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CHARACTERIZING AND MODELING THE ENERGY REQUIREMENTS OF AN INDUSTRIAL AQUAPONICS FACILITY

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Abstract

The Efficient Aquaponics Sustainability Effort (EASE) is focusing on a 30,000 square foot aquaponics facility located in Kenosha, Wisconsin called Natural Green Farms (NGF). At full production, energy expenses to run the facility will be approximately 30,000 USD and an estimated 15,000 lbs. of fish (tilapia) and 51,200 heads of lettuce will be produced per month. The goal of EASE is to improve the profitability and reduce the environmental impact of the business by reducing the energy requirement of the facility while maintaining the fish and lettuce production. The existing energy systems as well as new design ideas will be investigated and analyzed.

The objective of the EASE's project is to propose an efficient and cost-effective energy system which will supplement or replace NGF's current energy supply. The design shall meet all heating, cooling, airflow, water flow, and humidity requirements set forth by the owner of NGF. Major constraints to the project include using the existing structure and equipment, maintaining the temperatures of the rooms in the given ranges, and maintaining the given humidity levels in the lettuce area. The desired levels of nutrient concentrations for the fish and plants were provided by the owner of NGF, in addition to the temperature and humidity requirements of the fish and plants' respective areas.

The EASE team characterized the baseline energy usage of the facility, conducted feasibility studies on all potential design alternatives, and validated the final system model. Characterization of the NGF facility baseline energy usage was performed for each component of the building. The energy usage of each piece of equipment, derived with engineering methods, was used in determining the feasibility of each of the design concepts. Design concepts included integrating renewable energy technologies into the system, like solar photovoltaics, solar thermal, and wind power. Implementation of electrolysis and combined heat and power were also explored.

Introduction

Large-scale aquaponics offers financial, environmental, and health benefits that traditional food sources simply cannot. Because aquaponics is a process that takes place indoors, the yield is unaffected by extreme weather, such as drought or flooding. Indoor conditions are controlled, so a facility could also grow other plants that are atypical to the climate where the facility is located. The food is consumed locally, so it is always fresh and consumes less energy from transportation. The produce is also herbicide and pesticide free. By taking advantage of the symbiotic relationship between lettuce and fish, energy and water are conserved in their farming. The water from the fish is rich in ammonia, which is converted to nitrates through aerobic digestion in biofilters. The nitrate enriched water then travels to the lettuce which grows in water. The lettuce purifies the water and then it is sent back to the fish tanks, avoiding wastewater. The layout of Natural Green Farms' facility also uses space efficiently when compared to conventional farming methods. At Natural Green Farms, the facility farms fish on the lower level and grows lettuce in racks on the upper level. The stacking of the fish and lettuce maximizes the use of the facility's footprint. Finally, aquaponics reduces the carbon emissions of producing food as compared to traditional farming. By growing food in a controlled environment and reusing resources, less energy is required and thus carbon emissions are also reduced. At smaller scales, aquaponics is difficult to run and struggles to be profitable. In running a large-scale facility, the likelihood increases of an aquaponics operation becoming profitable.

Facility Description

Natural Green Farms is a 30,000 square foot aquaponics facility located in Kenosha, Wisconsin. The facility was built with the idea of being able to produce food in an efficient and environmentally friendly way. At full production, 15,000 pounds of tilapia and 51,200 heads of lettuce are predicted to be sold every four weeks. Figure 1 shows a modeled 3D cross section view of the building.

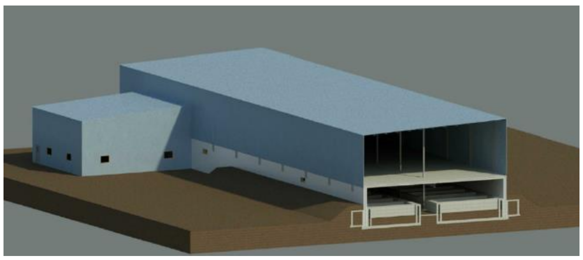

Figure 1: Rendering of Facility

Natural Green Farms is in its initial profit phases. As of April, 2017, NGF has sold their first fish yields and are ramping up production to full capacity. Once the fish are at full production, Natural Green Farms will introduce lettuce crops into the operation. Once the facility is at full operation, it will be a model for future urban aquaponics facilities, providing food in areas where fresh food is not available, often referred to as food deserts.

Existing Component Descriptions

The following components were modeled in order to determine a baseline for the existing operation:

Boiler

Natural Green Farms owns an Evergreen 399 high efficiency condensing boiler. The boiler runs on natural gas, has a heating capacity of 383,000 BTU/hr, and boasts an efficiency of 96.5%. The water must be kept at around 80 F and analysis of water heating needs has confirmed that this boiler will be sufficient for the building when running at full production.

Lights

The grow lighting for the lettuce will be the largest contribution to the heat being added to the lettuce room. The lights will be blue LED grow lights. The rated power for these lights will be 101 kW.

Blowers and Underground Pipelines

The type of blower being used at Natural Green Farms is an airfoil centrifugal fan rated at 5hp. These types of blowers typically have a peak efficiency range between 79-83% [1]. NGF has two of these blowers. They are not currently hooked up, but they will be placed in parallel in a separate room from the fish room on the east side of the building. They will draw up the hot and moist air from the fish room through underground pipelines (sets of 3 and 4 pipelines on the south and north side of the building, respectively) and will then be blown into the lettuce room after being conditioned in a dehumidifier (which is a proposed system to be put in place. See Airflow section). In order to determine if the blowers are sized appropriately, a duct analysis (taking into account the pipelines and future duct implants) was done to determine the static pressure the blowers would need to overcome, and what their corresponding flowrate would be at that point. Based on the analysis, it was determined that the blowers should be able to handle the required airflow rate discussed in the Airflow section.

Pumps

There are five water circuits in the building, with each circuit consisting of two parallel pumps, two parallel hydrocyclone filters, two biofilters, six fish rearing tanks, and a pump reserve tank. Ten 3 hp Pentair Aquatic Eco-Systems H3-Plus Series pumps are used to circulate the water in the building and are located in the pump room that is positioned on the south side of the building. An analysis of the water circuit determined that the existing pumps are insufficient. It is recommended that five 30 hp Flowserve D800 Series pumps be purchased to deliver the 550 gpm necessary to provide the recommended 1 water change per hour for all fish tanks [2].

Compressor

A Quincy QGV-75 rotary screw air compressor is currently being used by NGF. The compressor is expected to provide sufficient amounts of oxygen to the fish and biofilters by maintaining the water's oxygen level at 6.5 ppm. The compressor is located inside of the pump room while the air tanks are located outside of the building on the south side. An analysis of the compressor and air tanks confirm that the desired oxygen levels in the water will be maintained.

Building Heat Transfer

One of the major influences that goes into characterizing the energy flows of the system is the effects of weather conditions on the facility. Heat transfer analysis was vital in estimating the heating and cooling loads the dehumidifier would be experiencing. In order to accomplish this, heat transfer models were built in MATLAB for the various composite surfaces within the facility. Each of these models require relevant inputs such as the outside ambient temperature, fish room temperature, solar radiation, and sky temperature. The models were designed such that all types of day conditions occurring throughout the year could be analyzed.

Researched Energy Supply Alternatives

Energy supply alternatives were investigated to reduce the energy consumption and carbon footprint of Natural Green Farms. The renewable energy technologies analyzed include solar photovoltaics, solar thermal water heating, and wind. In addition, combined heat and power and electrolysis were explored.

The addition of a natural gas fired combined heat and power generator was investigated for NGF. Due to the fact that the boiler is very efficient and is sufficient in supplying heated water for the building, combined heat and power was not found to be a feasible investment. For the same reason, solar thermal water heating was determined to not be feasible as well. The use of electrolysis to produce pure hydrogen and oxygen gasses was explored due to Natural Green Farm's unique need for oxygen for the fish and biofilters. Electrolysis was deemed infeasible based on the fact that there were no cost savings on the electricity, so it would never pay back the large initial investment.

Solar photovoltaics was found to be a feasible option for investment. The roof of Natural Green Farms is south facing, but only has a tilt angle of about two degrees. Feasibility studies were performed for a larger array of panels lying flat on the roof and for a smaller array which would be racked. Based on solar irradiance data for Kenosha, Wisconsin, the payback period for either of the two systems would be about nine years.

Wind turbines were also investigated and found to be a feasible option for a renewable energy investment. Analysis was performed for a 5 kW turbine with a 10 m hub height and a 20 kW turbine with a 30 m hub height as can be seen in Table 1. The 20 kW turbine had a capacity factor of 20% and a payback period of only 5 years as shown in Table 2.

Both solar PV and wind were found to be feasible investments for NGF. They are both renewable energy options which provides PR value, especially to an establishment called Natural Green Farms. Due to the short payback period and the availability of land on the farm, wind was determined to be the best option for Natural Green Farms.

Table 1: 20kW Turbine Wind Analysis

Bin Num.	Average = 5.4 m/s Wind Speed (m/s) Min	Max	Rayleigh Prob.	Hours/year	V-avg. (m/s)	20 kW Turbine P-out (kW)	Energy Output (kwh/year)
1	0	0	0.0000	0	0.0	0.0	0
2	0	1	0.0266	233	0.5	0.0	0
3	1	2	0.0756	662	1.5	0.0	0
4	2	3	0.1131	991	2.5	0.0	0
5	3	4	0.1348	1181	3.5	0.0	0
6	4	5	0.1399	1226	4.5	1.0	1170
7	5	6	0.1308	1146	5.5	2.2	2532
8	6	7	0.1120	981	6.5	4.0	3921
9	7	8	0.0888	778	7.5	6.5	5041
10	8	9	0.0655	574	8.5	10.0	5764
11	9	10	0.0452	396	9.5	14.5	5722
12	10	11	0.0292	256	10.5	18.8	4800
13	11	12	0.0177	155	11.5	21.6	3357
14	12	13	0.0101	89	12.5	22.7	2011
15	13	14	0.0055	48	13.5	23.0	1098
16	14	15	0.0028	24	14.5	23.1	558
17	15	16	0.0013	12	15.5	23.0	266
18	16	And Above	0.0010	9	20.0	21.0	186
						Total	36426

Table 2: Turbine Payback Period

Turbine	Price	Energy Output [kwh/year]	Money Saved per year	Payback Period [years]	Capacity Factor
5kW	$8,750	5229	$749	12	11%
20kW	$26,546	36426	$5,217	5	20%

Airflow Design

It is well known that humans prefer specific atmospheric conditions, but plants, too, have specific atmospheric requirements. In addition to the temperature and pressure of the atmosphere, low humidity is one of the vital factors that affects the growth and comfort of the plants. Table 3 shows the optimum range of specific water and air parameters that are needed for both the fish and the lettuce to obtain the optimum yield.

Table 3: Optimum range of parameters [3, 4, 5, 6].

Parameter	Fish (Tilapia)	Plant (Lettuce)
Air temperature	80-85°F	62-82°F (Day) 37-54°F (Night)
Relative humidity	90-100%	60-65%
CO_2 concentration in air	Low	High
Raising Tank water temperature	80-86°F	64-78°F
PH level	6-8	5.8-6.2
Dissolved oxygen (DO)	> 5 ppm	> 4 ppm
Dissolved CO_2 concentration	< 60 mg/L	-
Biofilter temperature	-	77-86°F
Protein in feed	28-32%	-
Ammonia-Nitrogen in water	< 2 mg/L	-
Nitrite level in water	< 1 mg/L	-
Growth time	9-10 months	24-32 days

The biggest concern of Natural Green Farms is to maintain the humidity and temperature in the lettuce room. For the lettuce, it is necessary to sustain both the water and the air quality as mentioned in Table 5. However, for the fish, the water quality is more crucial than that of the air.

To capitalize on the benefits of greater carbon dioxide concentrations, air is blown from the fish room to the lettuce room. Unfortunately, this carbon dioxide-rich air is also high in temperature and humidity. Therefore, one of the main objectives of this project was to provide a design which can maintain the desired 65% relative humidity and 65°F.

To achieve the desired conditions, existing infrastructure of NGF includes an underground pipeline system to drop humidity and the temperature of the air leaving the fish room before it enters the lettuce room. The pipeline system is depicted in the complete system diagram in Figure 2. All relevant heat transfer to and from each room is detailed as well.

Outside atmospheric air is compressed into four air tanks that are connected in series. The air tanks provide air to the biofilter towers for the nitrification process and also to the fish tanks to give the fish oxygen. In order to provide enough oxygen to the fish, the total mass flow rate of air needed from the air tanks to the fish tanks and biofilters is 14.93 kg/min.

Generally, 15% of the supplied oxygen dissolves in the water that is held by the fish tank, and the remaining is released into the fish area, along with the CO_2 released by the fish and evaporated water. The hot and moist air is drawn from the fish area through the underground pipelines using two blowers that are located in a separate room. The underground pipelines are encased in concrete and located underneath the water storage tanks to take advantage of the

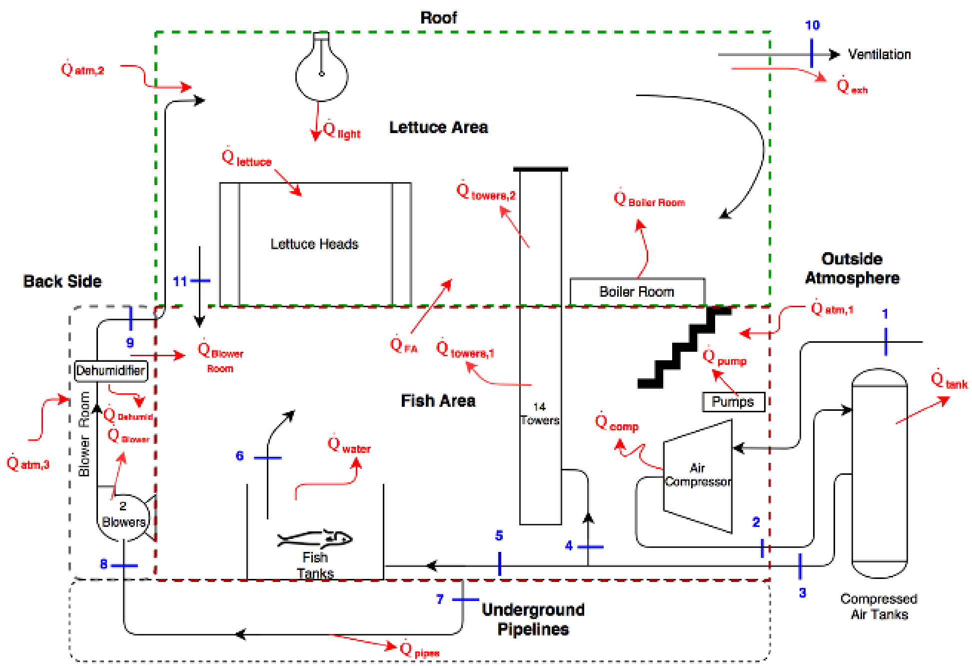

Figure 2: NGF schematic of NGF with heat flow

geothermal heat transfer between the hot air and the cool earth.

In order to determine if the pipelines would be sufficient to condense all the evaporated water picked up by the fish tanks and the decrease in temperature, a MATLAB code was written. The results showed that the pipeline would lower the temperature to nearly 55°F in most cases, but not much water would condense. As such, more conditioning is needed.

To remedy this, it is proposed that the facility incorporate a dehumidifier system that will condition the air coming from the pipelines such that the lettuce room air will be maintained at 65% relative humidity and 65°F. If the lettuce room is not generating enough heat (such as when the lights are off), then the system will first cool and condense the pipeline outlet air until the desired absolute humidity for the lettuce room is reached. Next, the air will be reheated such that enough heat flow is provided to compensate for the lack of heat being produced within the lettuce room. If the lettuce room is generating excess heat (such as when the lights are on), the dehumidifier system will supercool the air such that enough heat will be removed in order for the excess energy in the lettuce room to automatically reheat the air to the desired 65°F temperature. In order to compensate for the decreased humidity ratio, the client can uncover the biofilters to add more water vapor to the room.

According to ASHRAE standards, factory buildings such as this aquaponics facility need an air change rate of at least 2. Based on the volume of the lettuce room, the largest room in the facility, the airflow required is 9200 CFM. As the blowers are running in parallel, the required flowrate for each of them is 4600 CFM. Additionally, ASHRAE standards also dictate that an outside air infiltration rate of 15-35 CFM is required per person. The maximum number of people in the facility at any given time will be 5, so the system was designed accordingly. This flowrate can be achieved by maintaining a 120 CFM flowrate from the compressed air tanks to the fish tanks in order to compensate for the 15% reduced oxygenated air coming from the fish tanks.

Steady-State Simulation Results

The intent of creating a Simulink model was to estimate the amount of electricity and natural gas required to maintain the desired space conditions. Additionally, the energy use, utility costs, and the CO_2 emissions per pound of fish plus one head of lettuce were calculated. Figure 3 shows the system Simulink model.

The ambient temperature, sky temperature, and solar irradiation characterize any instant during the day and are necessary because the heat transfer into or out of the building is determined on the ambient conditions around the building. The ambient temperature affects the convective heat transfer while the sky temperature and solar irradiation affect the radiative heat transfer. This heat transfer into the building in turn impacts how hard the dehumidification system must work to maintain the desired conditions of the space.

The Simulink model was created to allow for inputs of hourly data that would be representative of one hour of real time in each iteration. As such, hourly

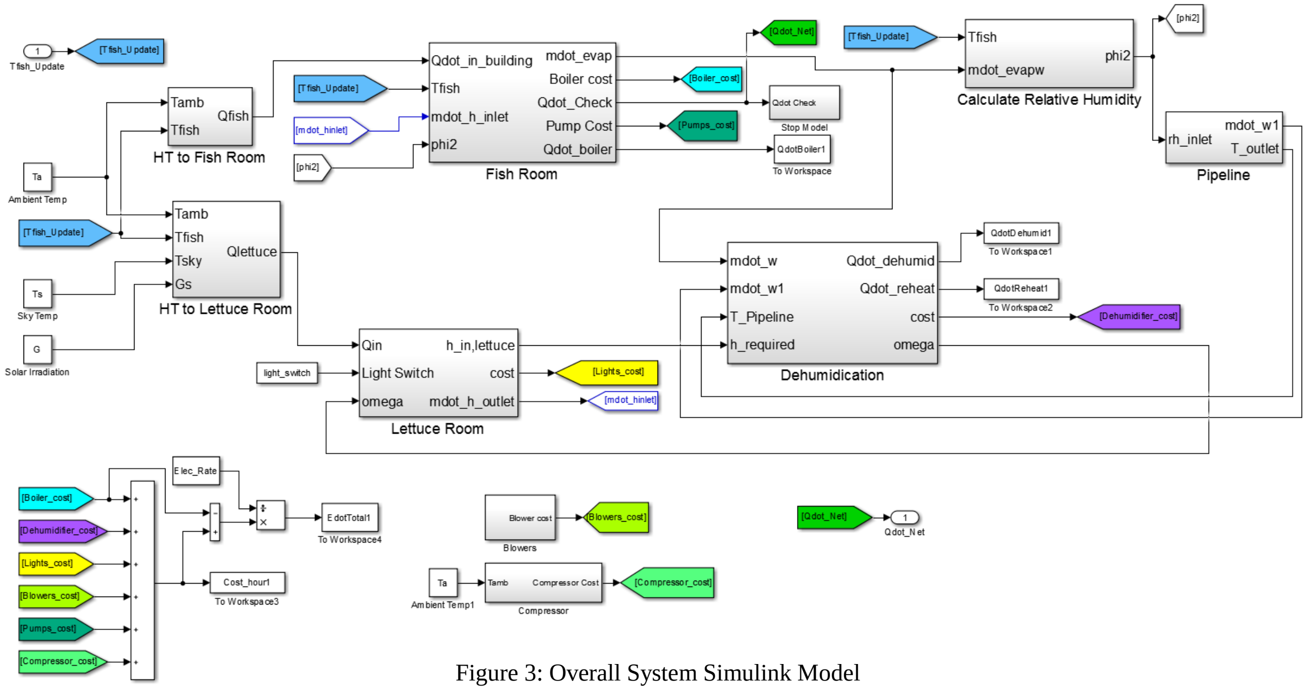

Figure 3: Overall System Simulink Model

temperature data near Kenosha, WI were gathered for the entire year of 2014 from the National Solar Resource Data Base. These input values are listed below:

- Ambient Temperature
- Dew Point Temperature
- Global Horizontal Irradiance

Other variable inputs include:

- On-peak and Off-peak electricity rates
  - On-peak: 9am – 9pm || Rate: $0.12101/kwh
  - Off-Peak: 9pm – 9am || Rate: $0.09017kwh
- Binary inputs for whether the lights are on or off
  - On: 7pm – 11am
  - Off: 11am – 7pm

Other constant inputs include:

- Air Mass Flow Rate = 5.2 kg/s
  - Natural Gas Rate: $0.56485/therm
  - Peak Electricity Rate: $6.86/kW

The following graphs detail the results of the entire Simulink model:

Hourly heating and cooling load breakdown for each day of the year was output as a plot. Examples for January 1st and July 5th are shown in Figure 4 and Figure 5, respectively.

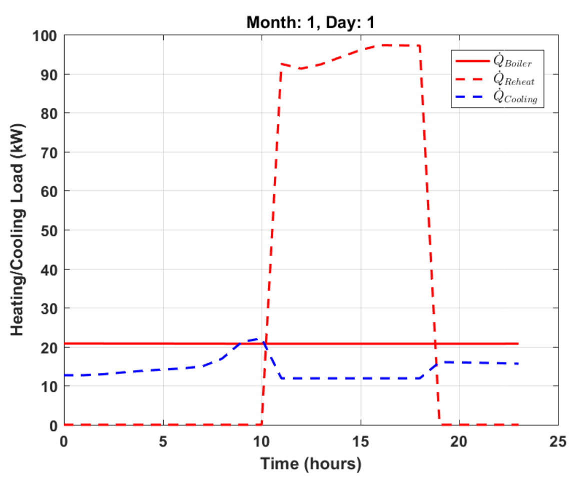

Figure 4: Hourly Heating and Cooling load, January 1st

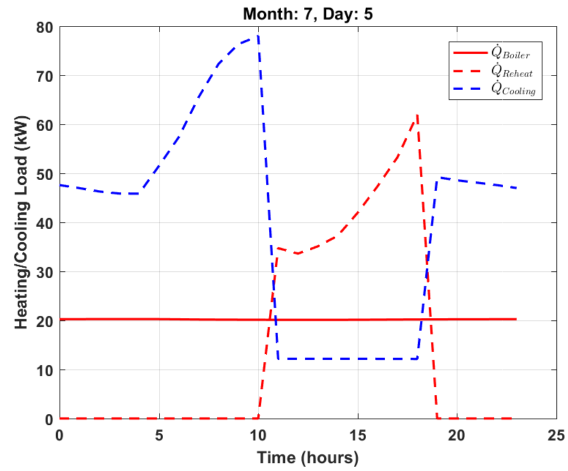

Figure 5: Hourly Heating and Cooling load, July 5th

Monthly cost for each component is shown in Figure 6.

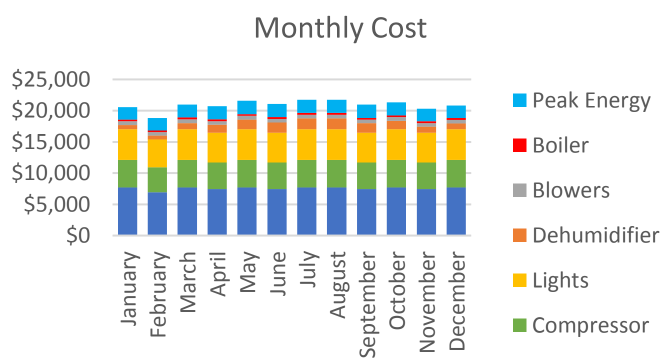

Figure 6: Monthly Component Cost Breakdown

Additionally, pie charts were created for each month displaying the percent cost breakdown for each of the components. An example for the month of January is shown in Figure 7.

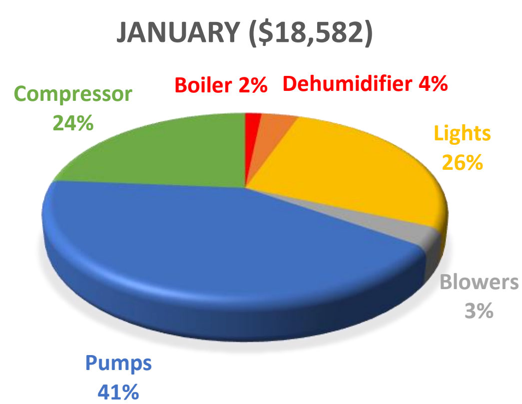

Figure 7: January Component Cost Breakdown

Monthly energy load for each component as shown in Figure 8.

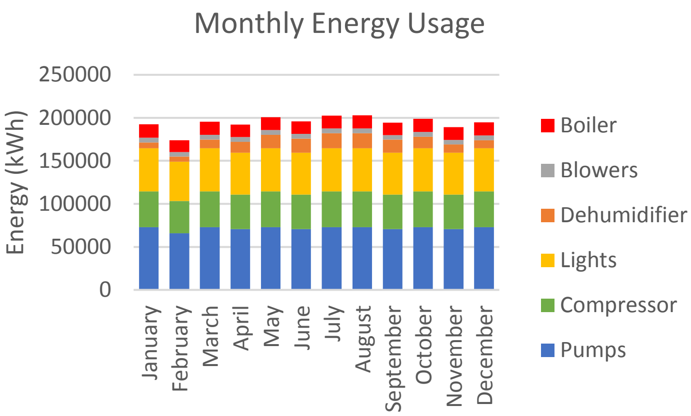

Figure 8: Monthly Component Energy Breakdown

Additionally, pie charts were created for each month displaying the percent energy breakdown for each of the components. An example for the month of January is shown in Figure 9.

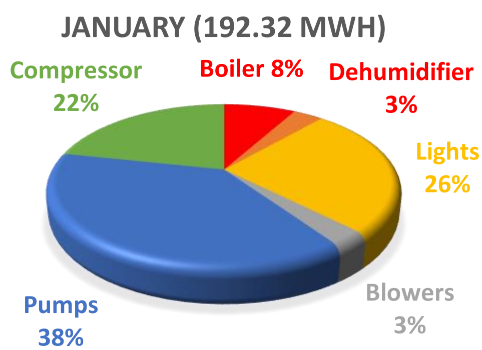

Figure 9: January Component Energy Breakdown

Amount of CO_2 produced per unit of food as shown in Table 4.

Table 4: Total CO_2 produced per pound fish plus lettuce head

Annual CO_2 Production (Tons)	lb CO_2 per lb Fish + Lettuce Head
2922.1	13.6

Cost of energy per unit of food as shown in Table 5.

Table 5: Cost per pound fish plus lettuce head

Annual Cost	Cost per lb Fish + Lettuce Head
$250,637	$0.58

According to a study conducted in California, a 1,500 acre farm could produce lettuce for $0.41 [7]. This is based on the fact that land is being rented and that all other labor, harvesting, and packaging costs are included.

The following interpretations were made based on the Simulink model results:

1) The dehumidification unit's reheat becomes necessary when the lights are turned off, as well as when the sun goes down. Throughout the day, the boiler is essentially constant and cooling ramps up as the sun rises. As expected, there are higher cooling loads in the summer.

2) Referring to Figure 6 and Figure 7, the majority of the monthly cost are the recommended pumps, compressor and the lights. Monthly costs are fairly constant with a slight increase during the summer months. The constant nature of the energy costs show that the insulation is doing its job and ensuring that the temperature fluctuations are not too dynamic.

3) Referring to Figure 8 and Figure 9, the energy usage increases slightly during the summer. The energy use distribution shows that the electricity demand is much higher than the heat demand. In situations that have consistently high electric and heat demand, a cogeneration plant could be considered. The base load for the cogeneration system would be fairly small and it would replace the need for the boiler. The addition of the cogeneration system would also displace some power requirements from the power plant, reducing CO_2 emissions, power transmission losses, and peak power demand charges. Since the existing boiler is sufficient for the heating requirement, the cogeneration unit is not immediately necessary for steady-state operation of NGF.

The carbon emission per unit of meat is detailed in Table 6 and the emission per pound of vegetables is detailed in Table 7. Note that the emissions in the following tables include emissions from transportation as well. The emissions for a pound of tilapia and a head of lettuce can easily compete with some of the highly demanded meats and vegetables. Fish is also the healthier option for protein when compared to fattier meats. Given this information, tilapia is the healthier, more environmentally friendly option.

Table 6: Carbon emission for animal based products

Meat	Lb. CO_2/lb. of food
Beef	26.5
Lamb	22.9
Veal	7.8
Pork	6.9

Table 7: Carbon emission for plant based products

Vegetable	Lb. CO_2/lb. of food
Asparagus	8.9
Avocado	1.3
Bell Peppers	1
Cabbage	0.3

Because the emission of CO_2 for the production of the lettuce cannot be separated from that of the tilapia, it is difficult to compare the lettuce to other produce. In general, the main contributor to the carbon emitted during the production of produce is transporting the food. Air freighting takes 50 times the energy of shipping by sea, 33 times the energy by rail, and 4 times the energy by truck transport [8]. By growing locally and selling locally, Natural Green Farms reduces its carbon footprint by tens of thousands of pounds each year. Through the incorporation of urban aquaponics facilities, communities could have access to a healthy, reliable food source that causes less of an impact on the environment.

Recommendations & Next Steps

Based on the research that has been conducted, the following recommendations can be made:

1) It is recommended that the pumps be replaced in order to achieve the required water exchange rate. More of the existing pumps can be purchased, which will have a low capital cost, but will require more space in the pump room and likely have a shorter useful life. Purchasing larger pumps will require a larger initial investment, but require less space in the pump room. Only five of the larger pumps would need to be purchased versus twenty of the smaller pumps.

2) Investing in a wind turbine is also recommended for Natural Green Farms. The payback period of 5-6 years is much less than the 9 year payback period of a solar PV array. A wind turbine would also provide a positive image for the sustainability effort of Natural Green Farms.

3) A nearly closed system of airflow is recommended for Natural Green Farms. The only inlet for air would be though the compressor. A closed system will deliver greater concentrations of CO_2 to the lettuce and minimize energy use for conditioning the air.

4) It is recommended that the proposed airflow scheme shown in Figure 2 be used as the primary airflow scheme for the facility.

5) Based on the results of the complete building model, a dehumidification plus reheat system will be required to obtain the desired atmospheric control in the lettuce area. Natural Green Farms should seek professional consultation in regard to the dehumidification plus reheat system. The heating and cooling loads produced by the building model can aid in the specification of a properly sized piece of equipment.

6) In the interest of reducing energy costs, waste heat from the dehumidifier should be salvaged and used for reheating the air that is entering the lettuce room.

7) Keep the food local. Keeping the food in the Southeast Wisconsin region keeps the CO_2 emissions low by avoiding transporting the food via airfreight. Minimizing the food's distance travelled will also minimize the cost per unit of food for NGF.

Next steps for this project would be to improve the model and provide better verification. The existing model only pertains to steady state production, so the model could be improved by making it include transient responses. The addition of the thermal mass of capacity of the lettuce room as well as the ability to vary the lettuce room temperature would also provide more versatility to the model. At this point in time, the farm is not running at full production. When full production is achieved, data could be collected for each of the subsystems in order to verify the model.

Acknowledgements

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References

[1] Bereau of Energy Efficiency, 2016, "Fans and Blowers," from http://www.saylor.org/site/wp-content/uploads/2011/09/Chapter-3.5-Fans-Blowers.pdf

[2] Bernstein, S., 2011, Aquaponic Gardening, New Society Publishers, Gabriola Island, BC, CA, Chap 4.

[3] C. Somerville, M. Cohen, E. Pantanella, A. Stankus, and A. Lovatelli, 2014. "*Small-scale aquaponic food production: integrated fish and plant farming*," Food and Agriculture Organization of the United Nations.

[4] J. E. Rakocy, M. P. Masser, and T. M. Losordo, 2006, "Recirculating aquaculture tank production systems: aquaponics—integrating fish and plant culture," *SRAC publication*, *454*, 1-16.

[5] Petcha, 2016, "Controlling Ammonia in a Fish Aquarium," from http://petcha.com/pets/controlling-ammonia-in-a-fish-aquarium/

[6] U. Yogev, A. Barnes, and A. Gross, 2016," Nutrients and Energy Balance Analysis for a Conceptual Model of a Three Loops off Grid, Aquaponics," *Water*, *8*(12), 589.

[7] Tourte, Laura, 2015, "Sample Costs to Produce and Harvest Romaine Hearts" from https://coststudyfiles.ucdavis.edu/uploads/cs_public/50/a0/50a0bad6-1cf0-4d61-a632-78b6fe2ff538/2015romainehearts-finaldraft_1-27-2016-1.pdf
[8] Haspel, Tamar, 2016, "The Surprisingly Big Carbon Shadow Cast By Slender Asparagus" from http://theplate.nationalgeographic.com/2016/02/09/the-surprisingly-big-carbon-shadow-cast-by-slender-asparagus/

