water was needed. I decided to use Springdale's water charges, particularly because this information was readily available online and because Springdale is in the Northwest Arkansas area, located close to Fayetteville. The cost of 1000 gallons of water was found to be $3.04 (Springdale Water Utility, 2017). In addition to water costs, the cost of electricity needed to be considered. As mentioned above, the commercial cost of electricity in Fayetteville, Arkansas, is $0.0674 per kilowatt hour (Electricity Local, 2019). To see how this price compares to selected other areas of the U.S., refer to Table 1 below.

Table 1. Average commercial price of electricity for selected states and the nationwide average.

Location	**Average Commercial Price (cents/kWh)**
Fayetteville, AR	6.74
Arkansas	7.71
Colorado	9.39
California	13.41
Iowa	8.01
New York	15.06
Wisconsin	13.19
Nationwide Average	11.88

How often the chosen LED lights are run throughout the year, as well as the pumps powering the hydroponic equipment themselves, were major contributors in the operational cost. The values for the electricity needed to power the pumps were obtained from Ms. Gould's work, and the values for the LED lights came from mine. For the analysis itself, I chose to use engineering economics. I looked at the Net Annual Cost associated with the purchase of the LED light fixtures, using the 5% for an interest rate to account for inflation over the warranty period for the LED lights. For the overall analysis I selected the interest rate of 5% to account for worst-case inflation. I selected the return period to be one year, as I know that Tri Cycle hopes to have the house and its systems paid for as soon as possible, and I wanted to see if it would be achievable. A basic Gross Annual Benefits analysis and Simple Payback Period analysis were applied to the Dutch bucket system using worst case scenario stipulations in order to determine their profitability and worth of investment. The capital cost of the Dutch bucket system was obtained from Ms. Gould's work, shown below in Table 2, and I calculated the electricity costs for the pumps and lights, with a period of 24 hours per day for 365 days per year and then 12 hours per day for 4 months per year respectively. These periods were chosen as the worst-case scenario, assuming that the pumps are pumping all day every day, and that there was a very snowy winter where significant additional lighting was needed each day. The analysis used in this report is very simple, and does not account for factors such as greenhouse construction costs on the land used for the Dutch buckets, insurance, personal worker time, or any loss factors associated with plants.

Table 2. Capital Cost Calculation for Dutch bucket equipment (Gould, 2019).

Type	Details	Supplier	Units needed	Unit Cost	Total cost
Accessory	Lids	FarmTek	144	$0.39	$56.16
Return Line	1/2" sch 40 10-ft	Home Depot	8	$2.31	$18.48
Pump	2/3 HP	---------------	4	$180.00	$720.00
Timer	--------------	---------------	4	$300.00	$1,200.00
Reservoir	55 gal 14" H	The Tank-Depot	4	$149.99	$599.96
Drip emitters	2 GPH	Home Depot	3	$6.88	$20.64
Stake Guide	1/8" x 250	Zen Hydro	1	$62.50	$62.50
Tubing coil	1/2" x 100'	Home Depot	3	$11.98	$35.94
Micro-tubing	3/16" x 100'	Zen Hydro	2	$11.44	$22.88
					$5,609.30

RESULTS

Design Objective 1: Lighting Fixture Chosen for Dutch Bucket System

Because tomatoes have a higher light demand, additional lighting was needed for winter and other low light conditions, and the sizing of supplemental lighting was completed for the Dutch bucket system. The worst-case scenario was used for this process, and thus, a DLI for vegetative tomatoes of 40 mol/m^2/day was used, assuming the most taxing of the DLI requirements. It is important to note that these calculations are completed for vegetative tomatoes, and tomato seedlings have different DLI requirements (Gómez & Mitchell, 2015). Although longer exposure to lighting can produce high yields of tomatoes and other plant species, there is a danger associated with too much light exposure. After my own research about continuous light exposure of plants, particularly with the buildup of starch in leaves (Demers & Gosselin, 2002), I decided to size the PPFD for this system with a 12-hour photoperiod per day due to light pollution concerns, as well as overexposure of other plant species to light. In some greenhouses, DLI values can become as low as 1-5 mol/m^2/day (Newkirk, 2018), particularly at times of lesser sunlight, such as on a cloudy day in the winter (Runkle, 2006). In the worst case scenario for Arkansas, a snowy day in winter, there is natural light entering the house for around 8 hours at an average of 100 μmol/m^2/s (Chidiac, 2019). Using Equation 1, shown below, this translates to a DLI of 2.88 mol/m^2/day. In Equation 1, x represents the chosen photoperiod.

$$DLI = PPFD\left(\frac{\mu mol}{m^2 * s}\right) * \frac{3600\ s}{hour} * \frac{x\ hours}{1\ day} * \frac{1\ mol}{1000000\ \mu mol} \qquad [1]$$

If the tomatoes need 40 mol/m^2/day, there is a deficit of 37.12 mol/m^2/day based on the 2.88 mol/ m^2/day given that needs to be supplied by additional lighting. For a 12-hour day, this translates to a PPFD of at least 859.3 μmol/m^2/s, using a reverse of Equation 1, shown below in Equation 2.

$$PPFD = DLI\ \left(\frac{mol}{m^2 d}\right) * \frac{1000000\ \mu mol}{1\ mol} * \frac{1\ day}{x\ hours} * \frac{1\ hour}{3600 s} \qquad [2]$$

In addition to this “worst case winter” scenario, referred to henceforth as Scenario 1, I decided to use another condition, Scenario 2, to make my determination of what grow light to use. Greenhouses typically are not able to allow more than 25 mol/m^2/day of light in (Torres & Lopez, 2010). Thus, even with a full day of sunlight, using the worst-case tomato DLI needed, 40 mol/m^2/day, at least 15 mol/m^2/day of supplemental light are needed. Using Equation 2, this translates to 347.2 μmol/m^2/s.

With these two scenarios in mind, I researched various PPFD’s for several LED producers. I looked into KIND LED lights, SpecGrade LED lights, and Lush Lighting LED lights and compared them based on their ability to provide the needed PPFD for two scenarios, the number of lights needed for the space, their power input needed, their initial cost, their life expectancy or warranty, and their hanging requirements. The lights needed to be sized for the Dutch bucket system Ms. Gould designed, which contains 72 one square foot “buckets” and is sized in such a way that 72 ft^2 of bucket space is separated from the other 72 ft^2 by a walkway to the head house. Additionally, the systems are further separated into subsections of 36 ft^2, or 2 ft by 18 ft. I calculated how many lights were needed based on each alternative’s light footprint, and how they could cover the 144 ft^2 space requirement for the Dutch buckets based on their footprint’s dimensions.

To calculate the total capital cost of each alternative, the number of lights needed were multiplied by the cost of each light, shown in Equation 3, where x represents the number of lights and X represents the alternative number.

$$Total\ Capital\ Cost\ of\ Alternative\ X = \ x\ lights\ needed * Cost\ \left(\frac{\$}{light}\right) \qquad [3]$$

The power costs were derived from the chosen worst-case power consumption scenario, outlined in the Methods section, of 12 hours per day for 4 months per year, or 1344 hours total per year. To calculate the kWh needed per year per fixture, Equation 4 was used, shown below.

$$Annual\ Power\ Requirement = Wattage\ required\left(\frac{W}{light}\right) * \ 1344\ hours * \frac{1\ kW}{1000\ W} \qquad [4]$$

To then calculate the power requirement for the lighting system that would need to be purchased for each alternative, the value for each power requirement per fixture was then multiplied by the number of fixtures needed, shown in Equation 5.

$$Annual\ Total\ Power\ Requirement = Annual\ Power\ Requirement\ (kWh) * x\ lights\ needed \quad [5]$$

To obtain the annual power cost, I then multiplied each power requirement by the cost of commercial electricity in Fayetteville Arkansas (Electricity Local, 2019), shown below in Equation 6.

$$Annual\ Power\ Cost = Annual\ Total\ Power\ Requirement\ (kWh) * \frac{\$0.0674}{kWh} \qquad [6]$$

These calculations, in addition to my overall comparison between the three lights from the three companies are shown in the Table 3 below, where Scenario 1 refers to the worst-case scenario in the winter, and Scenario 2 refers to full light in greenhouse plus worst-case tomato needs scenario.

Table 3. Overall Comparison of the 3 LED Lighting Alternatives. Technical information retrieved from www.kindledgrowlights.com, www.specgradeled.com, and www.ledgrowlightsdepot.com, respectively.

Required Information	**"K3 L600" KIND LED Grow Light**	**"Linea" from SpecGrade**	**"Vegetator 2X" from Lush Lighting**
PPFD Needed, Scenario 1, umol/m2/s	859.3	859.3	859.3
PPFD Needed, Scenario 2, umol/m2/s	347.2	347.2	347.2
PPFD, Average, umol/m2/s	537.0	944	400
Light Footprint (sq ft)	12	24	16
Hanging Height above vegetation (ft)	3	2	4
Units Needed	12	10	10
Cost per unit ($)	$595	$795	$650
Total Cost	$7,140	$7,950	$6,500
Power Requirement per unit (W)	320	333	330
Hours of Operation per year, worst case (h)	1344	1344	1344
Total Power Requirement per unit, worst case (kWh)	430.1	447.6	443.5
Annual Total Power Requirement, worst case (kWh)	5161.0	4475.52	4435.2
Cost of Electricity ($/kWh)	$0.07	$0.07	$0.07
Annual Power Cost ($)	$347.85	$301.65	$298.93
*System Net Annual Cost ($)	$2,184.30	$1,650.77	$3,218.17
*Power Savings Associated with Using LED	$304.37	$201.10	$244.58
Warranty (years)	5	7	3

In addition to the above calculations, I completed a net annual cost analysis for each lighting alternative based on their capital and operational costs and calculated the power savings from using a particular LED light, instead of a more traditional Metal Halide light or HID light, as a benefit. The calculated values are indicated in Table 3 above by the asterisk and “System Net Annual Cost” and “Power Savings Associated with Using LED.” To get the benefits associated with power savings, I first went to each producer’s website to determine their traditional light power equivalency. From the SpecGrade website, their lighting fixtures, particularly the Linea light, uses 40% less electrical power than do traditional Metal Halide bulbs (Kubota & SpecGrade LED, 2018). For the K3 L600 from KIND LED, their website listed their 320 W units as being equivalent to 600 W HID fixtures (KIND LED Grow Lights, 2019). For the Vegetator 2X from Lush Lighting, their website listed their 330 W units as being equivalent to 600 W Metal Halide fixtures. The total power requirement for the Linea lighting fixtures was 4,475 kWh, so using the 40% value, traditional Metal Halide bulbs would be likely to use 7,458 kWh instead of 4,475 kWh. For the other two alternatives, the power requirement was sized using Equations 4 and 5 with 600 W for 12 and 10 fixtures for the K3 L600 KIND LED and the Vegetator 2X from Lush Lighting respectively.

The total power cost was calculated using Equation 6 and the average cost of electricity in Arkansas (Electricity Local, 2019). The engineering economic values for converting present cost to annual cost for an ***i*** of 5% and **n**=7, 5, and 3 years, depending on the alternative’s warranty, were used to convert the capital cost of each LED lighting system into an annual cost. I subtracted the cost of electricity from the traditional bulbs from the LED bulb electricity cost to obtain the “net annual benefit” for each fixture, shown in Equation 7.

$$Net\ Annual\ Benefit\ for\ LED\ Alternative = Power\ Cost\ Traditional - Power\ Cost\ LED \quad [7]$$

The resulting analyses are shown in Tables 4, 5, and 6 and then shown in my alternative comparison table. This calculation allowed me to better understand how each light compared over their warranty time and how much money they saved annually.

Table 4. Net Annual Cost Calculation and Savings Associated with Using LEDs for K3 L600 KIND LED light fixtures.

	Linea Light	**Metal Halide Light Equivalency**
Power Requirement (kWh)	4476	7459
Cost of Elect in AR ($/kWh)	$0.07	$0.07
Power Cost ($)	$301.65	$502.75
Annual Benefits from Power Savings, MH-Linea ($)	$201.10	
Net Annual Costs, Operating+Capital ($)	$1,650.77	
Operating Cost ($)	$301.65	
Capital Cost, Present ($)	$7,950	
A/P, 5%, 7 years	0.1697	
Capital Cost, Annual ($)	$1,349	

Table 5. Net Annual Cost Calculation and Savings Associated with Using LEDs for the Linea-48XL light fixtures.

	Lush Lighting Vegetator 2X	**Metal Halide Light Equivalency**
Power Requirement (kWh)	4435	8064
Cost of Elect in AR ($/kWh)	$0.07	$0.07
Power Cost ($)	$298.93	$543.51
Annual Benefits from Power Savings, MH-Linea ($)	$244.58	
Net Annual Costs, Operating+Capital ($)	$3,218.17	
Operating Cost ($)	$298.93	
Capital Cost, Present ($)	$7,950	
A/P, 5%, 3 years	0.3672	
Capital Cost, Annual ($)	$2,919	

Table 6. Net Annual Cost Calculation and Savings Associated with Using LEDs for Lush Lighting Vegetator 2X light fixtures.

	K3 L600 KIND LED	**HID Light Equivalency**
Power Requirement (kWh)	5161	9677
Cost of Elect in AR ($/kWh)	$0.07	$0.07
Power Cost ($)	$347.85	$652.22
Annual Benefits from Power Savings, MH-Linea ($)	$304.37	
Net Annual Costs, Operating+Capital ($)	$2,184.30	
Operating Cost ($)	$347.85	
Capital Cost, Present ($)	$7,950	
A/P, 5%, 3 years	0.231	
Capital Cost, Annual ($)	$1,836	

After obtaining the values outlined in Table 3 I created a weighted objectives table with five objectives: meeting Scenario 1’s lighting requirement, meeting Scenario 2’s lighting requirement, having a comparative reasonable capital cost, having a long warranty length, and having a low annual power cost. I assigned a weight of 0.2, 0.2, 0.1, 0.3, and 0.2 respectively to each objective. It is important that the LED lights chosen have a long life, especially due to their higher capital cost, which is why I weighted that objective heavier than the others, and the reasonable capital cost lower. The K3 L600 light and the Vegetator 2X failed to provide a high enough PPFD for Scenario 1, which is why they both received a score of zero for that objective. There is a very strong difference in the warranty time for each alternative, which is reflected in the rating for each. Additionally, the low annual power cost objective refers to the operational cost of each system for a year, not the net annual cost discussed previously. The full results of my weighted objectives analysis are shown in Table 7.

Table 7. Weighted Objectives Table for the 3 LED Lighting Alternatives.

		1: "K3 L600" KIND LED Grow Light		**2: "Linea-48XL" from SpecGrade**		**3: "Vegetator 2X" from Lush Lighting**	
Objective	**Weight**	**Rating**	**Points**	**Rating**	**Points**	**Rating**	**Points**
1) Meets Scenario 1's Lighting Requirement	0.2	0	0	10	2	0	0
2) Meets Scenario 2's Lighting Requirement	0.2	10	2	10	2	10	2
3) Reasonable Capital Cost	0.1	8	0.8	7	0.7	9	0.9
4) Long Warranty	0.3	7	2.1	9	2.7	5	1.5
5) Low Annual Power Cost	0.2	7	1.4	8	1.6	8	1.6
Total	1		6.3		9		6

Based on the results of Table 7, I made the determination to use a Linea-48XL from SpecGrade LED due to the long warranty length, ability to meet the lighting requirements of Scenario 1 and 2, unlike the other two options, and the relatively low operating cost. Linea-48XL has an average PPFD value of 944 μmol/m^2/s (SpecGrade LED, 2018), which is more than needed and will function well in both scenarios. It has this average at a "recommended" height of two feet above vegetation, and at that distance has a 3 ft by 8 ft light footprint, or 24 ft^2. The light itself is long and thin, having dimensions of 48"x 4.5"x 4.5," shown below in Figures 4 and 5. I calculated the number of lights needed based on the dimensions for one half of the Dutch bucket system, since it was evenly split into 72 ft^2 on each side of the house, or 36 "buckets" on each side of the walkway. I found that if five lights are used for each 72 ft^2 section, although some of the light energy from the Linea lights will not be used, the full area of Dutch buckets can be covered, as shown below in Figure 3. Since there are two 72 ft^2 sections, ten Linea 48X lights will be needed. Each of these lights will cost approximately $795 each, but only ten of them are needed, totaling $7,950. The schematic of the Linea fixtures light footprint for one-half of the Dutch bucket system is shown in Figure 6. The projected light footprint for the whole system is shown in Figure 7.

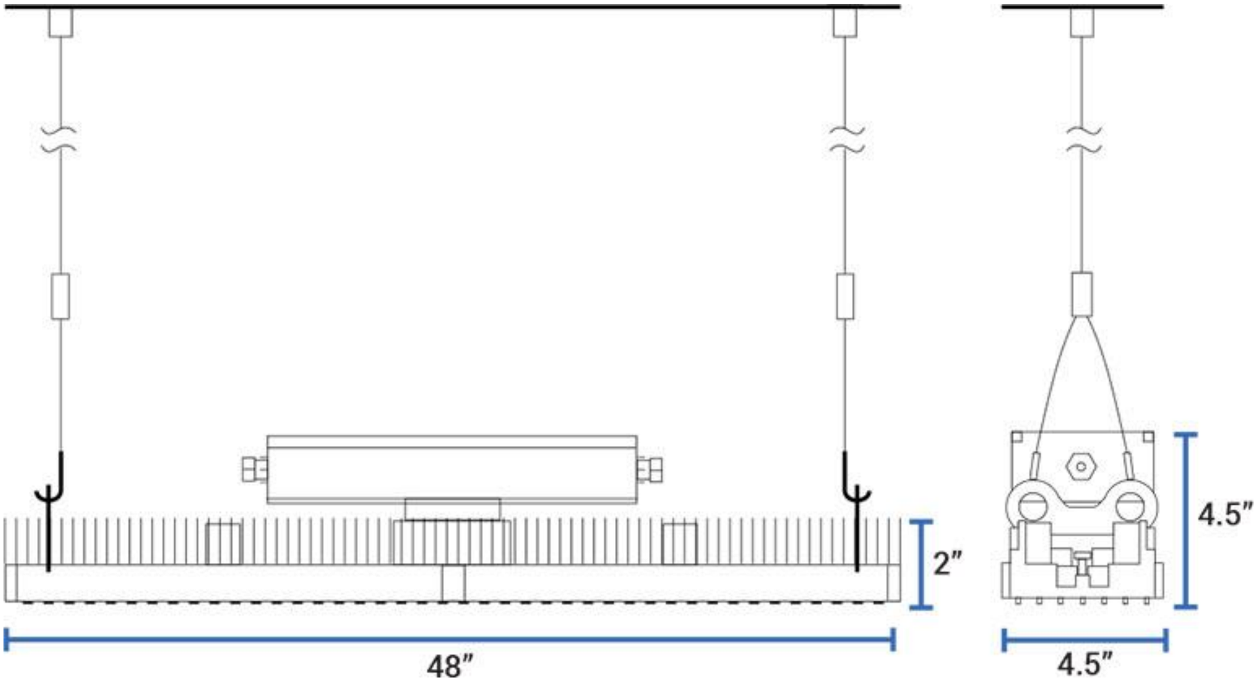
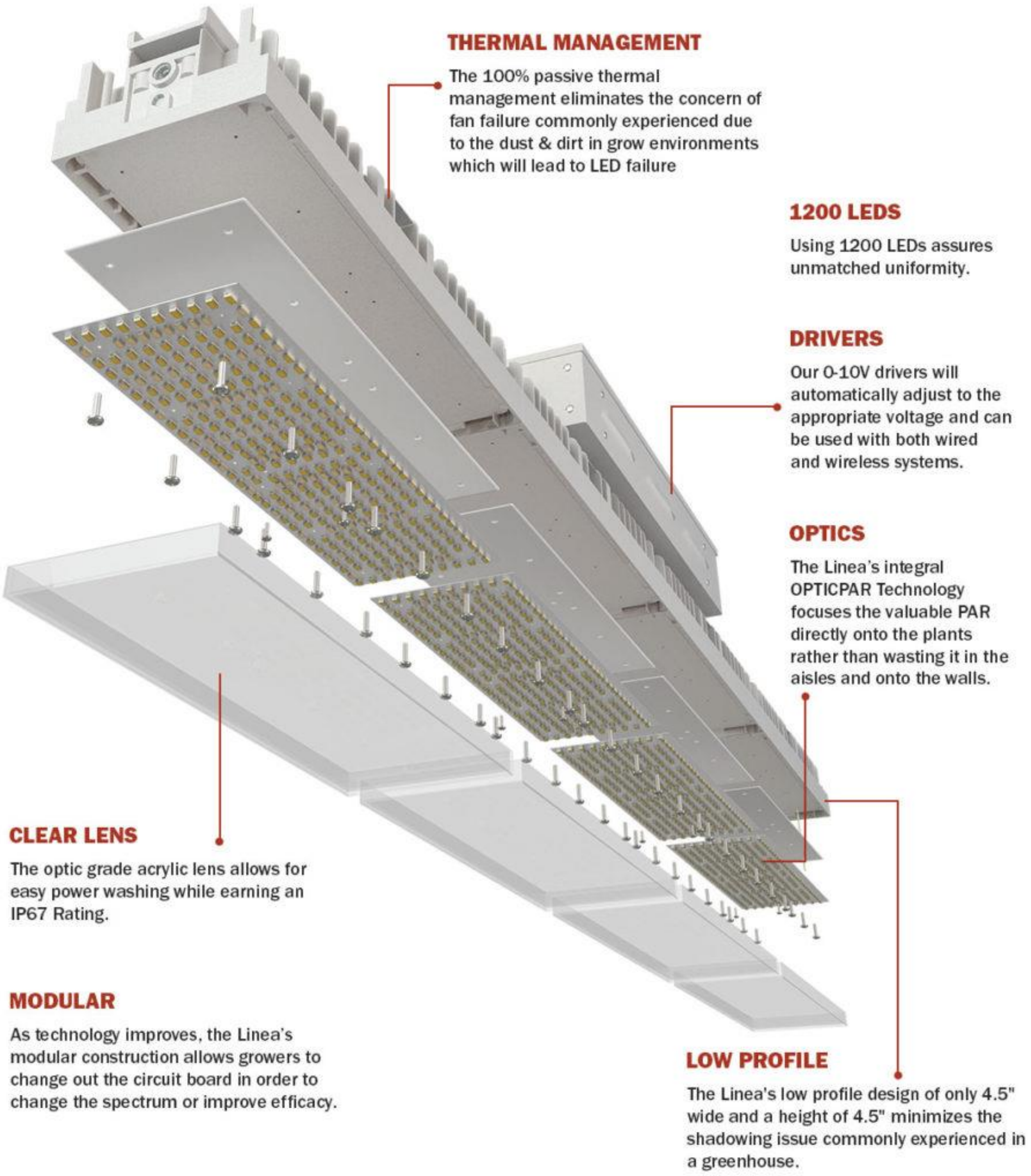


Figure 4. Dimensions and Schematics for the Linea-48XL light, from the SpecGrade LED Website.



THERMAL MANAGEMENT

The 100% passive thermal management eliminates the concern of fan failure commonly experienced due to the dust & dirt in grow environments which will lead to LED failure

1200 LEDS

Using 1200 LEDs assures unmatched uniformity.

DRIVERS

Our 0-10V drivers will automatically adjust to the appropriate voltage and can be used with both wired and wireless systems.

OPTICS

The Linea's integral OPTICPAR Technology focuses the valuable PAR directly onto the plants rather than wasting it in the aisles and onto the walls.

CLEAR LENS

The optic grade acrylic lens allows for easy power washing while earning an IP67 Rating.

MODULAR

As technology improves, the Linea's modular construction allows growers to change out the circuit board in order to change the spectrum or improve efficacy.

LOW PROFILE

The Linea's low profile design of only 4.5" wide and a height of 4.5" minimizes the shadowing issue commonly experienced in a greenhouse.

Figure 5. Figure advertising the Linea-48XL's attractive features, from the SpecGrad LED website.

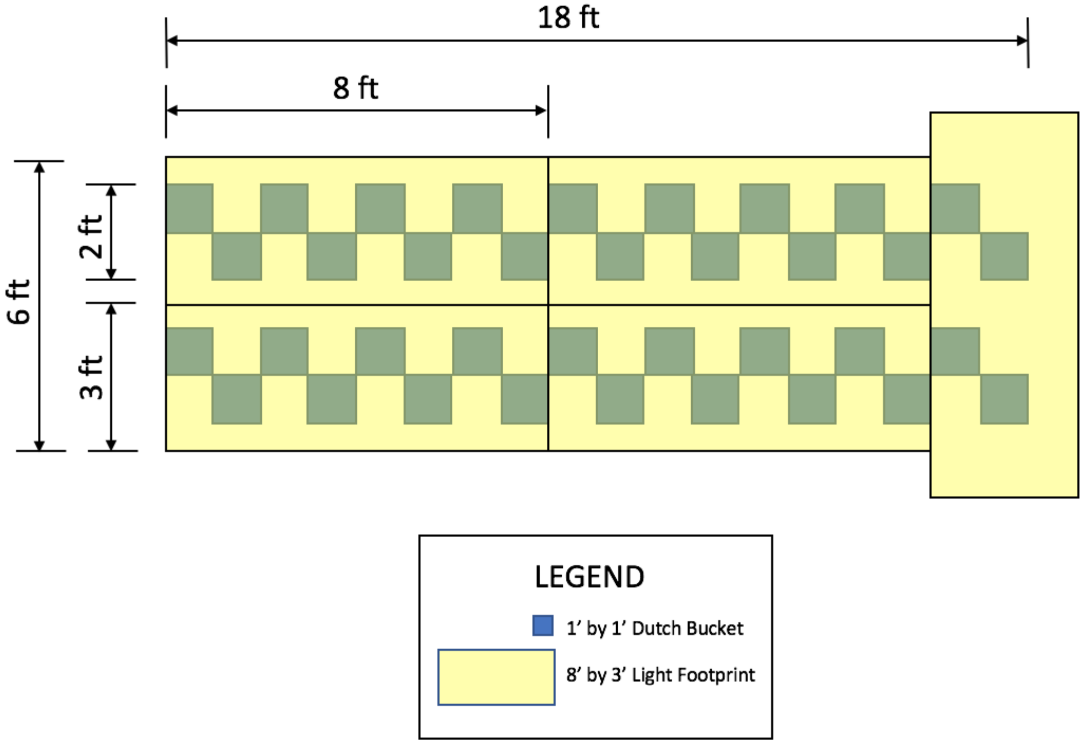


Figure 6. Representation of one-half of the Dutch bucket system with appropriate light footprints, according to the specifications listed on SpecGrad LED's website. Each Linea light can provide 8’ by 3’ of light, which with this layout is not ideal but is possible.

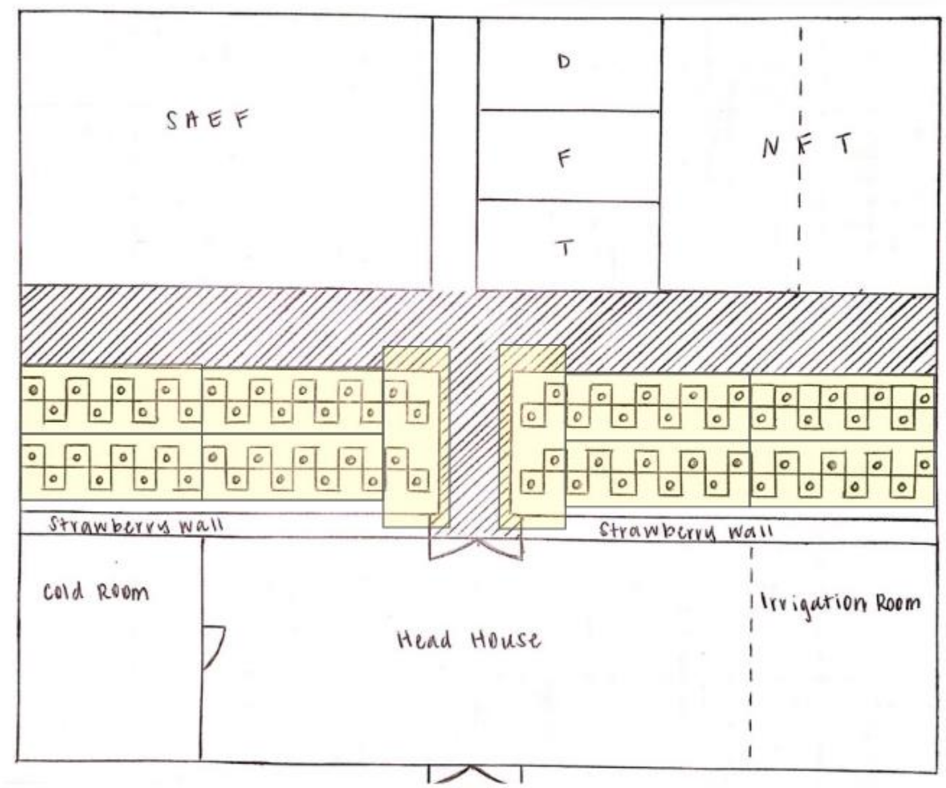


Figure 7. Internal Layout Design for the "HydroHouse" (Gould, 2019) with the chosen Linea lighting footprints for the Dutch bucket system.

Other Lighting Considerations

As mentioned previously, the sizing done in this report has been completed for the worst-case scenario and merely represents initial calculations for the lighting needed. When Tri Cycle Farms takes steps to purchase these lights, they will be able to work with the company, SpecGrade LED, in addition to a horticultural engineer, such as Joseph Chidiac, to take actual measurements of PFFD and DLI to create a more efficient lighting plan that will use fewer lights and can be placed at more appropriate heights for each plant species. The Linea grow light can likely be used for the other produce that Ms. Gould and I have selected for the "HydroHouse," such as lettuce, basil, and strawberries, and is advantageous to do so especially since there is a price break depending on how many Linea lights are purchased.

However, the aforementioned crops all have lower light requirements and thus DLIs than do the tomatoes. Lettuce typically have DLI in the range of 10-16 mol/m^2/day for larger plants (Gent, 2014), basil can range between 12-15 mol/m^2/day (Currey & Walters, 2014; Alger, 2019), and strawberries are typically around 12 mol/m^2/day (Kuack, 2017). Although these DLIs are lower, based on the Inverse-Square law of light mentioned earlier, the Linea lights can still be used, and can be placed at higher levels above the lettuce, basil, and/or strawberries. Based on real-time testing, growers in the "HydroHouse" will be able to adjust the height of the light in an efficient way, and determine which height will work best for the corresponding plants. This will provide a lower light intensity and thus lower PPFD to meet each particular plant species' supplemental lighting needs.

Design Objective 2: Economic Analysis for the Dutch Bucket System

As with other aspects of this report, a conservative economic analysis was completed using worst case scenarios. As mentioned previously, each Linea light cost \$795, and based on the layout, ten lights were required, giving a total capital cost of \$7,950 for the Linea lights. This cost was then added to the capital cost associated with the materials needed for the Dutch bucket system based on Ms. Gould's work, \$5,609.30, to give a total capital cost of \$13,559.30, shown in red in Table 8 below. The annual cost of the water for the system, using Springdale's water fees, was determined to be \$79.89, shown in blue in Table 8, annually. The annual calculated cost of electricity usage for the four pumps, assuming worst case of 24 hours per day 365 days per year, was \$111, or \$28 per pump, also shown in blue in Table 8. The annual calculated cost of electricity for lighting usage, assuming a worst-case scenario of four months of 12 hour days, was \$301.65, or approximately \$30 per light, also shown in blue in Table 8. Both electricity calculations were based on the average cost of electricity in Arkansas, discussed in the Methods section. The benefits associated with the system were derived from a conservative estimate of how much each tomato plant could produce, and how much each pound would sell for. This annual benefit was determined to be \$34,560, shown in green in Table 8. Using a Simple Payback Calculation, Equation 8, I determined the simple payback to be 0.43 years, or 5.1 months, for just the Dutch bucket system.

$$Simple\ Payback\ Period = \frac{Costs\ (\$/year)}{Benefits\ (\$/year)} \qquad [8]$$

Using a Gross Annual Benefit analysis where ***n*** was assumed to be 1 year and ***i*** assumed to be 5% to account for high inflation, I found that the Gross Annual Benefit, Equation 9, for the Dutch bucket system was approximately \$20,000 for the first year, and in following year, provided the equipment was functional, would be around \$34,000, only having to account for operational costs.

$$Gross\ Annual\ Benefit = Annual\ Benefits\ (\$) - Annual\ Costs (\$) \qquad [9]$$

This estimate does not include any maintenance and upkeep costs, however, and it is imperative to evaluate the status of all the equipment as the system ages once implemented. The Linea lights have a warranty of 7 years, but the other equipment in Ms. Gould's design likely does not have as long of a life. Based on this data, I endorse the viability of this system, especially since this was a conservative estimate with worst-case scenario conditions.

Table 8. Economic Analysis Calculations for the Dutch bucket system

Capital Costs	
Dutch bucket equipment, from Sarah	$5,609.30
Light Fixtures, 10	$7,950.00
Total ($)	$13,559.30

Annual Operating Costs	
Water for tomatoes	$79.89
Pumps, 4, electricity	$111.00
Light Fixtures, 10, electricity	$301.65
Total ($)	$492.54

Electricity Cost Calculation for 10 Light Fixtures	
Wattage needed for 1 light (W)	333
Hours per day, worst case (hours/day)	12
Months per year, worst case (months/year)	4
Total hours needed (hours)	1344
Kilowatt per Watt conversion (W/kW)	0.001
Cost of electricity ($/kWh)	$0.07
Number of Light Fixtures	10
Total Electricity Cost ($)	$301.65

Water Cost Calculation	
# of plants (tomato plant)	144
Water needed per plant, worst case (qt/day)	2
Days per year, worst case (days)	365
gallon/quart conversion (gal/qt)	0.25
Cost of water, per 1000 gallon ($/1000 gal)	3.04
Total Water Cost ($)	$79.89

Gross Projected Tomato Profit (Benefits)	
Yield per plant (lbs)	30
Number of Dutch buckets	72
Number of Plants per bucket	2
Value of Plant, Conservative ($/lb)	2
Number of months per cycle	3
Cycles per year	4
Benefits ($ per year)	$34,560.00

Electricity Cost Calculation for 4 Pumps	
Wattage needed for 1 pump (W)	47
Hours per day, worst case (hours/day)	24
Days per year, worst case (days)	365
Kilowatt per Watt conversion (W/kW)	0.001
Cost of electricity ($/kWh)	$0.07
Number of Pumps	4
Total Electricity Cost ($)	$111.00

Economic Analysis	
A/P Conversion for i=5%, n=1	1.05
Interest (5%)	5
Return Period	1
Capital Cost, present ($)	$13,559.30
Capital Cost, annual ($)	$14,237.27
Operating Cost, annual ($)	$492.54
Benefits, annual ($)	$34,560.00
Simple Payback Period, Costs/Benefits (years)	0.43
Simple Payback Period (months)	5.1
Gross Annual Benefits, first year ($)	$19,830.20
Gross Annual Benefits, post first year ($)	$34,067.46

DISCUSSION AND FUTURE OPPORTUNITIES

Moving forward with this project, there is much left to do. Although Ms. Gould and I completed the design considerations for the Dutch bucket system with tomatoes, there are still four other systems whose components need to be fully sized and purchased in addition to other operational costs and sizing to be considered, such as from heating in the winter. Although I believe the light fixture I selected can be used with the other systems and plants besides tomatoes, more calculations need to be completed to confirm this and to make a better lighting plan for the Dutch buckets that use fewer lights while still meeting supplemental lighting needs. Tri Cycle Farms already possesses two of the systems, the NFT and DFT systems, but they need to be thoroughly cleaned out prior to usage and installation. In addition, although Tri Cycle has bought the greenhouse itself from Ceres Greenhouse Solutions and have the pieces ready to assemble on-site at the farm, they have not been able to actually build the house itself yet. Building the house will require a significant amount of volunteer labor, as will the installation of the hydroponic systems and fixtures related to the systems. Unfortunately, there have been a number of delays with the contractor and initial construction, particularly because the greenhouse they purchased is highly efficient and relies on some geothermal-like technology to regulate the greenhouse temperature. This concept is great sustainability wise because it uses less electricity to heat or cool the house, but having to physically get clearance to dig into the ground to install that part of the greenhouse has caused delays that Tri Cycle hopes to finally clear soon.

Beyond our involvement, this hydroponic greenhouse is planned to be an educational resource for the Fayetteville community and the surrounding area. One of the initial design considerations in the original planning was to have enough walkway space inside of the house for tour groups to comfortably fit in. Tri Cycle explicitly told us that they wanted the community to be able to experience what hydroponics is, and learn how each kind of system works. They believe hydroponics to be an up-and-coming agricultural technology, and have a firm commitment to educating others about how most of our food could eventually be produced. Each system was also designed to be somewhat interactive. This means a demonstration or explanation can be done at any time of each system. Tri Cycle envisions classes of people coming out to learn about the house at a time, and coming away with a greater realization of the importance of hydroponic and cleaner farming techniques. Tri Cycle has also discussed classes specifically for children to come out and explore the house, and have them learn early the importance of understanding how food is produced and why it is essential. Additionally, Tri Cycle wants to have as much community involvement in the house as possible. For example, one side of the greenhouse, the north facing side, will be a normal wall, not transparent as in most greenhouses. Instead of simply leaving that wall as is, however, there are plans for a mural to be painted there by a community artist, or even an art student at the University of Arkansas.

In addition to community involvement, Tri Cycle hopes for higher levels of collegiate collaboration because of the house. Being only 1.4 miles away from campus, Tri Cycle is an already a popular place for college students to volunteer, but Tri Cycle is looking towards building even more involvement. From the beginning, Don Bennet has not only dubbed this project the “HydroHouse,” but also the foundation of what he calls the “Seed to Sell Service Learning Initiative,” a way for students do further service learning at Tri Cycle. This initiative encompasses a variety of roles, from interns who tend to each specific hydroponic system regularly, to research positions and opportunities utilizing the different spaces and hydroponic systems. Each system was designed with the possibility of research in mind, which is why there are more than one units of each system. This will allow students to be able to do research projects and challenges, or even other honors theses, based on the technology and potential from the hydroponics-based greenhouse.

Economically, this house has an incredible amount of potential. The Gross Annual Benefit from Dutch bucket system alone for the first year is projected to be approximately $20,000, and the system can be completely paid off in the first year. The benefits from the other systems, once sized and installed, will only increase this value, especially as more crops are grown. This house is sustainable and viable, as it makes a significant profit in addition to being built with more sustainable materials, such as LED lights, and the greenhouse Tri Cycle purchased is more efficient due to better insulation and energy regulation. Even though there is a high capital cost associated with the Dutch bucket system, it still can be paid off within one year and can provide a consistent, strong source of profit for Tri Cycle. As stated previously, many of the engineering assumptions I made for this report were "worst-case scenario," which at times seemed excessive or highly implausible. However, I believe that especially with the economic analysis, this was valuable because it illustrated how profitable hydroponic tomato growth can be, even with more expensive or strained conditions.

All the design considerations discussed and listed in this report are only the beginning. Ms. Gould and I came on board with this project in its beginning stages, but Tri Cycle has plans that reach into the next year, and potentially beyond our involvement with the project. Once the initial greenhouse has been built, and the hydroponics systems installed, there is still work to be done. Tri Cycle wants to build a head house next, which will be attached to the main portion of the greenhouse. This head house will include an irrigation room and a cold room, and will be used mainly to start the new cycles of plants and grow them until they are mature enough to be transplanted into the hydroponics systems in the main portion of the greenhouse. Lighting and other energy-related calculations will need to be completed for the head house, particularly since it will be used for plant seeding, which require different growing conditions than do vegetative plants. Once the head house is done, Tri Cycle wants to hire a full-time employee to be in charge with the upkeep of the house. Additionally, they would like to begin the process of powering the house utilizing grid-tied photovoltaics as a final phase of the project. This will offset a significant amount of the energy costs of the farm, and could eventually eliminate electricity costs for the "HydroHouse" itself. Throughout this process, multiple students have approached Ms. Gould and I to see how they can get involved, either through volunteering or through doing a share of the engineering work. Now that we are graduating, we are in the process of assembling a team of students who are committed to continuing the work and assisting in whatever way they can. Already, around eight students have expressed interest, and before the semester ends, we will have an in-person meeting with them, as well as Don Bennett and Joseph Chidiac, to officially pass the baton to a new class of students. Although I have only played a small part in this project, I am so honored to have been involved, and am thrilled to see where it goes in the future, how it improves Tri Cycle's economic prospects, and how it affects the community at large.

ACKNOWLEDGEMENTS

I would like to thank Don Bennett, the founder of Tri Cycle Farms Inc., for trusting and believing in myself and Ms. Gould as we took on this project almost two years ago, and for his endless support and encouragement along the way. Joseph Chidiac, an alumnus of the Biological and Agricultural Engineering Department and a now practicing horticultural engineer, has also been invaluable in his assistance with this project, and I want to extend a huge thank you to him for lending his expertise, critiquing my work, and for his continuous support, in addition to serving on my committee. I would like to thank Dr. Rogelio Garcia for meeting with me initially in August 2017 and granting Ms. Gould and I permission to compete in the Social Innovation Challenge, for introducing us to Don, and for guiding us through the initial stages of the project. Major acknowledgements go to Dr. Marty Matlock, my thesis advisor, for allowing Ms. Gould and I to work on this project together while providing valuable insight, direction, and practical ways to split the project while staying on-task, and for serving on my committee. I am very thankful to Dr. Costello for his continuing support throughout my collegiate career, and for serving on my committee as well. I also would like to thank Dr. David Hyatt and his sustainability capstone course for assisting us through the marketing survey they conducted in Northwest Arkansas that ultimately led to our decision about what crops to use within the “HydroHouse.” I would like to thank Dr. Haggard as well, for his help as we got closer to the official defense. I am also incredibly grateful for the University of Arkansas Honors College’s involvement with the project. Multiple Honors College staff members encouraged Ms. Gould and I, and provided as much information as possible to help us with funding and publicity, which was greatly appreciated. Lastly, I would like to thank Ceres Greenhouse Solutions for providing the greenhouse itself to Tri Cycle Farms at-cost, around a $15,000 discount, and for to the Walmart Foundation for sponsoring $20,000 of the project.

REFERENCES

Albright, L. D., Both, A., & Chiu, A. J. (2000). Controlling Greenhouse Light To A Consistent Daily Integral. *Transactions of the ASAE,43*(2), 421-431. doi:10.13031/2013.2721

Alger, H. (2019). Hydroponic & Container Basil Guide. Retrieved from https://www.johnnyseeds.com/growers-library/herbs/hydroponic-container-basil-guide.html

Anderson, M. (n.d.). Greenhouse Vegetable Production Economic Considerations, Marketing, and Financing. Retrieved from https://aggie-horticulture.tamu.edu/greenhouse/hydroponics/economics.html

Appendix C Compound Interest Tables[PDF]. (n.d.).

Arkansas Electricity Profile 2017. (2019, January 8). Retrieved from https://www.eia.gov/electricity/state/arkansas/

Barbosa, G., Gadelha, F., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., . . . Halden, R. (2015). Comparison of Land, Water, and Energy Requirements of Lettuce Grown Using Hydroponic vs. Conventional Agricultural Methods. *International Journal of Environmental Research and Public Health,12*(6), 6879-6891. doi:10.3390/ijerph120606879

Bradford, D. J. (2017, November 21). What Is the Average Yield for Hydroponic Year-Round Tomatoes? Retrieved from http://homeguides.sfgate.com/average-yield-hydroponic-yearround-tomatoes-100617.html

Chidiac, J. (2019). Hydroponics Consultation [Personal interview].

Cuce, E., Harjunowibowo, D., & Cuce, P. M. (2016). Renewable and sustainable energy saving strategies for greenhouse systems: A comprehensive review. *Renewable and Sustainable Energy Reviews,64*, 34-59. doi:10.1016/j.rser.2016.05.077

Currey, C. J., & Walters, K. J. (2016, February). *Slow basil growth*[PDF]. E-GRO Edible Alert.

Demers, D., & Gosselin, A. (2002). Growing Greenhouse Tomato And Sweet Pepper Under Supplemental Lighting: Optimal Photoperiod, Negative Effects Of Long Photoperiod And Their Causes. *Acta Horticulturae,*(580), 83-88. doi:10.17660/actahortic.2002.580.9

Dorais, M. (2003, October 9). Canadian Greenhouse Conference. In *The Use of Supplemental Lighting for Vegetable Crop Production: Light Intensity, Crop Response, Nutrition, Crop Management, Cultural Practices*. Retrieved from https://www.agrireseau.net/legumesdeserre/documents/cgc-dorais2003fin2.pdf

Electricity Local. (2019). Fayetteville, AR Electricity Rates. Retrieved April 29, 2019, from https://www.electricitylocal.com/states/arkansas/fayetteville/

Faust, J. E., & Logan, J. (2018). Daily Light Integral: A Research Review and High-resolution Maps of the United States. *HortScience,53*(9), 1250-1257. doi:10.21273/hortsci13144-18

Gent, M..N. (2014). Effect of Daily Light Integral on Composition of Hydroponic Lettuce, *HortScience horts*, *49*(2), 173-179. Retrieved Apr 12, 2019, from https://journals.ashs.org/view/journals/hortsci/49/2/article-p173.xml

Gómez, C., & Mitchell, C. A. (2015). Growth Responses of Tomato Seedlings to Different Spectra of Supplemental Lighting. *HortScience,50*(1), 112-118. doi:10.21273/hortsci.50.1.112

Gould, S. (2019). *Internal Design of a Hydroponics Greenhouse for Tri Cycle Farms* (Unpublished undergraduate thesis). University of Arkansas.

Hemingway, M. (2014, March 21). Growing Seedlings Under Indoor Grow Lights. Retrieved April 28, 2019, from https://gardeningproductsreview.com/indoor-grow-lights/

Hunger and food security - United Nations Sustainable Development. (2019). Retrieved May 10, 2018, from http://www.un.org/sustainabledevelopment/hunger/

KIND LED Grow Lights. (2019) K3 Series L600 Indoor LED Grow Lights. Retrieved from http://www.kindledgrowlights.com/products/k3-series-l600-indoor-led-grow-lights

KIND LED Grow Lights. (2019). KIND LED Grow Lights PPFD Readings. Retrieved April 11, 2019, from https://www.kindledgrowlights.com/pages/led-grow-light-par-ppfd

Kuack, D. (2017, July 24). Strawberries can be adapted to greenhouse production systems [Web log post]. Retrieved April 10, 2019, from https://urbanagnews.com/blog/exclusives/strawberries-can-be-adapted-to-greenhouse-production-systems/

Kubota, C., & SpecGrade LED. (2018). Case Study: The Ohio State University. Retrieved April 18, 2019, from https://www.specgradeled.com/grow/the-ohio-state-university/

LED Grow Lights Depot. (2019). Lush Lighting Vegetator 2X. Retrieved April 26, 2019, from https://www.ledgrowlightsdepot.com/collections/4-x-4-or-about-16-sq-ft/products/vegetator-2x-led-grow-light

Logan, J., & Faust, J. (2018). U.S. Daily Light Integral Map by Joanne Logan and James Faust [Map]. In *A Story Map ESRI*. Retrieved April 11, 2019, from https://myutk.maps.arcgis.com/apps/MapSeries/index.html?appid=d91ba9eb487d43f3a82161a1247853b6

MechaTronix. (2019). Typical PPFD and DLI values per crop. Retrieved April 27, 2019, from https://www.horti-growlight.com/typical-ppfd-dli-values-per-crop

Moore, M. (2016). How to Select the Best Grow Light for Your Greenhouse. Retrieved from http://www.greenhousecatalog.com/growlights-greenhouse

Morgan, L. (2016, February 01). Hydroponic Illumination & the Daily Light Integral. Retrieved April 25, 2019, from https://www.maximumyield.com/hydroponic-illumination-the-daily-light-integral/2/1450

NASA STEM Engagement. (2011). *583137main_Inverse_Square_Law_of_Light.pdf*[PDF]. NASA.

Newkirk, B. (2018, March 01). Understanding Light Using Daily Light Integral (DLI). Retrieved from https://growersnetwork.org/cultivation/understanding-light-using-daily-light-integral-dli/

Nexstar Broadcasting, Inc. (2015, November 22). Study Reveals Food Insecurity Statistics. Retrieved from http://www.nwahomepage.com/news/study-reveals-food-insecurity-statistics/277813606

Olle, M., & Viršile, A. (2013). The effects of light-emitting diode lighting on greenhouse plant growth and quality. *Agricultural and Food Science,22*(2), 223-234. doi:10.23986/afsci.7897

Park, Y., & Runkle, E. S. (2018). Far-red radiation and photosynthetic photon flux density independently regulate seedling growth but interactively regulate flowering. *Environmental and Experimental Botany,155*, 206-216. doi:10.1016/j.envexpbot.2018.06.033

Pillsbury, M. W. (2011, Fall). Price Differences: Organic Versus Non-Organic; Store Versus Farmers' Market. Retrieved from http://www.mofga.org/Publications/The-Maine-Organic-Farmer-Gardener/Fall-2011/Price-Differences

Resh, H. M. (2013). *Hydroponic Food Production: A Definitive Guidebook for the Advanced Home Gardener and Commercial Hydroponic Grower, Seventh Addition*[PDF]. Boca Raton: CRC Group: Taylor & Francis Group.

Runkle, E. (2006, December). Daily Light Integral Defined. Retrieved from https://gpnmag.com/article/daily-light-integral-defined/

SpecGrade LED. (2018). LINEA LED Grow Lights - SpecGrade LED | OpticPAR Technology. Retrieved April 16, 2019, from https://www.specgradeled.com/grow/linea/

Springdale Water Utilities. (2017, October 1). Water and Sewer Rates. Retrieved from https://www.springdalewater.com/water-services/monthly-water-rate-schedules/

Storey, A. (2016, December 22). Growing Hydroponic Basil? Read This First [Web log post]. Retrieved from https://university.upstartfarmers.com/blog/hydroponic-basil

Trabish, H. K. (2012, March 16). The Farm of the Future Will Grow Plants Vertically and Hydroponically. Retrieved from https://www.greentechmedia.com/articles/read/the-farm-of-the-future-will-grow-plants-vertically-and-hydroponically#gs.Yt_DHoM

Torres, A. P., & Lopez, R. G. (2010). *Commercial Greenhouse Production: Measuring Daily Light Integral in a Greenhouse*[Pamphlet]. IN: Purdue Extension.

Viviano, F. (2017). Retrieved May 10, 2018, from http://www.nationalgeographic.com/magazine/2017/09/holland-agriculture-sustainable-farming/

Watering length and frequency for hydroponic tomatoes. (n.d.). Retrieved from http://www.backyard-gardening-fun.com/watering-length-and-frequency-for-hydroponic-tomatoes.html

What Is PAR, PPF, PPFD, DLI, and Efficacy? Light Factors for Your Indoor Plants EXPLAINED! (2017, April 26). Retrieved from https://www.ledgrowlightsdepot.com/blogs/blog/what-is-par-ppf-ppfd-and-dli-light-intensity-factors-for-your-indoor-plants

Yeh, N., & Chung, J. (2009). High-brightness LEDs—Energy efficient lighting sources and their potential in indoor plant cultivation. *Renewable and Sustainable Energy Reviews,13*(8), 2175-2180. doi:10.1016/j.rser.2009.01.027