Increasing Winter Egg Production with Sustainable Technology

An Interactive Qualifying Project
submitted to the faculty of the Worcester Polytechnic Institute
in partial fulfillment of the requirements for
the Degree of Bachelor of Science

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Austin Brothers Valley Farm

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Abstract

This project addressed the problem of decreased winter egg production for free-range chickens on sustainable New England farms. Interviews with local farmers, farming organizations, and a review of scholarly research revealed that production could be increased with low-cost components that provide optimal heating, lighting, humidity, and water conditions for the birds. Using our system to increase winter egg production will increase farmer profits, ensuring that these farms can continue to provide benefits for food security, local economies, and environmental health.

Acknowledgments

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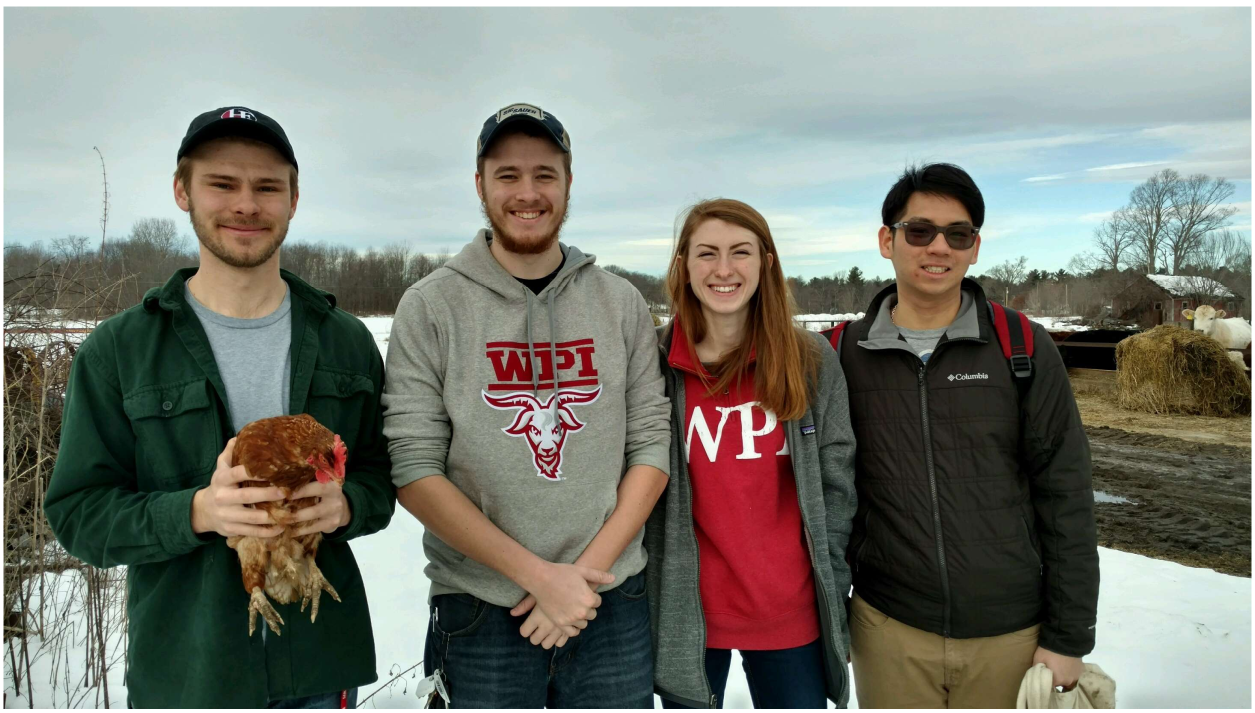

Authorship

Every team member worked together to write every section of this paper. The sections have all been reviewed and edited by every team member. There is no clear separation on who originally created which section as we all wrote them together.

Executive Summary

Small-scale farms make up 95% of Massachusetts farms, generating $492 million in agricultural goods per year (Department of Agricultural Resources, 2012). They provide a number of benefits to local communities, including increasing food security, supporting local economies, and providing valuable environmental services. Egg production alone accounts for around $156 million of this figure annually (USDA 2014). Over the last 5 years, our sponsor, Austin Brothers Valley Farm, experienced a sharp decline in egg production rates and profits common for New England farmers in winter months.

Through extensive background research, this project identified the limitations to winter egg production. It was found that heating, lighting, humidity, and access to water within the coop all had a large impact on production rates. To address this problem we conducted interviews to determine what methods are currently used to combat reduced production rates. The particular farmers interviewed were selected based on snowball sampling. The interviews indicated that there is no existing system that addresses heating, lighting, humidity, and water requirements for optimal egg laying. A farming association, FarmAid, when contacted about a potential guide to implement a Do-It-Yourself heating and lighting system, responded by saying:

> **"We get phone calls every day from farmers all across the country. It would be a great resource for us to have on hand to distribute to calls we get from New England egg producers." (FarmAid, 2017).**

Based on acquired knowledge from interviews and background research, the effectiveness of off-the-shelf products was evaluated with decision matrices. These decision matrices were scaled based on input from the sponsor and focused on reducing energy

consumption and operating cost. Once the best products were identified, a system of these products was assembled and implemented at the sponsor's farm. The modifications to the current setup included the addition of a green LED light bulb, an insulated and heated drinking water tank, a non-electric dehumidifier, and a heat source to the coop. This project also looked into powering these devices with alternative and renewable energy sources (wind and solar), however the energy consumption of the designed system was so low, the payback time on a renewable energy investment was deemed not feasible. Therefore, the system was powered using the electric grid, but managed to reduce energy consumption when compared to the farm's previous system.

Our system succeeded in increasing the sponsor's egg production rates. This system is proven to be a viable method of increasing winter egg production, and information outlining the process will be distributed electronically to farmers and farm organizations via an infographic (Appendix G) posted online, and physically via a tri-fold pamphlet at farmers markets. Our documents will be sent to three organizations, possibly reaching roughly 10,000 people. This information could be adapted for use by farmers in less developed countries to increase egg production, with benefits for food security and increase income generation (Rome, 2003). By implementing these best practices, free-range chicken farmers in regions that have seasons with cold weather and less sunlight hours all over the world can sustainably increase egg production.

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1. Introduction

Small-scale farms make up 95% of Massachusetts agriculture and generate $492 million per year (Department of Agricultural Resources, 2012). In 2014 alone, New England farms produced over 1.7 billion eggs, generating revenue of $156 million (USDA, 2014). A part of this revenue came from sustainable egg production. Recently, sustainably produced eggs have increased in popularity due to their high content of vitamins, minerals, and low amounts of cholesterol (Brower, 2013). Eggs from sustainable farms have high value in market and consumer appeal. Sustainable egg production benefits the environment, economy, and health of both people and animals. The pasture-based grazing system used in sustainable chicken farming allows for natural fertilization and reduced production of feed grain (Brower, 2013). Despite their benefits and increasing popularity, sustainably produced eggs are not consistently available in New England because they are a seasonal product. Chickens don’t produce as many eggs during the cold weather and shorter, darker days of New England’s approximately 4-month winter. This fluctuation in production leads to inconsistent profits for farmers in the region.

Figure 1: Austin Brothers Valley Farm's store[1]

[1] (Austin Brother Valley Farm, 2016)

Our sponsor, Austin Brother's Valley Farm, faces two major problems; how to increase winter egg production, and how to address this problem with a low-cost system. The objectives of this project were to analyze existing systems used at farms to increase egg production, determine elements that impact egg production, and decide if sustainable power is possible to implement. By meeting the goal and objectives of this project, we have developed and implemented a system that addresses both of our sponsor's problems, and created a guide for other small-scale farms to adapt this system to increase winter egg production on their own farm.

The following section will review the literature on the factors that impact the egg production process, ideal conditions for egg laying, and current commercial systems used to increase egg laying. After this section, we discuss the methodological approach we took meet our project goal and objectives. The methodology is followed by the results, which explains the findings of the project. The reader will then find a section explaining the team's recommendations for other New England farmers to increase egg production. Lastly, we conclude by discussing the immediate and broader impacts, as well as potential applications and future work.

2. Background

This section will cover the literature necessary to fully understand the problem of decreased egg production in New England. Topics included in this section are effects of chicken age, breed, and feed on egg production, problems with seasonal egg production in hens, effects of photostimulation on egg production, effects of heat on egg production, and current methods to increase sustainable egg production.

2.1 Effects of Age, Breed, and Feed on Egg Production

Some factors that influence egg production include the age of a chicken, breed, and feed. Age contributes considerably; older hens not only produce 20 fewer eggs per month than younger hens but lay later in the day. Additionally, “breeder broilers”, or chickens laying fertilized eggs for reproductive purposes lay fewer eggs than hens laying eggs for human consumption (Bell, 1998).

Water availability and feed content also have direct effects on lay rates and quality. In freezing conditions, an uninterrupted flow of warm water is recommended for more consistent egg production rates (Bell, 1998). Feed content is usually adapted to fit the specific needs of the breed. The content of a hen’s diet can generally influence production because insufficient vitamin, mineral, and protein levels limit egg size and the rate at which eggs are produced. Vitamin E, Vitamin C, calcium, and phosphorus deficiencies are common, and directly correlated to eggshell, yolk, and albumen quality (Bell, 1998). Additionally, vitamin and mineral needs shift depending on temperature and age, as older laying hens exhibit the effects of vitamin deficiencies more readily than young hens (Boling et al., 2000). Strategic increases in vitamin and mineral levels during different parts of the year and life of the chicken can increase egg production and egg quality.

2.2 Problems with Seasonal Egg Production in Hens

When environmental conditions fluctuate with seasonal changes, egg production follows. In the winter, lay rates decrease drastically as natural light levels diminish and colder weather demands more energy from the chickens. In the heat of the summer, egg production is also reduced as extremely high temperatures stress birds. Egg quality and marketability are also affected by seasonal fluctuations (Tumova & Gaus. 2012).

Temperature fluctuation corresponds to light levels, an important stimulus for laying hens. Lower light levels in the winter cause an overall lower lay rate, therefore the total number of eggs produced by a hen decreases. Since the 1920's it has been known that lighting a coop in December can increase egg production by more than 50% (Hooley 1920). This information has lead poultry farmers to try to optimize egg production by providing artificial light and heat.

A study completed in 1920 examined that both climate and natural lighting are affected by latitude, indicating that egg production rates also vary with latitude. In this study, egg production was examined at increments of 5° of latitude all over the world in both northern and southern hemispheres, starting at the equator and moving 50° north and 40° south. The further the distance is from the equator, the greater the rate of egg production. This is because flocks are not stressed by constant heat in the more temperate climate away from the tropics. At 40° north or south (Massachusetts is around 42° north) total egg production peaks and remains around the same in terms of annual production. Even though New England is located around one of the most ideal latitudes for total year round egg production, the area also experiences the most fluctuation in temperature and light availability. This is the reason that farmers in these latitudes fail to maintain steady egg supplies (Whethem, 1920).

2.3 Effects of Photostimulation on Egg Production

One effect of seasonal changes, availability of light, has the greatest influence on the rate of egg production in laying hens. Hens produce best when they average 12 hours of light exposure during the day, but during winter hens can get as few as eight hours (Bell, 1998). Increasing the number of lighted hours to mirror the exposure conditions in summer and spring encourages laying hens to exercise more and spend less time in their roosts. Artificial light can increase winter production rates by 50% or 60% (Dougherty, 1922). This information has lead poultry farmers to try to optimize egg production by providing artificial light and is cited as landmark research that is still valid today.

Specific intensities and wavelengths of the light can influence production rates further. Low intensity light is all that is needed to see these increased positive effects; hens exhibit a preference for low intensity light when given multiple fluorescent intensities (Ma et. al, 2016). One study showed that lower intensity fluorescent light is preferred for egg production as, "most of the eggs were laid in <1 lux (51.9% total) which was significantly higher than under other light intensities" (Ma et. al, 2016). Low intensity light of the appropriate wavelength can have a measurable effect on egg size and production rate. This can create consistent production year round despite natural fluctuations in laying rates caused by environmental conditions.

It has also been found that the chicken retina can distinguish between different light colors. These various light colors affect the egg production rates and quality differently (Er et. al, 2007). When using red, green, and blue lights emitted by LED lamps, it has been shown that green light produces eggs of the best quality (Er et. al, 2007). Exposure to red light produces the greatest increase in egg quantity with a decrease in overall quality (brittle eggshells). Hens under both blue and green light produce consistently larger eggs, though exposure to red light yielded higher production rates (Pyrztak et. al, 1987).

Too many lighted hours a day can also discourage hens from laying. Hens subjected to an overabundance of photo stimuli can become sensitized to the stimulus in a process known as photorefractoriness. This ultimately decreases egg production due to reduced instinctive reproductive drives. Observation of this phenomenon has lead agricultural scientists to determine optimal light levels for year round egg production and establish a baseline minimum number of hours for photostimulation to occur. This minimum is often referred to as "critical day length". Critical day length may vary based on species, and it was found that photostimulation spurs the greatest egg production for most breeds when days are 12 hours long. Egg production decreases with 14 hour long days and halts entirely after photorefractoriness sets in by 17 hour long days (Bell et al., 2002).

2.4 Effects of Heat on Egg Production

Temperature directly affects a laying bird's behavior and feeding patterns. Decreased caloric intake at lower temperatures in winter causes a decrease in egg size and shape, but the number of eggs produced remains almost constant between 10ºC (50ºF) and 25ºC (77ºF) (Marsden et al., 1987). Increasing the temperature of the hen's environment to ideal production temperatures (between 21ºC (70ºF) and 26ºC (79ºF)) could increase the quality of production in winter months. Eggs could be expected to increase in weight, content proportions, and shell strength as compared to those laid in lower temperatures. It was found that on average, laying hens produced eggs three grams heavier at a temperature of 20ºC (68ºF) as opposed to 28ºC (82ºF). This weight is insignificant, indicating that there is a consistent egg weight in this ideal egg production temperature range. The same study observed only a 0.4% difference in the actual number of eggs produced at the two temperatures (Tumova et al. 2012).

While appropriate heating levels can have positive effects of lay rates, excess temperatures can cause heat stress in chickens. This heat stress can lead to decreased egg production because chickens decreased their dietary intake similar to how they do in the cold. If the temperatures are kept within a moderate range, artificial heating and lighting in the winter have no detrimental effect on the hens in other laying seasons or over the duration of its life (Dougherty, 1922).

2.5 Current Methods to Increase Sustainable Egg Production

Other small-scale farms across the US have implemented environmentally sustainable and animal sensitive practices that increase egg production. The Henlight Lighting System is a commercialized system manufactured specifically to increase egg production sustainably. The system consists of a 40 watts solar panel that powers a LED light inside the coop. The LED increases the hens light exposure by extending daylight hours in the morning. This process was shown to increase production in winter by as much as 20% (The Henlight Lighting System, 2015). The Henlight system is comprehensive but fails to address an issue specific to northern climates: frigid temperatures that can inhibit production. Additionally, this system is the only one currently on the market. Individual items are sold (such as lights or heat lamps) as chicken specific products at marked-up prices when nothing about them is actually distinct for chickens.

Since the only commercially available system failed to meet our sponsor's requirements, we collected data on the current egg production statistics of Austin Brothers Farm without system intervention. We would conduct research to determine what products would best address factors affecting egg production outlined in this section. A proposition of a potential system would be drafted and submitted to our sponsor. Pending their approval, we would implement the system in their coop and continue to collect data to see the real world effect of our design. Next we described the methods used to complete these objectives in detail.

3. Methodology

The methodology section outlines the plan to achieve the project goal and to determine the best practices to increase winter egg production for small-scale chicken farms in New England. Heating and lighting needs were the primary concerns addressed, and renewable energy solutions were emphasized. To collect information on these topics a number of strategies, including interviews, participant observation, and secondary research, were utilized.

Objectives:

Our first objective was to analyze existing systems at Austin Brothers Valley Farm and potential systems used elsewhere to increase egg production. To meet this objective, we conducted semi-structured interviews as well as participant observations at our sponsor's farm (Austin Brothers Valley Farm). After this data was collected, we interviewed users and designers of chicken coop heating and lighting systems. All information was kept anonymous, therefore adhering to WPI's Institutional Review Board's guidelines.

The next objective was to understand the different elements that impact egg production. Information obtained in interviews led the team to investigate previously unknown factors that influence egg production such as humidity and chicken behavior. Using this information we conducted secondary research on potential heating, lighting, water, and humidity systems. In addition to secondary research using scholarly databases, we conducted semi-structured interviews with the sponsor to determine chicken behavior specific to their flock.

The final objective was to analyze sustainable energy production and storage methods. This objective required calculating energy consumption of Austin Brothers Valley Farm and energy consumption of various chicken support systems determined through manufacturer specifications. After this information was collected and calculated, the feasibility of the renewable energy storage and production methods was considered.

3.1 Analyze existing systems at Austin Brothers' Farm and potential systems used elsewhere to increase egg production

To meet this objective, existing heating and lighting models for chicken coops were analyzed. This analysis determined the most effective system for a small-scale farm. The result of this process was a list of the best practices for Austin Brothers Valley Farm and other New England farms. To achieve this objective, the following steps were taken.

a. Semi-structured interviews with the sponsor and participant observation at Austin Brothers Valley Farm

Typical egg production rates for different seasons, flock size, dietary intake of chickens, and heating and lighting methods were determined through semi-structured interviews with the sponsor and participant observation at their farm. In addition to collecting information on the chicken farming operation, our sponsor's preferences for sustainable energy systems, heat systems, and light systems were determined. The questions asked during this visit can be located in Appendix A.

b. Interview users of chicken coop heating and lighting systems.

Interviews were conducted with other New England farms to identify potential heating and lighting systems that could be used to increase winter egg production. The systems currently in use by other farmers were recorded from interviews initiated through a series of referrals (snowball sampling method). We received these referrals from our sponsor, and completed these interviews in person by visiting a local farmer's market in Amherst, Massachusetts. Additional references were collected at the market to contact other farmers for later face to face and phone interviews. Other interviews were initiated by calling egg-producing farms for The Farms and Food of Southern New England Registry of Egg Farmers database using a snowball sampling method. Other interviews were initiated by calling egg-producing farms for The Farms and Food of Southern New England Registry of Egg Farmers database using a snowball sampling method. Information gathered from these interviews was used to help identify systems that are applicable to small sustainable egg farming operations. These interviews assessed each farm's coop layout and methods for increasing production. Additionally, justification for using these methods were recorded, as well as the effect these practices had had on production and profits. All farms will be referred to by their given label of farm A, B, C, and etc., to maintain their anonymity. Interviews were performed using the questions in Appendix B.

c. Interview designers of chicken coop heating and lighting systems.

Interviews with designers of chicken coop heating and lighting systems provided information on how systems were developed to reduce energy use and increase production rates. Individuals were selected for sampling based on referrals from other farmers, or from Internet research. These interviews identified methods financially feasible for farms with a small-scale operation like our sponsor. The interviews asked questions about the types of systems with which these designers usually interact. This included the main issue the system addresses (heat or light) and how energy is provided to these systems. The questions for this interview are located in Appendix C.

d. Conduct secondary research on potential heating, lighting, water, and humidity systems.

The next step to complete our objective was to conduct secondary research on potential heating, lighting, water, and humidity systems. Information obtained from previous interviews pertaining to privately produced or commercially available systems was analyzed during this step. Secondary research was conducted to determine if these systems would work for our sponsor. This included analyzing the performance, energy efficiency, initial cost, operation cost, sustainability, effect on chickens, and difficulty of implementation of the systems. This decision matrix weighs the categories on a scale of 1-5, 1-10, or 1-15 based on how important the category was to our sponsor. Categories in the decision matrix with a higher number (10 or 15) were determined to be more important to the sponsor and thus weighted more heavily. In this manner we examined several products that addressed heating, lighting, humidity, and water issues within the coop. Definitions of decision matrix categories, their ranking scale, and examples of the scales are listed below.

- **Energy Efficiency:** The amount of power the system uses in comparison to the system's ability to perform its function.
  - 0 = High-energy use, low heat/light output.
  - 10 = Low energy use, high heat/light output.
- **Performance:** How well the system completes its needed function
  - 0 = Does not perform task or over performs.
  - 10 = System completes needed function.
- **Initial investment cost:** The cost for the system to be purchased/installed.
  - 0 = The system is incredibly expensive.
  - 15 = The system is incredibly cheap.
- **Operation cost:** The cost for the system to be run annually, including upkeep.
  - 0 = The system is expensive to operate.
  - 15 = The system is cheap to operate.
- **Effect on Chickens:** The social and physical effects that the system has on the chickens.
  - 0 = This product has a negative effect on the chickens/egg production by decreasing comfort or safety.
  - 5 = This product has no impact on the health/wellbeing of the chickens or is proven to benefit the chickens.
- **Sustainability:** The environmental effects that the system has
  - 0 = Larger carbon footprint than current setup
  - 5 = Significantly smaller carbon footprint than current setup
- **Difficulty of Implementation:** How complicated the installation process is, both initially and each year when they begin using it for the season.
  - 0 = must be installed professionally, and yearly start up is complicated
  - 10 = can be easily installed and implemented yearly

As previously mentioned, the scale for each of these categories was determined by the sponsors feedback on levels of importance. The scaling within each category was determined on an arbitrary basis dependent on the best product in each category for each criterion. There was no baseline metric to compare products to since each product served a different function.

3.2 Understand unexpected elements that impact chicken egg production.

The next objective was to understand unexpected elements that impact egg production. These factors were brought to light by semi-structured interviews with New England farmers and our sponsor. Secondary research was conducted on these topics using scholarly databases.

a. Conduct secondary research other necessary topics including research on humidity and chicken behavior

Before the semi-structured interviews with local farmers, the only factors that the team discovered impacted egg production were heat levels, light levels, and availability of water. A majority of research on newly discovered factors was conducted through secondary research on scholarly databases.

b. Semi-structured interviews with the sponsor about chicken behavior

To address chicken behavior at Austin Brothers' Farm, the team conducted semi-structured interviews with the sponsor about their chickens. During these interviews we specifically asked about the flock's response to certain known causes of bird stress and asked about other potential sources of stress.

3.3 Analyze sustainable energy production and storage methods

The next major objective was to analyze sustainable energy production and storage methods. In order to complete this objective, we investigated the current energy use of Austin

Brothers Valley Farms to develop a baseline for their energy needs. This was used to determine the total energy currently used by their chicken farming operation, and to estimate the energy required to supply potential heating, lighting, humidity, and water systems. From this energy budget we estimated the energy production required from a renewable source and determined if renewable energy was a possible solution for our sponsor.

a. Calculate energy consumption of Austin Brothers Valley Farm via manufacturer specifications

The first step to meeting the objective was to calculate the energy consumption of the chicken farming operation at our sponsor's farm using manufacturer specifications. An energy consumption and cost analysis was performed on the existing system's usage and efficiency. The electricity consumption was calculated based on the data provided by the manufacturers of the heating and lighting systems. During this process, the farmers were asked to record the number of hours of artificial light they had exposed their flock to, and the number of hours the electric fence used to protect the chickens had been turned on per day. Information on hourly usage and power consumption was used to determine energy cost. For example, a 60W bulb lit for three hours at $0.12 per kWh would cost $0.02. Full calculations for this energy budget can be found in Appendix E. After determining how much energy is consumed by the farm's current setup we were able to determine the resultant greenhouse gas emissions. To do this we took the amount of energy used by the farm, multiplied it by the percent of local energy that comes from fossil fuels, and then multiplied that by the amount of carbon emissions that burning fuel creates while producing a standard unit of energy. The full emissions calculations can be found in Appendix D.

b. Calculate energy consumption of various Chicken Support systems via manufacturer specifications.

The next step was to calculate and research the energy consumption of potential heating, lighting, humidity and water systems. Manufacturer's datasheets provided energy consumption rates for these products, which were then used to find energy consumption if installed at Austin Brother's Farm. An example of this calculation is located in Appendix E.

c. Assess feasibility of renewable energy storage and production methods.

Analysis of the costs and potential profits associated with energy sources determined their financial feasibility for Austin Brothers Valley Farms. The two renewable energy sources deemed potentially effective (through research) on our sponsor's farm were solar and wind energy. Secondary research provided the data to compare and contrast these two sources in relation to the specific needs of the farm. The comparative assessment explored an energy budget for the coop's electric systems, and a comparison between traditional and alternative resources. Payback time, investment cost, and annual operating cost were considered. The techniques that are available to gather this information are well known in the literature (US Dept. of Energy, 2015). During an interview, the sponsor indicated that solar energy is preferred if possible. When all of the data was collected, if no appropriate alternative energy source can be found, the team determined methods to decrease energy use without a renewable energy source while still increasing egg production.

4. Results

4.1 Investigate factors, beyond heating and lighting, that impact egg production

Based on the interviews with our sponsor, we were aware that issues of heat and light were primary factors that they considered the most responsible for affecting egg production rates. Analysis of secondary sources through our literature review confirmed that these were key areas of concern for winter egg production. To ensure a complete analysis of all the factors that could potentially impact production rates, especially those outside of our sponsor's range of knowledge and experience, we looked to outside sources of information as well. Semi-structured interviews with other farmers and secondary sources were used to analyze other potential factors affecting egg production beyond heat and light. Both humidity and stress were found to be influential factors in regulating production. Both are discussed in this section, drawing on information collected from semi-structured interviews, participant observation, and peer reviewed journal articles.

a. Impact of Humidity on Egg Production

During a semi-structured interview, a New England area farmer (Farmer A) voiced concerns that the effect of humidity on production was as significant as heat and light. Farmer A was concerned about the negative impacts of humidity on egg production, but did not have a system in place to manage humidity. Only a heating system was in place in Farmer A's chicken coop. Secondary sources confirmed that extreme humidity could impact egg production in ways similar to extreme heat. When comparing production in normal 63% (ambient) humidity to high 90% (belljar) humidity, egg production decreases. At ambient humidity, the chickens in one study laid around 1,173 eggs while they laid 1,082 eggs under belljar condition (Biu et. Al, 2012).

The sponsor was previously unaware that humidity could potentially be affecting their production. While we did not measure humidity levels on our sponsor's farm, drawing on data from farm interviews and published research that has documented humidity as a problem, we have concluded that humidity, in addition to light and heat, needs to be optimal to increase egg production on our sponsor's farm.

One study generated an equation for the relationship between relative humidity and egg yield showing that for each percent decrease in humidity there would be an eight egg decrease in production for a flock of the studied size (Olumide, n.d.) However, the impact of relative humidity on egg production differs, depending on the age of the hen. Research shows that relative humidity does not significantly affect egg production in hens from six to eight months old. Hens 16 to 18 months old showed a significant decrease in egg production when the relative humidity of the coop was between 60 and 65 percent. In older hens, a range of relative humidity from 40% to 55% will increase the egg production (Yahav et al., 2010). The ideal relative humidity for a coop is between 40% and 55% generally, though specific flock conditions may change this.

b. Impact of Stress on Egg Production

Research shows that stress can decrease egg production in chickens. There are a number of elements that can cause stress in laying hens. These including feed and water availability, relationships within the flock, extreme weather, and illness (El-lethey et al., 2000). Because stress can reduce egg production, we aimed to learn 1) If our sponsor's chickens were experiencing regular stresses that might play a role in their decreased egg production in the winter, and 2) If a proposed heating, lighting, and humidity systems could stress the chickens and negatively impact egg production.

Signs of stress in chickens include a freezing response from sudden stress (something that surprises them), while more intense stress can cause urination or defecation (Nagy et al., 2005). While these are extreme responses, less intense reactions to stress can be observed in other behaviors. Weight gain and feather picking (from both themselves and other birds) are all signs of stress. Feeding frustration and fasting are less visible signs – often it is hard to keep track if each individual bird is eating (El-lethey et al., 2000). A stress indicator specific to the Austin Brother Valley Farms flock is huddling – when stressed the chickens huddle together, sometimes so severely that they crush or suffocate chickens in the interior of the huddle (M. Austin, personal communication, December 4, 2016). However, this stress and other typical responses are not seen regularly by our sponsor, indicating that our sponsor's chickens are not regularly experiencing stress.

Another issue potentially related to stress that we considered was the death of 11 of sponsor's chickens over an 8-week period (between December 22nd and February 8th). This was about a quarter of the sponsors flock. Illness can cause stress, which could lead to a reduction in egg production. The first five birds died over a span of ten days, all looking sick and slightly wet-feathered the night before they were found dead. All exhibited stress behaviors such as fasting and pecking the nights before they died. They were determined to have died from prolapsed vents, a condition in which a chicken's egg gets stuck in the chicken's vent, which causes death if unresolved (Jacob, J.P. et. al, 1998). Our sponsor treated their birds with a regimen of vitamin D supplement in their water, and calcium supplement in their food, and have not seen a death since February 8, 2017.

While these deaths contributed to a decline in egg production, it was a result of a loss of birds, and not a result of slowed production of eggs from the birds. After the heating, lighting, humidity, and water systems were installed, we asked our sponsor to monitor the flock for stress behaviors. While the chickens were curious about the presence of the new materials in their coop, according to sponsor reports and participant observation, there has been no increase in stress behaviors.

4.2 Analyze existing systems at Austin Brothers' Farm and potential systems used elsewhere to increase egg production:

To analyze the current system at Austin Brother Valley Farms and other potential systems we conducted a series of semi-structured interviews with our sponsor, other New England Farmers, and chicken coop system designers. We also used participant observation, analyzed average user reviews of heating, lighting, humidity and water system and analyzed secondary sources in order to consider the best options to improve heating, lighting, and humidity for Austin Farms and other New England egg farmers.

a. Existing Systems at Austin Brothers Valley Farm

During our first visit to the farm, we discovered that the chicken coop had no heating system in place, just 2.5-inch fiberglass insulation rolls (Johns Manville ComfortTherm, R13) stuffed inside the vent holes of the roof. In addition, there was a hole in the wall covered with chicken wire for ventilation that was filled with a window (0.39 inch thick) when the temperature got colder (mid-November to April). For a lighting system, the farmers had hung a 40W incandescent light bulb from the ceiling. Additional electricity was used outside the coop to enclose a grazing area with an electric fence (Gallagher M300). The chickens were receiving water from two 5-gallon water feeders that were filled halfway twice a day. The coop's dimensions were eight by ten feet on the floor with a total volume of 810 cubic feet. Pictures of various systems installed in the coop can be seen in Figure 2 below.

Figure 2: Existing system at Austin Brother Valley Farm

At the time of the visit, the colder weather had not yet set in (daily average of around 50 °F) and the farmers estimated an average of 42 eggs per day were being produced with the current system during peak production months (roughly April through October/ November, the period of the year where it's normally above 40 °F). With 46 birds this is roughly 1 egg per bird per day in peak season, which is average for the breed (M. Austin, personal communication, December 4, 2016). During the rest of the year production decreases depending on the severity of the weather, as in the colder and more inclement the weather, particularly as it decreases below 30 °F consistently, the less eggs the chickens produce. In the off-season, production for Austin Farms dropped as low as one egg per two chickens per day (Between 30% and 50%

decrease in production depending on the severity of the weather). An outside view of the coop and the chickens at our sponsor's farm is shown in Figure 3 below.

Figure 3: The coop (above) and the chickens (below)

This production is below average for the hardier breeds such as the breed at Austin Brothers Valley Farm, a hybrid called a gold comet. This type of chicken can lay between 300 and 330 eggs a year (with production dispersed more heavily in peak seasons) if maintained in the proper conditions (Dunreath Farms, 2016). These chickens have adapted to live and continue producing eggs in the cold of New England, but there is a drop in egg production in the winter months. Our team was tasked with increasing the egg production up to the maximum capacity of the chickens. During this visit, the farmers had also indicated that they would like to have a system to keep the water from freezing in the winter.

b. Investigate Potential Chicken Heating, Lighting, and Humidity Control Systems at Other New England Farms

Through interviews with other small-scale New England farmers the team identified a multitude of potential heat and light systems, as well as a gap in the current knowledge and market. All of the farmers we spoke to were negatively impacted by their decreased winter production (a long-standing issue given the extensive history of chicken farming in New England), but they had no solution or comprehensive system to help them deal with the situation. The farmers expressed interest in not only helping us by providing information, but wanted to know our results and recommendations so they could consider implementing some or all of the solutions.

The first three interviews occurred at a local farmer's market in Amherst, Massachusetts, a location suggested by the sponsor. During one interview, Farm B claimed to use solar-heated hot water through radiant flooring (malleable water pipe and aquastat) as a heating system in their greenhouse connected to their coop, which provided residual heat to the coop. They did not operate a lighting system and had observed an 80% reduction during the wintertime (one egg per bird per day in peak season to one egg per five birds per day in the winter). The radiant heating system installed would be sufficient to warm the coop, so the severe decrease in production indicates that heating alone cannot improve egg production rates in the winter. According to the interviews with other local farmers, heat is an important factor in egg production rates, but it is not as influential as light. Most interviewees used lighting systems, but varied in their use of heating systems. None of these farms experienced such severe reductions in egg production. This provides further evidence of the importance of including a lighting system in the winter. While the heating system is sufficient as one component, a fully functional system needs to address all the potential issues of heat, light, water, and humidity.

Farm C only sold eggs produced in the winter, and had production of six to ten eggs per day for 17 hens (one egg per three to four chickens per day). They used a fluorescent light system. This is a low production rate when compared with that of an average hardy New England breed of chicken, which produces one egg per one to two chickens per day in the less productive season. Though the fluorescent light system is assisting in increasing production rates, use of additional elements to make a complete system (including heat/ humidity) is necessary to get the ideal rate of winter production.

Farm D observed 85 eggs in the peak season and about 60 in the winter, a decrease of only 17.7%. This is an improvement over the average 40%; therefore, the system is very successful at managing winter production. The systems implemented included a heated base water system, a halogen bulb and corner lights on timers to increase light exposure during early morning and night. Though they don't operate a heat system explicitly, the halogen bulb and water heater both produce heat within the coop. This indicates that a system that increases both heat and light has more success at improving egg production rates in the winter vs. using heating or lighting alone.

The next four interviews occurred with farmers identified from The Farms and Food of Southern New England registry of egg farmers (The Farms and Food of Southern New England, 2016). The three farms, E, F, and G, did not use any supplemental heat or light systems. While this did not give us any information on potential systems to pursue, it did give information on the average effects of winter on production – on average, their chickens' egg production dropped by 55%.

Farm A used a timed overhead LED light system. This system automatically turned on in the morning and at night to extend the birds lighted hours in a manner similar to their natural exposure (when the days are longer in summer). This system operated November through April, and even without the addition of a heating component, there was only a 25 to 30% decrease in production, half of the average decrease observed in farms operating no supplemental systems. This means that having at least a partial system of light can help increase the in egg production in the winter, but this must not be the only factor affecting production because it is not at it's full range even when light issues are resolved. A summary of the data collected from these farms is shown on Table 1 in the next page.

Table 1: Interviews with local farmers

Interviewee	# of Chickens	Heat System	Light System	Humidity System	Peak Production (per day)	Winter Production (per day)	Production Percent Decrease
Average for ABV's breed (gold comet)	100	N/A	N/A	N/A	100	90	10%
Austin Brother's Farm	47	N/A	Incandescent bulb	N/A	42	23 to 32	50% to 30%
Farm A	25	Solar hot water through radiant flooring (malleable water pipe and aquastat)	N/A	N/A	25	5	80%
Farm B	17	N/A	Fluorescent light	N/A	N/A (raise chicks in summer - no eggs)	6-10	N/A
Farm C	100	Halogen bulb produces heat, and they use a heated base water system	Halogen light and corner lights on timers to increase exposure during morning and night	N/A	85	60	17.65%
Farm D	75	N/A	N/A	N/A	66	33	50%
Farm E	20	N/A	N/A	N/A	20	5	75%
Farm F	10	N/A	N/A	N/A	10	6	40%
Farm G	70	N/A	LED lights to increase exposure for additional hours in the morning and at night Nov-Apr	N/A	70	52	33% to 25%

Note: Information on systems and average rates of production came from interviews with local farmers and Austin Brother's Farm.

c. Commercial Heating, Lighting, and Humidity Control Systems for Chicken Coops

The goal of our project was to form a comprehensive approach to increasing Austin Brother Valley farm's egg production by addressing the many issues that New England weather effects, including humidity, heat, and light. Current commercially available systems only address the issue of light. For example, Henlight, which consists of a small solar panel, battery pack, and light, only address one of the issues and would be insufficient for our sponsor's needs. (E. Silva, personal communication, February 2, 2017). A system that addresses all of these potential issues is not commercially available; therefore, we worked to create a system that addressed issues of heat, light, and humidity. The farming association, FarmAid, when contacted about a guide to implement heating and lighting systems responded saying, “We get phone calls every day from farmers all across the country. It would be a great resource for us to have on hand to distribute to calls we get from New England egg producers.” (FarmAid, 2017) This further supports our findings that there is no system or guide in place meeting the requirements necessary for successful winter egg production.

By speaking with the designer of a currently commercially available system (Henlight) we determined a pre-made, commercially available system would not meet Austin Brother Valley Farm’s needs. Local farmers confirmed this finding in our analysis of currently used systems – none of the individuals interviewed used or knew of a comprehensive commercial system to address all their needs.

4.3 Evaluate Potential Chicken Heating, Lighting, Humidity Support Systems

This section contains the evaluation of each potential system using the decision matrix evaluated based on the categories of energy efficiency, performance, initial investment cost, operation cost, effect on chickens, sustainability, and difficulty of implementation. These categories were determined through a brainstorming session based on the literature and discussion with the sponsor to determine what they value the most.

To organize and analyze the research on potential systems identified in the literature and interviews, a series of decision matrices were designed. A matrix was utilized to aid in the evaluation of each potential portion of the new winter system (heat for the coop and drinking water, light, and humidity) that evaluates these systems in the areas of energy efficiency, performance, initial cost, operation cost, effect on chickens (comfort and safety), and sustainability. According to the sponsor's response, "Another attribute you might want to consider is: difficulty/ease to implement. i.e. is it fairly simple to install (we could do ourselves) or is a complicated (need to hire someone)?" (M. Austin, personal communication, November 24, 2016). Therefore, our team added a new factor for the matrix, ease of implementation. Each attribute of the system is ranked on a scale of 0 - 5, 0 - 10, or 0 - 15. The rank of the category (5, 10, or 15) creates a weighted ranking system, based on our sponsor's ranking of how important each category was. In their response, they clearly show their focus is on the cost of the systems, stating "The overall (overarching) consideration/driver is going to be cost - is it worth the money invested (will there be a return to justify the investment)." (M. Austin, personal communication, November 24, 2016). As the result, initial investment cost and operation cost are ranked on a scale of 15. Definitions of these attributes, their ranking scale, and examples of the scales are listed below. Note that some categories, such as energy efficiency, were ranked based on relation to other products reviewed in the category, as we did not have a benchmark to relate to. Decision matrices are commonly used for making unbiased decisions between products (Martin, 2016).

- **Energy Efficiency:** The amount of power the system uses in comparison to the system's ability to perform its function.
  - 0 = High energy use, low heat/light output.
  - 10 = Low energy use, high heat/light output.
- **Performance:** How well the system completes its needed function
  - 0 = Does not perform task or over performs.
  - 10 = System completes needed function.
- **Initial investment cost:** The cost for the system to be purchased/installed.
  - 0 = The system is incredibly expensive.
  - 15 = The system is incredibly cheap.
- **Operation cost:** The cost for the system to be run annually, including upkeep.
  - 0 = The system is expensive to operate.
  - 15 = The system is cheap to operate.
- **Effect on Chickens:** The social and physical effects that the system has on the chickens.
  - 0 = This product has a negative effect on the chickens/egg production by decreasing comfort or safety.

- 5 = This product has no impact on the health/wellbeing of the chickens or is proven to benefit the chickens.

- **Sustainability:** The environmental effects that the system has
  - 0 = Larger carbon footprint than current setup
  - 5 = Significantly smaller carbon footprint than current setup
- **Difficulty of Implementation:** How complicated the installation process is, both initially and each year when they begin using it for the season.
  - 0 = must be installed professionally, and yearly start up is complicated
  - 10 = can be easily installed and implemented yearly

The scale for each of these categories was determined by the sponsor's feedback on levels of importance. The scaling within each category was determined on an arbitrary basis dependent on the best product in each category for each criterion. There was no baseline metric to compare products to since each product served a different function.

a. Light System

The potential light systems analyzed included fluorescent lights, halogen lights, and LED lights. A specific bulb was chosen based on the color, intensity, and user reviews. These user reviews were sourced from the product's site and used as third party verification of the product's quality. Low intensity green LED bulbs were selected based on research and are documented in the literature review. User reviews were used to weed out bulbs that were undesirable or poorly made. The decision matrix can be seen below (Table 2).

Table 2: Light system decision matrix

	Performance	Effect on Chickens	Difficulty of Implementation	Initial Investment Cost	Energy Efficiency	Operation Cost	Sustainability	Total Score:
Fluorescent Light	9	3	10	7	5	10	3	**47**
Halogen Light	9	3	8	7	3	3	2	**35**
Green LED Light	10	5	10	14	10	15	5	**69**

The potential light systems analyzed included fluorescent lights, halogen lights, and LED lights. A specific bulb was chosen based on the color, intensity, and user reviews. These user reviews were sourced from the product's site and used as third party verification of the product's quality. Low intensity green LED bulbs were selected based on research and are documented in the literature review. User reviews were used to weed out bulbs that were undesirable or poorly made.

The fluorescent light analyzed (Feit Electric ESL13T/G) has an 8,000-hour lifetime according to the manufacturer and received a nine in the performance section based on its user reviews (amazon.com, 2016). The initial investment cost is $8.15, leading to a score of seven in investment cost. The fluorescent bulb (Figure 4) uses 13 watts of electricity. If the bulb was operated for eight hours per day 150 days per year with the energy costing 13.1 cents per kilowatt-hour from National Grid, this bulb would cost $2.04 per year, scoring a ten for operating cost. For efficiency, the fluorescent light was ranked a three, as it is more efficient than incandescent (13 watts vs. 40 watts). As fluorescent bulbs can heat up and contain mercury vapor (Stern, 2001) they were ranked only a three in effect on chickens as they would likely injure the chickens if they came in contact with the bulb or broke it. For implementation, the fluorescent bulb uses a standard socket and therefore ranked a ten.

Figure 4: Green fluorescent bulb

The next light evaluated was a halogen light (Sunlite 50PAR20/HAL/FL/G, Figure 5) which has a reported 2,000-hour lifetime and ranked a performance score of nine based on user reviews (amazon.com, 2016). The initial investment cost for the 50-watt halogen light was $8.40, leading to a score of seven in that category. The halogen light costs $7.86 to operate for one year, scoring three in that category. Despite this value being very close to that of others, in the interest of optimization, the most cost effective products were rated. The halogen light received a three for energy efficiency as it uses a large amount of electricity. This bulb does not generate light very efficiently; therefore, for sustainability it was ranked a two. Halogen lights heat up to very high temperatures, so the system was ranked a three in the effect on chickens' category because it could potentially burn the chickens if they touch the bulb. For difficulty of implementation, the halogen light was ranked an eight, as it may need a heat shield to protect the chickens from being hurt but it also uses the standard socket.

Figure 5: Green halogen bulb

The next product reviewed was a green LED bulb (PLT LED-A19-GREEN, Figure 6) that has a reported 50,000-hour lifetime and currently has no user reviews, but lifetime alone warranted a performance ranking of ten. The green LED light has a low initial investment cost of $2.38, leading to the highest score in investment cost of 14. The green LED light costs only $0.16 per year to operate, scoring a 15. The energy efficiency for the LED is far more superior to the other products so it scored a ten. Since this product is on a magnitude of hundreds of times more efficient than other products, it received the highest scores possible for sustainability, energy efficiency and operating cost. For the same reason, it scored a five for sustainability. LED lights were not found to produce any negative effects on chickens so this bulb ranked a five in this category. Again, as this product uses the standard socket, it ranked a ten for difficulty of implementation.

Figure 6: Green LED bulb

b. Heating System

The heating systems analyzed included a halogen light, space heater, heat lamp, and small heating panels, options brought to light by previous interviews with farmers. All of these options are energy intensive and depend on electricity to operate. The halogen lamp performed very well, has a small initial investment, and is very easy to implement. The halogen lamp received the highest score out of the decision matrix featured below (Table 3).

Table 3: Heating system decision matrix

	Performance	Effect on Chickens	Difficulty of Implementation	Initial Investment Cost	Energy Efficiency	Operation Cost	Sustainability	Total Score:
Space heater	7	4	10	12	9	10	2	**52**
Halogen Light	8	2	10	14	9	11	3	**55**
Flat Panel Heater	7	5	9	12	8	13	3	**55**
Heat Lamp	8	3	10	13	9	12	3	**58**

Space heaters often supply supplemental heat to homes, but some have used these devices in chicken coops to keep their birds warm in winter. Some models rely on natural convection, which is unreliable as it varies with the shape and how drafty the coop is. This results in a performance score of seven. Space heaters (Figure 7) receive an initial investment score of 12. Some space heaters may make noises that could stress the birds, resulting in a score of four. Space heaters are large appliances, often with multiple power draws for the fan and the heater coils therefore earn a rank of two in the sustainability category.

Figure 7: Space heater

Halogen and incandescent lights are often used to heat chicken coops according to our interviews with local farmers. They perform well in small-enclosed spaces. Larger spaces may require multiple lights. The Producer Pride Brooder lamp received good customer reviews and therefore a score of eight in our decision matrix (amazon.com). The lights are very inexpensive to buy outright and therefore receive a score of 14 for initial investment cost. The light produced by the system may stress the chickens, hence the score of two in the effect on chickens' category. These devices can draw a varying amount of power based on what bulb is selected and therefore earn a rank of three for the sustainability category. These lights are very simple to install resulting in a score of ten for implementation.

Small portable electric heat pads can also be installed to heat coops. They perform very well for very small coops, but the coop at Austin Brothers Valley Farm would require multiple, giving a performance ranking of seven. They are $40 and therefore were given a score of 12 in initial investment. They are highly ranked amongst what we can assume are hobby chicken farmers from reviews on Amazon and have no side effect on chickens, thus earning a full score of five in that category. Electric Panel heaters (Figure 8) may consume smaller amounts of energy but do not dissipate the heat as well according to the reviews and therefore earn a score of three in the sustainability category. They need to be fixed into the coop so are a little harder to implement. All the ratings were confirmed by a customer, "My baby chicks love it."; "They peck at it but it is hard plastic and their little beaks can't penetrate it. It does not overheat. It just puts out enough warmth so the babies can sleep on it and not be too hot. They come to it when they are cold and move away when they are warm enough. I love it too!" (walmart, 2016).

Figure 8: Heat pad

Heat lamps can be made with incandescent or ceramic bulbs. Ceramic bulbs were assessed here because the halogen light assessment included incandescent light bulbs. Ceramic bulbs are typically used in reptile cages but could be used in coops. Because they aren't designed for heating larger areas it receives a performance rank of eight. The bulb and the fixture are more expensive than the standard halogen or incandescent bulb, earning it a rank of 13 for initial investment category. This device may get very hot resulting in potentially burning the birds, thus earning a score of three for effect on chickens. The score can be reflected from the concerned review of a customer, “I was using a hanging 175 watts (sic) metal lamp and was not happy with the heat distribution. It was also a potential fire hazard” (walmart, 2016). The ceramic bulb (Figure 9) consumes similar energy amounts as the incandescent bulb, and therefore earns a three in the sustainability category. It is very easy to implement; and therefore, earned a rank of ten for that category.

Figure 9: Ceramic heat emitter

The heating panel uses the least amount of energy while the space heater would use the most. This is simply based on the wattage of both devices. The most effective device in this case would be the halogen or incandescent light bulb. These are frequently used, very inexpensive to purchase, and perform very well according to reviews on Amazon. Part of the key of this device is its inexpensive replacement bulb that helps keep operating costs down.

c. Dehumidifier

The dehumidifying systems analyzed included one electric and one non-electric unit. The non-electric unit was selected to conserve energy while the electric dehumidifiers are more common. The electric system analyzed was the Gurin DHMD-210 Electric Compact Dehumidifier, a system meant for small spaces that collects moisture in an emptiable chamber. The non-electric system is a desiccant-based sealed unit that absorbs moisture. The non-electric dehumidifier received the highest score out of the decision matrix featured below (Table 4).

Table 4: Dehumidifier decision matrix

	Performance	Effect on Chickens	Difficulty of Implementation	Initial Investment Cost	Energy Efficiency	Operation Cost	Sustainability	Total Score:
Electric	7	2	8	5	8	12	4	**46**
Non - electric	8	5	10	13	9	14	5	**64**

The dehumidifying systems analyzed included one electric and one non-electric unit. The non-electric unit was selected to conserve energy while the electric dehumidifiers are more common. The electric system analyzed was the Gurin DHMD-210 Electric Compact Dehumidifier (Figure 10), a system meant for small spaces that collects moisture in an emptiable chamber. The non-electric system is a desiccant-based sealed unit that absorbs moisture.

Based on user reviews the electric system was given a performance rating of seven (amazon.com, 2016). Initial investment costs are high, around $80, which is why it received a low score of five. For effect on chickens, the system received a score of two, because though the system operates quietly, it will impede on the chickens' space, and they could potentially damage it. The electric system is easy to install, giving it a score of eight in that category. The electric system is relatively energy efficient, as it only requires 22.5 watts. This product resulted in its energy efficiency score of eight. The system received a 12 for operation costs because the high-energy efficiency of the system leads to a cost of $8.61 per year. Overall, this product receives a sustainability score of four.

Figure 10: Electric dehumidifier

The non-electric system (Figure 11) must be renewed every three to four weeks by light charging (the unit must be dried out by plugging it into a wall socket), but lasts up to ten years. The performance score, similarly based on user reviews, was eight (amazon.com, 2016). Initial investment cost scored a 13, because at just below $20 the system is relatively cheap, especially taking into account that it will need to be replaced likely less frequently than an electric system. For effect on chickens the system scored a five, because though desiccant by itself can be harmful because of their use of cobalt chloride, a colorant, this dehumidifier is a non-toxic spill proof system eliminates any potential risks to the chickens (CDC, 2015). Additionally, the system is so small and light that it can easily be placed out of the way where it cannot disrupt the chickens. For difficulty of implementation the system received a ten because it simply needs to be taken out of the box and placed in the coop. The non-electric system is almost 100% efficient because it uses little energy (just negligible time spent renewing every few weeks). The system scored a nine for this efficiency. Operation costs score equally well at 14, because the system only uses six to eight hours of very low wattage energy every three to four weeks to heat up the inner coil and dry the desiccant. For overall sustainability, the system scored a five, and a total score of 64. Therefore, the non-electric dehumidifier was our proposed system.

Figure 11: Non-electric Dehumidifier

D. Watering System

The sponsor requires an anti-freezing water feeding system that provides water for the chickens for one day, which means it needs to contain ten gallons of water. Researched anti-freezing water feeding systems were divided into four basic systems: insulated heated tank, insulated heated base, water pump tank, and water gravity. The decision matrix below (Table 5) shows the scores of the four systems with following determination. For further details see Appendix F.

Table 5: Water system decision matrix

	Performance	Effect on Chickens	Difficulty of Implementation	Initial Investment Cost	Energy Efficiency	Operation Cost	Sustainability	Total Score:
Insulated Heated Base	10	2	10	0	0	0	2	**24**
Water Pump	2	5	5	6	8	10	4	**40**
Water Gravity System	3	5	1	15	10	2	5	**41**
Insulated Water Tank	8	5	5	10	5	7	3	**43**

The insulated heated base consists two water feeders, five gallons each, with two heated bases and a thermostatically controlled outlet. As the water is directly heated from the base of the feeder with 125 watts; this system gets a 10 for performance. However, it costs $150 to implement this system, which gives it a zero in investment cost. As chickens have high water demand, they will mainly surround the water feeder with the heater base (Figure 12). Adding to that, the heat sources are exposed to air, which has a high possibility to burn the chickens. As a result, it was rated two for effects on chicken. Contrasting to that, this system can be installed by simply putting the feeder on the base, and that makes it rated ten out of ten for implementation.

The insulated heated base requires 125 watts, so it receives a zero for energy efficient. The annual winter cost to operate them is about $50 that makes it a zero in operation cost. With a requirement of 125 watts to operate, the bases release more energy; therefore, it is rated two over five in sustainability.

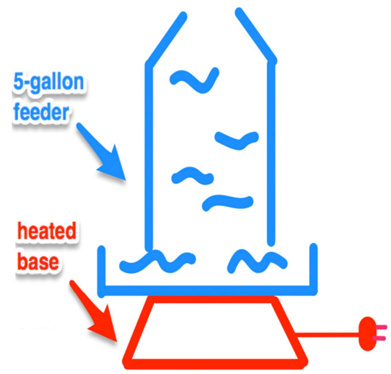

Figure 12: Heated base setup[2] (left) and Heated base[3] (right)

The water pump tank includes a pump, a thermostatically controlled outlet, chicken nipples, a ten-gallon tank, 10 ft. 2'' pipe with insulation for both tank and pipe (Figure 13). It is rated as two for performance because it can only keep the water unfrozen but not heated for the chickens. The cost of this system is around $90, so the score for initial investment cost is six. It is shown to have no impacts on chickens, and so it receives a score of five for effects on chickens. However, the water pump tank is ranked five for difficulty in implementation as it requires extra tools, skills and a drawing before installation. The water pump tank, which needs only four watts to operate, makes it an eight in energy efficiency and a four out of five in sustainability. For operation costs, the water pump is rated highest with ten because it requires only $10 per winter. The pumps only require four watts for operation.

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[2] (Tan, 2017)
[3] (ruralking, 2016)

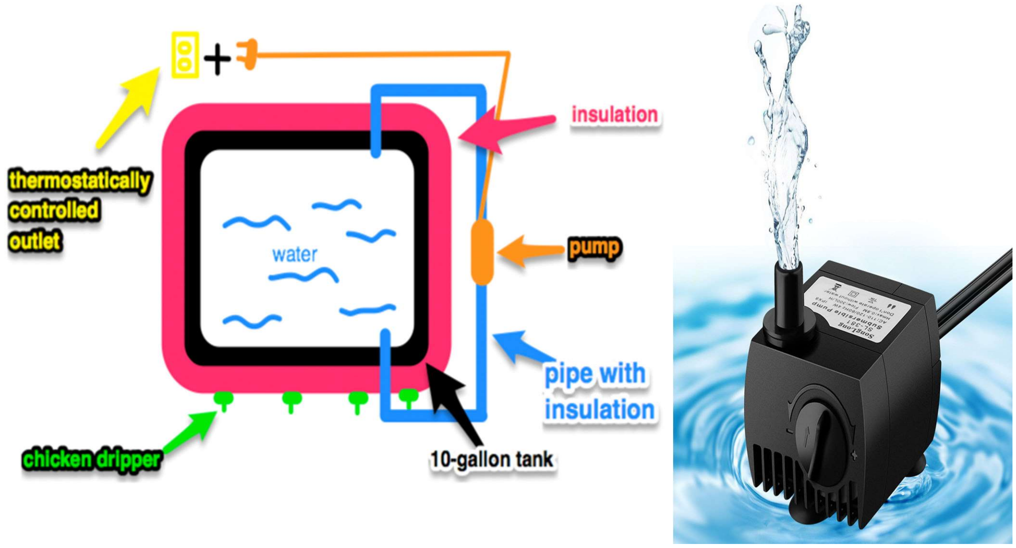


Figure 13: Insulated pump tank setup[4] (left) and Pump[5] (right)

The gravity-based system needs a bucket, pipe, and a hose to provide continuous water flow. It is considered a three because it is not completely protected from freezing; there might be a thin, breakable layer of ice on the surface in very cold conditions. According to the simple materials listed above, the gravity water feeder is the most economical with a capital price under $15. Therefore, it is rated 15 for investment cost. No effects on the chickens were found, so it is ranked five for effects on chicken. On the other hand, this system is required to have a hose plumbed uphill from the bucket, which requires certain geographical conditions. Therefore, a score of one is given in difficulty in implementation. The gravity water tank (Figure 14) does not require electricity to function. As the result, this product receives a ten in energy efficiency. The annual winter cost to operate it is about $50 due to the continuous flow of water. However, this extra water can be reused for other purposes. As a result, the water gravity tank has a score of

[4] (Tan, 2017)
[5] (amazon.com, 2016)

two for operation cost. The gravity system is rated with five in sustainability because there is no energy release.

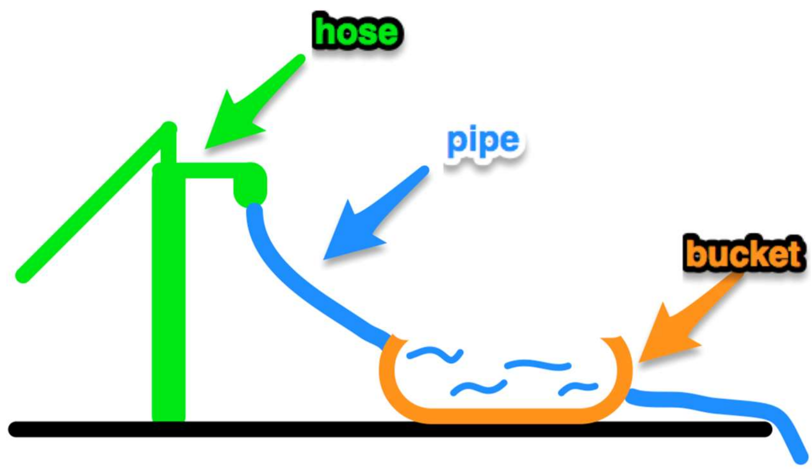


Figure 14: Gravity System[6]

The insulated heated tank requires a ten-gallon tank, a heater, chicken nipples, a thermostatically controlled outlet (35-45 °F), and insulation for the tank (Figure 15). The heater prevents freezing and rated an eight, based on user reviews. (amazon.com, 2016). Based on the cost in Appendix F, the insulated heated tank has the second lowest cost with about $60, so it is rated 10 for initial investment. Based on the setup and data from the manufacturer, the system should not have any negative effects on the chickens; therefore, it ranked a five for the effects on chickens' category. To install the insulated heated tank, extra tools are required, and a drawing is necessary before implementation, so that its score is five. When making the design, our team does not recommend attaching the chicken drippers to pipelines because the cold weather will freeze the fittings of the pipe, which will lead to leaking in the coop. For example, a farmer using

[6] (Tan, 2017)

the same concept designed his water system, and he reviewed, "the heater kept the water on the inside of course from freezing that was fine but it just didn't transfer enough heat out into the pipe portion of this to keep this from freezing even with the insulation on there" (SSLFamilyDad, 2016). In terms of energy efficiency, the heater in the insulated heated tank operates at 50 watts, which is a large amount of electricity. This makes it a five in the category. It would cost about $18 for an insulated heated tank to operate in the winter and this is rated as seven in operation cost. The insulated heat base has a heater at 50 watts, which gives it a score of three for sustainability. Finally, a former user of this concept concluded about this type of water system, "I think it is a great concept. I think that with a little modification, this could be great" (SSLFamilyDad, 2016).

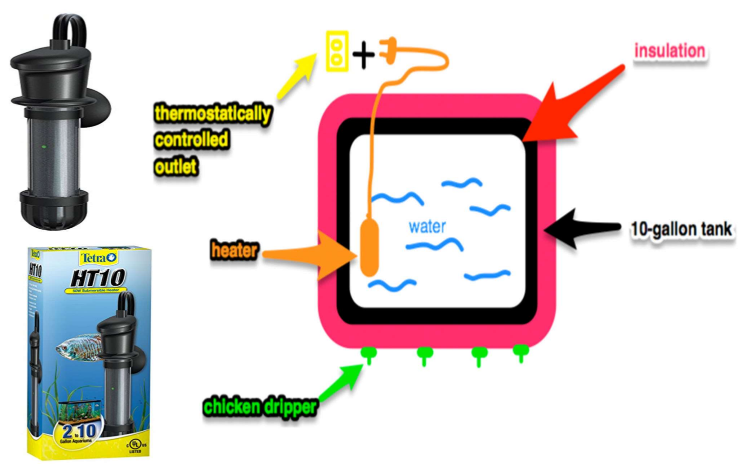


Figure 15: Heater[7] (left) and Insulated heated tank setup[8] (right)

[7] (amazon.com, 2016)
[8] (Tan, 2017)

4.4 Analyze sustainable energy production to power heating, lighting, and humidity systems and energy storage methods

a. Consumption at Austin Brothers Farm

The initial conditions of heating and lighting system at Austin Brothers Valley Farm were analyzed by considering key variables such as power draw and time operation per day. Descriptions of electrical appliances used in the coop and the electrical provider's rates were used to calculate the farm's energy consumption and electrical operating costs. There are two main electrical appliances in the farm's current setup. There is a 40-watt incandescent light and a five-watt electric fence. If the light is on 16 hours a day for every day of the year the device will use 233.6 kilowatt-hours. This equates to a cost of $30.60 a year. The electric fence consumes 43.8 kilowatt-hours a year when run all day every day, at a cost of $5.74. Electricity in MA comes from two carbon-emitting sources: coal and natural gas. This electricity reaches the farm by travelling down transmission lines, which have their own inefficiencies. When these factors are considered, the total carbon emissions from the farm's electric consumption is 242.75 lbs. of CO_2. The emissions rate is small due to the size of the system. However, one goal of this project was to reduce or limit the emissions, thus increasing the sustainability of the farm. This number reflects the emissions associated with energy use in operating the coop only, not any of the farms other operations. All variables and calculations used to determine the results above can be located in Appendix D.

b. Feasibility of renewable energy storage and production methods.

Due to the very low annual energy costs (approximately $36.34) and the high investment cost of most suitable energy sources on the market, a long payback time will be expected with the implementation of any alternative energy resource. A full analysis below determines the exact figures of size of a possible system, cost of a possible system, and payback time of the system were it to be implemented. Small annual profit margins also hinder the installation of an alternative energy resource as smaller profits contribute to longer pay back times. Energy consumption can still be reduced without installing an energy storage/production system while increasing egg production, as there will be less energy used in the installed system compared to what the sponsor had previously.

c. Solar energy

According to the U.S. Department of Energy, the solar energy potential of Belchertown, MA, where our sponsor is located, is approximately 402 watt-hours per square foot per day (U.S. Department of Energy, 2016). See Figure 16 for details. The proposed system requires 2,528 watt-hours per day. Assuming there is approximately eight hours of sunlight per day in the winter, the solar panels will need to supply 316 watts and cover approximately 6.5 square feet, which is a moderately large sized solar panel, thus increasing the cost.

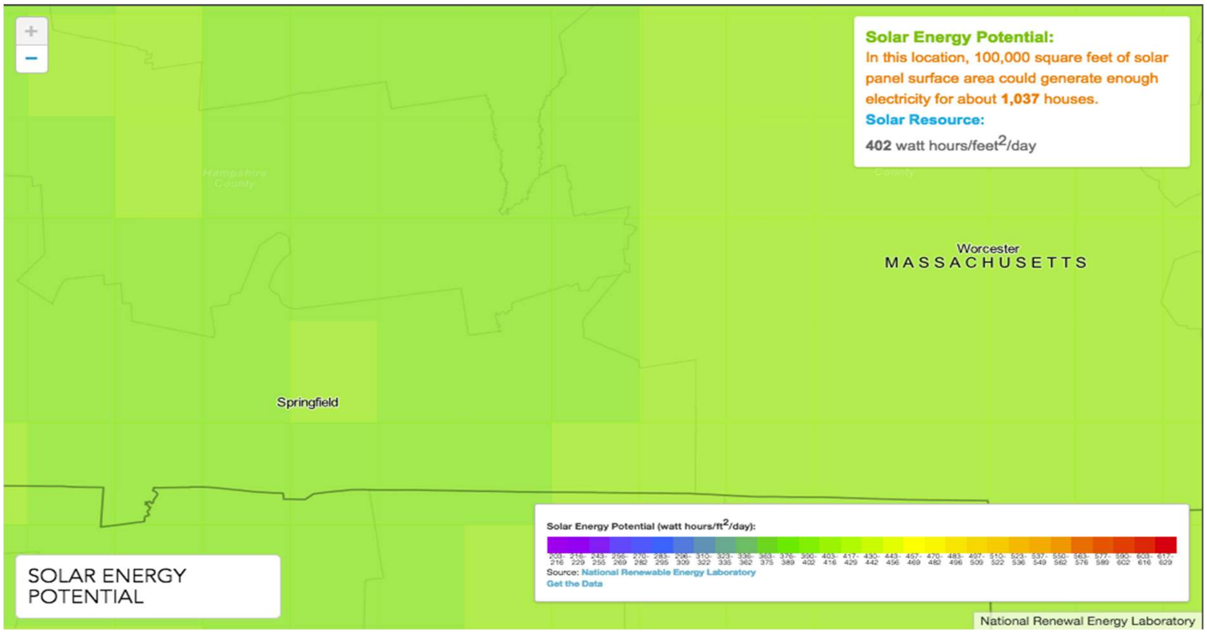
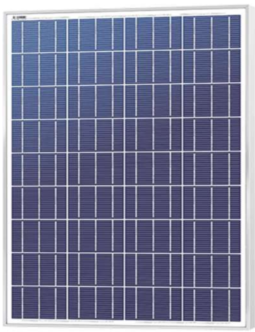
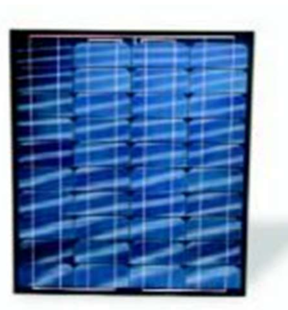


Figure 16: Map showing the potential amount of solar energy that could be acquired from a solar panel located in Palmer, MA where Austin Brother Valley Farms is[9]

Aside from the panels themselves, solar powered systems require many other components such as an inverter, a battery, an optimizer, etc. To ensure compatibility of all the components it would be best if a full solar kit were purchased. Some potential kits were analyzed below using a decision matrix. The categories used for this matrix are the initial price, output of the system, and payback time. The table determines the feasibility of solar systems to operate our recommended systems. Due to the long-term payback time, the team determined that a solar system is not worth the investment at this time but was still was proposed to our sponsor in case they did not mind the investment.

9 (Energy.gov)

Table 6: Solar Power System decision matrix

Solar Panel	Initial Price	Output	Pay off Time	Sources
 "King of the Road RV Solar kit"	$1,464	400W	57 years	(Richard, 2005)
 "DIY Solar kit"	$600	800W	24 years	(amazon.com, 2016)
 "Windy Nation Complete 400 watt Kit"	$805	400W	32 years	(amazon.com, 2016)

d. Wind energy

Another renewable energy source considered for this application was wind power. According to the US Dept. of Energy, there is only 4 m/s (8.9 mph) wind available at 80 meters in the air for Belchertown MA as shown in Figure 17 below.

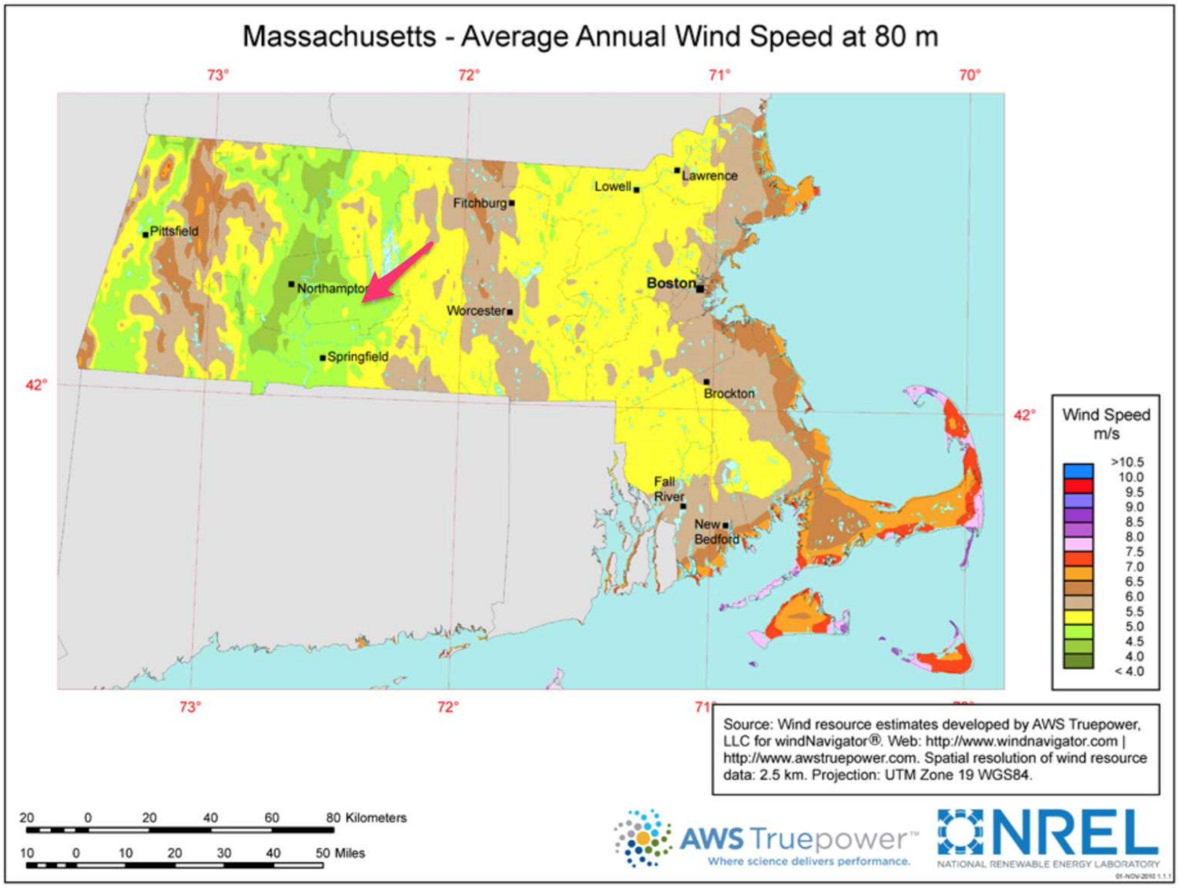


Figure 17: Wind Energy Potential[10]

The U.S. Department of Energy notes that suitable wind conditions are at least 6.5 meters per second wind at a height of 80 meters (U.S. Department of Energy, 2015). The farm's location has an average wind speed below the suitable wind speed for energy production of this form and therefore wind will not be considered for a renewable energy source. As illustrated by the above graphic, much of Massachusetts is below the requisite 6.5 meters per second (21.32 feet per second) to make wind energy effective. Therefore, wind energy on this scale (at least in Massachusetts) is not effective for this application.

[10] (U.S. Department of Energy, 2015)

e. Electric energy from the Grid

Since solar and wind energy are not viable options for Austin Brothers Valley Farm, standard electricity from the grid will be used to power our implemented systems. With the current electric rate in Massachusetts, it is reasonable for the farm to fully operate the system at a low cost. The annual energy cost of the new system is $25.55, 30% less than the cost of existing system ($36.34). Although the implemented system does not run on completely sustainable energy, the implemented system still reduces the CO_2 footprint of Austin Brothers Valley Farm while increasing winter egg production.

5. Recommendations

The implementation of heating, lighting, humidity, and water heating systems are recommended to increase winter egg production in chickens. To build the best potential system, information was gathered from primary literature and interviews with New England farmers.

Potential products were assessed on energy efficiency, performance, initial investment cost, operation cost, effects on chickens, sustainability and difficulty of implementation through the use of a decision matrix. System cost and efficiency were weighed more heavily than the other variables. Additionally, the possibility of reducing reliance on fossil fuels was investigated.

5.1 Temperature

Research has shown that an ambient temperature in the coop between 70 °F and 79 °F is optimal for maximum egg quality. If the temperature goes above this range, it has been shown to induce heat stress in the birds and a reduction in egg weight of up to 3 grams may occur. If the temperature drops below this range, the chickens will not produce as many eggs per day (Tumova et al. 2012). After reviewing a number of heating products on the market, an incandescent/halogen heat lamp is recommended. This product is readily available, inexpensive, extremely easy to install, and bulb power can be selected to tune heat output. Such devices are available at retailers such Tractor Supply Co, or online for around $10. Our energy consumption calculations represented a 75W light bulb. A picture of the recommended system is shown in Figure 18 below.

Figure 18: Brooder Pride heat lamp[11]

5.2 Light

Photostimulation has been shown to influence egg production. This has a large impact on laying hens in northern latitudes where natural sunlight can occur for as little as eight hours per day. Artificial lighting has been shown to increase winter egg production by 50% when utilized to simulate spring/summer light conditions (Dougherty, 1922; Keshavarz, 1998). Furthermore, exposure to light of different colors has been observed to have an effect on egg production. For example, hens exposed to green light produce the highest quality eggs, while hens exposed to red light produces the largest quantity of lower quality eggs (Pyrztak et. al, 1987). Low intensity light of the appropriate wavelength (perceived as color) can have a measurable effect. Out of the products reviewed, a green LED bulb PLT LED-A19-GREEN (1000bulbs.com, 2017) is recommended. This product has a reported 50,000-hour lifetime and costs only $2.38. This LED bulb can be used in a standard socket and is very easy to implement (Figure 19).

[11] (tractorsupply, 2016)

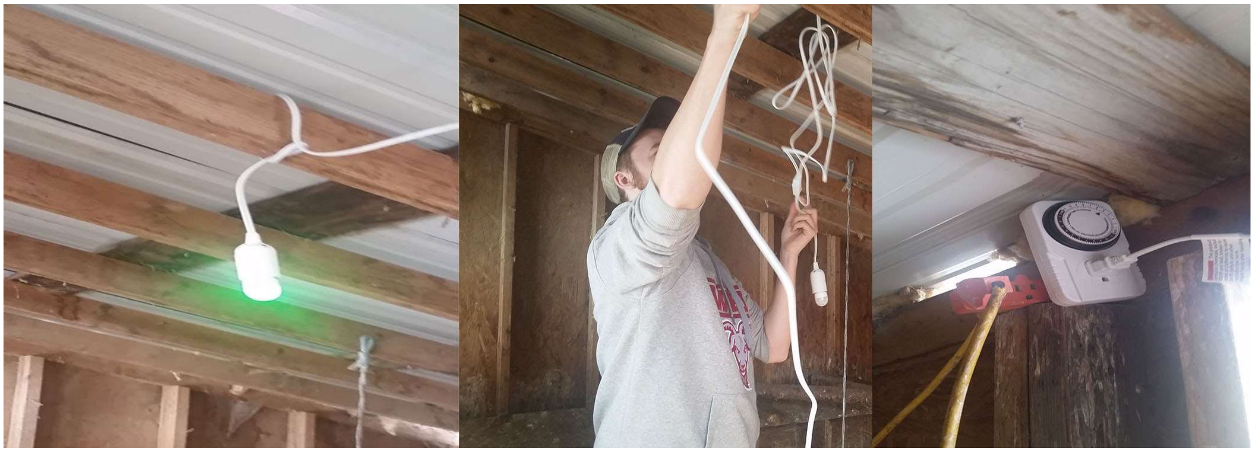


Figure 19: The LED light (left), students install the light (center) and timer (right)

5.3 Drinking Water

To solve the issue of frozen drinking water, four systems were evaluated. Based on this evaluation, the insulated heated water tank is recommended. This system has an initial cost of $58.32, as it requires a 10-gallon tank, a heater, chicken drippers, a thermostatically controlled outlet (35-45 F), and insulation for the tank. With an annual operating cost of $7.86, the tank will keep the water warm in the winter. A diagram of this water system is shown in Figure 20 below.

Figure 20: Insulated heated tank

Table 7: Insulated heated tank materials (amazon.com, 2016)

Material	Initial price
Tank (12 gal)	$19.99
Heater (50 W)	$10.77
Chicken drippers	$2.63
Thermostatically controlled outlet	$12.95
Insulation for tank (R=4)	$11.98
Total	**$58.32**

5.4 Humidity

Talking to other New England farmers during the course of our research lead the team to consider humidity as having a larger impact on egg production than we had originally considered. Primary literature showed that chickens' egg production is increased in ambient humidity (anywhere from 40 to 65%) when compared to high humidity (Biu et. Al, 2012). The ideal range of humidity for hens is between 40% and 55% (Yahav et al., 2010). To address a potential humidity problem, a non-electric dehumidifier, specifically the Eva-dry E-333 Renewable Mini Dehumidifier, is recommended. The desiccant based system is roughly the size of book, easy to implement, and has a low cost of $16.36 for a system that will work for 10 years.

Figure 21: Non-electric dehumidifier[12]

5.5 Renewable Energy

Ultimately, the research has concluded that the most suitable energy source is electrical power coming from a standard wall outlet. As detailed in the results section, we are not recommending solar energy, considering the benefits of the system and the payoff time. If one would prefer a solar system installed for educational or branding purposes, considerations for alternative options such as powering only the light and heater from solar panels, reducing the overall energy consumption and cost of a solar system kit would make the system more feasible. In addition, we are not recommending wind energy as a source of energy, as it is not viable in the sponsor's location. Overall, according the US Department of Energy's wind map, there are relatively few locations that would be able to sustain the necessary wind speeds.

[12] (amazon.com, 2016)

5.6 Summary

In general, our research has shown that a small chicken farming operation would benefit from a green LED bulb, a non-electric dehumidifier, a halogen heat lamp, and a heated water supply. Our sponsor was worried about the potential danger of fires due to the heat lamp and so that was not included in our solution for them. However, we still stand by our recommendation, as heat was determined to be a major factor in increasing chicken egg production. Fire is always a concern with halogen lamps as they can heat up and become very hot. However, there are systems, such as a cage around the lamp, which can make the system safer. If one is too worried about the possibility of a fire, then the group recommends a flat panel heater (Figure 8).

The entire system at Austin Brothers Valley Farm would have a startup cost of $93.89 with annual operating cost of $25.55. As the sponsor concerned about fire hazards from the heating system, the final cost of the system is $79.89 with annual operating cost of $13.76. The energy consumption on the farm using all of the recommended systems installed would be 1,048 watt-hours per day.

5.7 Response from our Sponsor

There are not enough data points to prove definitively that the system works, however, the team and the sponsor feel confident that the system will have benefits. In addition, we recommend that other teams in the future continue to the work in order to evaluate and improve the systems set in place.

The sponsor wrote to us, “Your watering system is great!! No frozen water over the past 2 nights. Stuck my finger in the cooler this afternoon and water was nice and warm.” (M. Austin, personal communication, March 4, 2017). They were especially happy that they did not have to manually thaw out the water for the chickens noting that the water stayed warm during a cold snap. In another email our sponsor wrote, “Water stayed warm all weekend--YEA--we did find that the nipples were frozen yesterday (Sunday) morning. Just had to free them with our fingers.” (M. Austin, personal communication, March 6, 2017). The chickens actually can free the drippers when the temperature rises in the day. The implemented system has made it so that the sponsor does not have to add additional hot water multiple times during the day to unfreeze the water supply for the chickens. Beyond reducing the labor required by our sponsor, water availability have direct effects on lay rates and quality. In freezing conditions, an uninterrupted flow of warm water has been shown to result in consistent egg production rates (Bell, 1998).

6. Conclusion

This project developed a system to help improve egg production on a local farm by optimizing heating, lighting, access to water, and humidity within a chicken coop. Our sponsor was very pleased with our system and saw some immediate benefits with the watering system. Based on our interviews with farming associations and local farmers, we know reduced winter egg production is a widespread and significant issue in New England. To address this issue, we have disseminated physical pamphlets to local farmers markets (roughly 50 pamphlets) and an electronic infographic (Appendix G) that discuss our recommendations in detail. Several organizations including Farm Aid, New England Sustainable Agriculture Research and Education, and New England Food have received our media. This will allow us to reach an audience of over 10,000 people. Future work could look at the application of this system in other communities using regional resources, cultural context, and economic considerations. For example, in more developing countries, reduced seasonal egg production is a problem for subsistence and low-income farmers (Rome, 2003). Increasing production rates could help to improve food security and increase economic opportunities.

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Appendix A – Questions for Sponsors

1. What is the typical rate of egg production for spring and summer months?
2. How many chickens do you currently have?
3. What and when do you feed your chickens?
4. What methods do you currently have in place to maintain egg production rates in the winter?
5. What methods have you considered to increase egg production?

Appendix B– Local Farmers Interview Questions

1. How long have you been farming chickens?
2. What is the size of your flock?
3. Do you notice any seasonal changes in your chickens' health?
4. Can you describe how you raise your chickens? For example do they only stay in a coop? Do they have access to outdoor space?
5. How many eggs does your flock produce on a daily basis in and around peak laying season?
6. How do winter conditions affect your flock's production? How much of a change in production would you estimate you see in the winter (in percent)?
7. How are your profits affected in winter?
8. What changes do you make to the coop and your chicken raising methods the winter? For example do they have reduced access to outside?
9. What methods do you currently use to combat decreased winter egg production?
10. Do you use an artificial light source for your flock? What is the arrangement, color, and intensity of the light?
11. Do you use an artificial heat source for your flock? Describe your heating system (arrangement, temperature).
12. What methods have you previously used? How did those work?

Appendix C– System Designers Interview Questions

1. What kinds of systems do you find yourself designing most often for coops to use to combat decreased winter egg production?
2. What kind of light do you use in the systems you've designed?
3. Where do you locate this heating system in the coop?
4. What kind of heating systems have you designed?
5. How are they organized in the coop?
6. How much energy do your systems require on average?
7. How have you acquired energy for previous designs? Have you used sustainable energy?
8. What do you think is the most viable low impact energy source for winter coop arrangements?

Appendix D– Austin Farms Energy Use Calculations

Table A: Insulation material

	Manufacturer	Name/model	Cost	Thickness	R value
Insulation material	Johns Manville ComfortTherm	N/A	N/A	5 in (r=2.5 in)	13

Table B: electric fence

	Manufacturer	Name/model	Power from measurement	Operation time	Cost
Electric fence	Gallagher	M300	3 J (manufacture data)	24h	$170.18 (amazon) 239.99 (Gallagher)

Table C: Coop dimensions

	Height 1	Height 2	Width	Length	Volume
Coop dimension (living area only)	5.5 ft.	8 ft.	12 ft.	10 ft.	5.5*10*12+1/2*10*12*(8-5.5)= 810 ft^3

Table D: Water information

	Volume	General description
Water feeding	5 gal X 2	Fill half full twice a day

Table E: General egg production

	Peak season	Winter
Daily egg production	42	32 (current)

Table F: Electricity Source and Current Setup Analysis

	Company	$/kWh
Electricity	National grids	13.1 cent

Electricity Calculations:

- Electric Fence:
    - On time: 24 hours / day = 8760 hours/year
        - Number hours/year = 24 hours / day * 365 days/year = 8760 hours/year
    - Power Consumption: 0.005 kW (Restractors.com)
        - 5 W = 0.005 kW
    - Yearly Energy use: 43.8 kWh / year
        - Energy = Power * time = 0.005 kW * 8760 hours / year = 43.8 kWh / year
    - Cost (@13.1 cents/kWh): $5.74 / year
        - Cost ($ / year) = $0.131 /kWh * 43.8 kWh / year = $5.74 / year
- Light:
    - On time: 16 hours / day = 5840 hours / year
        - 16 hours / day * 365 days / year = 5840 hours / year
    - Power Consumption: 0.04 kW
        - 40W = 0.04 kW
    - Yearly Energy use: 233.6 kWh / year
        - 0.04 kW * 5840 hours / year = 233.6 kWh / year
    - Cost (@13.1 cents/kWh): $30.60 / year
        - $0.131 / kWh * 233.6 kWh / year = $30.60 / year

Total yearly electricity cost: $30.60/year + $5.74 / year = $36.34 / year

CO2 Emissions:

Electricity in MA comes from the following sources in the following proportions:
-64% Natural Gas
-7% Coal
- The rest comes from nuclear and renewable energy sources (such as hydro)
(US Energy Information Administration, 2016)

Coal fired power plants produce about 2.16 lbs of CO2 per kwh of electricity
Natural Gas fired power plants produce 1.22 lbs of C02 per kwh
(US Energy Information Administration, 2016)

Energy Transmission lines lose 8-15% energy transmitting power between the plant and the consumer. Assume about 11.5% as a media value for this range
(Schneider Electric 2007)

This means that even though the farm only consumes 233.6 kwh annually in actuality another 8-15% of this value is lost in transmission so:

233.6 kwh * .115 = 26.84 kwh

26.84 kwh + 233.6 kwh = 260.464 kwh

The farm actually uses 260.464 kwh, 64% of this comes from natural gas so calculating the carbon emissions goes as follows:

260.464 kwh * .64% = 166.6969 kwh

166.6969 kwh * 1.22 lbCO2/kwh = 203.37 lbs CO2

7% of the energy is from coal calculating its carbon emissions goes as follows:

260.464 kwh * .07 = 18.232 kwh

18.232 kwh * 2.16 lbsCO2/kwh = 39.38 lbs kwh

The total carbon emission is:

203.37 + 39.38 = 242.75 lbs CO2

This figure is based on electrical consumption only and does not include emissions used to produce other goods essential to raising chickens such as feed, water, manufacturing of packaging etc.

Appendix E– Potential System Energy Cost Calculations

Example energy calculation using fluorescent bulb information:
(13 W)(1 kW / 1000 W)($0.131 / kWh)(8 hours/day)(150 days/year) = $2.04 / year

Water calculation:
(.1 gpm)(60 min/ 1 hour)($6.551 / 1000 gal)(8 hours/day)(150 days/year) = $47.17 / year

System	Watts	Amount of Time Used	Total
Fluorescent Light	13	8 hours/day, 150 days/year	$2.04/year
Halogen Light	50	8 hours/day, 150 days/year	$7.86/year
LED	1	8 hours/day, 150 days/year	$0.16/year
Incandescent Light	300	8 hours/day, 150 days/year	$47.16/year
Space Heater	800	8 hours/day, 150 days/year	$125.76/year
Heat Lamp	100	8 hours/day, 150 days/year	$15.72/year
Flat Panel Heater	40	8 hours/day, 150 days/year	$6.29/year
Tank heater	50	8 hours/day, 150 days/year	$6.29/year
Two heater base	125 * 2	8 hours/day, 150 days/year	$39.3/year
Tank pump	4	8 hours/day, 150 days/year	$.63/year
10 Gallons of water		150 days/year	$9.83/year
Electric dehumidifier	22.5	8 hours/day, 365 days/year	$8.61/year

Appendix F– Water System Initial Investment Cost

	Basic requirement	Cost	Sources
Insulated heated tank	Tank (10 gal)	$19.99	(amazon.com, 2016)
	Heater (50 W)	$10.77	(amazon.com, 2016)
	Chicken nipples	$2.63	(amazon.com, 2016)
	Thermostatically Controlled Outlet	$12.95	(amazon.com, 2016)
	Insulation for tank (R=4)	$11.98	(amazon.com, 2016)
	Total	**$58.32**	
Insulated heated base	Water feeder X2 (5gal)	$74.24	(walmart, 2016)
	Thermostatically Controlled Outlet	$12.95	(amazon.com, 2016)
	Heated base (125 W) X2	$59.96	(Rural King, 2016)
	Total	**$147.15**	
Water pump	Tank	$19.99	(amazon.com, 2016)
	2" pipe schedule 40	$7.7	(The Home Depot, 2016)
	Insulation for pipe	$11.96	(walmart, 2016)
	Insulation for tank	$11.98	(amazon.com, 2016)
	Pump (4 W)	$8.49	(amazon.com, 2016)
	Thermostatically Controlled Outlet	$12.95	(amazon.com, 2016)
	Chicken nipples	$2.63	(amazon.com, 2016)
	Tee X4	$12.72	(The Home Depot, 2016)
	Total	**$88.42**	
Water gravity	Bucket	$5	(amazon.com, 2016)
	2" pipe schedule 40	$7.7	(The Home Depot, 2016)
	Total	**$12.7**	

Appendix G– Infographic