Collaboration for Aquaponics Sustainable Energy

A Low Carbon Emitting Energy Source for Urban Aquaponics Systems

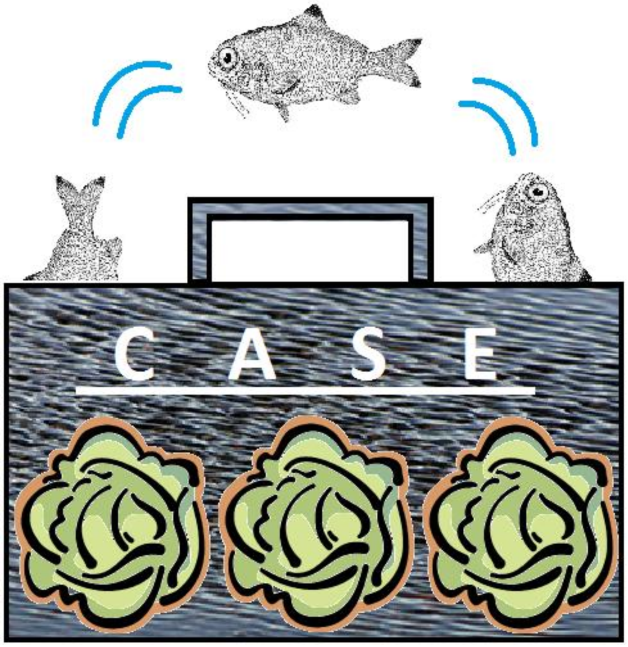
Team Members:
Chris Chapman
Brandon Jackson
Daniel Neumann
Ben Steffes
Nate Weber

Advisor:
Dr. Chris Damm

Submitted:
5/18/12

MILWAUKEE SCHOOL OF ENGINEERING – ME 492

DESIGN REPORT


CASE

EXECUTIVE SUMMARY

Aquaponics is a new and emerging practice which joins agriculture and aquaculture. Although there are functioning systems in existence, the fact that aquaponics is so new has left the optimization of the operation overlooked. Through this analysis, a best practices manual will be developed and help make aquaponics an efficient and more sustainable process. The best practices manual will help to determine an efficient way to power varying sizes of aquaponics operations and provide an engineered approach towards making the system cost effective and environmentally responsible.

Aquaponics systems are cyclic in nature where fish effluent provides nourishment to plant life while the plant life, in return, filters toxic fish waste from the fish tank water. Background information is provided to show advantages of aquaponics over more traditional methods of farming as well as the primary types of aquaponics systems in use. Important aquaponics design parameters used in this proposal are hydraulic loading rate, hydraulic retention time, fish tank size, grow bed area and water flow rates.

Mechanical power requirements of an aquaponics system are primarily due to the needs to both pump and aerate the water. All of the aquaponics systems studied utilized an elevation difference between each component of the system thus requiring a pump. Water aeration is essential to achieving high fish stocking densities and also functions to keep nutrients suspended in the water. Artificial lighting power estimates are also given for supplemental lighting needed for an 18 hour grow period in a greenhouse. Although artificial lighting is not required for aquaponics, it is an option that farmers have chosen to implement and therefore is considered.

An interactive Excel spreadsheet where a user can input design parameters was created. The user can utilize this tool to estimate pumping, aerating, and artificial lighting power requirements as the scale changes. A publication by the University of the Virgin Islands (UVI) provided a representative aquaponics system that was studied in order to obtain key proportioning constants that facilitate scaling of systems. The system proposed by the University of the Virgin Islands can be used as an effective starting point in the design and construction of other aquaponics systems.

Power calculations made with the interactive Excel spreadsheet were verified by the values quoted by the UVI system. Pumping resulted in a power requirement of ½ Hp which was exactly what was specified by UVI. Aeration was 1.1 Hp which is 26% lower than the UVI system.

An estimated 51.9 MWh would be required to run artificial lighting to supplement sunlight in order to achieve 18 hours of grow time per day throughout the year in Milwaukee, WI. The artificial lighting energy takes into account the changes of the daily natural sunlight available through year.

The proposed energy system for aquaponics is cogeneration. Cogeneration is when one fuel source satisfies two different power requirements. In the design presented in this paper, natural gas will satisfy both heat and power requirements for an aquaponics system. This is known as combined heat and power (CHP). The generator will provide electrical power for water aeration, circulation, and artificial lighting. The thermal capacity of the CHP system will be used to maintain tank temperatures at approximately 80°F year round. The benefit of using cogeneration for this application, when properly

sized for the thermal load, is an overall efficiency as high as 90% compared to an efficiency of 35%-40% for coal-fired power plants. This results in a reduction of greenhouse gas emissions along with lower operating expenses.

To quantify thermal demand on the CHP system from the aquaponics pond, a comprehensive thermal model was developed. Primary sources of heat transfer were identified, they include: conduction into the ground, evaporation, convection, and grow bed losses. Radiative heat transfer was determined to be an insignificant source of thermal gains/losses and was thus not included in the developed thermal model. Convection estimates from the side of the tank were based of empirical equations developed from flat plate analyses. Surface evaporation was determined from an empirical model designed to estimate evaporation from indoor swimming pools, while surface convection was determined from an energy loss ratio developed by I.S. Bowen.

Due to the high uncertainty inherently present in the thermal modeling, an investigative study was conducted to measure the accuracy of the model. This experiment was conducted in the Psychrometric Chamber installed in the Johnson Controls Laboratory at the Milwaukee School of Engineering. Results from this study yielded excellent correlation between the measured and predicted heat transfer for all mechanisms of losses studied. Based on this successful verification, the thermal model developed was used to create the load profile for the aquaponics pond, which was used to both size the CHP system and develop an economic model.

Two main design approaches were considered for a CHP energy solution and are listed as follows.

1. Use a natural gas engine to supply mechanical demands for pumps and integrate heat exchangers to recover thermal energy.
2. Use commercially available CHP generator set to provide electricity for pumps and lighting and hot water for the aquaponics tank.

Complications were found when considering both design options. Using a natural gas engine led to problems with supplying power to artificial lighting, adapting to multiple tank systems, adding lubrication to two-stroke engines, efficient heat recovery, safety issues, and space demands. An issue that was common between the two design options was short maintenance cycles due to continuous use.

A solution found which resolves the aforementioned complications is the Marathon Engine System's 'ecopower'. The ecopower system is a CHP system that provides 2.0 – 4.7 kW of electrical power at power factor of 0.98 that is single phase 240 V at 60 Hz. The maintenance cycle allows for 4000 hours of continuous use (166 days) before an oil change is required. The system is only 25% efficient at generating electricity; however, the combined efficiency of the ecopower system is 90%. An additional benefit to the Marathon CHP system is that it has a built-in controller that allows for thermal load following; therefore, the system can adapt changing thermal demands by varying engine operation conditions.

The ecopower system is already equipped with all necessary heat exchangers; as a result it only became necessary to design a heat exchanger for the aquaponics tank. Both metals and non-metallic materials were considered for the heat exchanger design. Ultimately, 2205 Duplex stainless steel was selected as the build material due to its low environmental impact. The design heat exchangers were sized to deliver 12.5 kW into the aquaponics pond through lengths of submerged piping. A mixture of Propylene glycol and water was selected as the heat exchanger transfer fluid due its nontoxic nature.

The outcomes of this senior design project were to develop a combined heat and power system configured to meet the energy demands of an aquaponics system. Additionally, the design process was detailed in a report to guide CHP design and improve energy efficiency for different size aquaponics systems. Software was developed to complement the detailed design report which can be used for parametric studies.

TABLE OF CONTENTS

TABLE OF FIGURES

LIST OF TABLES

1 PROJECT STATEMENT

Aquaponics is a new and emerging practice which joins agriculture and aquaculture. Although there are functioning systems in existence, the fact that aquaponics is so new has left the optimization of the operation largely overlooked. Additionally, the recent interest in green energy makes an engineered energy solution all the more vital. Through this analysis, a best practices manual will be developed to help make aquaponics an efficient and more sustainable process. The best practices manual will help to determine an efficient way to power varying sizes of aquaponics operations and provide an engineered approach towards making the system cost-effective and environmentally responsible. Although the best practices manual will be the main outcome of the project, the general goal is to power an aquaponics system through the conversion of rejected biomass into heat, electricity and compressed air. The designed system will reduce the carbon footprint of green urban farming and lower operating expenses.

2 DESIGN SPECIFICATIONS

The overall project goals are:

- To develop a thermal model of an aquaponics system and greenhouse
- To determine the electrical and/or mechanical needs of an aquaponics system
- To develop an economic model for a combined heat and power (CHP) system
- To quantify the environmental benefit of incorporating a CHP system
- To develop a best practices manual based on thermal, electrical, and mechanical needs
- To create software which allows users to calculate a best practice approach

In order to develop a best practices guide for an aquaponics energy system, goals and constraints must be set in order to focus the effort. The goals and constraints for both the aquaponics system and the energy system are outlined as follows.

Aquaponics:

- Maintain fish tank temperature between 75-85°F
- Greenhouse environment between 45-60% relative humidity and 55-85°F
- Consider both natural and artificial lighting for best practices simulation
- Fish tank size constrained between 1,000-20,000 gallons
- Aquaponics system located in a greenhouse or indoor factory space

Power Production:

- Less CO_2 emissions than those required for independent generation using Milwaukee area emission factors
- Meet environmental standards for noise and ventilation
- Provide power to aerate, heat, and pump tank water
- Provide power to artificial lighting
- Least environmental impact with consideration of costs
- Minimize initial expense

- Minimize payback time
- Operating on natural gas and/or biogas
- Continuous operation with expectation of maintenance shut-downs
- Backup for fish aeration and pump system

3 BACKGROUND

3.1 BACKGROUND RESEARCH

3.1.1 URBAN AQUAPONICS

The term aquaponics refers to “the cultivation of fish and plants together in a constructed, re-circulating ecosystem utilizing natural bacterial cycles to convert fish wastes to plant nutrients” [1]. The idea of aquaponics can be deemed somewhat revolutionary, due to the fact that it is less than fifty years old and still not very well researched or known. This simple, yet brilliant, idea is constantly evolving and motivating others towards conservation and sustainable programs.

The early beginnings of aquaponics began in the 1970’s with a couple from the New Alchemy Institute, a research center located near Cape Cod, Massachusetts. This couple formulated the idea that through combining fish tanks with vegetable plants, nourishment would be gained by converting ammonia from fish waste into nitrogen for plant fertilizer. This nitrogen is critical to plant growth. Aquaponics saw larger growth during the 1980’s, when college professors and colleges began bringing this idea to the forefront of the conversation on hydroponics, which is the growing of plants in nitrogen rich water with no soil. The alternative, aquaponics, has proven to be more effective than its predecessor hydroponics. Aquaponics truly began to take off when Will Allen began experimenting with a piece of land on the outer edges of Milwaukee. His successful experiments proved the potential of aquaponics and sustainable agriculture in transforming the surrounding urban community [2].

Aquaponics takes into account the advantages of both hydroponics and aquaculture, while minimizing the disadvantages of each system. The comparison can be seen in Table I.

TABLE I: COMPARISON OF VARIOUS FORMS OF FOOD PRODUCTION (ADAPTED FROM [3])

	Advantages	Disadvantages
Organic Farming	- Presumed as a healthier method of growing food than commercial farming and thus has become popularized - Uses organic wastes as fertilizers. - Uses natural pest control. - Tends to produce better tasting and at times more nutritional crops.	- Requires more land than conventional farming. - Often higher costs to grow and certify crops. - Agribusiness is quickly replacing small-scale organic operations.
Inorganic Hydroponics	- High volumes of food are produced in a small space. - Has potential for year-round production if controlled.	- Highly dependent on costly manufactured/mined fertilizers.
Recirculating Aquaculture	- High biomass of fish produced in a small space.	- High rate of failure due to small margin for error. - Large waste stream produced.
Aquaponics	- All of the advantages of the other methods and additionally: - Reuse of fish waste as nutrients for plants. - Fish don’t carry the pathogens (e.g. E. coli and Salmonella) found in warm-blooded animals. - Imitates a natural cycle and is the most sustainable of the four methods. - Consistent fish biomass in the fish tanks lets plants grow and thrive.	- Operator must have knowledge of both fish and plant production. - Major fluctuations in fish stocks in the tank can disrupt plant growth.

The use of aquaponics eliminates the need for costly fertilizers by using the large waste stream produced in aquaculture operations. The fish waste, which is harmful to the fish if not re-circulated and filtered, is used by the plants as the fertilizer substitute. As the water from the tank funnels over the plants and the roots, the roots filter out the toxins and are used as nutrients before they re-enter the watershed. This represents a continuous closed-loop system [4].

There is no single model for the aquaponics design. However, several designs standout above the rest and are determined by the components it uses and whether or not it employs a media for the plant roots. The four most common types of aquaponics systems are media filled, flood and drain, nutrient film technique, and floating raft systems [4].

Media filled systems are important because they use a media in which plant roots are grown. This brings down the bottom line for the cost of the project. Fish waste is collected in the medium and is processed by the bacteria present in it. The need for a biofilter and separate settling tank can be avoided. If the medium is not present, the biofilter and separate settling tank are needed so that the water can be cleaned and deemed habitable by the fish occupying the tank [4].

Another type of system is the flood and drain system. The flood and drain system is known for its simplicity, reliability, and user-friendliness. Plant roots are soaked in a concentrated nutrient solution until the solution has been drained. This procedure can be repeated several times a day to supply the plants with the necessary nutrients. This system does not require a medium for the roots, but media can be used [4].

Nutrient film technique relies on the plant roots being exposed to a thin sheet of nutrient water, which runs through a pipe. This technique relies on the need for the water to reach the bottom layer of the roots. The remaining layer of the roots is portioned off to allow for a sufficient oxygen supply. In this system, the biofilter becomes critical as there is no medium for bacteria to be sustained [4].

The last common system is the floating raft system. In this system, the plants are grown on floating rafts, most commonly made of Styrofoam. The plants are suspended by nets, and the roots are allowed to extend into the water. With this system, the nutrients tend to become less concentrated and therefore higher feeding rates for the fish are needed. The water still needs to be circulated, and a biofilter may be required [4].

3.1.2 COMBINED HEAT AND POWER COGENERATION

The current electrical infrastructure which utilizes large, centralized power plants is inefficient due to high transmission and distribution losses in addition to high conversion losses [5].The result is that approximately one third of the energy contained in the fuel is converted to electricity made available for use, while the remaining two thirds is lost as heat [6]. It is possible to capture this ‘waste’ thermal energy and use it for a practical purpose. This is considered combined heat and power (CHP).

CHP is difficult to implement effectively with centralized power plants because these plants are generally located far from where the electricity is ultimately used. Certain power plants, such as the Valley Power Plant in Milwaukee, are located where combined heat and power is practical. The Valley Power Plant is a coal based power plant adjacent to downtown Milwaukee that provides both electricity and steam [7]. The Valley Power Plant is located where the thermal energy can be utilized, but most often this is not the case. Although CHP can be done at centralized power plants, it is not common.

Distributed power generation is where the electricity is generated at the site where it is to be used. The efficiency of these systems in electricity generation is generally lower than the efficiencies achievable by large power plants, but transmission and distribution losses are minimal for the distributed power generation systems [8]. A great advantage of distributed power generation systems is the ability to implement combined heat and power. The ‘waste’ heat normally associated with electricity generation can be used more easily than with a centralized power plant. Distributed combined heat and power is capable of achieving high overall efficiencies which can lead to cost savings when compared to purchasing electricity and energy for heating separately. The increase in overall efficiency also leads to lower emissions of CO_2 [5].

The general idea that includes combined heat and power (CHP) is cogeneration. Cogeneration is the use of a single fuel source to achieve multiple forms of useful energy [9]. This often includes thermal, mechanical, and electrical energy. The useful forms of energy obtained using a CHP system are electrical and thermal power [9]. CHP is most often implemented using a reciprocating internal combustion rather than other technologies such as fuel cells and gas turbines. This is mostly due to the versatility of reciprocating internal combustion engines and their low cost made possible by high production volumes.

A reciprocating internal combustion engine – generator with combined heat and power is comprised of five core components. The first is the prime mover, or in this case, the engine. The second is the generator which is often synchronous to allow for net metering with the local electric utility. The third, fourth, and fifth are the heat recovery system, heat rejection system, and electrical connection system [10].

CHP systems are generally identified by the prime mover. In general, diesel and natural gas engines are common and economical. Diesel engines are known for high efficiencies and are capable of operating with a large range in fuel quality which can include bio-diesel or algae-based diesel. Diesel engines have relatively high emissions of NO_X and particulates, while natural gas spark ignition engines have superior emission profiles [10]. Natural gas generators are the most common for CHP applications and routinely achieve overall efficiencies between 65-80% when combining electrical and thermal power output [10]. Natural gas engines are also capable of using different fuel qualities to allow for the use of field gas, pipeline quality gas, or biogas [10]. It should be noted that using alternative fuel sources requires careful consideration due to compositional differences and contaminants.

CHP systems are normally sized based on the thermal load required. This allows the generator to run near fully loaded where it is most efficient. If there is excess electrical capacity, it can often be sold back to the local electric utility.

Aquaponics and CHP are a natural fit. Pumps and compressors must be run, and the tank must be heated when warm-water fish are raised. There are both thermal and electric load requirements which could be met with a CHP system. This can be used to reduce operating costs and CO_2 emissions. It may also be possible to use the waste stream of an aquaponics system to create biogas by anaerobic digestion to power a natural gas, reciprocating internal combustion engine for cogeneration.

3.2 CONCEPTUAL DESIGNS

One potential design is to use a natural gas engine to provide for the total energy needs of an aquaponics system. This includes mechanical, thermal, and electrical loads. The natural gas engine will be fitted with heat exchangers to recover thermal energy and use it to heat the water in an aquaponics system. The pumps, compressors, and alternators required for the aquaponics system can be driven from the engine shaft power through a gearbox or pulley system. Alternatively, electric pumps and compressors could be used, and the engine could be used to turn an alternator only. The tank temperature can be regulated in several ways depending on the heating method used. This includes turning on and off the pump that circulates water through the heat exchangers, bypassing the heat exchangers, or regulating the flow rate through the heat exchanger.

The second potential design is to use a commercially available CHP generator set to provide electricity and hot water for the aquaponics operation. Excess electricity generated can be sold back to the utility. This option is much easier for a farmer to implement in comparison to designing and building a custom CHP system. The tank temperature can be regulated by using built-in thermal load following controllers which vary the generator electrical output to match the thermal load.

Two options were identified as methods of transferring thermal energy from the CHP system to the aquaponics system.

- Method 1: The tank water would serve as the heat transfer medium between the CHP system and the tank.
- Method 2: A secondary heat transfer fluid in a closed loop serving as a heat transfer medium.

Method 1 would likely yield higher heat transfer effectiveness since less heat exchangers would be necessary in the circuit. This method, however, poses contamination issues where suspended matter in the fluid would pass through the heat exchangers on the CHP system and can potentially obstruct flow the system. Therefore, method 2 was selected.

The selection of the heat transfer fluid in the closed loop is of high importance in the design of the system. In the event of a leakage, the fluid within the loop could be released into the tank and eventually into a food supply. As a result, it is necessary to select a heat transfer fluid that is neither dangerous to humans or the aquaculture. Potential fluids that meet this criterion include water and a propylene glycol water mixture.

A schematic of a potential design is shown in Figure 1.

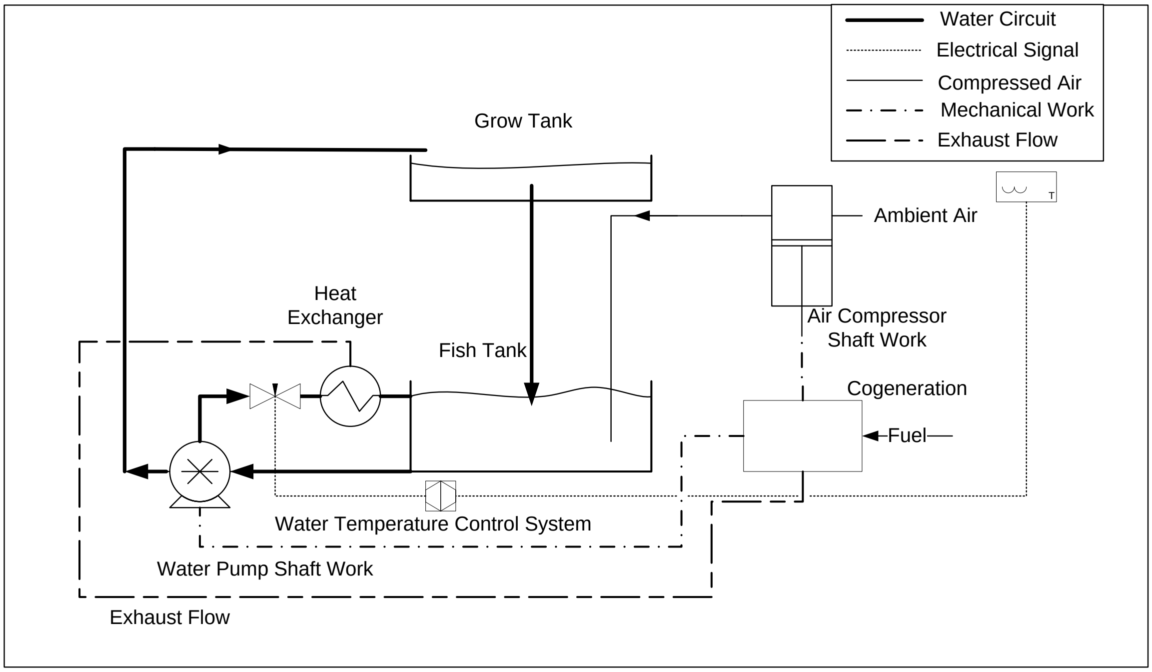


FIGURE 1: SCHEMATIC OF POTENTIAL SYSTEM

3.2.1 ALTERNATIVE DESIGN OPTION

An alternative design that could be used to deliver the thermal loads for the aquaponics system is a solar thermal system. A solar thermal system would have a large initial cost but the benefit would be the fact that there is no fuel cost since the system uses the sun's energy to create hot water. The benefit to using the solar thermal system would be that depending on the size of the aquaponics system, the fish tank can act as the storage tank as well as having no fuel cost or harmful emissions associated with the energy generated by the system. However, an additional storage tank would still be needed in scenarios in which the fish tank was at maximum temperature. This additional storage tank would prevent energy from being wasted in this scenario where the tanks cannot be used for thermal storage. Swimming pools have been heated in a similar fashion with notable success and can be used as a good approximation for a system to be installed on an aquaponics system. An example of a solar thermal system for a pool can be seen in Figure 2.

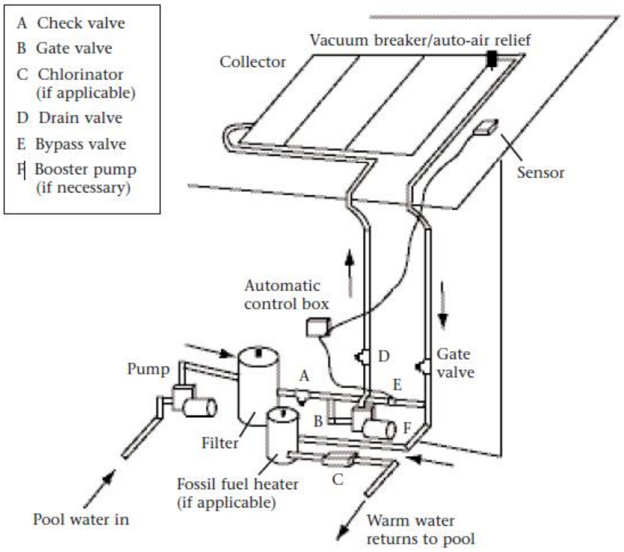


FIGURE 2: SOLAR POOL HEATING SYSTEM (ADAPTED FROM [11])

The biggest concern when using a solar thermal system would be the economic feasibility. A cost analysis was performed using twenty eight different prepackaged solar thermal systems from Caleffi. System costs ranged from \$12,000 – \$25,000 excluding installation costs. Using a simple payback method as seen in equation (3.2.1), the simple payback time was calculated.

$$\text{Years} = \frac{\text{System Cost}}{(\$/\text{kWh})(\text{kWh/day})(\text{days/year})} \tag{3.2.1}$$

With the results from equation (3.2.1) it was found that the payback times ranged from 13 – 26 years when replacing electric resistance heaters. The simple payback time for replacing natural gas water heaters with 80% efficiency ranged from 32 – 67 years. The shorter payback times were for the larger systems in which an output of at least 30 kWh/day was required. An additional simple payback was calculated when a 30% federal tax credit was factored in as seen in equation (3.2.2). The federal tax credit was found to be one of the only incentives for the state of Wisconsin outside of loans [12].

$$\text{Years} = \frac{\text{System Cost - 0.3 SystemCost}}{(\$/\text{kWh})(\text{kWh/day})(\text{days/year})} \tag{3.2.2}$$

With the results from equation (3.2.2) it was found that the payback times ranged from 22 – 47 years for natural gas hot water heating and 9 – 18 years for electrical hot water heating. Additional time would need to be account for installation costs in both scenarios. Furthermore, this analysis assumes is that the price per kWh to be saved is constant at \$0.11/kWh for electricity and \$0.02729/kWh for natural gas.

For this project, payback time is too long for solar thermal systems to be considered when replacing a natural gas hot water heater. Additionally, the only systems that have reasonable payback times are the larger systems which make the scalable process dependent on the size of the solar thermal system and not on the size of the aquaponics system. Despite the long payback time, solar thermal systems have been previously incorporated in aquaponics systems including those used at Growing Power, but this project goal is to explore combined heat and power systems which have been proven to be beneficial conceptually. The proposed design path uses a CHP system alone to validate the conceptual benefit.

3.3 INITIAL FEASIBILITY

Initial feasibility studies showed that using a combined heat and power energy system for aquaponics is feasible with a simple payback period of approximately 5 years. The project utilizes proven technology and is technically feasible. The details are given in the remainder of this section.

3.3.1 INITIAL ECONOMIC FEASIBILITY

Economic feasibility is important when considering if the proposed design solution would benefit a farming operation. In this model, the system’s payback periods were calculated using both natural gas and biogas.

To start the model, a few inputs were needed and are shown in Table II. The daily thermal needs were determined using the thermal modeled discussed later in this report. The daily electric needs of the system were again modeled for size of the tank and needs of the mechanical systems. The utility charge for gas and electricity were gathered from the We Energies site for the average household. The cost for biogas was taken from a renewable energies website and used as an example if the generation was powered by biogas. The maintenance cost was a generalized value that would cover needs such as oil changes, part repair, or part replacement. The overall efficiency is the fraction of total energy recovered by burning the fuel. This includes both electrical and thermal energy.

TABLE II: INPUT VARIABLES FOR ECONOMIC MODEL [13][14][15]

Variable	Value
Daily Thermal Needs (BTU)	61828 (18.12 kWh)
Daily Electric Needs (kWh)	6.55
Utility Charge for Gas ($/kWh)	$0.0298
Utility Charge for Electricity ($/kWh)	$0.129873
Cost for Biofuel ($/kWh)	$0.023885
Cost per kW for System ($/kW)	Varies ($1500)
Size of System (kW)	1
Maintenance Cost per Year (dollars)	$250.00
Overall Efficiency of CHP System (%)	85
Efficiency of Gas Water Heater (%)	85

This preliminary investigation involves several assumptions which include running the system 24 hours a day and not shutting down the system for maintenance. Additionally, the daily thermal and electric need is an average taking into account daily temperature changes which vary with the climate region. For this initial investigation, the tank size was simulated at 1,000 gallons for both the electrical and thermal models.

The yearly fuel needs were calculated based on the initially estimated load for a 1,000 gallon tank. Refer to section 5 for details of the thermal load estimation. The cost of the building a custom system from a small engine was estimated to be $1,500, and the annual benefit was estimated to be $289 while using biogas as the fuel. This analysis considers replacing a natural gas water heater that is 85% efficient. This resulted in an estimated payback period of 5.2 years. These results can be seen in Table III.

TABLE III: CALCULATED VALUES FOR PRELIMINARY ECONOMIC ANALYSIS

Parameter	Value
Yearly Thermal Need (BTU)	2.65×10^7 (7780.90 kWh)
Yearly Electrical Need (kWh)	2390.75
Yearly Gas Cost (dollars)	$185.85
Yearly Electrical Cost (dollars)	$0.00
Yearly Maintenance (dollars)	$250.00
Yearly Savings (dollars)	$289.02
Cost of System (dollars)	$1500.00
Payback (years)	5.2

The yearly savings for using biofuel as the main fuel source was approximately $289 per year, while the yearly savings for using natural gas is approximately $243 per year. This analysis considers replacing a natural gas water heater that is 85% efficient. A payback period of approximately 6.2 years was estimated when running the system on natural gas rather than biogas.

3.3.2 INITIAL TECHNICAL FEASIBILITY

Aquaponics systems have been around for half a century. As time passes, technology improves, and the cost of operation decreases. This project does not need any under-developed or cost inhibitive pieces of equipment. Equipment such as engine, pumps, and generators are all readily available in the required sizes. The necessary maintenance is not overly burdensome and could be done by a properly trained individual.

4 DETAILED DESIGN

An initial design consideration was to use an engine and then configure it to be used as a CHP system. This was to use the mechanical power generated by the engine to drive a shaft and pulley system that would run the water and aeration pumps for the fish tanks, while an exhaust gas heat exchanger would be used to heat the fish tank. This potential solution was to use a two-stroke engine to mechanically power the system, but using a two-stroke engine would lead to lubrication issues since the oil is added to the fuel. Even though the initial cost of the two-stroke engine would be small, the shorter life span and added configuration cost and problems would offset the initial economic benefit.

It was proposed to replace the two-stroke engine with a four-stroke engine. The change from two-stroke to four-stroke resolved the issue of introducing lubrication into the engine. Even with changing the engine, problems still existed with mechanically powering the aquaponic system. An initial design flaw was the inability to mechanically power artificial lighting if the aquaponic system required it. Another drawback to this design was it was dependent on the design of a singular tank with an appropriately sized engine. Otherwise, if the design incorporated multiple tanks, there would be shafts and pulleys to each tank in the design. The increased number of shaft and pulley systems leads to larger safety issues and space demand. The required area for the shaft and pulley systems would reduce the amount of space that could be utilized in the greenhouse, thus reducing their growth potential. From a safety standpoint, the shaft and pulley systems would require shielding so that the possibility of injury would be reduced; this requirement would lead to an added cost and additional space demands. An additional concern was the maintenance cycle for four-stroke engines. Commercially available engines have recommended oil changes every 100 - 400 hours, or 4 - 16 days under continuous use. The issue with such a short maintenance cycle is the requirement to shutdown the engine and energy system every other week. Having to shutdown the engine on such a frequency would lengthen the payback period due to the engine not being utilized and add additional labor costs. As a result, a change in design was needed, so mechanically powering the pumps was deemed inefficient.

It was also found that to have a system with maximum efficiency, there needed to be a water jacket to recover waste heat as well as an exhaust gas heat exchanger. A study was done using the MSOE CHP system to determine the parameters of such a system. The results can be seen in Table IV and Figure 3. From the six trials it was seen that the engine water jacket produced the highest percentage of total heat recovery. The engine jacket produced an average of 59.5% of the total heat recovered. Additionally, the exhaust gas heat exchanger produced an average of 37.1% of the total heat recovered.

TABLE IV: HEAT RECOVERED FROM MSOE CHP SYSTEM

Trial #	**Percentage of Total Heat Recovery**		
	Generator	**Engine**	**Exhaust Gas**
1	4.1	58.1	37.8
2	3.4	58.2	38.4
3	4.1	58.6	37.4
4	4.7	57.9	37.5
5	2.7	60.2	37.1
6	1.6	64.2	34.2
Average	3.4	59.5	37.1

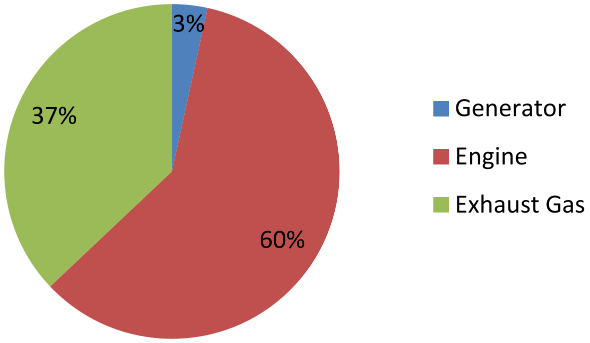


FIGURE 3: PERCENTAGE OF TOTAL THERMAL ENERGY RECOVERED

Therefore, from the data collected during the CHP study, it was confirmed that using an exhaust gas heat exchanger alone wouldn't provide the most efficient system. A need for having the water cooled engine led to the requirement for having a larger size engine, because small four-stroke engines commercially available are air cooled. To make the best practices manual possible, the smallest economical sized system needed to be found.

Another design that was considered along with the mechanical system included a commercially available generator set that could power the water and aeration pumps as well as artificial lighting and an exhaust gas heat exchanger to heat the fish tank. The generator system resolved the spatial issues that plagued the mechanical system. The generator system could adapt to a multiple tank system much more efficiently and with less difficulty than the four-stroke engine system. However, the issues of maintenance cycles and proper heat recovery still arose. Most available generator sets are available for reliable backup power and the design calls for the generator to be the primary source of power.

Thus, a design was needed to be of smaller power, while being water cooled and having a longer maintenance cycle. The Marathon ecopower generator was found to solve the maintenance cycle issues with a run time of 4,000 hours, 166 days continuous, between recommended oil changes. The ecopower was the smallest water cooled engine found that also featured a long maintenance cycle.

4.1 CHP GENERATOR SET

Marathon Engine System's 'ecopower' is a micro combined heat and power system that provides 2.0 – 4.7 kW of electrical power at a power factor of 0.98 that is single phase 240 V at 60 Hz. This engine system is fitted with heat exchangers that allow for 13,000 – 39,000 BTU/hr thermal output. The overall efficiency of the system is listed at 90% where the generator is 25% efficient.

The ecopower has a built-in controller which allow for thermal load following. Under thermal load following, the engine speed will change to meet the thermal demand, and the electricity generated can be used to run pumps or be sold back to the utility by net metering. When the thermal load is below a specified threshold, the engine will automatically shut down. When the thermal load increases, the engine will automatically turn on to provide hot water and electricity.

The ecopower can operate for 4000 hours between maintenance. After 4000 hours, the engine oil, oil filter, and spark plug must be replaced. It is estimated that an engine overhaul well be required after 10 years of use.

The ecopower system is also quiet at 56 dB(A) at a distance of 3.3 ft. This is important to consider when farmers will be working near the generator set. It should be noted that while the system can be installed indoors, the exhaust must be properly vented.

A typical installation for aquaponics may include (See

Figure 4):

- Possible 2nd self-contained heating circuit
    - Allows for control of 2nd tank
- Remote monitoring
    - Enables service technician to monitor the system
- Grid connection
    - 2nd meter to run net metering
    - Allows for excess generated electricity to be sold to utility
- Thermal load following
    - Changes engine speed to respond to varying thermal demands
    - Transfer switch allows aquaponics system to be run off of utility power when thermal demands do not require running the engine

It should be noted that multiple ecopower units can be run in parallel if the size of the aquaponics system were increased.

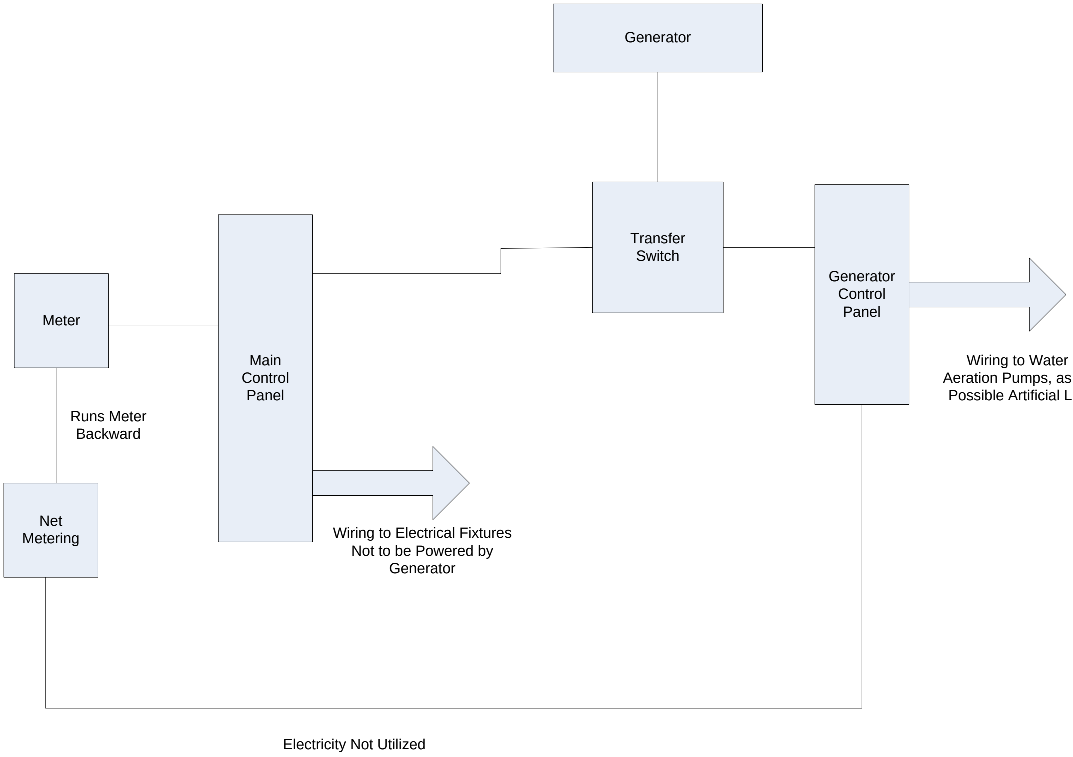


FIGURE 4: GENERAL SCHEMATIC FOR GENERATOR SYSTEM WITH NET METERING AND TRANSFER SWITCH

In the event that the ecopower unit is not running due to low thermal demand, maintenance, or some other unforeseen issues, the aquaponics system still needs be able to operate. The thermal demand of the tank needs to be met as well as the electrical demand required for pumping, aerating, and artificial lighting. For almost all instances, the included transfer switch will take care of such issues. In the case of providing electricity to the pumps and lighting, the transfer switch moves the primary source of power from the ecopower unit to utility. To ensure that any thermal demand is being met, resistance heaters can be put in the aquaponics tanks and be run off of the utility as well. If a problem occurs with the transfer switch, temporary measures can be taken until the matter is resolved. Pumps, resistance heaters, and lighting can be plugged directly into a utility powered outlet. If the resistance heaters are not supplying the necessary energy to meet the thermal load, the temperature of the greenhouse may be increased using the building heater to slow heat transfer out of the tanks.

4.2 HEAT EXCHANGER

In order to get a proper correlation between tank size and heat losses from the tank, it was necessary to select a tank size that can be met with the thermal load supplied form the Marathon ecopower microCHP system. Since one of these systems was not purchased, information was derived from the pamphlet and used in thermal models for the selection of the heat exchanger material as well as necessary length.

Table V lists the specifications provided by Marathon for the ecopower microCHP system.

TABLE V: MARATHON ECOPOWER MICROCHP SYSTEM

Specifications	**Natural Gas**	**Propane Gas**
Electrical Power	2.0 – 4.7 kW	2.2 – 4.7 kW
Thermal Power with max. flow temp. 167 °F [75 °C]	6.0 – 12.5 kW	6.6 – 13.8 kW
Overall Efficiency	>90% (approx. 25% electrical + approx 65% thermal)	
Engine	Single-Cylinder, 270 cm^3, 1,700 – 3,600 rpm	
Exhaust Gas Figures [at 5% O_2]	NOx < 1.98 mg/ft^3 CO < 11.33 mg/ft^3	Temp < 194 °F [90 °C]
Grid Feed [Single Phase]	250 VAC, 50/60 Hz, Power Factor = 1	
Sound Level	< 56 dB [A]	
Dimensions/ Weight	54 in. L x 30 in D x 43 H 858 lb	
Approvals	CE – Certificate, ETL - Approved	

The thermal power that can be used by the system is 42,500 BTU/hr (12.5 kW). This is the value that was used to size the tanks. In order to get a 20°F temperature drop, a mass flow was needed to be found. The 20°F temperature drop was selected as it would allow for a reasonably length of tube. The specific heat of the 50/50 by volume water propylene glycol mix was found to be 0.85 BTU/lb ˚F [16]. Using a manipulation of Equation (4.2.1), the mass flow can be found.

$$Q = \dot{m}C_P(\triangle T) = \dot{m}_{coolant}C_{P-coolant}(\triangle T_{in-out}) \tag{4.2.1}$$

$$\dot{m} = \frac{Q}{C_{P-coolant}(\triangle T_{out-in})} \tag{4.2.2}$$

Using the mass flow, the necessary velocity can be found using the Equation (4.2.3).

$$\dot{m} = \rho A \mathrm{v} \tag{4.2.3}$$

Where v is the velocity of the fluid flow. The density of water and propylene glycol mixture was found to be 64.93 lb_m/ft^3 [17]. The equation resulted in a velocity of 6 inches per second.

The overall heat transfer coefficient, *U*, takes into account the local heat transfer coefficients of both fluids and the separating barrier between the fluids. When the effects of fouling are negligible, Equation (4.2.4) can be used.

$$\frac{1}{U} = \frac{1}{h_o} + \frac{r_1}{k}\ln(\frac{r_2}{r_1}) + \frac{1}{h_i} \tag{4.2.4}$$

In order to find the outside heat transfer, a cylinder in cross flow was used. It was estimated there was a flow of 8 inches per second due to a current generated by the movement of fish as well as pumping of the water. The empirical relationship is given in Equation (4.2.5) [18].

$$\overline{Nu}_D = \frac{\bar{h}D}{k} = C\,\mathrm{Re}_D^m\,\mathrm{Pr}^{1/3} \tag{4.2.5}$$

The Reynolds number is characterized as [18]:

$$\mathrm{Re}_D = \frac{VD}{\nu} \tag{4.2.6}$$

With a velocity of 8 inches per second, a Reynolds number of 4000 was found using the ¾ inch stainless steel pipe and the dynamic viscosity of water at 80 degrees Fahrenheit. After finding this Reynolds, the recommended values were C = 0.193 and m = 0.618 [18]. The outside heat transfer coefficient was found to be 384.7 BTU/hr-ft^2°F.

The inside heat transfer coefficient for the propylene glycol mix was used with the constant heat flux model as the pipe would be considered to be fully developed and laminar flow with a Reynolds number of 599. This relationship is seen below [18].

$$Nu_D = 4.36 = \frac{hD}{k} \tag{4.2.7}$$

The inside heat transfer coefficient was found to be 18.3 BTU/hr-ft^2°F.

The conduction heat coefficient of 2205 Duplex stainless steel is 8.78 BTU/hr-ft°F [19]. The outer radius of the tube was 0.375 inches and the inner radius was 0.3425 inches.

The overall heat transfer coefficient was found to be 17.54 BTU/hr-ft^2°F.

Using the overall heat transfer coefficient, the overall length necessary can be calculated using Equation (4.2.8).

$$Q = UA\Delta T = U(2\pi rL)\Delta T \tag{4.2.8}$$

$$L = \frac{Q}{U2\pi r\Delta T} \tag{4.2.9}$$

Since the tank is to be split into two separate tanks, the heat to be supplied into each tank is approximated to be 20,487 BTU/hr. Using this number for the heat loss, it was determined that the necessary length of tube was found to be 165 ft in length. This would require the tube to run nearly two and a half loops with a 68 foot perimeter.

The process for designing the heat exchanger started with looking for individual components that would be necessary to complete the design. The developed schematic for the heat exchanger can be seen in Figure 5:

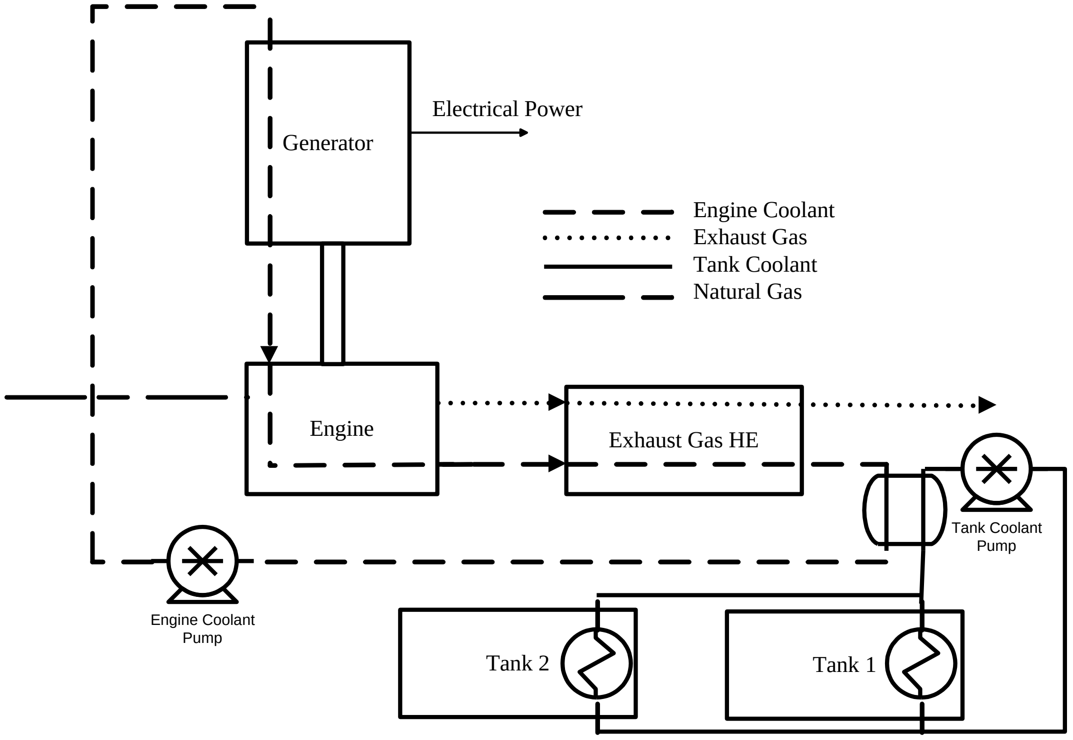


FIGURE 5: SCHEMATIC OF CHP SYSTEM INCORPORATED INTO PROPOSED AQUAPONICS OPERATION

Shown in Figure 5, to effectively capture available heat from the system, specific components are needed, which include: exhaust gas heat exchanger, engine heat exchanger, heat exchanger for the tank, and working fluid.

The first selection began with selecting the working fluid for the coolant loop. One of the most common heat exchanger working fluids is ethylene glycol. The properties of ethylene glycol are known to be completely soluble in water; therefore, ethylene glycol can be mixed with water to lower the freezing point.

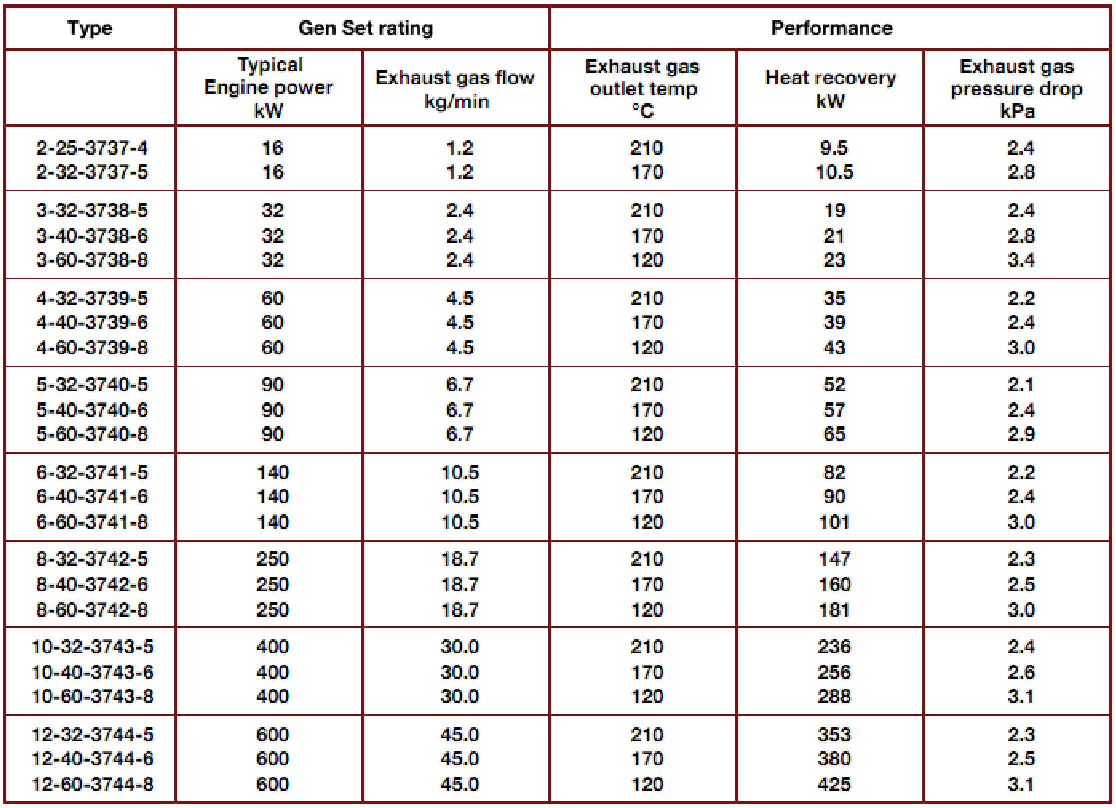
The second working fluid that had potential for our system was propylene glycol. In terms of performance, ethylene glycol and propylene glycol are very comparable. A few of the comparable differences can be found in the table presented below.

TABLE VI: GLYCOL COMPARISON ADAPTED FROM [20]

Property	Ethylene Glycol (50%)	Propylene Glycol (50%)
Viscosity (cPs)	3.4	5.4
Specific Gravity	1.082	1.050
Density (lb/ft^3)	67.05	65.14
Freezing Point (˚F)	-34	-29

However, for the use in this application, the toxicity of ethylene glycol can prove lethal to fish in small quantities [21]. With ethylene glycol being as toxic as it is, the selection of the working fluid was propylene glycol. Propylene glycol is considered to be virtually non-toxic to fish and aquatic invertebrates on an acute basis except in high concentrations [22]. Since raising fish is one the foundations of an aquaponics system, it is vital that the health not be threatened with the presence of a potentially harmful substance.

Preliminary research and design was also done on the selection of exhaust gas heat exchanger. The type of heat exchanger to be used in this application would a shell and tube heat exchanger. This would be ideal as the exhaust gas would flow opposite to the flow of the propylene glycol mix. One supplier that was found to have a wide range of products was Bowman. The exhaust gas heat exchanger performance table from Bowman is shown below.



Type	Gen Set rating		Performance		
	Typical Engine power kW	Exhaust gas flow kg/min	Exhaust gas outlet temp °C	Heat recovery kW	Exhaust gas pressure drop kPa
2-25-3737-4	16	1.2	210	9.5	2.4
2-32-3737-5	16	1.2	170	10.5	2.8
3-32-3738-5	32	2.4	210	19	2.4
3-40-3738-6	32	2.4	170	21	2.8
3-60-3738-8	32	2.4	120	23	3.4
4-32-3739-5	60	4.5	210	35	2.2
4-40-3739-6	60	4.5	170	39	2.4
4-60-3739-8	60	4.5	120	43	3.0
5-32-3740-5	90	6.7	210	52	2.1
5-40-3740-6	90	6.7	170	57	2.4
5-60-3740-8	90	6.7	120	65	2.9
6-32-3741-5	140	10.5	210	82	2.2
6-40-3741-6	140	10.5	170	90	2.4
6-60-3741-8	140	10.5	120	101	3.0
8-32-3742-5	250	18.7	210	147	2.3
8-40-3742-6	250	18.7	170	160	2.5
8-60-3742-8	250	18.7	120	181	3.0
10-32-3743-5	400	30.0	210	236	2.4
10-40-3743-6	400	30.0	170	256	2.6
10-60-3743-8	400	30.0	120	288	3.1
12-32-3744-5	600	45.0	210	353	2.3
12-40-3744-6	600	45.0	170	380	2.5
12-60-3744-8	600	45.0	120	425	3.1

FIGURE 6: EXHAUST GAS HEAT EXCHANGER PERFORMANCE TABLE FROM BOWMAN [23]

As one can see from the Gen Set Rating column, the models available have a typical engine power size of 16 kW. This is significantly larger than the size of the system needed for aquaponics. This was a common occurrence in the research for the exhaust gas heat exchanger. Many of the commercially available exhaust gas heat exchangers were easily oversized for the desired need. Since the project includes making the system cost effective as possible, the cost to purchase individual components can become detrimental to economical feasibility rather quickly. This was one of the key factors that led to the decision to purchase a generator set with the components built in.

The decision to move towards the purchase of a generator set that included the exhaust gas heat exchangers and engine heat exchangers meant that there was no longer a need to pursue further research and select the necessary components. The new direction of the design went towards selecting a suitable tube that could be used to effectively transfer heat and cause no harm to the fish living in the tank.

The new heat exchanger setup can be seen below. It should be noted that there would be two separate tanks as shown in Figure 7. This is a simplified schematic for conciseness.

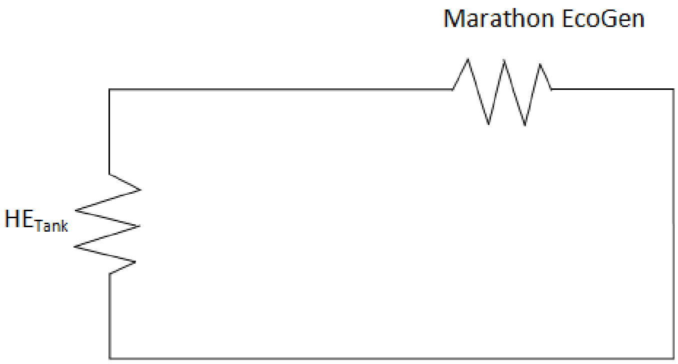


FIGURE 7: SECOND HEAT EXCHANGER SETUP

With the new approach, the necessary tube material was to be found. One of the most common heat exchanger materials is copper. A brief look into copper found that excessive concentrations of copper have a negative impact on the fish and plants. Additionally, non-metallic tubes were looked at such as PEX-AL-PEX. This synthetic tube was found to harden become unstable when exposed to sunlight, so this application of the tube was found to be not compatible. Stainless steel was the next consideration. Two types of steel were identified as primary heat exchanger materials. They were 409 and 2205 Duplex steel [24]. The next search was to find either of these tubes in a commercially available stock. 2205 Duplex stainless steel was the steel tubing that had the better selection of stainless steel tubes. Arch City Steel and Alloy, Inc. was one such company that provided a stock tube [25]. The selected tube was a ¾ inch diameter with a 0.0325 inch thickness. These numbers would be used for all heat transfer equations.

5 THERMAL LOAD MODELING AND VALIDATION

To better understand the thermal demands of an aquaponics operation a thermal model was developed quantify the energy losses from the pond and develop an energy balance for the pond-greenhouse system. To perform this analysis a MATLAB program for the tank and greenhouse was created. The following sections will detail the development of the thermodynamic model for the pond, the greenhouse, and the verification of the aquaponics thermodynamic model.

5.1 AQUAPONICS THERMAL MODELING

Several sources of heat transfer were identified, of which four were determined to be of importance while developing the thermal model for the aquaponics pond. They include: conduction into the ground, evaporation, convection, and hydroponic tank losses. Radiative heat transfer was not determined to be a significant source of thermal gains/losses and was thus not included in this model. See section 5.1.7 on page 34 for a detailed justification.

A diagram of the modeled system with the considered methods of heat transfer is presented in Figure 8.

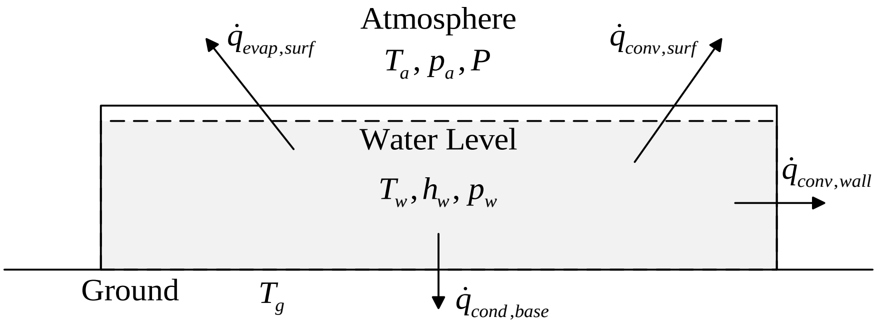


FIGURE 8: TANK HEAT TRANSFER DIAGRAM

The following subsections will detail the development of the model for each form of heat transfer presented in the previous figure.

5.1.1 WALL CONVECTION

To analyze losses through convection from the sides of the tank, a free convection model was chosen as opposed to a forced convection. The indoor environment of greenhouses and re-purposed industrial buildings eliminate the presence of wind, thus making a free convection model more representative. The convective heat loss coefficient is present in the Nusselt number, which is function of the Grashoff and Prantdl numbers for the modeled system. The following derivation has been adapted from Heat Transfer by F.A. Holland et. Al [26].

For a vertical plate with uniform wall temperature, no horizontal flow, and upward flow of the natural convection the following relations can be used to link the previous mentioned quantities:

$$Nu = 0.13(\mathrm{Gr}\,\mathrm{Pr})^{1/3} \tag{5.1.1}$$

When $(\mathrm{Nu}\,\mathrm{Pr}) = 10^9$ to 10^{12} and:

$$Nu = 0.59(\mathrm{Gr}\,\mathrm{Pr})^{1/4} \tag{5.1.2}$$

When $\left(\mathrm{Nu}\,\mathrm{Pr}\right)=10^4$ to 10^9.

In the previous equations, the Nusselt number, Nu, is:

$$Nu = hL/k \tag{5.1.3}$$

which expresses the ratio of convective to conductive heat transfer accross a boundary.

The Grashof number, Gr, is:

$$Gr = g\beta\rho^2 L^3 \Delta T / \mu^2 \tag{5.1.4}$$

which is used to approximate the ratio of buoyancy to viscous forces acting on a fluid. For this analysis, the fluid mentioned will by dry air.

The β term in Eq. (5.1.5) is the coefficient of cubic thermal expansion, given by:

$$\beta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_{\mathrm{P=cont}} \tag{5.1.6}$$

for ideal gases, the previous equation simplifies to:

$$\beta = \frac{1}{T} \tag{5.1.7}$$

where T is the absolute temperature of the ideal gas.

Finally the Prandtl number, Pr, is:

$$\mathrm{Pr} = \frac{\nu}{\alpha} = \frac{C_p \mu}{k} \tag{5.1.8}$$

which expresses the ratio of the viscous diffusion rate to the thermal diffusion rate where the meanings of the symbols in the previous equations are given in Table VII.

TABLE VII: DEFINITIONS OF SYMBOLS PRESENT IN SIDE CONVECTION THERMAL MODEL [27]

Property	Units	Description
h	BTU/(h ft^2 F)	convective heat transfer coefficient
L	ft	height of vertical surface
k	BTU/([h ft^2 (F/ft)]	thermal conductivity of fluid
g	ft/h^2	gravitational acceleration
β	K^{-1}	coefficient of cubic thermal expansion
ρ	lb/ft^3	density of fluid
ΔT	F	temperature difference between outside surface and atmosphere
μ	lb/(h ft)	dynamic viscosity of fluid
C_p	BTU/(lb F)	specific heat of air

A diagram showing the cross section of the tank walls is presented in Figure 9.

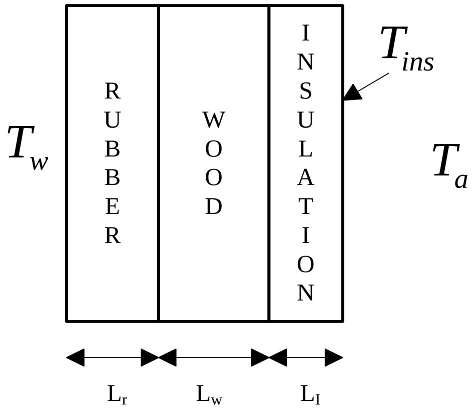


FIGURE 9: CROSS SECTION OF TANK WALL

The $\triangle T$ is the temperature difference between the outside surface of the tank, T_{ins}, and the atmospheric temperature, T_a, at a distance great enough such that it is not influenced by the tank. The temperature at the surface is dependent on the heat flux through the tank, which depends on the film heat transfer coefficient which is a function of the surface temperature. As a result, it is necessary to involve an iterative technique to determine the surface temperature and heat flux through the walls. This process can be performed through solving the following equations:

$$\dot{q}_1 = \frac{T_w - T_a}{R_{Total}} \tag{5.1.9}$$

$$\dot{q}_2 = \frac{T_w - T_{ins}}{R_{wall}} \tag{5.1.10}$$

Where T_w is the water temperature, R_{Total} is the total thermal resistance, including the convective heat transfer coefficient, and R_{wall} is the thermal resistance of the tank wall. The thermal resistances previously mentioned can be determined through the following equations:

$$R_{total} = \left(\sum_{i=1}^{n} \frac{L_i}{k_i} \right) + \frac{1}{h} \tag{5.1.11}$$

And:

$$R_{wall} = \left(\sum_{i=1}^{n} \frac{L_i}{k_i} \right) \tag{5.1.12}$$

When a T_{ins} found through an iterative approach such that $\dot{q}_1 = \dot{q}_2$, the resulting $\dot{q}$ is used to determine the thermal losses from the tank.

5.1.2 SURFACE EVAPORATION

The process of evaporation, which is the most significant source of thermal losses for the system, is also the thermal loss mechanism with the greatest uncertainty. Original models for evaporation date back to John Dalton, who based his model on his law of partial pressures. Since, there has been a cornucopia of empirical equations developed; however, most are only applicable for the situations in which they were fit and are often improperly used [28].

The process of evaporation serves to cool a body of water by removing molecules on the higher end of the kinetic energy distribution. The result shifts the distribution and results in a drop in average kinetic energy (temperature) of the water. This process is shown below in Figure 10:

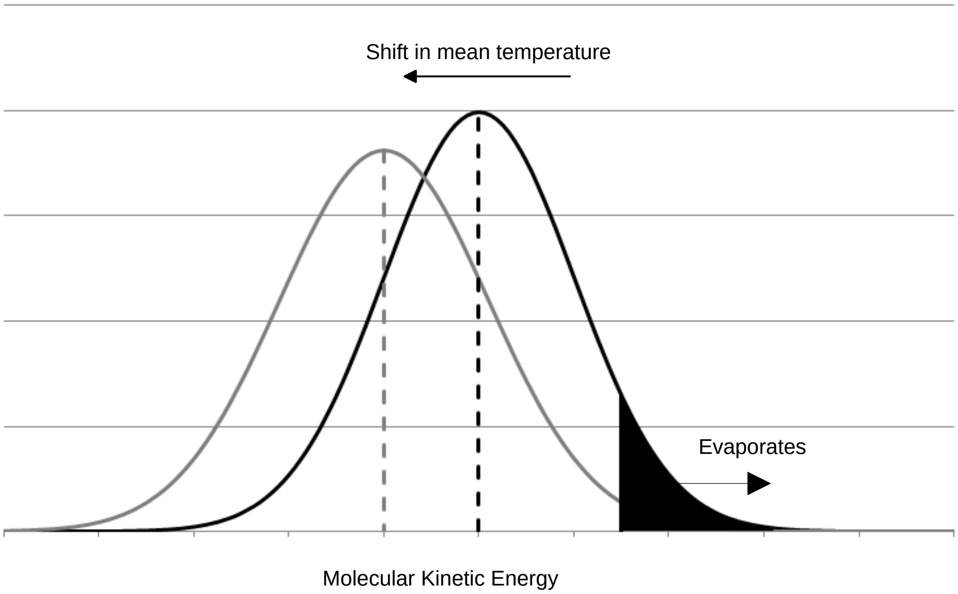


FIGURE 10: EFFECTS OF EVAPORATION ON MEAN MOLECULAR KINETIC ENERGY

In the analysis prior to the conduction of the psychrometric chamber verification an evaporation model was developed for the pond which was based on a model for solar distillation ponds developed by R.V. Dunkle. The conduction of the model verification experiment in the psychrometric chamber (See Section 5.2 on page 35) showed that the initial model poorly represented the evaporation losses from the model pond. A second theory was investigated which was developed through tests W.H. Carrier which when applied to the conditions of the psychrometric chamber yields results which correlate well with the measured response.

The following subsections will detail both evaporation models and the results are compared against the psychrometric testing in Section 5.2.2, Pg. 37. Ultimately, the model by W.H. Carrier was selected for incorporation into the final thermal model. The decision to proceed with this model is based on both the correlation of the psychrometric test results along with similarities between the aquaponics pond and the pools investigated by Carrier.

5.1.2.1 EVAPORATION BY R.V. DUNKLE

R.V. Dunkle performed extensive researched into the modeling of solar distillation ponds and has developed a model for evaporation heat transfer. The environmental conditions of these ponds are very similar to those of aquaponics tanks, thus the theory was initially adopted for this analysis. Dunkle concluded that the evaporation heat transfer can be approximated by the following equation [29]:

$$\dot{q}_e = 0.0254\left[\left(T_w - T_a\right) + \left(\frac{p_w - p_a}{39 - p_a}\right)\left(T_a + 460\right)\right]^{1/3}\left(p_w - p_a\right)h_{fg} \quad (5.1.13)$$

Where:

$$p_a = \phi p_{sat@T_a} \quad (5.1.14)$$

The definitions of each constant are presented in Table VIII.

TABLE VIII: EVAPORATIVE CONSTANTS FOR R.V. DUNKLE MODEL DEFINED [29]

Term	Units	Definition
$\dot{q}_e$	BTU/(hr-ft^2)	Evaporative losses
T_w	°F	Water temperature
T_a	°F	Ambient temperature
p_w	psi	Saturation pressure at the water temperature
p_a	psi	Partial pressure of the water in the atmosphere
$p_{sat@T_a}$	psi	Saturation pressure at atmospheric temperature
ϕ		Relative humidity
h_{fg}	BTU/lb$_m$	Heat of vaporization of water

5.1.2.2 EVAPORATION BY W.H. CARRIER

In 1918, Willis H. Carrier performed research into evaporation rates from unoccupied swimming pools and developed an empirical formula which can be expressed as follows for when the surface is subjected to parallel air flow, it is perhaps the most well used empirical formula for predicting evaporative losses from a water pool and is recommended for use by the ASHRAE. Tests conducted by Carrier were based on pool models which air was blown and no tests were performed without forced air flow. However, the equation has been widely applied to pools without airflow by setting the velocity term equal to zero [30]. The evaporation rate relationship developed by Carrier for pools subjected to parallel airflow is expressed in the following equation:

$$G = \left(0.491\right)\frac{\left(98.7 + 0.43V\right)}{h_{fg}}\left(p_w - p_a\right) \tag{5.1.15}$$

The thermal energy losses resulting from the evaporation expressed in the previous equation become:

$$\dot{q}_{evap} = \left(0.491\right)\left(98.7 + 0.43V\right)\left(p_w - p_a\right) \tag{5.1.16}$$

The definitions of each constant in the previous equations are expressed in Table IX:

TABLE IX: EVAPORATIVE CONSTANTS FOR W.H. CARRIER MODEL DEFINED

Term	Units	Definition
G	$lb_m/(hr\text{-}ft^2)$	Evaporative losses
p_w	psi	Saturation pressure at the water temperature
p_a	psi	Partial pressure of the water in the atmosphere
h_{fg}	BTU/lb_m	Heat of vaporization of water
V	ft/min	Air velocity
$\dot{q}_{evap}$	$BTU/(hr\text{-}ft^2)$	Evaporative losses

5.1.3 SURFACE CONVECTION

I.S. Bowen has shown that the process of energy loss through evaporation and diffusion of water vapor from any surface into a body of air is proportional to that energy losses resulting from convection into the same body of air [31]. The relationship is based on the ratio of the temperature gradient to the vapor pressure gradient and is represented by the following formula:

$$\frac{\dot{q}_c}{\dot{q}_e} = 0.004943\left(\frac{T_w - T_a}{p_w - p_a}\right)\frac{P}{14.7} \tag{5.1.17}$$

Where $\dot{q}_c$ is the convective (BTU/hr-ft^2) and P is the barometric pressure in (psi). The relationship has been shown to be relatively accurate and remains in standard practice today in many industries [32].

However, it should be noted that if the relationship is to be used to approximate the convective losses, as it is for this model, any uncertainties in the evaporation estimates will be transferred into the convective estimates.

5.1.4 BASE CONDUCTION

A simple conduction model was assumed for the heat transfer between the bottom of the aquaponics tank and the ground. For the development of this model, it was assumed the ground was a semi-infinite body of constant temperature. The resulting heat transfer becomes:

$$\dot{q}_{cond,base} = \frac{\left(T_w - T_g\right)}{R_{base}} \tag{5.1.18}$$

Where R_b is the combined thermal resistance of the bottom of the tank determined by:

$$R_{base} = \frac{1}{A}\left[\sum_{i=1}^{n} \frac{L_i}{k_i}\right] \tag{5.1.19}$$

For this model, it is assumed that no additional insulation other then the wood and rubber tank liner is present as a result of the structural requirements of supporting the tank weight.

5.1.5 HYDROPONIC TANK LOSSES

As a result of the circulation of water from the aquaculture tank to the hydroponics tank for filtration of the fish effluent, additional thermal losses occur. The magnitude of these losses are highly dependent on the construction of the tanks, the flow rate of the water, and the bedding material utilized and, therefore, varies greatly with the operation. Further detail into the variation of the grow bed styles of operation can be found in Section 6.1 Page 45. The style selected by the operation is related to the desired crop and yield. As a result, an exact model to predict the thermal losses associated with the grow bed was not created due to this variation. However, given the mass flow rate of water to the grow beds, the tank temperature, and an approximation of the return water temperature the thermal losses by this mechanism can be determined through the following equation:

$$\dot{Q}_{growbed} = \dot{m}_{growbed} c_{p,water} \left(T_{tank} - T_{return}\right) \tag{5.1.20}$$

This equation makes the assumption that the return mass flow rate of the water from the hydroponics operation is equivalent to the mass flow leaving the tank. A small mass lost will be associated with the process, mainly due to evaporation and absorption by the plants; although, these losses will be insignificant relative to the mass flow rate to the grow bed and can thus be ignored.

Through this method the thermal losses associated with the hydroponics portion of the aquaponics operation can be determined with great accuracy; however, an informed approximation of the return temperature must be made. For aquaponics operations which are converting to the use of a CHP system from a traditional heating method, the return temperature can be measured from the current system arrangement. For systems which are being constructed from inception to be compliant with the practices presented in this paper, an approximation will need to be made. A highest load case can always be assumed where the water will be returning to the ponds at a temperature equal to the ambient temperature of the greenhouse.

5.1.6 EFFECTS OF PUMPING AND AERATION ON THERMAL ENERGY

The process of pumping the tank water to the grow bed is closed loop system; as a result, all the mechanical energy associated with pumping will eventually be converted to thermal energy for the water. When the grow bed water returns to the tank, the pressure head resulting from the pumping has already either (a) been converted into thermal energy of the water or (b) been transferred to the surrounding greenhouse environment, assuming that the return flow velocity is small. Therefore, by using the difference between the tank and return flow temperatures, the effects of the pumping energy on the thermal losses of the tank can already be accounted for.

Power requirements for aeration are much greater than those for pumping; however, unlike pumping, this energy does not result in significant power inputs into the water. Since the aeration compression is located outside of the tank, inefficiencies from that process cannot enter the water. Bubbles resulting from the aeration in the tank displace water at the submerged depth of the aeration tube. The force on a single bubble within the tank is:

$$F_{bubble} = V_{bubble}\left(\rho_{water} - \rho_{air}\right) g \tag{5.1.21}$$

where ρ_{air} is the density of air at the mean tank depth and the water temperature. Therefore, the power input from the rising bubbles can be estimated from the following equation:

$$\dot{W}_{bubble} = \dot{V}_{bubbles}\left(\rho_{water} - \rho_{air}\right) g\ h \tag{5.1.22}$$

where h is the depth of the aeration system. For a 75 cubic-feet per minute system, equivalent to that of the UVI system, the resulting work from the aerating bubbles for a 4 foot depth tank is only 360 BTU/hr.

5.1.7 RADIATION

As previously mentioned, radiative heat transfer was neglected in the thermal model as being a considerable source of thermal losses/gains. There are two cases in which radiation would result in thermal gains or losses for the tank.

The first case, solar insolation from the sun is absorbed by the tanks surface, resulting in a temperature increase of the water. Traditionally, this would be a major consideration since solar insolation can reach as rates as high as 300 BTU/hr-ft^2. However, foliage is often located above the surface of the pond and as a result, direct solar insolation does not reach the pond surface.

For the second case, thermal losses or gains can be achieved on the tank as a result of a temperature difference between its surface and the surrounding ambient conditions. As a non-ideal black body, the radiative heat transfer from the tank to the ambient environment can be expressed as:

$$\dot{Q}_{rad} = \varepsilon\sigma A\left(T_{\mathrm{surf}}^{4} - T_{amb}^{4}\right) \tag{5.1.23}$$

With the value of the Stefan-Boltzmann constant, σ, being 0.174x10^{-8} BTUhr^{-1}ft^{-2}R^{-4}, and the close proximities of the two temperatures, the resulting radiative heat transfer which is between a factor of 10 and 20 less than the evaporative losses.

5.1.8 MATLAB MODELING

The wall convection, surface evaporation (Dunkle and Carrier), surface convection, and base conduction models introduced in the previous sections were incorporated into a MATLAB program. The program was designed to both verify the accuracy of the models and develop a thermal load profile prediction for the tank and greenhouse. When the thermal model was incorporated with the greenhouse model, yearly thermal loads can be obtained. There two models were used in the development of a thermal model.

The MATLAB scripts developed can be found in **Error! Reference source not found.**.

5.2 THERMAL MODEL VALIDATION

Due to the high uncertainty inherently present in the thermal modeling a model verification experiment was conducted to measure the accuracy of the model. This experiment was conducted in the Psychrometric Chamber installed in the Johnson Controls Laboratory at the Milwaukee School of Engineering.

The Psychrometric Chamber is capable of maintaining a precisely controlled room temperature and relative humidity through the use of air conditioning, duct heating, and air humidifiers. The chamber is instrumented for precise monitoring of these conditions which can be stored through a data acquisition interface.

5.2.1 METHODOLOGY

The greatest uncertainty in the thermal modeling lay with the prediction of the evaporative and convective losses from the tank surface. As a result, these losses were of primary interest, and the experiment designed to minimize wall convection and base conduction losses. This was done by insulating the sides and base of a fish tank with foam sheet insulation. By heating the tank water through a submersible electrical-resistive heater the operating environment of the aquaponics system was established. A schematic of the tank used for the verification is shown in Figure 11:

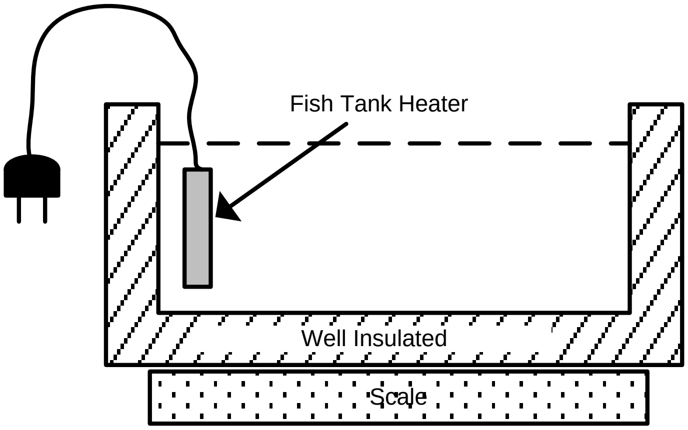


FIGURE 11: FISH TANK SETUP FOR PSYCHROMETRIC TESTING

Through measuring the mass of the tank water, the rate of evaporative heat transfer was approximated through the following equation:

$$\dot{q}_{\mathrm{evap}} = \dot{\mathrm{m}}_{\mathrm{loss}} \mathrm{h}_{\mathrm{fg,H_2O)}@T_{water}} \tag{5.2.1}$$

The mass of the water was determined through the weight of the water on an electric scale which could obtain an accuracy of 0.1 $\mathrm{lb_m}$. It was debated implying mass loss through the change in volume of water in the tank, however this method would only have been able to achieve a accuracy of approximately 0.64 $\mathrm{lb_m}$. Additionally, implying mass through the volume would be subjected to uncertainties as a result of the effects of water temperature on density.

Energy input into the tank can was measured though an inductive current sensor attached in-line with the electric resistive heater. Knowing the energy input, the convective heat losses can be approximated through the following equation:

$$\dot{q}_{conv,surf} = \dot{q}_{in} - \dot{q}_{evap} - \dot{q}_{conv,wall} - \dot{m}c_{p,water}\frac{dT_{water}}{dt} \tag{5.2.2}$$

It should be noted that in the previous equation the wall convection term cannot be measured precisely; therefore, the convection term from the model will be applied.

To minimize the effects of the last term of the previous equation, which incorporates the energy needed to change the temperature of the water in the tank, the water temperature was held approximately constant. This was done through a controls system included in the heater utilized. It was later noticed that due to random deviations in the temperature measurements of the tank water, the resulting slope dT/dt from first order numerical differentiation methods resulted in unrealistic energy transfer associated with the change in water temperature. This was solved by applying a smoothing function to the tank water temperature, which eliminated short term deviations while maintaining long term trends.

Two tests were conducted on the model tank. The testing conditions for each run are shown in Table X:

TABLE X: TESTING ENVIRONMENT FOR PSYCHROMETRIC EXPERIMENT

	Trial 1	Trial 2
Tank water temperature (F)	~72	70
Atmospheric temperature (F)	50	60
Relative humidity (%)	50	31
Total run time (min)	100	210

During Trial 1 it was found that the water heater was incapable of providing the power to maintain a constant tank temperature at any point during the run. Although the thermal relationship shown in Eq. (5.2.3) can account for these transient conditions, it was decided to perform a second run, Trial 2. During this trial the ambient temperature was set slightly higher such as to decrease the evaporative losses slightly. Although both trials results correlated well with the thermal dynamic model, the following section will focus primarily on Trial 2 since the testing environment during this run was closer to that which the pond will experience in its normal operating environment.

5.2.2 RESULTS

Atmospheric and tank temperatures, relative humidity, and heater power for Trial 2 of the validation testing are presented in Figure 13. From this plot it can be seen that the system took approximately one hour of run time until steady state operating conditions could be reached. Additionally, from the power plot it can be seen that the fish tank heater operated in a cyclical patter, switching between on and off to maintain the water temperature. This duty cycle was built into the hardware of the heater and was not able to be controlled during this investigation. As a result of the thermal capacitance of the system the duty cycle of the heat can be approximated as a steady input into the system with an equivalent energy input. This average is shown in the bottom plot of Figure 13.

From the evaporation rate plot, shown in Figure 12, it was apparent that the R.V. Dunkle model was not accurately predicting the evaporative mass losses experienced by the fish tank during the investigative study performed. From this realization, a second theory was investigated which resulted in the adoption of the W.H. Carrier model previously described. A wind speed of 150 ft/min was incorporated into the model to account for the wind velocity term in the model. This estimate was based on typical indoor airspeed resulting from duct heating.

Shown in Figure 14, the primary heat losses for the tank are compared against the predicted values. From this plot it can be seen that the model developed accurately predicts the thermal losses when compared against the losses measured in the investigative study.

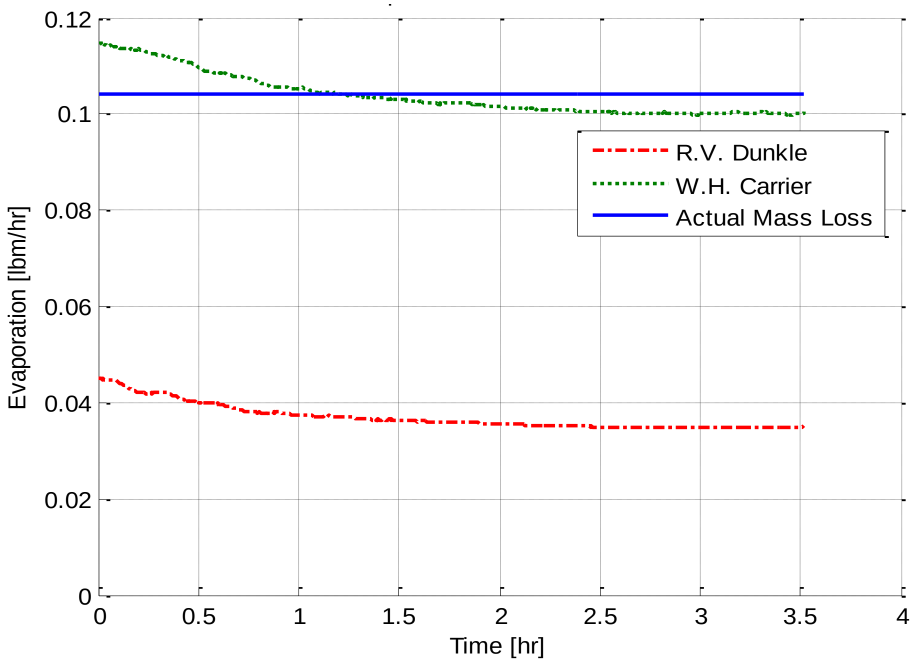


FIGURE 12: COMPARISON OF PREDICTED EVAPORATIVE LOSSES FOR TANK BASED ON R.V. DUNKLE AND W.H. CARRIER MODELS.

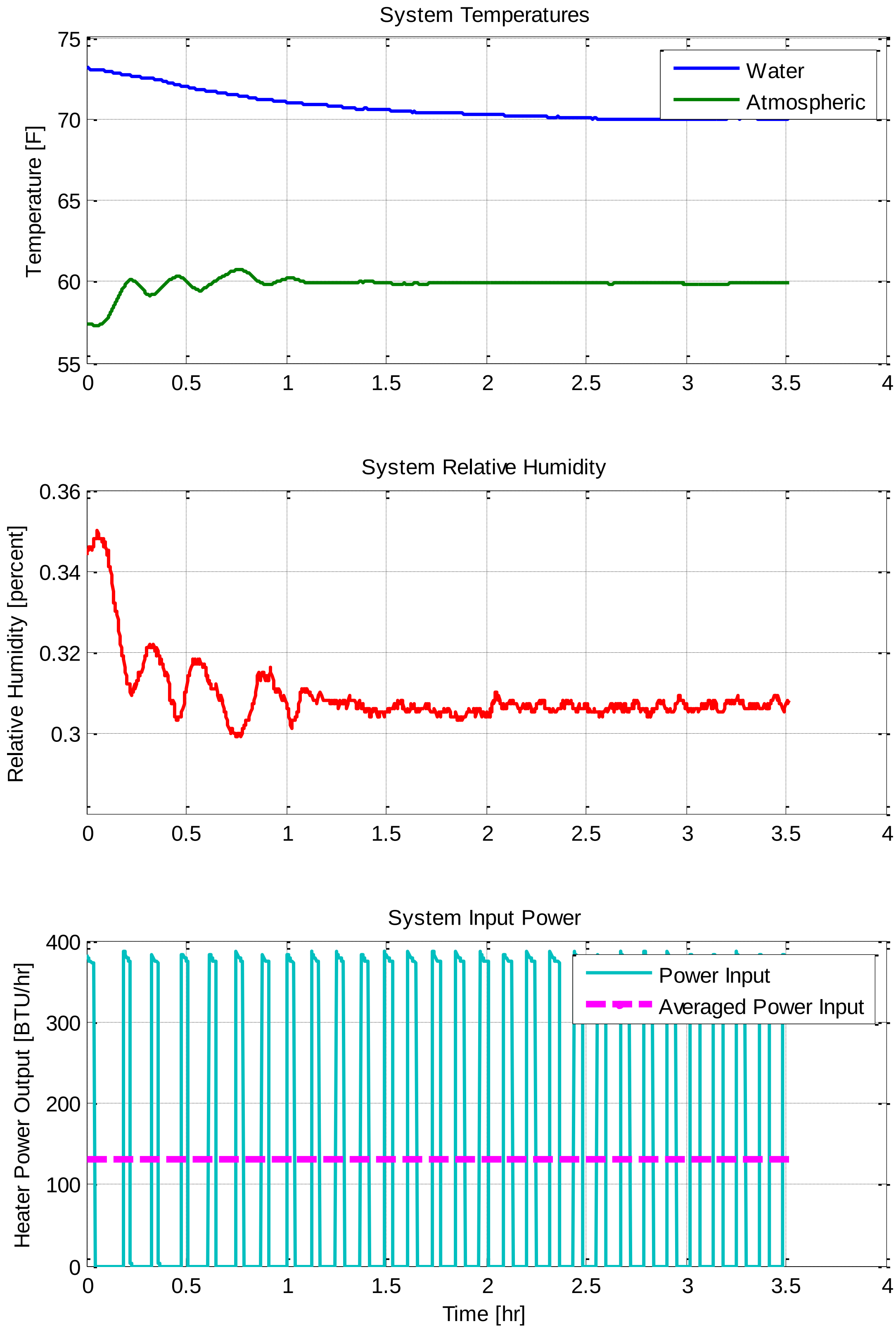


FIGURE 13: SYSTEM TEMPERATURE (TOP), RELATIVE HUMIDITY (MIDDLE) AND HEATER INPUT POWER (BOTTOM) FOR PSYCHROMETRIC TESTING EXPERIMENT (TRIAL 2).

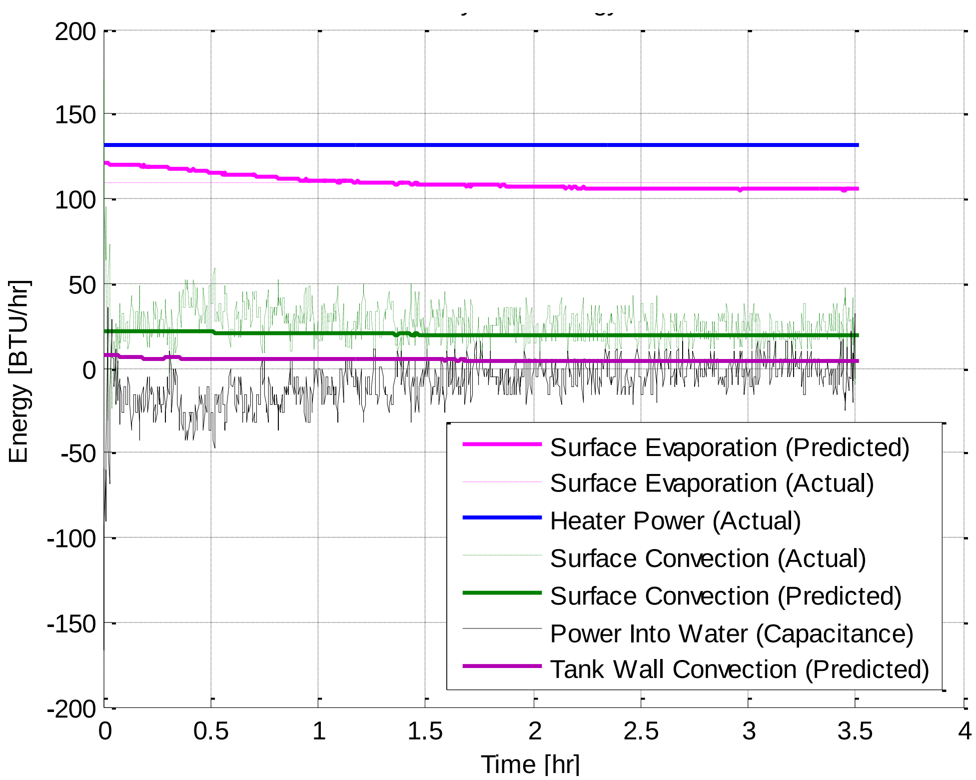


FIGURE 14: COMPARISON OF PREDICTED AND ACTUAL THERMAL LOSSES FOR TANK MODEL (UTILIZING W.H. CARRIER EVAPORATION MODEL)

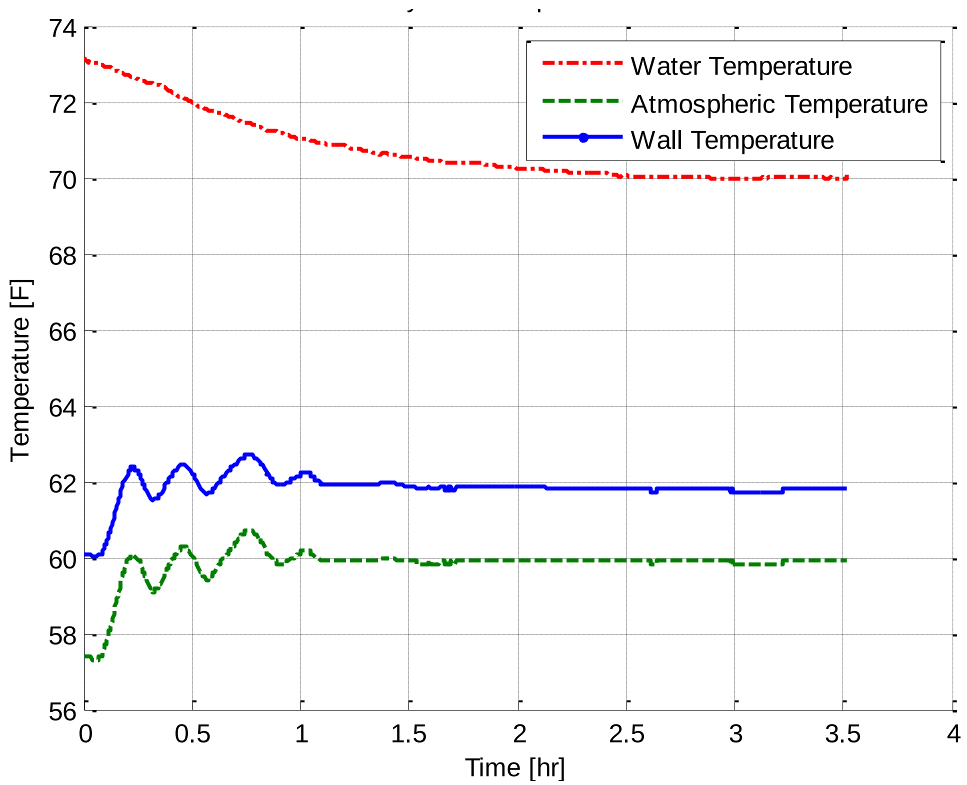


FIGURE 15: PREDICTION OF TANK WALL TEMPERATURE BASED ON THERMAL WALL CONVECTION MODEL.

5.2.3 VALIDATION RESULTS SUMMARY

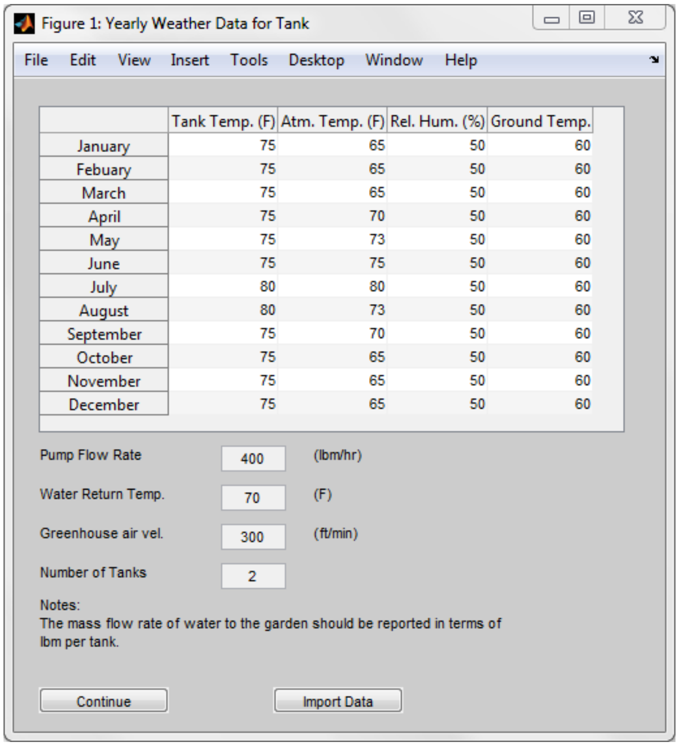
As presented in the previous figures, the thermal model with the W.H. Carrier evaporation equation fits well with the thermal results from the investigative study performed in the Psychrometric Chamber. Based on this verification, the thermal model presented was used to develop the load profile for the aquaponics pond.

5.3 MONTHLY LOAD PROFILE PREDICTION

Based on the success of the thermal model verification experiment, a monthly load profile program was developed. This program was designed to estimate the thermal output of the pond into the greenhouse to determine the loading on the CHP system along with energy savings to the greenhouse. It is important to mention that the evaporative and convective thermal losses from the pond serve as direct thermal inputs into the greenhouse; therefore, they can be discounted from the economic costs of maintaining the temperature of the greenhouse. The program presented in this section will focus solely on predicting the thermal losses from the pond. A model presented in Section 5.4 on Page 43 will discuss the thermal model for the greenhouse, which when combined will develop a monthly load cycle for the combined systems. The combined load cycle will be used estimate payback period and greenhouse gas emissions.

The program developed allows the user to import monthly temperature, relative humidity, pump flow rates, water return temperature, and greenhouse air velocity. The program will also prompt the user for a parameters sheet containing the dimensions and insulation values for the tank. Based on these inputs and the thermal model presented previously, section monthly loading estimates can be obtained for the aquaponics pond. Since the program estimates the losses for the tank, ambient conditions such as temperature and relative humidity should be based on the indoor conditions of the greenhouse.

The user interface for the program is shown in Figure 16. The data presented in the window is not representative of the final design presented in this report. The values were included for demonstration purposes only. Based on these values a yearly load profile based on the entered data is shown in Figure 17.



	Tank Temp. (F)	Atm. Temp. (F)	Rel. Hum. (%)	Ground Temp.
January	75	65	50	60
Febuary	75	65	50	60
March	75	65	50	60
April	75	70	50	60
May	75	73	50	60
June	75	75	50	60
July	80	80	50	60
August	80	73	50	60
September	75	70	50	60
October	75	65	50	60
November	75	65	50	60
December	75	65	50	60

Pump Flow Rate: 400 (lbm/hr)

Water Return Temp.: 70 (F)

Greenhouse air vel.: 300 (ft/min)

Number of Tanks: 2

Notes:
The mass flow rate of water to the garden should be reported in terms of lbm per tank.

FIGURE 16: GRAPHICAL USER INTERFACE FOR AQUAPONICS MONTHLY LOAD PROFILE PROGRAM

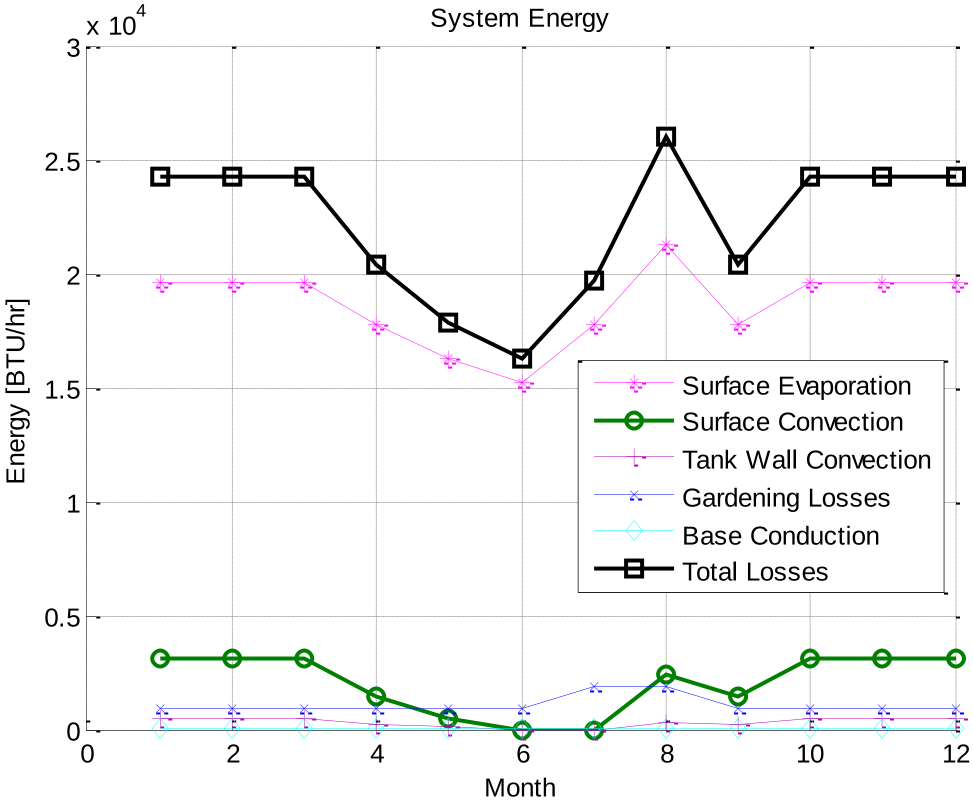


FIGURE 17: THERMAL LOSSES BY SOURCE OBTAINED FROM MONTHLY LOAD PROFILE PROGRAM

5.4 GREENHOUSE MODELING

Greenhouses are used to maintain an ideal environment for the growth of crops where they can be protected from undesirable weather along with protection from destructive parasites and wildlife, without the use of pesticides. Although repurposed industrial spaces can be used for aquaponics operations, the greenhouse is preferred since the transparent covering material allows for natural solar irradiance to be used for plant growth, eliminating the need for artificial lighting.

Both active and passive control systems are used to modify the conditions produced within the greenhouse to further maintain the desired ideal internal environmental conditions. These active controls include heating during the winter months and cooling during the summer along with humidification. The presence of plants can greatly affect the environment within a greenhouse. In some instances plants, can serve as a buffer, resisting change while in other cases plants can serve as a driving force of change. The magnitude of these changes can often dwarf all other factors which effect the environment within a greenhouse [33]. Since the prediction of these factors lies in the biology of the plants a complete model for the greenhouse is beyond scope of this project and outside the field of the project team members. While we did not specifically address the biology in developing a thermal model, a model was obtained based on a developed by the Canadian Plan Service and is presented in Plan M-6701 – Greenhouse Heating Requirements.

The greenhouse thermal model presented in this paper is designed to estimate the average thermal losses for a greenhouse and can take into account factor which include, but not limited to: building material, quality of construction, and purpose.

The greenhouse heat losses can be determined by the following [34]:

$$\dot{Q}_g = \left[\sum_{i=1}^{n} \frac{A_i}{R_i} \right] (t_i - t_o)(f_w)(f_c)(f_s) \tag{5.4.1}$$

The definition of the terms present in the equation are defined in Table XI:

TABLE XI: DEFINITION OF SYMBOLS PRESENTED IN GREENHOUSE HEATING EQUATION

Property	Units	Description
$\dot{Q}_g$	BTU/hr	Thermal losses from greenhouse
A_i	ft^2	Surface areas of various components
R_i	Ft^2-F/BTU	Thermal resistances of various components
t_i	F	Inside desired ambient temperature
t_o	F	Outside design temperature
f_w	-	Wind exposure factor
f_c	-	Construction quality factor
f_s	-	System purpose factor

The model presented in this paper was modified slightly to account for the effects of solar radiation. From the National Oceanic and Atmospheric Administration (NOAA) average monthly insolation for any location can be obtained. If it is assumed that the thermal capacitance of the greenhouse with the aquaponics pond is great enough that there are minimal temperature fluctuations between night and day, the thermodynamics of the greenhouse can be analyzed on a monthly basis. The net thermal loss from the greenhouse can be expressed as:

$$\dot{Q}_{g,netloss} = \dot{Q}_{g,loss} - \frac{I_{month}}{24} \tag{5.4.2}$$

Using an example greenhouse from the Plan M-6701 publication, which is approximately 40 by 100 ft, a representative size for an aquaponics greenhouse using average monthly temperature and insolation data for Milwaukee, a thermal profile was generated. The energy profile generate is presented in Figure 18. From this plot, it can be seen that between the months of October through April, the greenhouse heating requirements are greater than the aquaponics losses. Therefore, during these months the aquaponics losses can be directly subtracted from the heating requirements for the greenhouse.

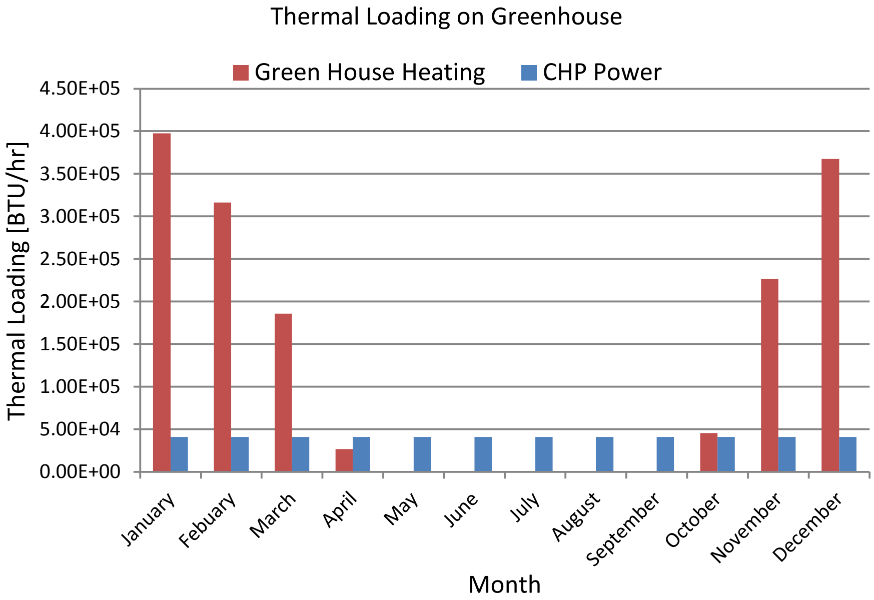


FIGURE 18: ANNUAL PROFILE FOR GREENHOUSE HEATING FROM MODIFIED PLAN M-6701

6 NON-THERMAL LOADING

Mechanical power requirements of any aquaponics system are primarily to pump and aerate the water. All of the aquaponics systems studied utilized an elevation difference between each component of the system thus requiring a pump. Water aeration is essential for the rearing tank in order to have greater fish stocking densities it also functions to keep nutrients suspended in the water. Additionally, in some systems, particularly raft type aquaponics, aerating the hydroponic tank water is important to promote healthy root growth. Artificial lighting power estimates are also given for supplemental lighting needed for an 18 hour grow period in a greenhouse. Although artificial lighting is not required for aquaponics, it is an option that farmers have chosen to implement and therefore is considered. Artificial lighting has the added benefit of inducing plants to fruit quicker than sunlight. At higher latitudes, grow lights can be especially helpful during winter months when the sun has less intensity at the wavelengths plants thrive at as well as the shorter duration light is available.

An interactive Excel spreadsheet where a user can input design parameters was created. The user can use this tool to estimate pumping, aerating, and artificial lighting power to investigate power requirements as the scale changes. The University of the Virgin Islands (UVI) provided a representative aquaponics system that was studied in order to obtain key proportioning constants that facilitate scaling of systems. This system can be used as a model to construct others due to the proven functionality as well as a connection to a university.

Power calculations were verified by the values quoted by the UVI system. Pumping resulted in a power requirement of 1/2 HP, which is the same as specified by UVI. Aeration was 1.1 Hp which is 26% lower than the UVI system; however, it is uncertain what type of blower is used as well as the sizing method. It was estimated that if artificial lighting was used for this setup in Milwaukee Wisconsin to ensure an 18 hour grow time throughout the year is 51.9 MWh. The power requirements to cover 2304 ft^2 of grow bed with artificial lighting is 24.5 kW.

6.1 COMMERCIAL SCALE RAFT AQUAPONICS SYSTEM

A raft aquaponics system developed by Dr. James Rakocy and the University of the Virgin Islands (UVI) will be used to verify calculated power requirements such as pump work, and tank aeration as well as provide a standard model that can be scaled proportionately to. The UVI raft aquaponic system has four fish rearing tanks and six hydroponic tanks. There are also water conditioning components such as two clarifiers and two degassing tanks. The system pump is located between the sump and the rearing tanks. Gravity draws the water through the hydroponic tanks and other components. A schematic is shown in Figure 19. Tilapia and leaf lettuce are grown using this system. Lettuce is grown with its roots draped in the effluent water stream and supported by Styrofoam rafts. Fish are stocked in each tank at a density of 0.5 lb/gallon.

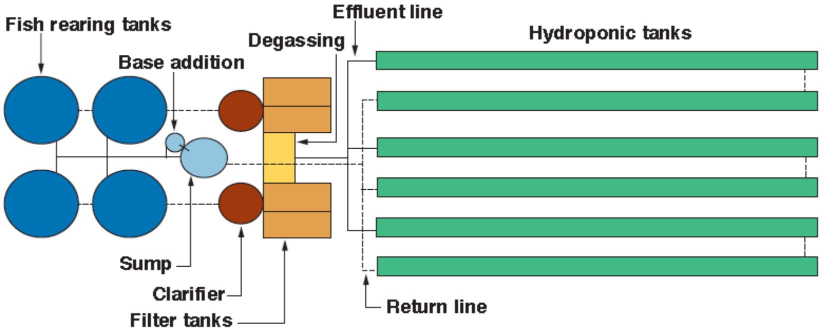


FIGURE 19 UVI SYSTEM SCHEMATIC LAYOUT [35]

Power requirements and major dimensions of the UVI system are given in Table XII. Hydraulic retention time and hydraulic loading rate will be two design parameters calculated from this system. These two parameters along with feed conversion ratio of the fish and feed rate will be used to proportion the rearing tanks to hydroponic tanks at varying fish tank capacities. The net energy consumption per day for continuously running blower and water pumps is 53 kWh. It is assumed that the UVI system was run using electrical energy and has no thermal energy requirements due to the Caribbean climate.

TABLE XII: PHYSICAL DIMENSIONS OF THE UVI RAFT AQUAPONICS SYSTEM [35]

Parameter	Dimension
Rearing Tanks (4x2060gal)	8,200 gallons
Total System Water	29,300 gallons
Total Growing Area	2300 sq. ft.
Flow Rate	100 GPM
Water Pump	0.5 HP
Hydroponic Tank Aeration	1.0 HP
Rearing Tank Aeration	1.5 HP
Daily Energy Consumption	53 kWh

The hydraulic loading ratio (HLR) is a ratio of influent waste stream to the total hydroponic surface area shown in Equation (6.1.1). Once the HLR is known, flow rate can be calculated for any given hydroponic tank grow area. According to a study performed on three 264 gal rearing tanks in a small scale recirculating aquaponics system, an optimal HLR was found to be 4.2 ft/day [36]. The HLR of the UVI system is 8.35 ft/day; therefore, caution should be used when proportioning a system that is much less than the UVI system since it appears the HLR can change. Commercial scale aquaponics systems are within the scope of this project, therefore the HLR from UVI will be used.

$$HLR = \frac{Flowrate}{A_{GrowBed}} = 8.35\, {}^{ft}\!/_{day} \tag{6.1.1}$$

The hydraulic retention time (HRT) is a measure of the time the effluent water resides in the hydroponic tank. This is the second design parameter chosen to scale an aquaponics system. The HRT is a proportion of water volume and its flow through a medium shown in Equation (6.1.2). In flood and drain aquaponics systems effluent flows through a medium such as gravel, sand or coconut husk. In these instances the porosity would be something less than 1. For instance Growing Power uses a coconut husk biofilter material the porosity (Φ) of the material is 0.47 [37].

$$HRT = \frac{WaterDepth\left(A_{GrowBed}\right)\theta}{Q_w} = 172\min \tag{6.1.2}$$

The feed conversion ratio varies for the different types of fish the system will use. Tilapia have an average FCR of 1.7. This is to say that 70% of what tilapias eat will be excreted and used as plant fertilizer. The feed rate ratio establishes the relation between total hydroponic tank surface area to the total feed that is being introduced to the system shown in Equation (6.1.3). The UVI system quotes feed rates 0.0123 lb/ft^2-day to 0.0205 lb/ft^2-day. The feed rate was solved from given parameters in the UVI system report [35].

$$A_{GrowBed} = \frac{SC(FCR)}{T(FRR)} = 2304\,ft^2 \qquad (6.1.3)$$

Where:

- S is the fish stocking density
- C is the rearing tank capacity
- FCR is the feed conversion ratio
- T is the maturation period of the fish
- FRR is the feed rate per area of tank surface

Hydraulic loading, retention time, and feed rate are the system characteristics that will remain constant when a system is scaled. These calculations result in a ratio of rearing tank volume to hydroponic tank volume for a raft style system of 0.48.

6.2 PUMPING POWER CALCULATIONS

The schematic of an aquaponics system given in Figure 20 represents a generalized system configuration. There are many variations on how a system could be set up, but this represents common elements in all systems: elevation difference, single pump, and piping entrance and exit conditions. The Excel spreadsheet gives the user a choice for pipe length, pipe diameter, number of elbows, check valves, gate valves and elevation difference. The pump will supply fish effluent to the top grow bed and gravity will drain back to the fish tank. There are a variety of other configurations possible, but this can be used for a general approximation for pump power requirements.

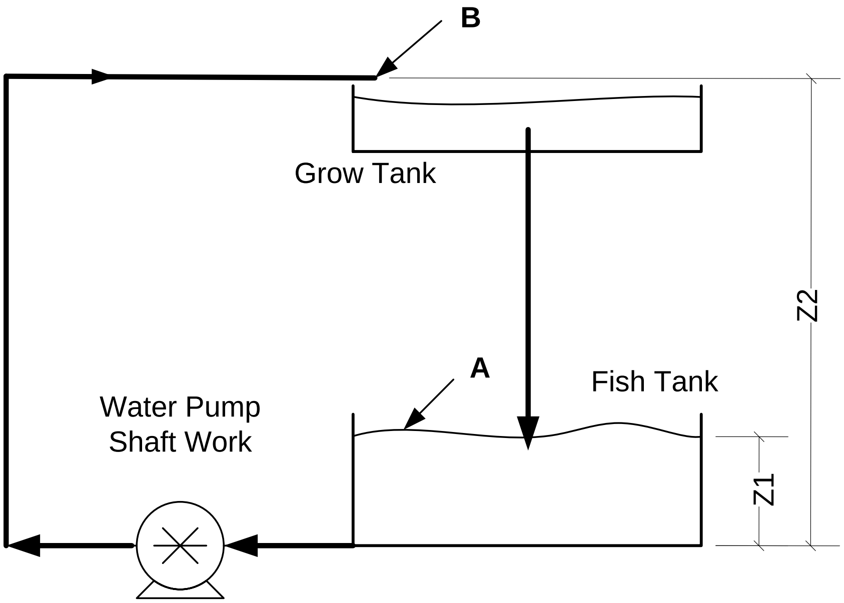


FIGURE 20: AQUAPONICS PLUMBING SCHEMATIC

A modified Bernoulli equation can be written between points A and B and is shown in Equation (6.2.1). It is assumed constant 1” diameter cross section and smooth plastic tubing is used. The pressure at A and B are both at atmospheric. The simplified is shown in Equation (6.2.2).

$$\frac{P_A}{\rho g}+\frac{v_A^2}{2g}+z_1+h_{Pump}=\frac{P_B}{\rho g}+\frac{v_B^2}{2g}+z_2+K_L\frac{v_B^2}{2g} \tag{6.2.1}$$

Where P_A, P_B, and v_A all equal zero.

$$h_{Pump}=\frac{v_B^2}{2g}(1+K_L)+(z_2-z_1) \tag{6.2.2}$$

In order to calculate the loss coefficient, K_L, the flow in the pipe must be determined either turbulent or laminar flow. The Reynold’s number, Re, is a dimensionless parameter used to determine this and is calculated in Equation (6.2.3) where dynamic viscosity, μ, density, ρ, are fluid properties specific to water and “d” is the pipe diameter used. The second parameter needed to find the dynamic friction factor is the relative roughness which is the roughness of the pipe per diameter. A Moody chart was used to reference the friction factor and was found to be 0.011 [38].

$$\mathrm{Re}=\frac{\rho v_B d}{\mu}=107714 \tag{6.2.3}$$

$$\mathrm{Re}>10{,}000 \therefore \text{Fully Turbulent Flow}$$

The equivalent pipe length method [38] of determining friction loss in pipe flow is akin to replacing the elbow in a pipe with a straight length of pipe that would yield the same frictional losses. The equation used to calculate the effective loss coefficient for two elbows is Equation (6.2.4) which uses an equivalent length to diameter ratio of 30 for each elbow. It was estimated that 12 ft of piping and two elbows were used in the system shown in Figure 20.

$$K_L=(number\,of\;elbows)(f)\left(\frac{PipeLength}{Diameter}\right)=0.66 \tag{6.2.4}$$

Table XIII shows the applicable loss coefficients and the corresponding equivalent length per diameter. A pipe diameter of 3” was chosen according to the UVI system. The total loss coefficient is 2.71. The pipe entrance was assumed to be a sharp-edged inlet and the exit was assumed to be an inward projecting pipe.

TABLE XIII: CALCULATING THE EFFECTIVE LOSS COEFFICIENT USING THE EQUIVALENT PIPE LENGTH [39]

	Quantity	Equivalent Length [L/D]	Loss Coefficient K_L
Elbow:	2	30	0.66
Pipe Friction:	N/A	48	0.55
Entrance Loss:	N/A	N/A	0.5
Exit Loss:	N/A	N/A	1
	Effective Loss Coefficient:		2.71

An elevation difference between Z_1 and Z_2 was chosen to be 8 feet. This is slightly taller than the typical elevation difference seen at Growing Power. It is important to note that this elevation difference must drive the water to flow through the hydroponic tanks and other system components. Solving for the pressure head added by the pump "h_{pump}" from Equation (6.2.2) pump must add 8.874 ft of H_2O. The mechanical pump work is then found from Equation (6.2.5). An estimated 45% electrical to pumping work conversion efficiency "η" was used. This efficiency was calculated from a standard commercially available centrifugal pump operating at its maximum efficiency.

$$\dot{W}_{mech,actual} = \frac{\rho g h_{Pump} Q}{\eta} \tag{6.2.5}$$

A ½ HP pump is sized for this system according to the foregoing calculations, which equivalent to that of the UVI system.

6.3 TILAPIA INTENSIVE STOCKING AERATION POWER REQUIREMENTS

Aerating the water is another power requirement of the proposed aquaponics system. When the water falls from the grow tank back into the fish tank, the water is aerated. However, the large tank sizes required for commercial operations as well as the high fish stocking densities require additional aeration. As a rule of thumb tilapia shouldn't be stocked at greater than 0.5 lb/gal [40]. However, red tilapia can be stocked at a density of 0.59 lb/gal [40]. In order to survive tilapia will require dissolved oxygen (DO) concentrations greater than 5ppm [40]. This DO requirement can be supplied through flow rates of 6 to 12 GPM for moderately stocked systems. Intensive tank culture seen on the commercial scale requires additional aeration to supplement oxygenation from water flows. However, this will only supply enough oxygen for moderate stocking densities.

Tilapia consumes oxygen at a rate three times greater while eating than they do at rest. It is chosen to use the highest DO requirement in sizing an aerator. However, the farmer should consider using maximum power during feed times and reducing power during rest times to conserve power and lessen electrical load requirements. During feeding tilapia use as much as 135 mg O_2 per pound of fish each hour. Therefore the actual oxygen requirement (AOR) can be calculated by Equation (6.4.1).

$$AOR = SC(DO) = 0.021\,{}^{lb}\!\!/_{\min} \tag{6.4.1}$$

Where

- AOR is the actual oxygen requirement
- DO is the dissolved oxygen

A procedure for adjusting the AOR to a standard oxygen requirement (SOR) will be provided using a formula commonly used in wastewater treatment [41]. Wastewater treatment aerates soiled water as well as supplying proper DO levels to biological organisms in the effluent. This is the most scientific and applicable approach to converting AOR to SOR found in researching the topic. In converting the AOR to a SOR there are a few factors that adjust the solubility of water. Firstly, the temperature and altitude must be considered. An increase in temperature acts to decrease solubility of oxygen in water. Higher altitudes have a similar effect on oxygen solubility. Additionally, the amount of dissolved particles and suspended solids will make an impact on the AOR/SOR conversion. Equation (6.4.2) is the conversion equation used.

$$\frac{AOR}{SOR} = \alpha \left[\frac{\left[\beta \left(\frac{P_f}{P_{MSL}} \right) C_{sat_T} \right] - DO_{Field}}{C_{sat_{20}}} \right] \theta^{T-20} = 0.20 \tag{6.4.2}$$

A complete explanation of the variables as well as charts to aid in determining the adjustment factors can be found in a guide produced by SANITAIRE available publicly [41].

Alpha (α) represents a ratio of mass transfer coefficients for the rearing tank water to clean tap water. In the absence of testing, a recommended range of 0.5-0.6 is to be used for fine bubble aeration systems. A value of 0.6 was chosen for the rearing tanks since round rearing tanks are more favorable and there are fewer suspended solids than wastewater treatment.

Beta (β) is a factor that adjusts for dissolved solids. A value of 0.98 based on recommendation from the article.

Pressure at the field (P_f) and pressure at mean sea level (P_{MSL}) were figured from atmospheric data for Milwaukee, WI.

Dissolved Oxygen (DO_{Field}) requirement was a reference value found in a tilapia tank culture study done by Dr James Rakocy and is 5ppm.

The two solubility (C_{SAT}) variables were calculated from tables for an aeration device submersed at 4 ft in 85°F water. The solubility of the device at 68°F is approximately 9.4 ppm and solubility at 85°F is 8.0 ppm.

Theta (θ^{T-20}) represents a water temperature correction factor. This factor was interpolated from a table produced by Sanitaire. The resulting factor was 1.25 at a temperature of 85°F.

The SOR for the UVI system is roughly five times larger than the AOR. Primary drivers are the water temperature, and the mass transfer coefficient ratio. The SOR for the system is 0.10 lb of oxygen per lb of fish every hour.

Oxygen transfer efficiency (OTE) refers to the amount of oxygen a particular air bubble moving through the water will transfer to the water. This efficiency is a strong function of submersion and bubble size. Empirical studies performed by Sanitaire provide these two rules of thumb. Course bubble aeration will typically add 0.75% for each additional foot submersed. Fine bubble aeration will gain 2% for each additional foot submersed. It is expected that most aquaponics systems will diffuse air at a depth of 4 feet which would result in an OTE of 3% for coarse and 8% for fine bubbles.

Equation (6.4.3) combines all that has been discussed into one equation to convert AOR to the standard cubic feet per minute (SCFM) blower output requirement.

$$\text{Blower Output} = \frac{(AOR)}{0.2(OTE)0.0173\, {}^{lbO_2}\!/_{SCFM}} = 75.3\ \text{SCFM} \tag{6.4.3}$$

In order to quantify how much power the blower requires, the pump will be approximated by an adiabatic compression process. The adiabatic approximation will then be adjusted by pump efficiency. Regenerative blowers are quite commonly used for aeration processes. They feature medium to large volume of air movement at relatively low pressures (1-5 psi). Approximately 15 different models of regenerative blowers of ranging power from 0.25 HP to 3 HP were evaluated for electrical to fluid power conversion efficiency. This range of regenerative blowers had an average of 66% efficiency and standard deviation of 2%. Unit conversions as well as air properties evaluated at standard temperature and pressure were used in calculating the 0.22 factor.

$$\dot{W} = \frac{Q\rho C_p T}{\eta}\left[\frac{P_2}{P_1}^{\frac{\gamma-1}{\gamma}} - 1\right] = 1.1Hp \tag{6.4.4}$$

The output pressure requirement of the blower has two components one being the pressure head from being submersed in a column of water and the second being the minor losses due to piping.

In order to estimate the head loss of the aeration piping the method of equivalent pipe length was used. Quantifying the pipe losses were significant enough that they could not be neglected. However, the methods for aerating tanks depend on number of tanks, tank geometry, distance between tanks, as well as the number of pipe branches, diameter of pipe, and flow rate. In order to use this power estimation calculator as a planning tool for future farmers, two scenarios were used to bracket the head loss as a percentage of the water column pressure due to submersion. A high estimate of pressure head loss is 35% and a low estimate is 15%. The equivalent pipe length method for estimation, four rearing tanks and the flow rate of the UVI system were used in both scenarios. The low estimate used an equivalent straight length of tubing of 82 ft and 2” dia. The high estimate used an equivalent straight length of 207 ft of pipe diameters varying from 2” to 1” and 12 branches. In both cases, blower diffusers are submerged in 48” of water. Using the high estimate of head loss the total output pressure would be 64.5 in H_2O, or 2.3 psig.

The UVI system uses a 1.5 HP blower for the rearing tanks. The blower is sized as 1.1 HP using this method which is 26% lower. It is unknown which type of blower the UVI system uses, but if the electrical-water flow conversion efficiency of the blower is 47% the size is proper.

6.4 ARTIFICIAL LIGHTING POWER ESTIMATION

Artificial lighting is a requirement for some systems such as Sweetwater Organics in Milwaukee, WI. Sweetwater Organics must use artificial lighting to illuminate the old warehouse housing the urban farm. Other commercial aquaponics systems do not use artificial lighting such as Growing Power in Milwaukee, WI. Still others decide to supplement the sun with artificial light due to the advantage of quicker growing times and lessening the impact of seasonal daylight fluctuations.

The approach to artificial lighting is to determine the number of hours the lighting will be on and then find the power required to illuminate a given growing surface area. In calculating the number of hours artificial lighting is used a day with 18 hours of sunlight will be considered as this is the maximum time that plants will grow for before darkness is required [42].

Sunrise and sunset data for Milwaukee, WI were used to calculate the amount of supplemental lighting is required to achieve 18 hours of light each month. For instance, the month of December requires 277 hours of supplemental lighting. Dusk and dawn was considered sufficient sunlight and no adjustment was made to accommodate them. If only one kilowatt is used to illuminate the farm a load of 277 kWh would be needed for the month of December. This is $34.95 assuming one kWh costs $0.126. Yearly load was calculated as 2120 kWh and $267.30. Figure 21 shows the monthly totals of supplementary artificial lighting for 18 hours of daylight. In the case of little or no access to sunlight, artificial lighting can be used to grow plants. An 18 hour grow period in this case would result in a monthly energy demand of 558 kWh for a 1 kW system or $70.31 per month.

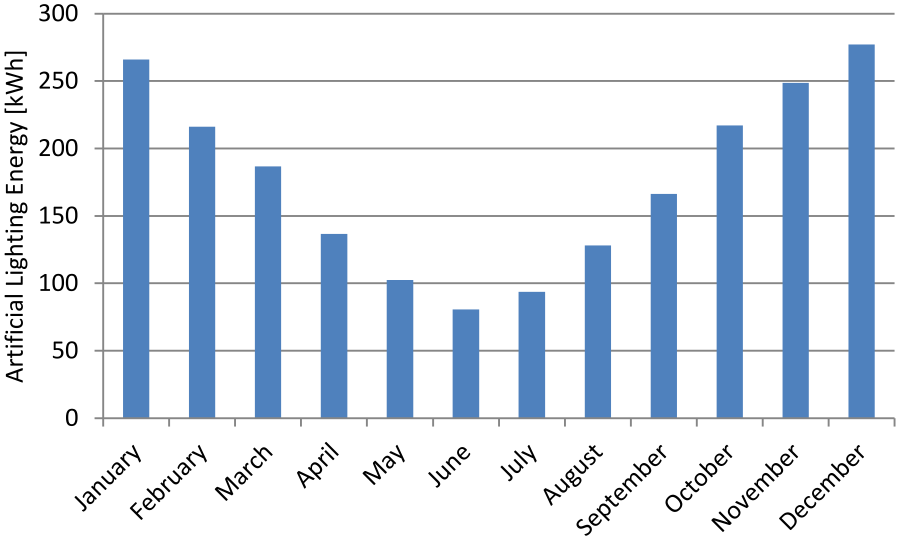


FIGURE 21: ENERGY REQUIREMENT PER MONTH TO IMPLEMENT 18 HOURS OF DAYLIGHT FOR A 1 KW LIGHTING SYSTEM

The second component of artificial lighting power calculation is the size of the system. Guidelines for mounting metal halide and high pressure sodium (HPS) lights and fixtures are given in Figure 22. Metal Halide light is designed for vegetable growing whereas HPS lights are generally used to induce a plant to fruit. These are the two most common lights used in commercial operations. Using the manufacturer's guidelines, the power flux for a 1 kW system in a supplemental lighting function is 6.9 W/ft^2, 600 W is 6 W/ft^2, and 430 W fixture is 6.7 W/ft^2. These power fluxes are calculated from the supplementary lighting area.

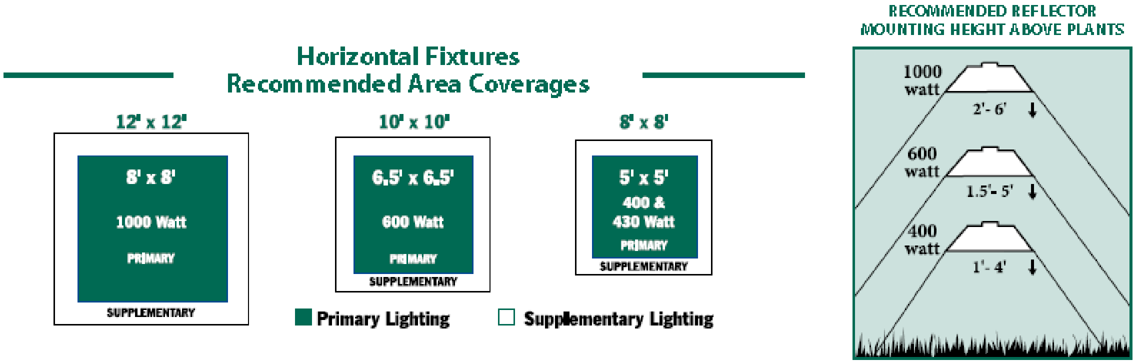


FIGURE 22: GROW LIGHT RECOMMENDED COVERAGE AREA AND MOUNTING HEIGHT [42]

The power requirement for lighting is calculated from the total growing area previously calculated. A width is chosen from Figure 22. As an example calculation, a width of 5 ft is chosen. The UVI system has a growing area of 2304 ft^2. Thus lights providing supplemental lighting must cover a growing bed length of 461 ft. Lights will be spaced at 8 foot intervals. This would require 57 fixtures and consume 24.5 kW. The yearly energy load is 51.9 MWh for supplemental lighting.

6.5 KEY RESULTS

A summary of the calculated power sinks of a commercial scale aquaponics system is shown in Table XIV. These results are scalable through the use of proportioning parameters calculated from the University of the Virgin Islands commercial aquaponics system. Artificial lighting was not used in the UVI system however, water pumping matches exactly what UVI has specified. The rearing tank aeration power is 0.4HP lower than what the UVI system uses. This could be attributed to a less efficient lower cost blower or possibly sized larger than need be.

TABLE XIV: SUMMARY OF POWER REQUIREMENTS OF THE UVI COMMERCIAL RAFT TYPE AQUAPONICS SYSTEM

Source	Power			
Centrifugal Pump	0.50	HP	(0.37	kW)
Rearing Tank Aeration Blower	1.1	HP	(0.80	kW)
Artificial Lighting	32.9	HP	(24.51	kW)
Total Power Input	**34.35**	**HP**	**(25.61**	**kW)**

7 COMBINED MODELS AND TANK DESIGN

Through iterating tank sizes through the thermal model and grow bed pumping model, a system size based on the power rating of the ecopower system was determined. The process used to iterate to this tank size will be further developed in the third quarter of this project through the creation of an aquaponics system optimization software. The tank design parameters for the system are presented in Table XV:

TABLE XV: SYSTEM PROPERTIES UTILIZED IN ENERGY SYSTEM SIZING

Property	Value	Units
Tank Temperature	80	F
Greenhouse Temperature	70	F
Relative Humidity	50	F
Flow Rate	67	Gallons per minute
Return Temperature	78	F
Tank Size	7 width 3.5 height 30 length	Ft
Number of Tanks	2	
Rubber Liner	0.25	Inch
Lumber	1.5	Inch
Additional Insulation – R7 Foam Insulation	1.5	Inch

Ambient temperatures and relative humidity were based on typical values for a greenhouse for winter months. The tank return temperature was based on reasonable estimates assuming that the surface of the grow tank is covered with insulating foam. During the third quarter of this project an investigative study will need to be performed to verify these estimates for the development of the optimization software. Thermal losses and obtained using these parameters are presented in Figure 23 and Table XVI.

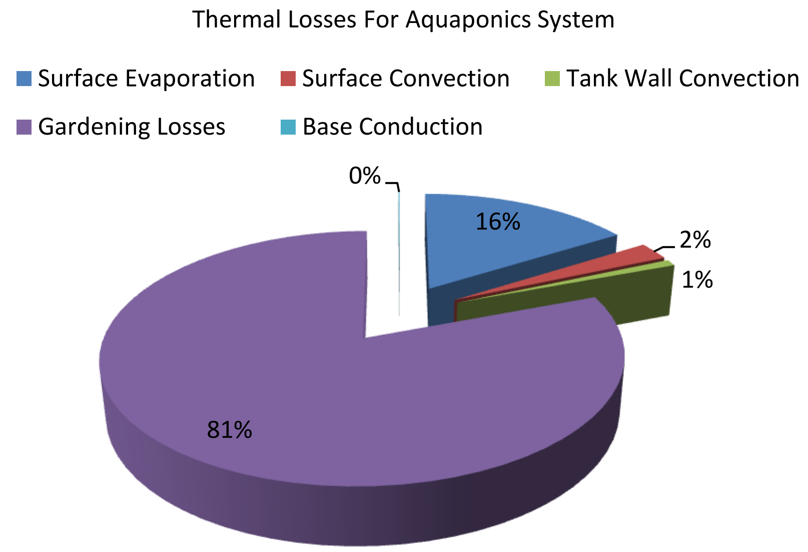


FIGURE 23: DISTRIBUTION OF THERMAL LOSSES FOR AQUAPONICS SYSTEM

TABLE XVI: THERMAL LOSSES FOR AQUAPONICS SYSTEM

Source	**Losses [BTU/hr]**
Surface Evaporation	6383
Surface Convection	957
Tank Wall Convection	341
Gardening Losses	32031
Base Conduction	32
Total Losses	39743

8 ENVIRONMENTAL IMPACT

The environmental impact of the proposed design is influential in three areas: greenhouse gas emissions, hazardous chemicals, and safety.

8.1 GREENHOUSE GAS EMISSIONS

One of the design parameters for the CHP system requires a decrease in emissions of greenhouse gases, the primary of which will be carbon dioxide. The emission of greenhouse gases from the designed system per unit energy will be compared against those released to produce the same ratio of energy from conventional electrical and thermal energy generation sources independently. A method of determining the resulting net emissions resulting from independent generation is presented in the following equation.

$$\Upsilon_{net} = \Upsilon_{electricity} + r_{thermal}\Upsilon_{thermal} \tag{6.5.1}$$

Where $\Upsilon_{electricity}$ and $\Upsilon_{thermal}$ are the direct emissions associated with the production of electrical and thermal power independently per kWh, and Υ_{net} is the net emissions associated with the production of the energy. Finally, $r_{thermal}$ is the ratio of thermal output to electrical output, which will hereafter be referred to as the power ratio. If the demand for onsite electrical consumption is less than the power provided by the system and net metering is used, the returned electricity will be discounted from the net emissions of the CHP unit at a rate equivalent to what is emitted by the utility.

To understand the emissions of unit energy of electricity it becomes necessary to quantify the carbon emissions per unit energy based on the energy profile of the local utility. The energy profile for Wisconsin Energy Corporation is compared against the national average in Table XVII.

TABLE XVII: ELECTRICITY GENERATION SOURCES

Energy Source	We Energies [43]	US Standard [44]
Renewable	3.4	10.6
Biomass	0.8	1.4
Hydroelectric	1	6.9
Solar	0	0
Wind	1.6	1.9
Geothermal	0	0.4
Coal	53.9	44.45
Natural Gas	11	23.31
Nuclear	27.7	20.22
Oil	0	0.99
Other	4	0.57
Total	100	100

For this analysis, the CO_2 emissions per unit energy will be considered over an entire life cycle of the generator. Sources that have emissions associated with construction and demolition of the plant include these emissions along with the direct emissions of the technology. As a result, renewable sources, which include hydroelectric, solar, and wind, result in minor CO_2 emissions per unit energy produced. For comparison on a similar basis, the CO_2 emissions associated with the manufacture of the CHP system are estimated. The CO_2 emissions are shown in Table XVIII.

TABLE XVIII: CO_2 EMISSIONS BASED ON FUEL AND SOURCE [45]

Source	Configuration/Fuel	Estimate gCO_2e/kWh
Wind	Onshore	9
Hydroelectric	Run-off-river	10
Biomass	Forest wood	22
Solar PV	Polycrystalline silicone	32
Geothermal	Hot dry rock	38
Nuclear	Various reactor types	66
Natural Gas	Various combined cycle turbines	443
Heavy Oil	Various generator and turbine types	778
Coal	Various generator and turbine types with scrubbing	960

Applying the previous emissions to the energy profile Wisconsin Energy Corporation and the US standard yields estimated emissions per kWh of electricity produced for both Milwaukee and the national average. These results are presented in Table XIX.

TABLE XIX: CO_2 EMISSIONS FOR ELECTRICITY PRODUCTION ([43] AND [44])

Profile	Estimate gCO_2e/kWh
Milwaukee	610
National Average	555

Typically, thermal energy for aquaponics operations is generated through natural fired gas water heaters. Therefore, quantifying emissions associated with the production of thermal energy will be based on typical efficiencies for natural gas water heaters sized for residential use. Assuming complete combustion and lower heating values, the ideal system (100% efficient) yields a CO_2 production rate of 197.8 gCO_2e/kWh per kWh of thermal energy. To obtain CO_2 emissions for real systems, the previous emission rate can be divided by the rated thermal efficiency of the system. Thermal efficiencies in the range of water heaters and their resulting emissions are presented in Table XX.

TABLE XX: NATURAL GAS WATER HEATER EMISSIONS AND EFFICIENCY [46]

Efficiency	Estimate gCO_2e/kWh
0.60[1]	330
0.75	263
0.86[2]	230

1. Conventional Gas Storage
2. Condensing Gas Storage

A mid-range efficiency of 75 percent was selected for this analysis. The annual thermal requirement of the selected aquaponics system is approximately 83,000 kWh while the annual electrical capacity using thermal load following is approximately 33,000 kWh. Using Marathon Engine System's ecopower micro-combined heat and power generator set results in approximately 14.5tCO_2 avoided annually based on the national average emission profile and 16.4tCO_2 avoided annually based on the emission profile of Milwaukee. This is equivalent to approximately 3.5 acres of forest absorbing CO_2.

8.2 HAZARDOUS CHEMICALS

It is understood that a regular maintenance schedule must be followed to ensure a reliable and long-lasting power system. This maintenance includes regular inspections of critical parts as well as replacement when needed. The engine used must undergo regular replacement of the oil, oil filter, and spark plug. The oil must be replaced every 4,000 hours of operation.

Used motor must be properly disposed in accordance with local regulations. Ideally, the oil will be recycled. Used motor oil should not be included with regular trash, burned, or dumped. Oil filters should be fully drained before disposal. Empty oil filters and used spark plugs should then be recycled.

The engine coolant loop may utilize water or a water and propylene glycol mixture. Unused propylene glycol is generally not toxic and is quickly biodegraded. The primary hazard associated with propylene glycol is as a slip hazard in case of a spill. Used propylene glycol should be disposed of at a recycling center in accordance with local regulations.

MSDS sheets for chemicals used are appended to this report. These include engine oil, propylene glycol, and natural gas.

8.3 SAFETY GUIDELINES

The proposed energy system imposes risks on the plant life, fish life, and persons working with or near the system. These risks include, but are not limited to, the following.

- Carbon monoxide poisoning
- Burn hazards
- Hazards to fish and plant life in the event of component failure
- Fuel leakage
- Oil spill
- Coolant

These risks can be minimized by the adhering to the following guidelines.

- Ensure proper ventilation of engine exhaust gas
- Monitor carbon monoxide levels
- Label and/or cover hot surfaces
- Be aware of potential natural gas leaks
- Contain coolant and engine oil if a spill occurs

9 DETAILED ECONOMIC CONSIDERATIONS

The installed cost of the ecopower is approximately $35,000. This cost can be reduced through government and utility incentives for operating combined heat and power systems. The economic analysis of the design assumes that the system is installed in Milwaukee, WI. The greenhouse and aquaponics thermal models described in this report were used to estimate the thermal load placed on the system. The

The peak process thermal load placed on the system was sized to be just below the maximum thermal load capacity of the ecopower unit at 12kW. The cost of natural gas was set at $0.946/ 100 ft^3.

The thermal base load characteristics were estimated using the thermal model described in this report. The average thermal load required as a percentage of the peak process thermal load is shown in Table XXI.

TABLE XXI: MONTHLY THERMAL LOAD REQUIREMENTS AS A PERCENTAGE OF THE MAXIMUM

Month	Load (%)
January	100
February	100
March	100
April	100
May	100
June	25
July	0
August	25
September	100
October	100
November	100
December	100

The maximum electrical power capacity of the system is 4.7 kW. This is available when the system is run to meet the full thermal load. Using thermal load following, the system can generate approximately 31,000 kWh of electricity annually and provide 83,000 kWh of water heating all while using 461,600 ft^3 of natural gas ($4,362). The electricity generated is worth $0.11/kWh which is the same price the utility charges. Excess electricity generated by the ecopower is sold back to the utility at the same rate.

The thermal energy delivered by the ecopower is offsetting thermal energy that would normally be delivered by a natural gas water heater with an efficiency of 75%. In order to get the same 83,000 kWh of thermal energy, the system would need to burn 416,000 ft^3 of natural gas ($3,931).

Using the ecopower to provide that thermal capacity and generate electricity leads to an annual operating profit of $3,016. With an installed cost of $35,000, the system has a simple payback time of 12 years. The equity payback time assuming a 3% inflation rate is 10 years. These payback periods include $100 for annual maintenance costs. It should be noted that there are often tax incentives for operating combined heat and power systems. A $5,000 tax credit would reduce the simple payback time to approximately 10 years, and reduce the equity payback time to approximately 9 years.

A RETScreen analysis is shown in Appendix B: RETScreen.

9.1 FEDERAL AND STATE INCENTIVES FOR CHP SYSTEMS

In order to minimize the payback period of the proposed design, the system will be designed for compliance with existing standards for federal and state green energy incentives. Incentive programs were found and have been taken into account for the design criterion. It should be noted that not all operations are eligible for every incentive programs since many are designed for corporate and nonprofit organizations only. The federal government sponsors several programs which are available to applicants around the country in addition to programs which are sponsored by the states for which their respective residents are eligible. Of the discovered incentive programs, only one federal program was found (See Section 9.2). Several state programs exist in Wisconsin through the Focus On Energy Program all of which have since expired (see [47] and [48]). It was noticed that the requirements for the federal incentives are very similar to the expired state programs. Therefore, through meeting the requirements for the federal program the system will likely be eligible for any state incentives upon their reenactment.

9.2 ENERGY IMPROVEMENT AND EXTENSIONS ACT

The Energy Improvement and Extensions Act enacted in 2008 established a corporate tax credit program for the development and installation of CHP systems. This program provides federal incentives for CHP systems up to 50 MW. In 2009 the act was again further expanded under The American Recovery and Reinvestment Act of 2009. This federal incentive program is available for any CHP system installed prior to January 1, 2017 and meets the stated criteria [49]:

- Installed system must not exceed 50 MW
- Must obtain a minimum of 60 percent minimum efficiency.
- Systems operating on 90 percent or more biomass based fuels are exempt from the previous limitation.
- At minimum 20 percent of the useful energy must be utilized for heating and 20 percent electrical needs.

Systems which met the previous criteria are eligible for up to 10 percent tax credit based on investment costs for the installation year. In order to minimize the payback period of the project the previous criteria will be incorporated into the design constraints of the system.

9.3 BUDGET

The project budget includes labor and overhead costs. The labor in the project includes all time required to create a best practices guide and software. The labor costs are given in Table XXII.

TABLE XXII: PROJECTED LABOR COSTS

Labor Resources	**Hours**	**Hourly Rate**	**Subtotal**	**Source**
Team Members	2700	$16	$43,200	Donation
Advisor	90	$75	$6,750	Donation
Professional Expertise	40	$50	$2,000	Donation

The estimated overhead costs are given in Table XXIII.

TABLE XXIII: PROJECTED OVERHEAD COSTS

Overhead Costs	Subtotal	Source
Building Space	$3,420	Donation
Test Lab	$3,420	Donation

The budget totals are given in Table XXIV.

TABLE XXIV: BUDGET TOTALS

Subgroup Totals	
Labor	$51,950
Overhead Costs	$6,840
Grand Total	**$58,790**
Donation	**$58,790**
Adjusted Total	**$0**

10 SOFTWARE DEVELOPMENT

A software package was developed which allows a user to conduct a preliminary analysis to determine if CHP is a suitable solution for their aquaponics operation. This software estimates the load of the aquaponics system, the financial benefit of the CHP system, and the avoided CO_2 emissions.

10.1 OPERATION INSTRUCTIONS

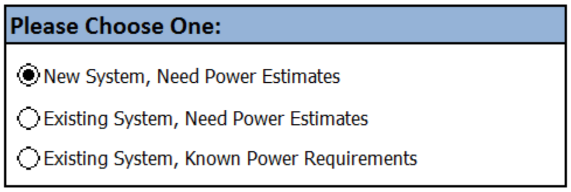
This software can help a user determine if combined heat and power (CHP) is a suitable source of energy for their aquaponics system. The software uses different scenarios for users who have no existing system, or users that have an existing system in place. Additionally, for those who have a system in place the software has a different scenario for those who know the thermal requirements for the system and for those who don't. The users that do not have an existing system the software can also help determine what size of a water pump and aeration pump should be used as well as how much power would be required to artificially light a greenhouse based upon geographical location and required amount of grow time per day.

Summary:

1) Open the Excel file "Test_Structure (Macro-Enabled)"
2) Select the correct scenario
3) Enter in all known parameters
4) Save the file
5) Close the Excel file
6) Open and run "Aquaponics_Energy_Tool.exe"
7) Select the Excel file "Test_Structure (Macro-Enabled)" if prompted to "Find File to Import"
8) Review outputs to determine if combined heat and power is a feasible option as the energy supply system

Open the Excel File “Test Structure (Macro-Enabled)”

Choosing the right scenario:



Please Choose One:

● New System, Need Power Estimates
○ Existing System, Need Power Estimates
○ Existing System, Known Power Requirements

1: “***New System, Need Power Estimates”***
The first scenario is where no aquaponic system is in place but the user is in the process of building a system. The user is looking to learn more about the thermal and electricity demands of a potential aquaponic system and if combined heat and power (CHP) could be beneficial for that system. On the initial page the user should select “*New system, Need Power Estimates.”*

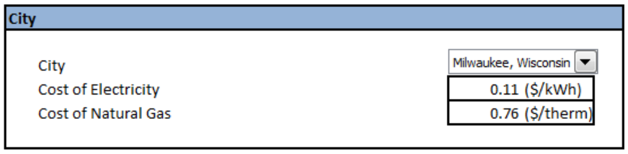
2: ***“Existing System, Need Power Estimates”***
The second scenario is an existing aquaponic system, but none of the thermal or electrical demands are known. The user is looking to find the estimated loads of the existing system and if CHP could be a feasible option for the operation in place. On the initial page the user should select “*Existing System, Need Power Requirements*.”

3: ***“Existing System, Known Power Requirements”***
The third scenario is where there is an existing system and the thermal loads of the system are known. The user will input the known loads and the software will determine if CHP could be feasible for the existing system. On the initial page the user should select “*Existing System, Known Power Requirements*.”

Entering the known inputs:

Depending upon the scenario selected the user will be asked to enter different inputs to help determine if CHP is a feasible for supplying thermal load to the aquaponic system.

For all three scenarios the following inputs will be asked:

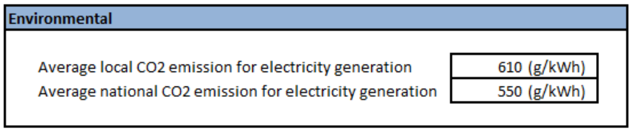


City

City	Milwaukee, Wisconsin
Cost of Electricity	0.11 ($/kWh)
Cost of Natural Gas	0.76 ($/therm)

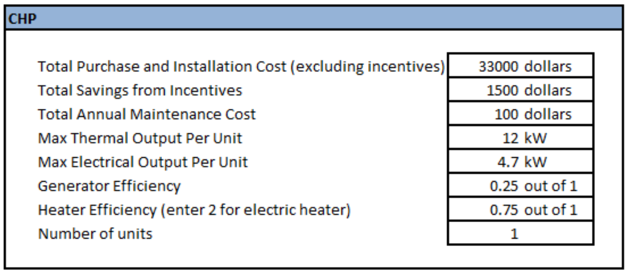
City: For this input the user will select the city in which the aquaponic system is going to be built or where it exists. This helps determine the differing electrical loads determined for possible artificial lighting.

Cost of Electricity/Cost of Natural Gas: For these inputs the user will set the price of both the electricity and natural gas. The prices can be found from the local utility. These help determine the payback period for a possible CHP system.



Environmental	
Average local CO2 emission for electricity generation	610 (g/kWh)
Average national CO2 emission for electricity generation	550 (g/kWh)

Average Local/National CO_2 Emissions for Electricity Generation: For these inputs the user inputs the local and national CO_2 emissions for electricity generation. These help determine the annual amount of CO_2 avoided. The values shown are the current national emissions profiles for the United States and for Milwaukee, WI.



CHP	
Total Purchase and Installation Cost (excluding incentives)	33000 dollars
Total Savings from Incentives	1500 dollars
Total Annual Maintenance Cost	100 dollars
Max Thermal Output Per Unit	12 kW
Max Electrical Output Per Unit	4.7 kW
Generator Efficiency	0.25 out of 1
Heater Efficiency (enter 2 for electric heater)	0.75 out of 1
Number of units	1

Total Purchase and Installation Cost: For this input the total purchase price of the CHP unit(s) is used. Be sure to use the TOTAL price of all units and not the INDIVIDUAL price of a single unit. However, if the user is only interested in one unit, there is no issue. Be sure to exclude any incentives or annual maintenance costs from the total purchase cost, as they are entered separately. The values shown are for the Marathon ecopower CHP system.

Total Savings from Incentives: For this input use any savings acquired from incentives. Any incentive will help lower the payback period for the CHP system(s).

Total Annual Maintenance Cost: For this input include any costs that may be needed to help keep the CHP system(s) in running condition. Costs could come from oil changes, new parts, etc.

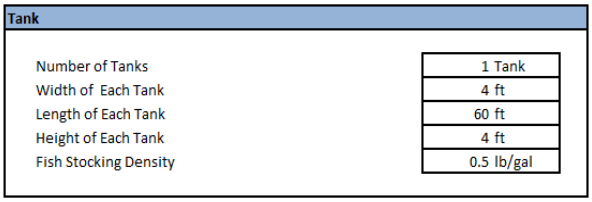
Max Thermal Output Per Unit: For this input use the max thermal output per CHP system. If different sized systems are of interest average the thermal output. The max thermal output should be included in a CHP system's specification sheet.

Max Electrical Output per Unit: For this input use the max electrical output per CHP system. If different sized systems are of interest average the electrical output. The electrical output should be included in a CHP system's specification sheet.

Generator Efficiency: For this input use the efficiency of the electrical generator in the CHP system.

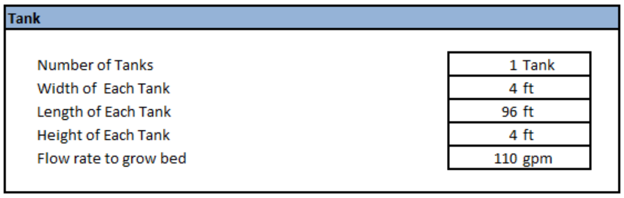
Heater Efficiency: For this input, enter the efficiency of the natural gas heater that the CHP system would be replacing or supplementing. Enter a value of 2 if using an electric heater to prompt the software to use the proper analysis type.

Number of Units: For this input use the total number of CHP units being considered.



Tank

Number of Tanks	1 Tank
Width of Each Tank	4 ft
Length of Each Tank	60 ft
Height of Each Tank	4 ft
Fish Stocking Density	0.5 lb/gal



Tank

Number of Tanks	1 Tank
Width of Each Tank	4 ft
Length of Each Tank	96 ft
Height of Each Tank	4 ft
Flow rate to grow bed	110 gpm

Number of Tanks: For this input use the number of tanks being considered in the aquaponic system to be coupled with the CHP system.

Width of Each Tank: For this input use the width of each tank in the aquaponic system. If the widths of the tanks are different, average the widths of all the tanks being used.

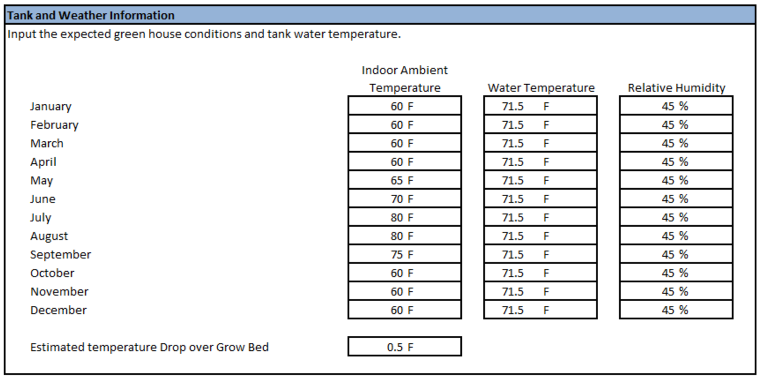
Length of Each Tank: For this input use the length of each tank in the aquaponic system. If the lengths of the tanks are different, average the length of all tanks being used.

Height of Each Tank: For this input use the height of each tank in the aquaponic system. If the heights of the tanks are different, average the height of all the tanks being used.

Fish Stocking Density: For this input use the stocking density of the fish being used. This is applicable in only scenario 1 where there is no aquaponic system in existence.

Flow Rate to Grow Bed: For this input use the flow rate of the water circulating between the fish tank and grow bed. This is only applicable in scenarios where an aquaponic system is already in existence.

<u>The following input is used only in scenario 1 and 2.</u>



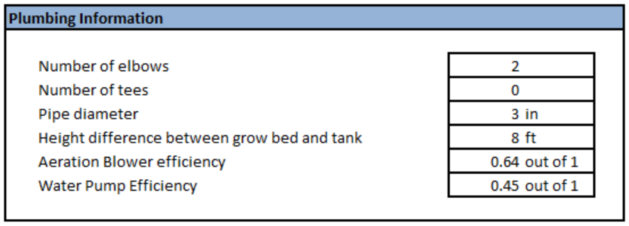
Tank and Weather Information

Input the expected green house conditions and tank water temperature.

	Indoor Ambient Temperature	Water Temperature	Relative Humidity
January	60 F	71.5 F	45 %
February	60 F	71.5 F	45 %
March	60 F	71.5 F	45 %
April	60 F	71.5 F	45 %
May	65 F	71.5 F	45 %
June	70 F	71.5 F	45 %
July	80 F	71.5 F	45 %
August	80 F	71.5 F	45 %
September	75 F	71.5 F	45 %
October	60 F	71.5 F	45 %
November	60 F	71.5 F	45 %
December	60 F	71.5 F	45 %
Estimated temperature Drop over Grow Bed	0.5 F		

Tank and Weather Information: For these inputs the monthly greenhouse indoor temperature, relative humidity, and the fish tank water temperature are used. Additionally, the estimated temperature drop over the grow bed is used. This helps determine the amount of thermal load existing in the aquaponic system.

<u>The following inputs are used only in scenario 1 “New System, Need Power Estimates.”</u>



Plumbing Information	
Number of elbows	2
Number of tees	0
Pipe diameter	3 in
Height difference between grow bed and tank	8 ft
Aeration Blower efficiency	0.64 out of 1
Water Pump Efficiency	0.45 out of 1

Number of Elbows: For this input the number of elbows used in the piping starting from the pump and ending in the grow bed are used.

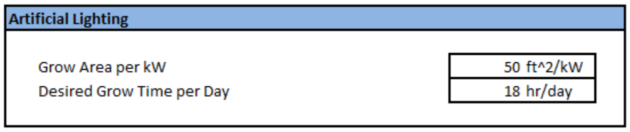
Number of Tees: For this input the number of tees used in the piping starting from the pump and ending in the grow bed are used.

Pipe Diameter: For this input the diameter of the pipe in the piping from the fish tank to the grow bed is used.

Height Difference between Grow Bed and Tank: For this input the height difference between the pump and the grow bed is used.

Aeration Blower Efficiency: For this input the efficiency of the aeration blower is used. If the efficiency of the blower is 64% use 0.64.

Water Pump Efficiency: For this input the efficiency of the water pump is used. If the efficiency of the water pump is 45% use 0.45.

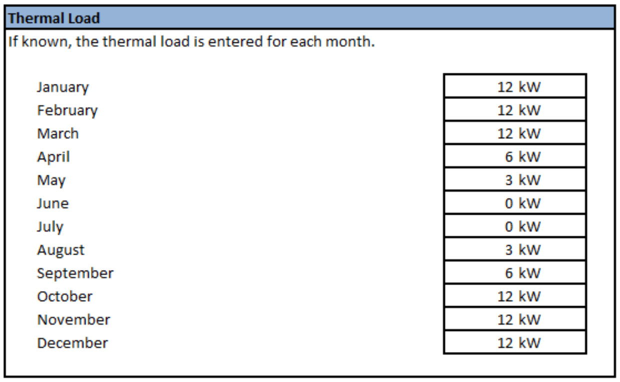


Artificial Lighting	
Grow Area per kW	50 ft^2/kW
Desired Grow Time per Day	18 hr/day

Grow Area per kW: For this input the lighting coverage of the artificial lighting is used. The grow area per kW can be found from the lighting specifications.

Desired Grow Time per Day: For this input the desired amount of time that the plants will be under actual or simulated sunlight is used.

__The following inputs are used only in scenario 3, “Existing System, Known Power Estimates.”__



Thermal Load

If known, the thermal load is entered for each month.

January	12 kW
February	12 kW
March	12 kW
April	6 kW
May	3 kW
June	0 kW
July	0 kW
August	3 kW
September	6 kW
October	12 kW
November	12 kW
December	12 kW

Thermal Load: Since the thermal loads are known in this scenario, the monthly required thermal loads for the aquaponic system are used.

__After the known inputs are entered:__

1) **Save the Excel file**

It is necessary that the user now saves the document in order to update all the parameters. All that is necessary is to press the “Save” key. Be sure not to” Save As”, but to simply save over the existing file without changing the file name.

2) **Exit the Excel program**

Once the file has been saved, close the Excel program completely. The excel program will be re-opened by the following software.

3) **Open and run Aquaponics_Energy_Tool.exe**

Double click on the executable file after the Excel file is closed.

4) **Select the Excel file “Test_Structure (Macro-Enabled)”**

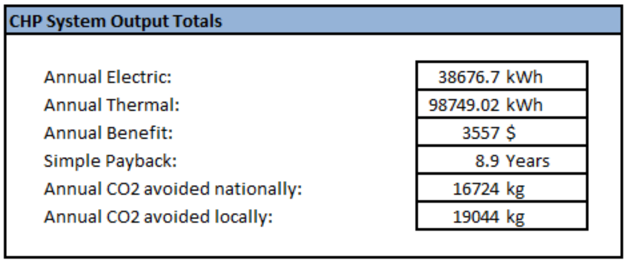
The program may ask the user to “Find File to Import”. Select the Excel file saved earlier titled “Test_Structure (Macro-Enabled).” The program will continue to run and will re-open the Excel file when the analysis is complete.

5) **Scroll through and review outputs**

Once the Excel file has been re-opened be sure to scroll through to see the desired outputs. The initial inputs will be available for viewing as well in case the user forgot what was entered. The type of outputs can be seen and described in the following section.

Reviewing the outputs:

The following parameters are found in the outputs for all three scenarios.



CHP System Output Totals

Annual Electric:	38676.7 kWh
Annual Thermal:	98749.02 kWh
Annual Benefit:	3557 $
Simple Payback:	8.9 Years
Annual CO2 avoided nationally:	16724 kg
Annual CO2 avoided locally:	19044 kg

Annual Electric: This output shows the total annual amount of electricity generated by the CHP system(s).

Annual Thermal: This output shows the total annual amount of thermal energy supplied to the fish tanks by the CHP system(s).

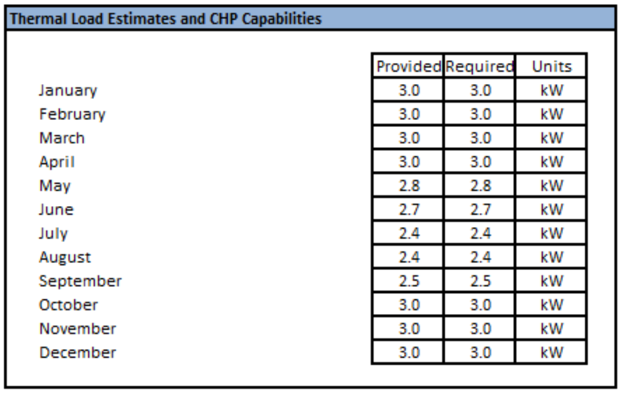
Annual Benefit: This output shows the amount of dollars saved each year by using a CHP system in combination with the aquaponic system.

Simple Payback: This output shows the simple payback period of the CHP system(s), or the time period in which the CHP system(s) will pay itself off.

Annual CO_2 Avoided Nationally: This output shows the annual amount of CO_2 avoided in comparison to the national statistic.

Annual CO_2 Avoided Locally: This output shows the annual amount of CO_2 avoided in comparison to the local statistic.

The following parameters are found in the outputs for only scenario 1 and 2.

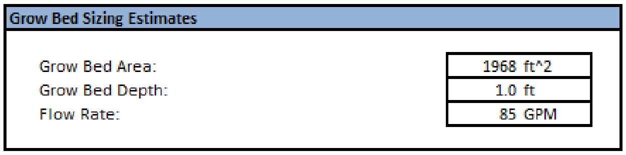


Thermal Load Estimates and CHP Capabilities

	Provided	Required	Units
January	3.0	3.0	kW
February	3.0	3.0	kW
March	3.0	3.0	kW
April	3.0	3.0	kW
May	2.8	2.8	kW
June	2.7	2.7	kW
July	2.4	2.4	kW
August	2.4	2.4	kW
September	2.5	2.5	kW
October	3.0	3.0	kW
November	3.0	3.0	kW
December	3.0	3.0	kW

Thermal Load Estimates and CHP Capabilities: This output shows the amount of monthly thermal load required by the aquaponics system and the monthly thermal load provided by the CHP system(s). The provided load will only be as high as the required load.

-The following parameters are found in the outputs for only scenario 1.



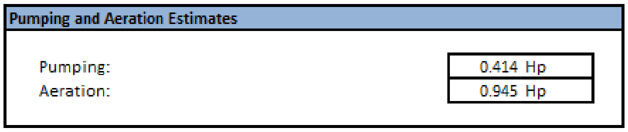
Grow Bed Sizing Estimates

Grow Bed Area:	1968 ft^2
Grow Bed Depth:	1.0 ft
Flow Rate:	85 GPM

Grow Bed Area: This output shows the recommended amount of surface area for the grow bed.

Grow Bed Depth: This output shows the recommended amount of grow bed depth in combination with the grow bed surface area.

Flow Rate: This output shows the recommended flow rate of the water through the piping that connects the grow bed to the fish tanks.

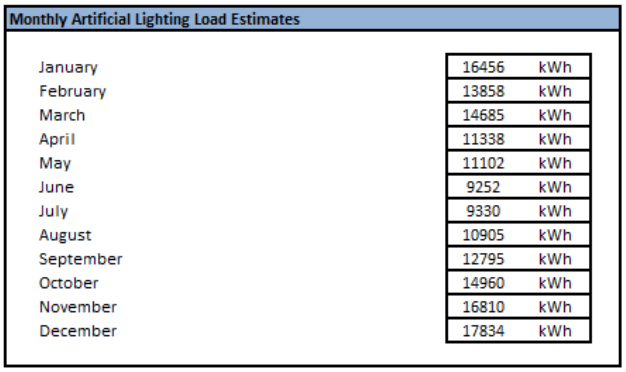


Pumping and Aeration Estimates

Pumping:	0.414 Hp
Aeration:	0.945 Hp

Pumping: This output shows the recommended power for a water pump to be used in the piping. It will not return a standard value for a pump.

Aeration: This output shows the recommended power for an aeration blower to be used in the fish tank. It will not return a standard value for a blower.



Monthly Artificial Lighting Load Estimates

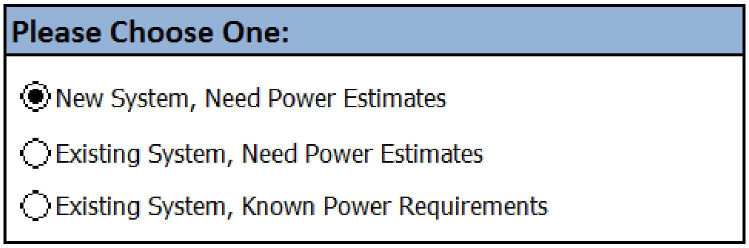
January	16456	kWh
February	13858	kWh
March	14685	kWh
April	11338	kWh
May	11102	kWh
June	9252	kWh
July	9330	kWh
August	10905	kWh
September	12795	kWh
October	14960	kWh
November	16810	kWh
December	17834	kWh

Monthly Artificial Lighting Load Estimates: This output shows the amount of supplemental lighting will be required if you choose to use artificial lighting based upon the geographical location and the selected hours of grow time.

10.2 SAMPLE

In order to demonstrate the capabilities of the program that was designed and written, it is necessary to run a case study. This sample shows just one of the ways which this program can be used. In this sample, data was provided by Sweet Water Organics in Milwaukee, WI.

This sample estimates the loads of a system which are then compared to the data provided by Sweet Water Organics. With that being known, the selection tool “New System, Need Power Estimates” is selected as shown in Figure 24.



Please Choose One:

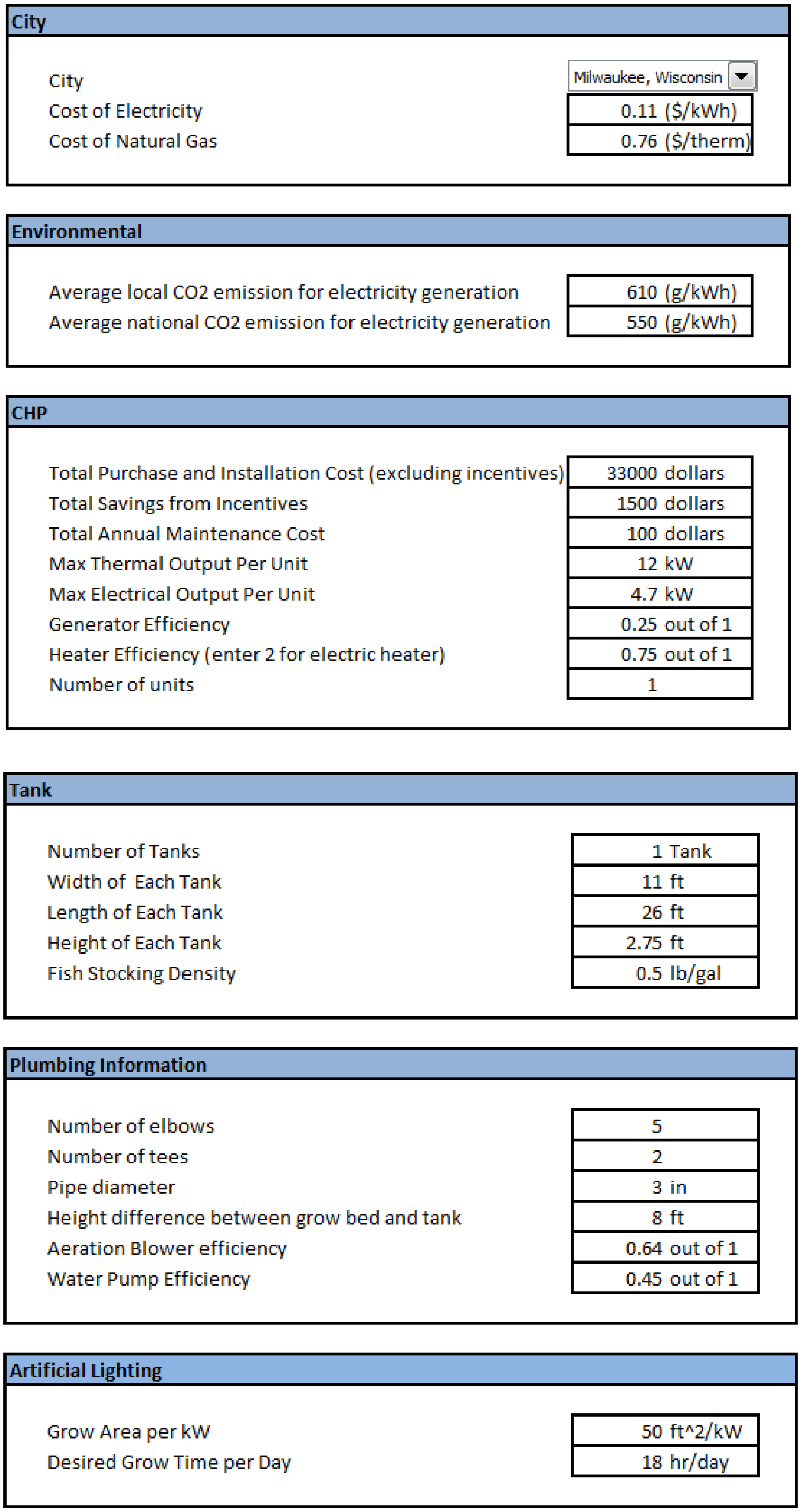
● New System, Need Power Estimates

○ Existing System, Need Power Estimates

○ Existing System, Known Power Requirements

FIGURE 24: SOFTWARE TITLE SCREEN

Once the option is selected, the input screen opens and prompts the user to enter known data. If the data for certain criteria are not known, values are predetermined so that the program can operate correctly. For this case, the known values are the current utility pricing for the Milwaukee area. Additionally, the environment data is known for local and national CO_2 emissions. The performance data for the CHP system are taken from a Marathon ecogen. The tank dimensions as provided by Sweet Water are entered. All other unknown information is estimated or the default values are used. All values can be seen in Figure 25 and Figure 26.



City

City	Milwaukee, Wisconsin
Cost of Electricity	0.11 ($/kWh)
Cost of Natural Gas	0.76 ($/therm)

Environmental

Average local CO2 emission for electricity generation	610 (g/kWh)
Average national CO2 emission for electricity generation	550 (g/kWh)

CHP

Total Purchase and Installation Cost (excluding incentives)	33000 dollars
Total Savings from Incentives	1500 dollars
Total Annual Maintenance Cost	100 dollars
Max Thermal Output Per Unit	12 kW
Max Electrical Output Per Unit	4.7 kW
Generator Efficiency	0.25 out of 1
Heater Efficiency (enter 2 for electric heater)	0.75 out of 1
Number of units	1

Tank

Number of Tanks	1 Tank
Width of Each Tank	11 ft
Length of Each Tank	26 ft
Height of Each Tank	2.75 ft
Fish Stocking Density	0.5 lb/gal

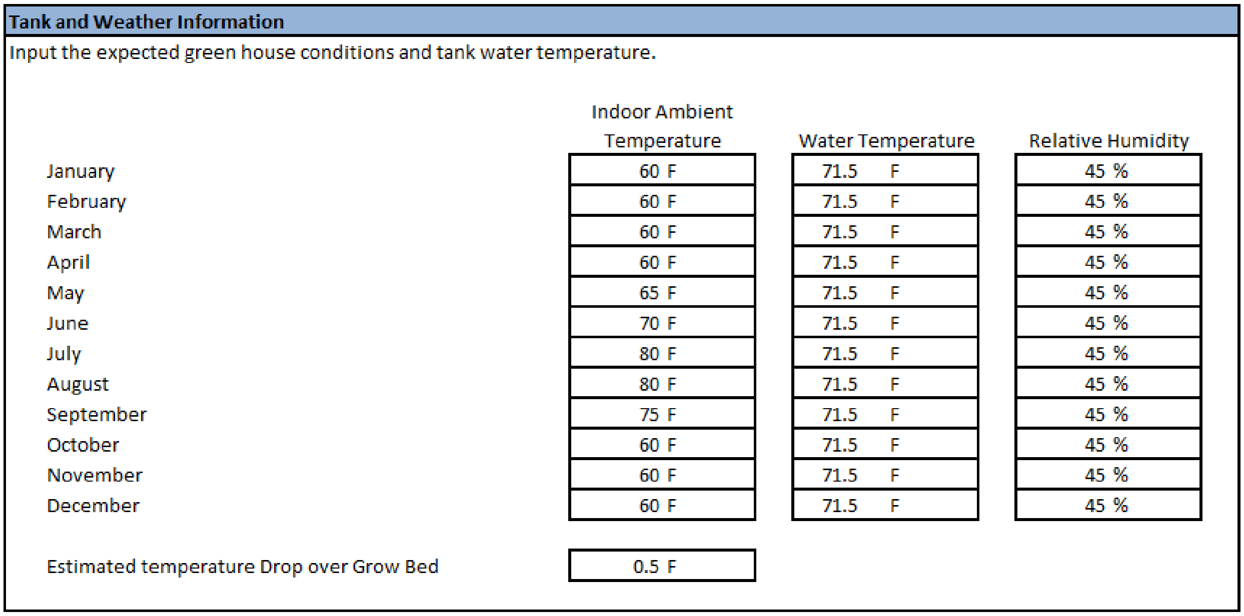
Plumbing Information

Number of elbows	5
Number of tees	2
Pipe diameter	3 in
Height difference between grow bed and tank	8 ft
Aeration Blower efficiency	0.64 out of 1
Water Pump Efficiency	0.45 out of 1

Artificial Lighting

Grow Area per kW	50 ft^2/kW
Desired Grow Time per Day	18 hr/day

FIGURE 25: SOFTWARE INPUTS



Tank and Weather Information

Input the expected green house conditions and tank water temperature.

	Indoor Ambient Temperature	Water Temperature	Relative Humidity
January	60 F	71.5 F	45 %
February	60 F	71.5 F	45 %
March	60 F	71.5 F	45 %
April	60 F	71.5 F	45 %
May	65 F	71.5 F	45 %
June	70 F	71.5 F	45 %
July	80 F	71.5 F	45 %
August	80 F	71.5 F	45 %
September	75 F	71.5 F	45 %
October	60 F	71.5 F	45 %
November	60 F	71.5 F	45 %
December	60 F	71.5 F	45 %

Estimated temperature Drop over Grow Bed: 0.5 F

FIGURE 26: SOFTWARE ENVIRONMENT INPUTS

Two charts are generated showing the monthly humidity profile as well as monthly temperature profile. This changes as data is entered and can be seen in Figure 27.

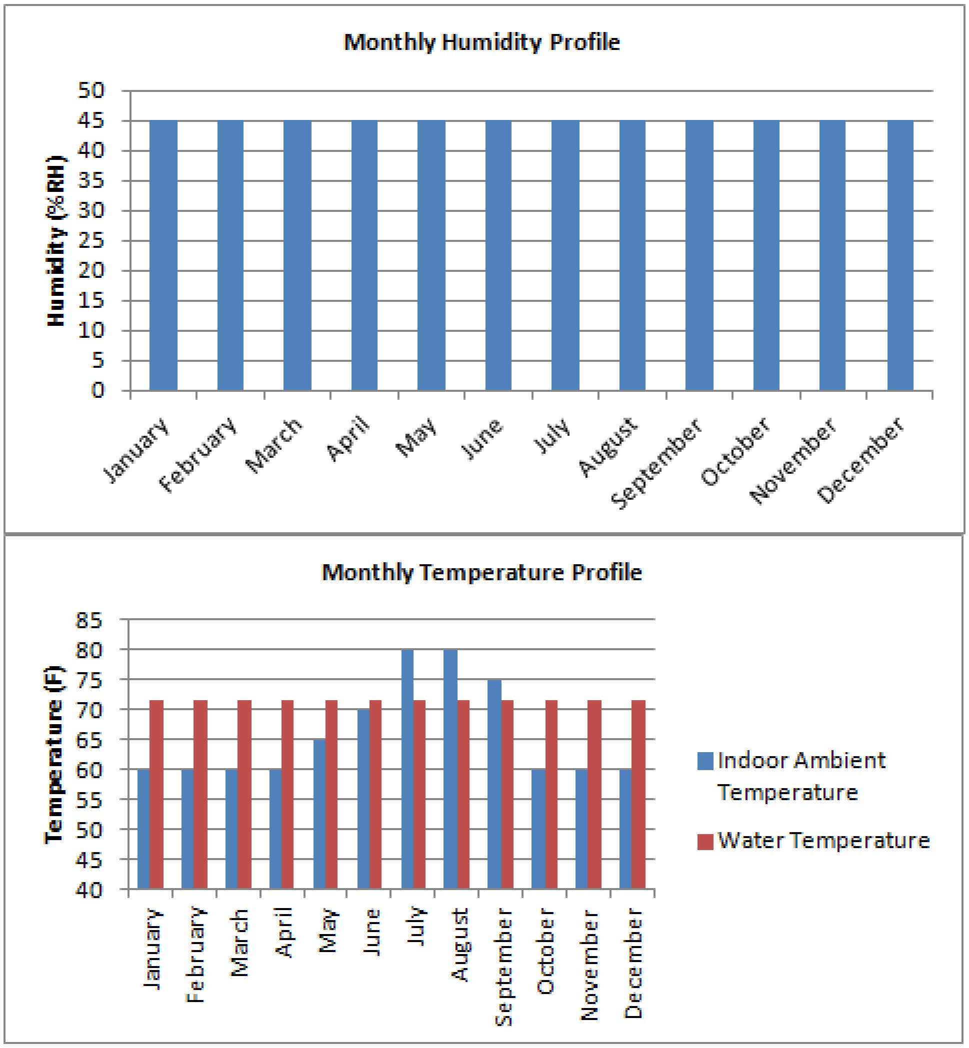
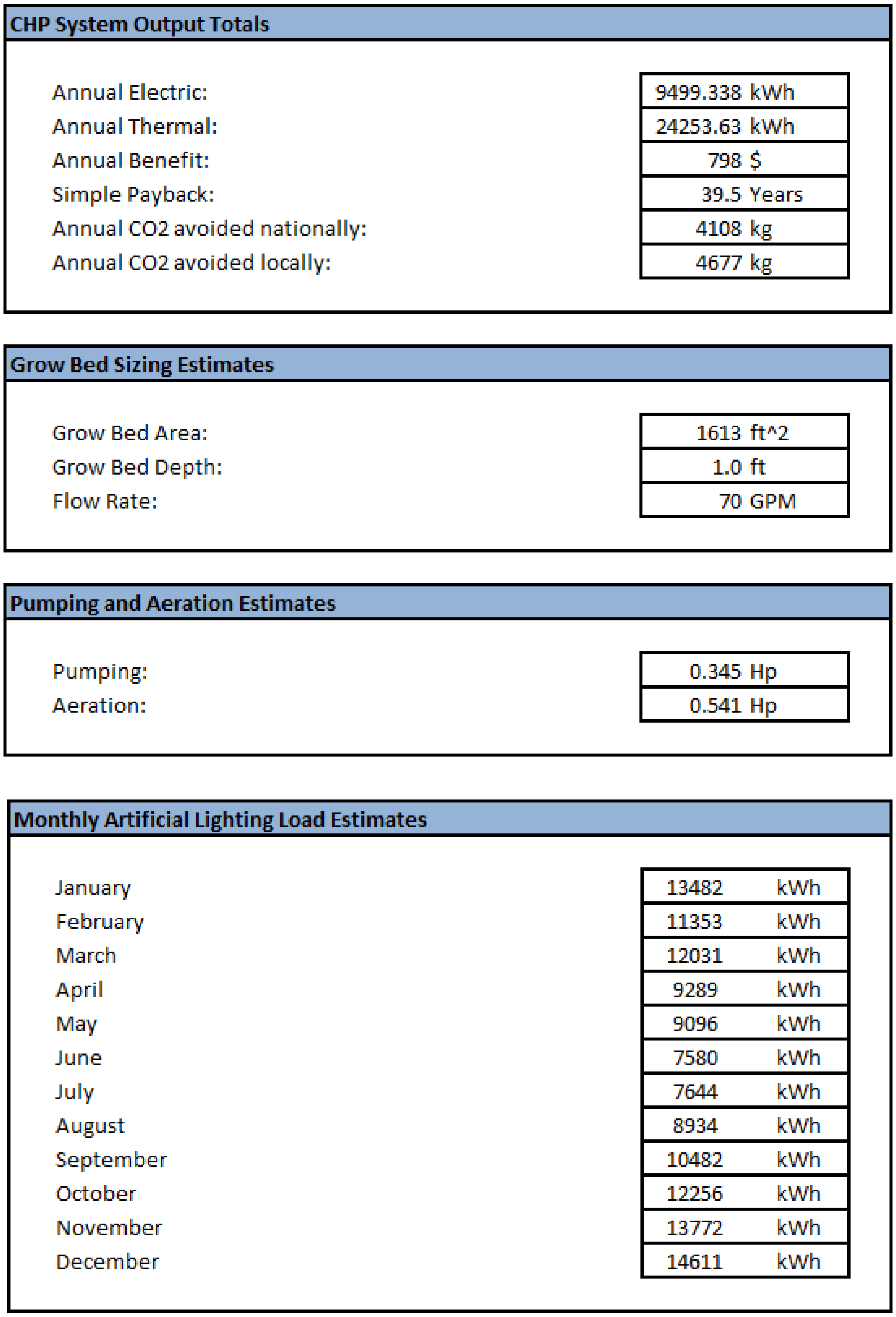


FIGURE 27: MONTHLY HUMIDITY AND TEMPERATURE PROFILE

The outputs were returned as shown in the following figures.



CHP System Output Totals

Annual Electric:	9499.338 kWh
Annual Thermal:	24253.63 kWh
Annual Benefit:	798 $
Simple Payback:	39.5 Years
Annual CO2 avoided nationally:	4108 kg
Annual CO2 avoided locally:	4677 kg

Grow Bed Sizing Estimates

Grow Bed Area:	1613 ft^2
Grow Bed Depth:	1.0 ft
Flow Rate:	70 GPM

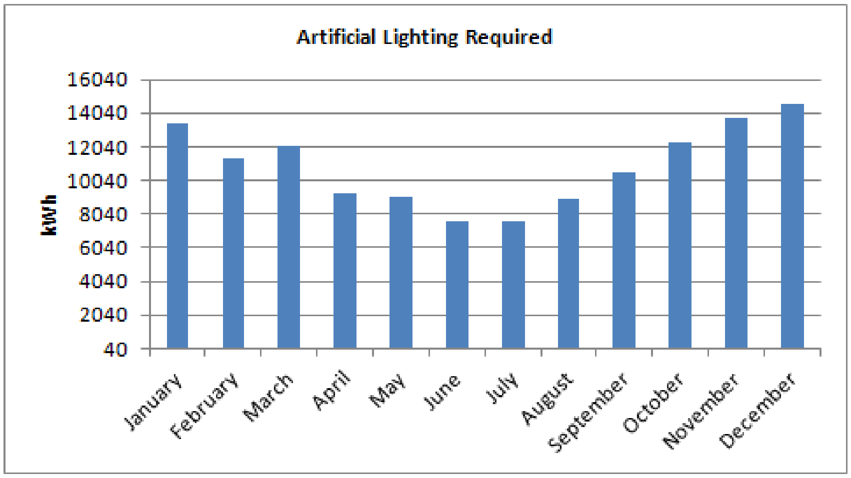
Pumping and Aeration Estimates

Pumping:	0.345 Hp
Aeration:	0.541 Hp

Monthly Artificial Lighting Load Estimates

January	13482	kWh
February	11353	kWh
March	12031	kWh
April	9289	kWh
May	9096	kWh
June	7580	kWh
July	7644	kWh
August	8934	kWh
September	10482	kWh
October	12256	kWh
November	13772	kWh
December	14611	kWh

FIGURE 28: SAMPLE OF SOFTWARE OUTPUTS (PAGE 1)



Thermal Load Estimates and CHP Capabilities

	Provided	Required	Units
January	3.0	3.0	kW
February	3.0	3.0	kW
March	3.0	3.0	kW
April	3.0	3.0	kW
May	2.8	2.8	kW
June	2.7	2.7	kW
July	2.2	2.2	kW
August	2.2	2.2	kW
September	2.5	2.5	kW
October	3.0	3.0	kW
November	3.0	3.0	kW
December	3.0	3.0	kW

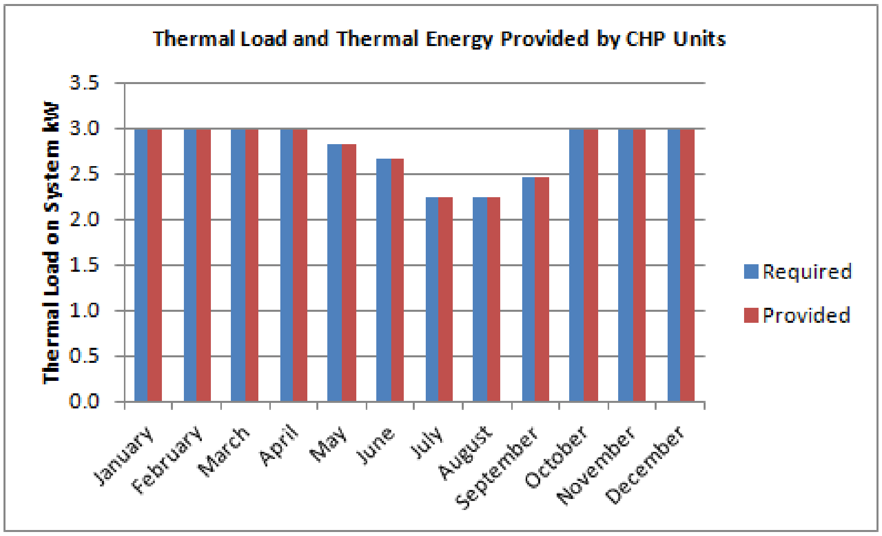
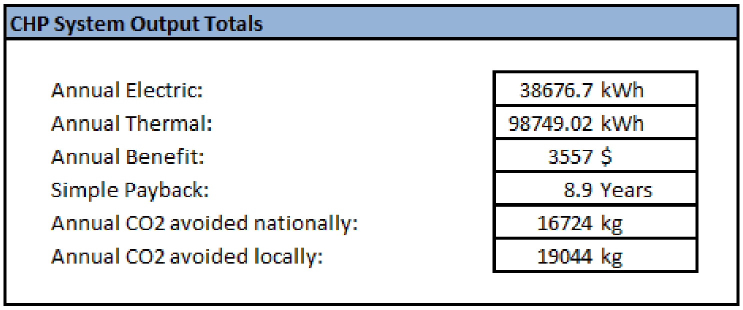


FIGURE 29: SAMPLE OF SOFTWARE OUTPUTS (PAGE 2)

One common measurement for investments is the payback time. The simple payback calculated for this system is 39.5 years. This lengthy payback time could be discouraging to a company or individual looking to invest in CHP for purely economic reasons; however, there is encouraging reason to use CHP based on avoided CO_2 emissions. In this case, it can be seen that the thermal load is met each month by the CHP system, but the thermal capacity of the CHP system 4 times higher than what is required by the aquaponics system. The system size should be changed to properly match the thermal load of the tank with the thermal capacity of the CHP system. In doing so, the payback time can be reduced to 8.9 years as shown in Figure 30.



CHP System Output Totals

Annual Electric:	38676.7 kWh
Annual Thermal:	98749.02 kWh
Annual Benefit:	3557 $
Simple Payback:	8.9 Years
Annual CO2 avoided nationally:	16724 kg
Annual CO2 avoided locally:	19044 kg

FIGURE 30: SAMPLE OUTPUTS WHEN THERMAL LOAD MATCHES CAPACITY

11 CONCLUSION

The use of a combined heat and power energy supply system in an aquaponics operation will reduce CO_2 emissions and, if properly sized, can provide an economic benefit. Those who are interested in doing so may wish to use the software developed by this senior design team as part of a preliminary investigation.

REFERENCES

[1] The Definition of Aquaponics, 2010, The Aquaponic Source, http://theaquaponicsource.com/2010/11/15/the-definition-of-aquaponics/

[2] Past – Present – Future, 2010, Sustainable Design Group, http://www.aquaplanetonline.com/history.cfm

[3] Nelson, R. L., 2008, ”Aquaponic Food Production - Raising fish and plants for food and profit,” Nelson and Pade, Inc.

[4] Connolly, K., and Trebic, T., 2010, “Optimization of a Backyard Aquaponic Food Production System,” McGill University

[5] Shipley, A., Hampson, A., Hedman, B., Garland, P. and Bautista, P., 2008, “Combined Heat and Power: Effective Energy Solutions for a Sustainable Future,” ORNL/TM-2008/224, U. S. Department of Energy.

[6] Electricity Flow, 2007, DOE Energy Information Administration Annual Energy Review 2007, from http://www.eia.doe.gov

[7] We Energies, 2010, We Energies’s Generating Systems: Coal: Valley Power Plant, from http://www.we-energies.com/home/ValleyPP.pdf

[8] Willis, H. L. and Scott W. G., 2000*, Distributed Power Generation: Planning and Evaluation*, Marcel Dekker, Inc., New York, NY, Chap. 1.

[9] Vanek, F. M. and Albright L. D., 2008**,** *Energy Systems Engineering: Evaluation and Implementation*, The McGraw-Hill Companies, Inc., New York, NY, pp. 142-156.

[10]U. S. Environmental Protection Agency, Combined Heat and Power Partnership, 2008, “Catalog of CHP Technologies,” from http://www.epa.gov/chp/documents/catalog_chptech_full.pdf

[11]Office of Energy Efficiency and Renewable Energy, 2003, “Heat Your Water with the Sun”, U.S. Department of Energy, pp. 9.

[12]North Carolina State University, 2009, “Federal Incentives/Policies for Renewables & Efficiency”, Database of State Incentives for Renewables & Efficiency.
http://dsireusa.org/incentives/incentive.cfm?Incentive_Code=US02F

[13]Economic Benefits, 2011, Combined heat and Power Partnership,
http://www.epa.gov/chp/basic/economics.html

[14]Harrison, J., 2011, “Is micro CHP Worth the Money?”
http://www.microchap.info/economics.htm

[15]Biogas, 2010, Renewable Energy Vermont,
http://www.revermont.org/main/technology/bioenergy/biogas/

[16]Lyondell, 2006, "Specific Heat of Aqueous Propylene Glycol Solutions",Lyondell Chemical Company, Lyondellbasell.com, Web. <http://www.lyondellbasell.com/techlit/techlit/2516.pdf>.

[17]Lyondell, 2006, "Density of Aqueous Propylene Glycol Solutions", Lyondell Chemical Company, Lyondellbasell.com, Web. <http://www.lyondellbasell.com/techlit/techlit/2510.pdf>.

[18]Incropera, F.P., 2007,"External Flow", Introduction to Heat Transfer, Hobokenm NJ: Wiley,. Print.

[19]AvestaPolarit. "Duplex Stainless Steel." 2012. Web. <http://www.avestapolarit.com/upload/documents/technical/datasheets/AVPDuplex.pdf>.

[20]The Dow Chemical Company. "Comparison of Ethylene Glycol vs. Propylene Glycol." 1999. Web. <http://msdssearch.dow.com/PublishedLiteratureDOWCOM/dh_0032/0901b8038003266c.pdf?filepath=heattrans/pdfs/noreg/180-01397.pdf&fromPage=GetDoc>.

[21]"Merck Veterinary Manual." The Merck Veterinary Manual. 2011. Web. 17 Feb. 2012. <http://www.merckvetmanual.com/mvm/index.jsp?cfile=htm/bc/210900.htm>.

[22]"Propylene Glycol." Dow Chemical Corporate Website - The Dow Chemical Company. 2012. Web. 11 Feb. 2012. <http://www.dow.com/productsafety/finder/prog.htm>.

[23]Bowman. "Exhaust Gas Heat Exchangers." 2012. Web. <http://www.ejbowman.co.uk/pdf/exhaust_gas_brochure_v1.pdf>.

[24]AK Steel. "Stainless Steel Comparator." 2012. Web. <http://www.aksteel.com/pdf/markets_products/stainless/Stainless_Steel_Comparator.pdf>.

[25]"Stainless Steel Tube - Available in Various Customize Size, Specifications & Types."Stainless Steel Pipe, Tubes, Fittings, Sheets, Plates & Hollow Bars by Arch City Steel. Arch City Steel and Alloy, Inc. Web. 19 Feb. 2012. <http://archcitysteel.com/stainless-tubing.html>.

[26]Holland, F. A., 1970, Heat Transfer, American Elsevier Pub., New York, NY

[27]Rohsenow. W. M., et. Al, 1961, Heat, Mass, & Moment Transfer, pp. 522

[28]Li, Z. and Heiselberg, P. 2005 “CFD Simulations for Water Evaporation and Airflow Movement in Swimming Baths,” Aalborg University

[29]Dunkle, R. V., 1961, Solar Water Distillation; The Roof Type Still and Multiple Effect Diffusion, International Heat Transfer Conference, pp. 895-902

[30]Carrier W. H., 1918, “The Temperature of Evaporation,” Transactions American Society of Heating and Ventilation Engineers

[31]Bowen, I.S., 1926, The Ratio of Heat Losses by Conduction and by Evaporation From Any Water Surface, Journal Physics Review Volume 27, pp 779-787

[32]Shah, M. 1998, “Analytical Formulas for Calculating Water Evaporation from Pools,” ASHRAE

[33]Mackenzie, A., "Titan Omni0Sensor Data Request – Student Project", Email to Brandon Jackson 19 January, 2012.

[34]M-6701, "Greenhouse Heating Requirements," Canada Plan Service

[35]Rakocy, J.E., Masser, M.P., Losordo, T.M., (2006). Recirculating Aquaculture Tank Production Systems: Aquaponics – Integrating Fish and Plant Culture. Southern Regional Aquaculture Center, Publication No. 454, 1-16

[36]Endut, A., Jusoh, A., Ali, W.B., Wan Nik, Hassan, A. (2010) A Study on the Optimal Hydraulic Loading Rate and Plant Ratios in Recirculation Aquaponic System. Bioresource Technology, 1511-1517.

[37]Colombo Quality Coir Products. (2011). Coco Peat (Coir Pith). Retrieved November 4, 2011 from Colombo Quality Coir Products: http://coconutcoirsrilanka.com/products_horti.html

[38]Munson, B. R., and Okiishi, T. H., 2009, Fundamentals of Fluid Mechanics, J. Wiley & Sons, Hoboken, NJ

[39]Avallone, E.A.; Baumeister, T., III (1996). Marks' Standard Handbook for Mechanical Engineers (10th Edition). (pp:3- 50 thru 3-51). McGraw-Hill.

[40]Rakocy, J.E.(1989) Tank Culture of Tilapia. Southern Regional Aquaculture Center, Publication No. 282

[41]Sanitaire Company, (accessed 2012). Diffused Aeration Design Guide.

[42]XTRASUN High Intensity Lighting Fixtures, (accessed 2012). Information and Operating Instructions.

[43]We Energies, 2011, Energy for Tomorrow, http://www.we-energies.com/residential/acctoptions/eft.htm

[44]U.S. Energy Information Administration, "Electric Power Annual 2009," DOE/EIA-0348(2009) United States Department of Energy, Washington DC 20585

[45]Sovacool, B., 2008 "Valuing the greenhouse gas emissions from nuclear power: A critical survey,"

[46]American Council for an Energy-Efficient Economy (ACEEE), 2011, "Water Heating," http://www.aceee.org/consumer/water-heating

[47]Financial Incentives for your Business, 2011, Focus On Energy, http://www.focusonenergy.com/Incentives/Business/

[48]Renewable Energy Incentives for Homes and Businesses, 2011, Focus On Energy, http://www.focusonenergy.com/Incentives/Renewable/

[49]United States Internal Revenue Code 26, Subtitle A, Chapter 1, Subchapter A, Part IV, Subpart E § 48. Found using DSIRE: http://dsireusa.org/incentives/incentive.cfm?Incentive_Code=US02F

APPENDIX A: CITED EMAIL CORRESPONDENCES

From: Brandon Jackson
Sent: Thursday, January 19, 2012 11:36 AM
To: Argus
Subject: Titan Omni-Sensor Data Request - Student Project

Greetings -

My name is Brandon Jackson, I am a senior Mechanical Engineering student at the Milwaukee School of Engineering (WI, USA). I am currently working as part of a students senior design team with the goal of designing a Combined Heat and Power (CHP) system for use in aquaculture operations located within greenhouses and re-purposed industrial sites. We have developed a complex thermal model for the energy demand of the aquaponics pond which has proved successful in a controlled psychrometric chamber. We would like to subject the thermal model to yearly environmental profile of a greenhouse to develop an economic and maintenance model; However, due to the time frame of the project a study of this length is not feasible. If we had time to conduct this study we would likely select your Titan Omni-Sensor.

We were wondering if Argus Controls would be able to assist us through providing relative humidity and temperature data from one of your sensors for a representative greenhouse, similar to what our system would be installed in. Using our model and the provided data, a load profile will be developed for the heating demands of the aquaponics pond which will be used to develop a load profile on the CHP system.

Aquaponics operations are typically linked with the growth of vegetable; Therefore a vegetable based greenhouse in northern USA - southern Canada would be most applicable.

Best regards and thank you for your time,
Brandon Jackson

From: Alec Mackenzie
Sent: Thursday, January 19, 2012 3:28 PM
To: Brandon Jackson
Subject: Re: Titan Omni-Sensor Data Request - Student Project

Brandon,

I will try to help you.

We do some work with customers who do Aquaculture production in conjunction with Vegetable production in greenhouses and also some who are doing research in Aquaponics. None fit your requested profile.

We also do a lot of greenhouses!

I don't think answering your direct request will be sufficient to help your project, but I can hopefully help your understanding of greenhouse environments. This might lead you to a different approach for your modeling. I may be missing something in your request so feel free to set me on the correct path if needed.

Some review points:

1. Crops are major environmental modifiers. empty greenhouses perform very, very differently from greenhouses full of crops. Plants respond dynamically to their environment, in some instances buffering change, in others causing it. The magnitude of these effects can dwarf all other considerations. For this reason I think you are on the right track with your request.
2. Greenhouses act as a buffer and also establish an equilibrium between indoor and outdoor climates (stating the obvious here)
3. Active control attempts to modify the greenhouse conditions produced by the second point. Modification is not always possible because of fundamental constraints in input conditions and controlled equipment capability.

Measured temperature and humidity climate data is the final product of all three points and means very little for your project (from the tank-greenhouse system perspective). About all it could do would be to allow you to calculate net energy flux between the two environments (water/air). Even this would not be perfect because the tank is likely to modify the greenhouse climate and you cannot model this with just greenhouse temperature and humidity data.

Apart from Plant behaviour, you also need to consider solar radiation. This is the primary driver of all environmental processes in the greenhouse (including plant response) so you need this in your consideration. It will also likely have a major effect on your tank environment unless fully shielded from radiation.

In our observations, the thermal couple between greenhouse air and water tanks is weak as compared with most other thermal couples in greenhouses. Likewise the moisture couple between an open tank and the greenhouse air is relatively weak compared the moisture couple driven by plants. Both these couples can be further reduced by simple insulation and vapour barriers.

So, where does that leave your project? I am not sure, but I think there are several things to consider:

1. You can certainly use real climate data or a climate model to calculate heat gain and loss from your tanks, but this result will have a very narrow application, mostly from the tank's perspective.
2. Greenhouses typically have a strong diurnal response so you will find that daily energy exchange will be much less than peak exchange which is quite likely going to be buffered out by the large thermal inertia of your tanks.
3. If the tank needs net heat addition, it is quite likely that much of that can come from direct solar gain or from the kinetic energy imparted by pumps and aeration systems. You need to consider that in your design
4. In a greenhouse system, it is quite likely that any heat you add to your tank will simply be taken away from the heat that would otherwise need to be added to the greenhouse (assuming similar temperature targets in both cases) From a system heat energy perspective there should be a net reduction because of the thermal buffering the tank confers on the greenhouse environment.

I have focused more on heat than humidity, which is even more complex. sometimes crops want humidity addition, sometimes they want less. either way, changes have complex ramifications that are not easily modeled. If water vapour loss from your tank system is low, life is simple; otherwise you will need to think a lot more about this.

If you are looking for a place to use heat from a CHP system, a greenhouse is a good candidate on a seasonal basis. I would consider the tank to be an intermediary, functioning primarily to buffer the CHP output on the one side and the greenhouse climate on the other. The tank would not be the direct focus, but rather it would apply limits to how much buffering it can do. Aquaculture tanks cannot do very much thermal buffering because of the constraints placed by the requirements for the fish.

Most of our CHP and biomass burning customers use very large, high temperature storage tanks in order to gain sufficient thermal buffer. Think 5 million litres; think 90 degree C water.

If Greenhouse climate data is still of interest to you for this project, what sort of sample interval would interest you. (we typically produce fully integrated values for each data point at whatever interval you desire). Let me know and I will see what I can come up with.

Alec Mackenzie
Director, R&D
Argus Control Systems

From: Brandon Jackson
Sent: Saturday, January 21, 2012 10:13 AM
To: Alec Mackenzie
Subject: Re: Titan Omni-Sensor Data Request - Student Project

Mr. Mackenzie –

Thank you for your very quick and knowledgeable response. You gave us more information then we could ever have expected.

I met with my design team today and we discussed several of the considerations you mentioned. Most of the points you made we have already taken into account into our design minus the coupling between the greenhouse and the pond itself.

We did not take into high consideration, up to this point in the design, of the coupling between the tank and the greenhouse. We were working under the assumption that a separate control system would be used to maintain a desired temperature and relative humidity, and our CHP system would focus primarily on the energy demands of the tank. This is consistent with the methodology of one of the aquaponics operations we were initially working with.

However, we now realize that from an economic model standpoint, it would be beneficial to analyze both systems coupled since thermal losses from the pond are energy inputs to the greenhouse. We have since incorporated a simple greenhouse model into our energy program to estimate the average monthly heating demands based on average solar insolation and temperature data. This will give us a load profile for a per month basis, which we feel will suffice for the current portion of the design.

A few other comments/questions:

- “Apart from plant behavior, you are also in need to consider solar radiation”

We are focusing primarily on urban aquponics operations which are typically in repurposed industrial sites (old warehouses) and greenhouses. In the greenhouses, plant beds are typically placed on top of the aquaponics ponds to maximize greenhouse space. It was recognized that solar radiation has a significant impact on greenhouse thermodynamics but since the tanks themselves are not direct exposed in either site, the effects of radiation were not considered to be a direct energy input into the tank.

Could you explain what you mean by "… the moisture couple between an open tank and the greenhouse air is relatively weak compared to the moisture couple driven by plants." Do you mean to say that in your experience open tanks don't have a significant effect on greenhouse humidity relative to the agriculture?

- "If water vapor loss from your tank system is low, life is simple; otherwise you will need to think a lot more about this"

Our early thermal models, which agree very well with the psychrometric chamber testing we conducted, predicts a water loss of about 5-10 kg/hr for our larger tank sizes. We are trying to develop a universal approach so the size of the installation greenhouse/warehouse is not well understood to take this factor into consideration.

You mentioned the heat additions from the pump and aeration needs. Our current models show that the thermal demands are several times greater than the electrical (pump and aeration) demands of the system. But for our final load profile we will assume that the pumping demands will result in a net equal heat input into the system.

- "Think 5 million liters; think 90 degrees C"

Quite impressive, thanks for sharing.

We would be happy to share the continued progress of our project with you if you are interested. By the end of February will finish our initial design report. In the following months we will be prototype minor components of the system, such as the engine control module along with adding complexity to our greenhouse/aquaponics model.

Thanks again for your help and best regards,

Brandon Jackson
Mechanical Engineering '12
Milwaukee School of Engineering
jacksonb@msoe.edu

From: Alec Mackenzie [alec8@shaw.ca]
Sent: Saturday, January 21, 2012 1:02 PM
To: Jackson, Brandon A.
Subject: Re: Titan Omni-Sensor Data Request - Student Project

Brandon,
Your response is very good.

Just a couple of answers to your questions and comments:

I assumed this project had an economic component since you are going to the effort of considering CHP. CHP should be justifiable solely on the potential carbon footprint reduction, but since no one cares about that, you are forced to make an economic case against current energy prices. If you assume thermal energy demands are met by pumping energy, you will need some other use for the heat produced by the CHP system. With heat storage, the greenhouse can use significant amounts of CHP generated heat (mostly at night and in the colder months of the year). Greenhouse heat demand profiles usually don't match electrical demand profiles very well some decoupling is necessary in most applications. I would look to your fish tanks as the most obvious place to store and recover heat, going to separate heat storage tanks once that capacity is exceeded.

Moisture couple... In simple terms, a major portion of the solar radiation striking leaf surfaces is absorbed and then rejected through latent heat transfer. In vegetable greenhouses almost all solar radiation strikes leaf surfaces, with very little absorbed in structure or ground.

An open tank has a relatively small exchange area and its evaporation is limited to the equilibrium formed between the vapour pressure of the water and that of the air. Greenhouses often run at low vapour pressure deficits, so there is little difference between the tank and the air unless the tank is much warmer than the air or if there is greatly increased surface area (bubbles in aeration systems for example). The tank water surface can be assumed to have a VPD of zero and a temperature close to the water temperature. The ambient air will likely have a VPD in the range of 3 - 12 or so at ambient temperature. For more on this, view the following:

http://www.arguscontrols.com/articles/VPD_Application_Note.pdf

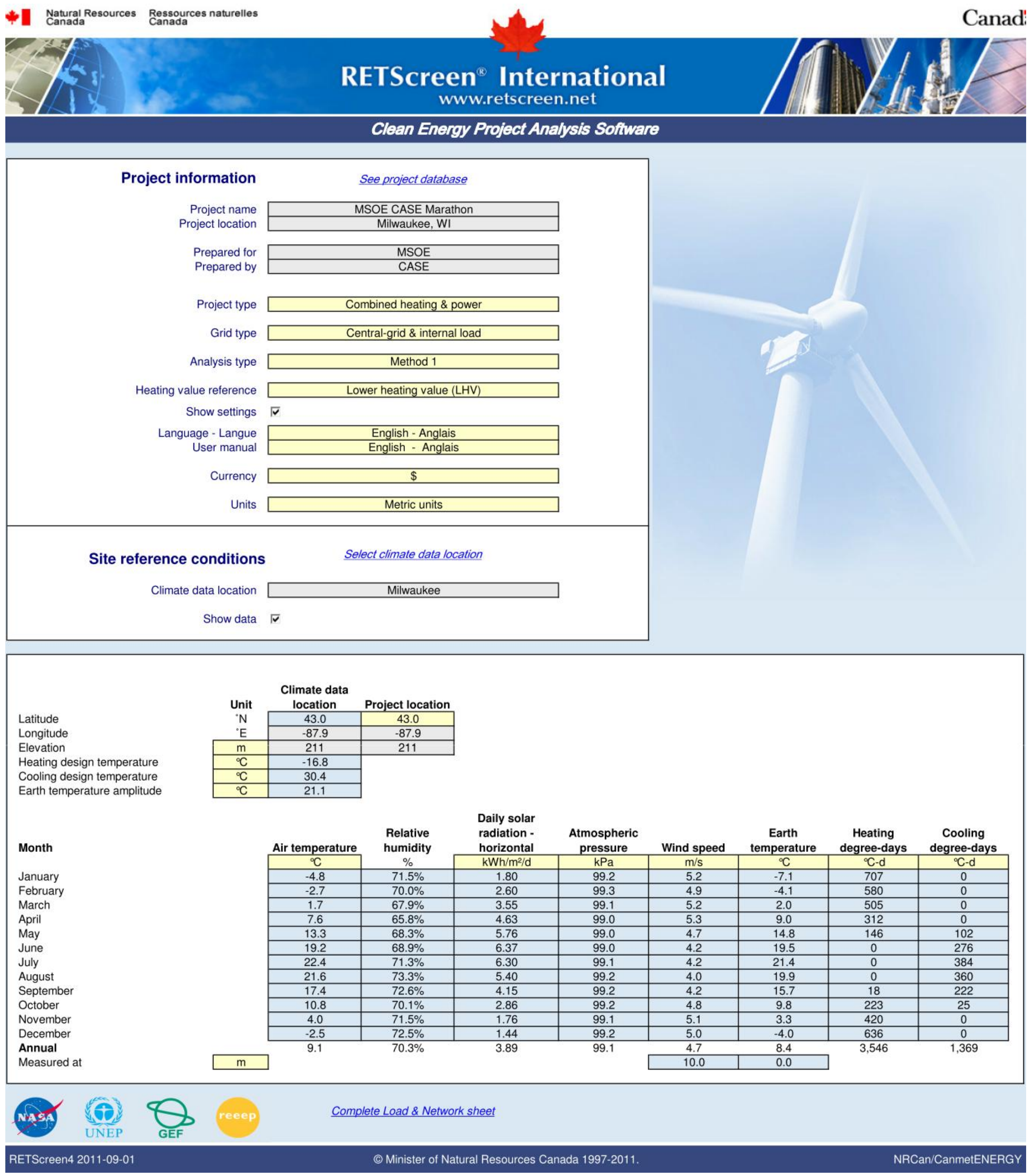
Very active greenhouse vegetable crops under maximum insolation will consume (vaporize) in the order of perhaps 5 litres per square meter of greenhouse floor area on a summer day. I suspect your tanks will have much less evaporation expressed as a ratio of the total greenhouse floor area. In Dark conditions your Tank will have a much larger effect since plants don't evaporate water if they don't need to. If this is an issue, I would cover the tank to block water vapour exchange.

I would be interested in your future published results.

Best wishes with the project - it is ambitious and you should learn a lot!

Alec

APPENDIX B: RETSCREEN



Project information

Project name	MSOE CASE Marathon
Project location	Milwaukee, WI
Prepared for	MSOE
Prepared by	CASE
Project type	Combined heating & power
Grid type	Central-grid & internal load
Analysis type	Method 1
Heating value reference	Lower heating value (LHV)
Show settings	☑
Language - Langue	English - Anglais
User manual	English - Anglais
Currency	$
Units	Metric units

Site reference conditions

Climate data location	Milwaukee
Show data	☑

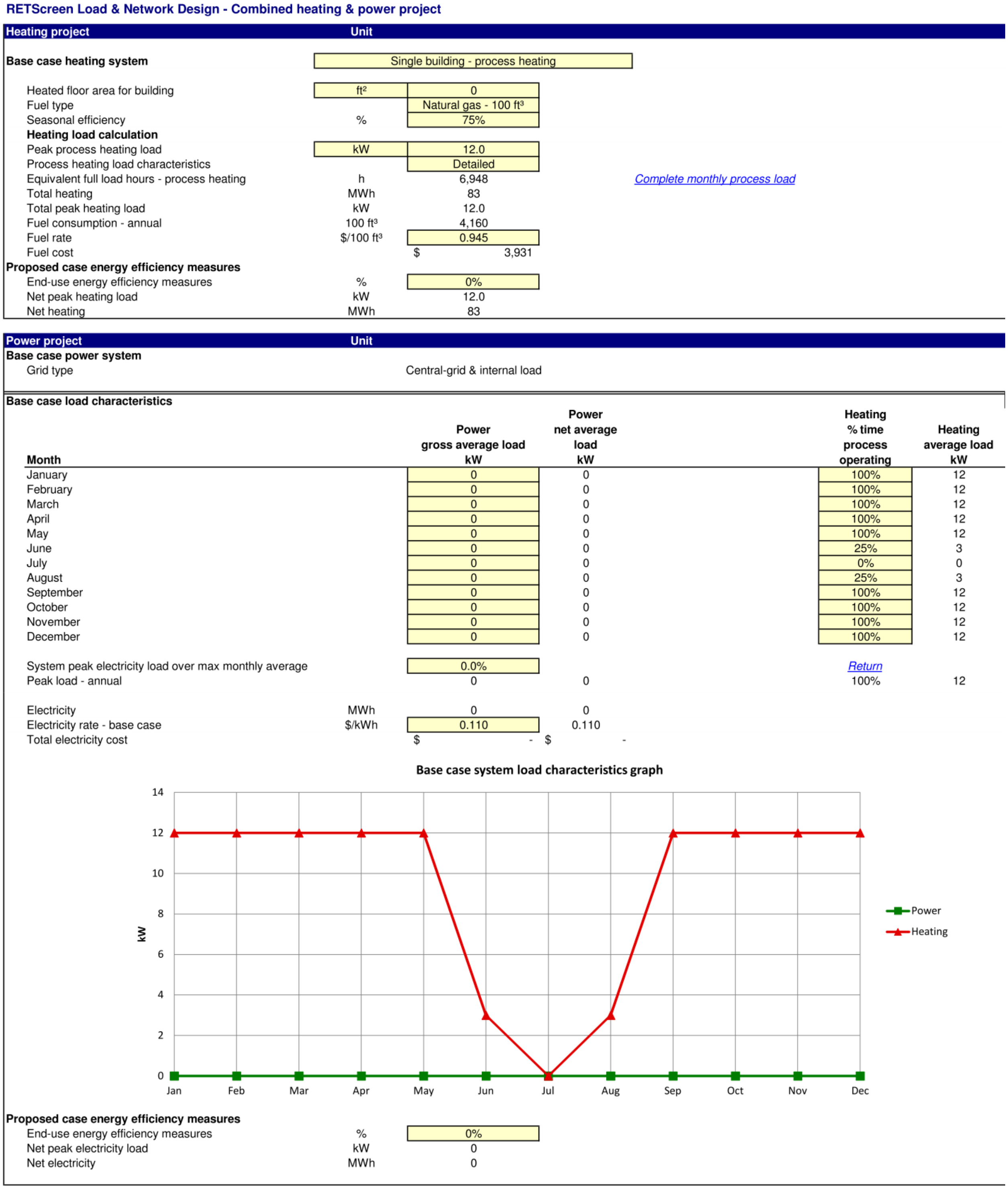
	Unit	Climate data location	Project location
Latitude	˚N	43.0	43.0
Longitude	˚E	-87.9	-87.9
Elevation	m	211	211
Heating design temperature	℃	-16.8	
Cooling design temperature	℃	30.4	
Earth temperature amplitude	℃	21.1	

Month		Air temperature	Relative humidity	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days	Cooling degree-days
		℃	%	kWh/m²/d	kPa	m/s	℃	℃-d	℃-d
January		-4.8	71.5%	1.80	99.2	5.2	-7.1	707	0
February		-2.7	70.0%	2.60	99.3	4.9	-4.1	580	0
March		1.7	67.9%	3.55	99.1	5.2	2.0	505	0
April		7.6	65.8%	4.63	99.0	5.3	9.0	312	0
May		13.3	68.3%	5.76	99.0	4.7	14.8	146	102
June		19.2	68.9%	6.37	99.0	4.2	19.5	0	276
July		22.4	71.3%	6.30	99.1	4.2	21.4	0	384
August		21.6	73.3%	5.40	99.2	4.0	19.9	0	360
September		17.4	72.6%	4.15	99.2	4.2	15.7	18	222
October		10.8	70.1%	2.86	99.2	4.8	9.8	223	25
November		4.0	71.5%	1.76	99.1	5.1	3.3	420	0
December		-2.5	72.5%	1.44	99.2	5.0	-4.0	636	0
Annual		9.1	70.3%	3.89	99.1	4.7	8.4	3,546	1,369
Measured at	m					10.0	0.0		

RETScreen4 2011-09-01

© Minister of Natural Resources Canada 1997-2011.

NRCan/CanmetENERGY



RETScreen Load & Network Design - Combined heating & power project

Heating project	**Unit**	
Base case heating system		Single building - process heating
Heated floor area for building	ft²	0
Fuel type		Natural gas - 100 ft³
Seasonal efficiency	%	75%
Heating load calculation		
Peak process heating load	kW	12.0
Process heating load characteristics		Detailed
Equivalent full load hours - process heating	h	6,948
Total heating	MWh	83
Total peak heating load	kW	12.0
Fuel consumption - annual	100 ft³	4,160
Fuel rate	$/100 ft³	0.945
Fuel cost		$ 3,931
Proposed case energy efficiency measures		
End-use energy efficiency measures	%	0%
Net peak heating load	kW	12.0
Net heating	MWh	83

Complete monthly process load

Power project	**Unit**	
Base case power system		
Grid type		Central-grid & internal load

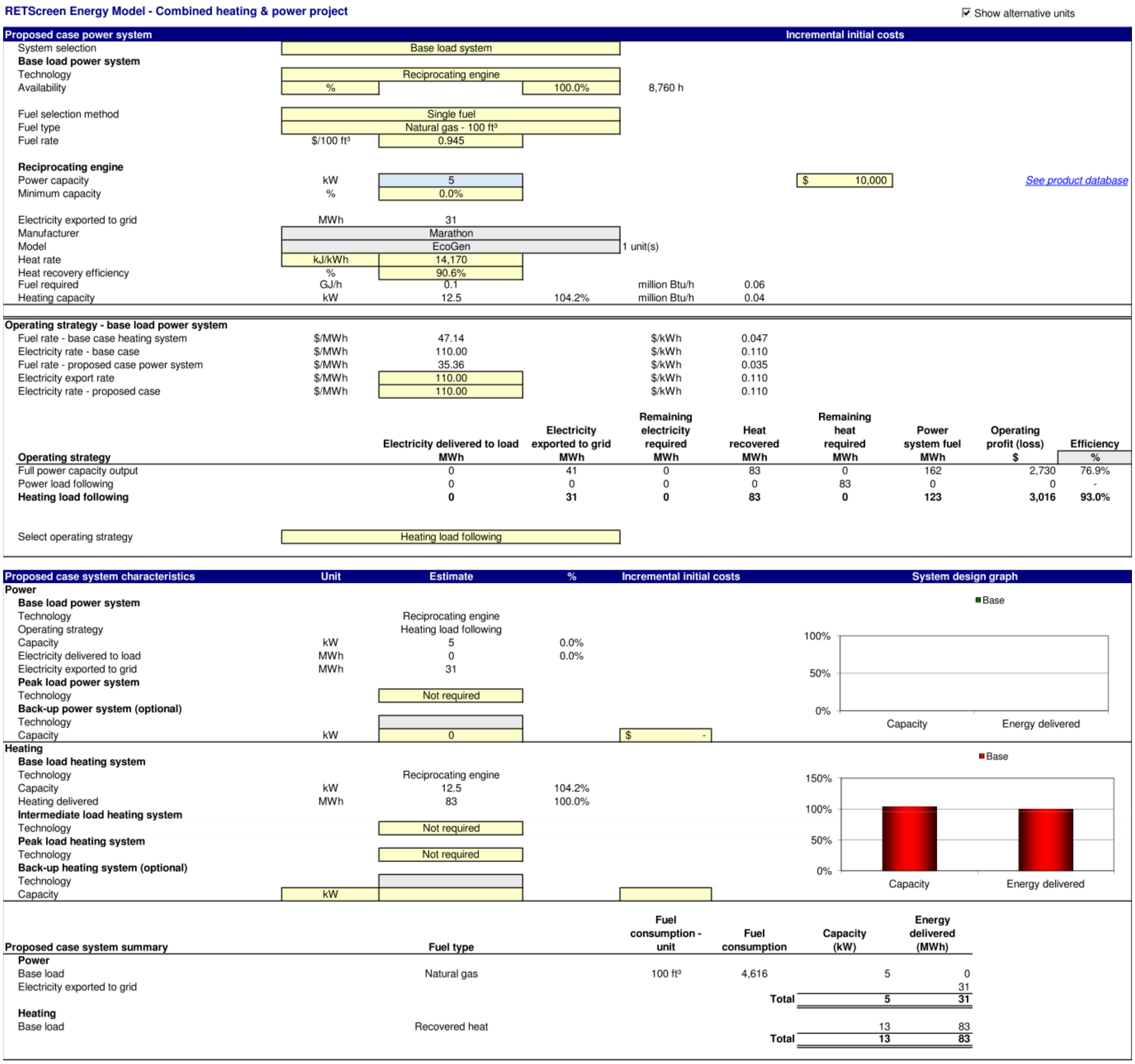
Base case load characteristics

Month	**Power gross average load kW**	**Power net average load kW**	**Heating % time process operating**	**Heating average load kW**
January	0	0	100%	12
February	0	0	100%	12
March	0	0	100%	12
April	0	0	100%	12
May	0	0	100%	12
June	0	0	25%	3
July	0	0	0%	0
August	0	0	25%	3
September	0	0	100%	12
October	0	0	100%	12
November	0	0	100%	12
December	0	0	100%	12

System peak electricity load over max monthly average		0.0%		*Return*	
Peak load - annual		0	0	100%	12
Electricity	MWh	0	0		
Electricity rate - base case	$/kWh	0.110	0.110		
Total electricity cost		$ -	$ -		

Base case system load characteristics graph

Proposed case energy efficiency measures		
End-use energy efficiency measures	%	0%
Net peak electricity load	kW	0
Net electricity	MWh	0



RETScreen Energy Model - Combined heating & power project

☑ Show alternative units

Proposed case power system						Incremental initial costs	
System selection		Base load system					
Base load power system							
Technology		Reciprocating engine					
Availability	%		100.0%	8,760 h			
Fuel selection method		Single fuel					
Fuel type		Natural gas - 100 ft³					
Fuel rate	$/100 ft³	0.945					
Reciprocating engine							
Power capacity	kW	5				$ 10,000	See product database
Minimum capacity	%	0.0%					
Electricity exported to grid	MWh	31					
Manufacturer		Marathon					
Model		EcoGen		1 unit(s)			
Heat rate	kJ/kWh	14,170					
Heat recovery efficiency	%	90.6%					
Fuel required	GJ/h	0.1		million Btu/h	0.06		
Heating capacity	kW	12.5	104.2%	million Btu/h	0.04		

Operating strategy - base load power system				
Fuel rate - base case heating system	$/MWh	47.14	$/kWh	0.047
Electricity rate - base case	$/MWh	110.00	$/kWh	0.110
Fuel rate - proposed case power system	$/MWh	35.36	$/kWh	0.035
Electricity export rate	$/MWh	110.00	$/kWh	0.110
Electricity rate - proposed case	$/MWh	110.00	$/kWh	0.110

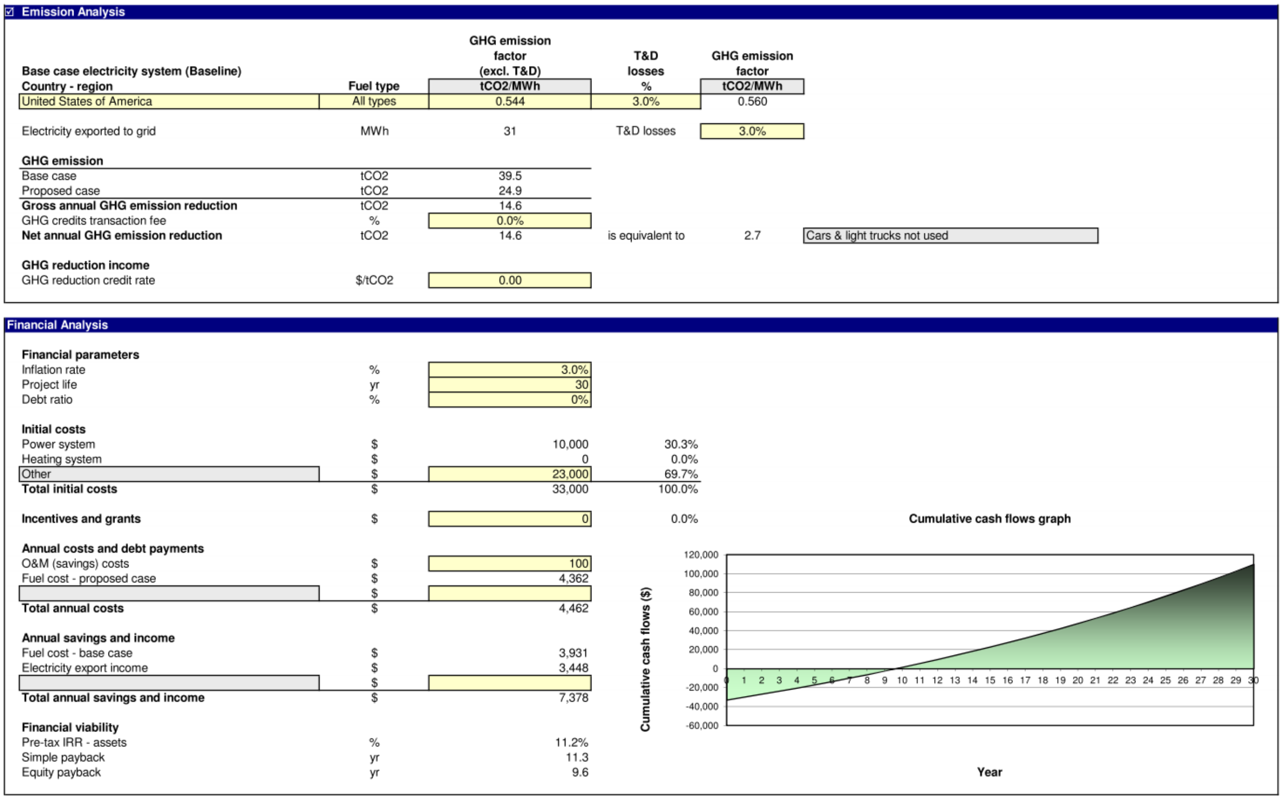
Operating strategy	Electricity delivered to load MWh	Electricity exported to grid MWh	Remaining electricity required MWh	Heat recovered MWh	Remaining heat required MWh	Power system fuel MWh	Operating profit (loss) $	Efficiency %
Full power capacity output	0	41	0	83	0	162	2,730	76.9%
Power load following	0	0	0	0	83	0	0	-
Heating load following	**0**	**31**	**0**	**83**	**0**	**123**	**3,016**	**93.0%**

Select operating strategy: Heating load following

Proposed case system characteristics	Unit	Estimate	%	Incremental initial costs
Power				
Base load power system				
Technology		Reciprocating engine		
Operating strategy		Heating load following		
Capacity	kW	5	0.0%	
Electricity delivered to load	MWh	0	0.0%	
Electricity exported to grid	MWh	31		
Peak load power system				
Technology		Not required		
Back-up power system (optional)				
Technology				
Capacity	kW	0		$ -
Heating				
Base load heating system				
Technology		Reciprocating engine		
Capacity	kW	12.5	104.2%	
Heating delivered	MWh	83	100.0%	
Intermediate load heating system				
Technology		Not required		
Peak load heating system				
Technology		Not required		
Back-up heating system (optional)				
Technology				
Capacity	kW			

System design graph

Proposed case system summary	Fuel type	Fuel consumption - unit	Fuel consumption	Capacity (kW)	Energy delivered (MWh)
Power					
Base load	Natural gas	100 ft³	4,616	5	0
Electricity exported to grid					31
			Total	**5**	**31**
Heating					
Base load	Recovered heat			13	83
			Total	**13**	**83**



☑ **Emission Analysis**

Base case electricity system (Baseline) Country - region	Fuel type	GHG emission factor (excl. T&D) tCO2/MWh	T&D losses %	GHG emission factor tCO2/MWh	
United States of America	All types	0.544	3.0%	0.560	
Electricity exported to grid	MWh	31	T&D losses	3.0%	
GHG emission					
Base case	tCO2	39.5			
Proposed case	tCO2	24.9			
Gross annual GHG emission reduction	tCO2	14.6			
GHG credits transaction fee	%	0.0%			
Net annual GHG emission reduction	tCO2	14.6	is equivalent to	2.7	Cars & light trucks not used
GHG reduction income					
GHG reduction credit rate	$/tCO2	0.00			

Financial Analysis

Financial parameters			
Inflation rate	%	3.0%	
Project life	yr	30	
Debt ratio	%	0%	
Initial costs			
Power system	$	10,000	30.3%
Heating system	$	0	0.0%
Other	$	23,000	69.7%
Total initial costs	$	33,000	100.0%
Incentives and grants	$	0	0.0%
Annual costs and debt payments			
O&M (savings) costs	$	100	
Fuel cost - proposed case	$	4,362	
	$		
Total annual costs	$	4,462	
Annual savings and income			
Fuel cost - base case	$	3,931	
Electricity export income	$	3,448	
	$		
Total annual savings and income	$	7,378	
Financial viability			
Pre-tax IRR - assets	%	11.2%	
Simple payback	yr	11.3	
Equity payback	yr	9.6	

APPENDIX C: MATERIAL SAFETY DATA SHEETS

Material data safety sheets for chemicals which will likely be used are given after this page.

MATERIAL SAFETY DATA SHEET

QUAKER STATE® PEAK PERFORMANCE CONVENTIONAL MOTOR OIL - ALL GRADES

1. PRODUCT AND COMPANY IDENTIFICATION

MSDS Number: 14938

Version Date: 07/16/02

Product Name: QUAKER STATE® PEAK PERFORMANCE CONVENTIONAL MOTOR OIL - ALL GRADES
Product Use: Engine oil
Synonyms: 5W-30, 10W-30, 10W-40, 20W-50, 15W-40

Company Information
SOPUS Products
P.O. Box 4427
Houston, TX 77210-4427
USA

Phone Numbers
Medical Emergency: 1-800-546-6040
Transportation Emergency (USA): 1-800-424-9300
Transportation Emergency (International): 1-703-527-3887 (Call Collect)
MSDS Assistance: 1-800-546-6227
Fax On Demand: 1-800-546-6227
Technical Assistance: 1-800-458-4998
Customer Service: 1-800-468-8397
Fax Number: 713-217-3181
Internet Address: www.MSDS.PZLQS.com

2. COMPONENT INFORMATION

Component	CAS No.	Weight Percent Range	Hazardous in Blend
HYDROTREATED HEAVY PARAFFINIC PETROLEUM DISTILLATES	64742-54-7	< 70	No
SOLVENT-DEWAXED HEAVY PARAFFINIC DISTILLATE	64742-65-0	< 70	No
DETERGENT/DISPERSANT	MIXTURE	5 - 10	No
VISCOSITY MODIFIER	9003-29-6	< 10	No
POUR POINT DEPRESSANT	MIXTURE	< 2	No

Under normal conditions of use or in a foreseeable emergency, this product does not meet the definition of a hazardous chemical when evaluated according to the OSHA Hazard Communication Standard, 29 CFR 1910.1200.

Other: No information available

3. HAZARDS IDENTIFICATION

Emergency and Hazards Overview
CAUTION: Contains Petroleum Lubricant. Repeated skin contact can cause skin disorders.

ATTENTION: Used motor oil is a possible skin cancer hazard based on animal data. Repeated exposure to oil mist in excess of the OSHA limit (5mg/m3) can result in accumulation of oil droplets in pulmonary tissue.

NFPA Ratings: **Health** 1 **Flammability** 1 **Reactivity** 0

Primary Route of Exposure: **Skin** X **Inhalation** -- **Eye** X

Health Effect Information

Eye Contact: This product is practically non-irritating to the eyes upon direct contact. Based on testing of similar products and/or components.

Skin Contact: Avoid skin contact. This product is minimally irritating to the skin upon direct contact. Based on testing of similar products and/or components. Prolonged or repeated contact may result in contact dermatitis which is characterized by dryness, chapping, and reddening. Prolonged or repeated contact may result in oil acne which is characterized by blackheads with possible secondary infection. Avoid prolonged and repeated skin contact with used motor oils. See Section 11 - Toxicological Information.

Inhalation: This product has a low vapor pressure and is not expected to present an inhalation hazard at ambient conditions. Caution should be taken to prevent aerosolization or misting of this product. On rare occasions, prolonged and repeated exposure to oil mist poses a risk of pulmonary disease such as chronic lung inflammation. Signs of respiratory effects vary with concentration and length of exposure and include nasal discharge, sore throat, coughing, bronchitis, pulmonary edema and difficulty breathing. Shortness of breath and cough are the most common symptoms.

Ingestion: Do not ingest. This product is relatively non-toxic by ingestion. This product has laxative properties and may result in abdominal cramps and diarrhea. Exposure to a large single dose, or repeated smaller doses, may lead to lung aspiration, which can lead to lipid pneumonia or chronic lung inflammation. These are low-grade, chronic localized tissue reactions.

Medical Conditions Aggravated by Exposure: Drying and chapping may make the skin more susceptible to other irritants, sensitizers and disease.

Other: No information available

4. FIRST AID INFORMATION

Eye Contact: Immediately flush eyes with large amounts of water and continue flushing until irritation subsides. If material is hot, treat for thermal burns and seek immediate medical attention.

Skin Contact: No treatment is necessary under ordinary circumstances. Remove contaminated clothing. Wash contaminated area thoroughly with soap and water. If material is hot, submerge injured area in cold water. If victim is severely burned, remove to a hospital immediately.

Inhalation: This material has a low vapor pressure and is not expected to present an inhalation exposure at ambient conditions. If vapor or mist is generated when the material is heated, and the victim experiences signs of respiratory tract irritation, remove to fresh air.

Ingestion: No treatment is necessary under ordinary circumstances. Do not induce vomiting. If victim exhibits signs of lung aspiration such as coughing or choking, seek immediate medical assistance.

Notes to Physician: No information available

Other: No information available

5. FIRE AND EXPLOSION INFORMATION

Flammable Properties

Flash Point: 415 F, 212.8 C **Test Method:** ASTM 3278 - Closed Cup

Flammable Limits in Air

Upper Percent: No data available

Lower Percent: No data available

Autoignition Temperature: No data available **Test Method:** No information available

NFPA Classification: Class III-B combustible liquid

Extinguishing Media: Use dry chemical, foam, or carbon dioxide.

Fire Fighting Measures

Special Fire Fighting Procedures and Equipment: Water may be ineffective but can be used to cool containers exposed to heat or flame to prevent vapor pressure buildup and possible container rupture. Caution should be exercised when using water or foam as frothing may occur, especially if sprayed into containers of hot, burning liquid.

Unusual Fire and Explosion Conditions: Dense smoke may be generated while burning. Carbon monoxide, carbon dioxide, and other oxides may be generated as products of combustion.

Hazardous Combustion By-Products: None

Other: No information available

---

6. ACCIDENTAL RELEASE MEASURES

Personnel Safeguards: Consult Health Effect Information in Section 3, Personal Protection Information in Section 8, Fire and Explosion Information in Section 5, and Stability and Reactivity Information in Section 10.

Regulatory Notifications: Notify appropriate authorities of spill.

Containment and Clean up: Contain spill immediately. Do not allow spill to enter sewers or watercourses. Absorb with appropriate inert material such as sand, clay, etc. Large spills may be picked up using vacuum pumps, shovels, buckets, or other means and placed in drums or other suitable containers.

Other: No information available

---

7. HANDLING AND STORAGE INFORMATION

Handling: Fire extinguishers should be kept readily available. See NFPA 30 and OSHA 1910.106--Flammable and Combustible Liquids.

Storage: Do not transfer to unmarked containers. Store in closed containers away from heat, sparks, open flame, or oxidizing materials.

Empty Container Warnings

Drums: Empty drums should be completely drained, properly bunged and promptly returned to a drum reconditioner, or properly disposed.

Plastic: Empty container may retain product residues.

Other: No information available

---

8. EXPOSURE CONTROLS / PERSONAL PROTECTION INFORMATION

Exposure Limits and Guidelines

This product does not contain any components with OSHA or ACGIH exposure limits.

Personal Protective Equipment

Eye/Face Protection: Eye protection is not required under conditions of normal use. If material is handled such that it could be splashed into eyes, wear plastic face shield or splash-proof safety goggles.

Skin Protection: No skin protection is required for single, short duration exposures. For prolonged or repeated exposures, use impervious clothing (boots, gloves, aprons, etc.) over parts of the body subject to exposure. If handling hot material, use insulated protective clothing (boots, gloves, aprons, etc.). Launder soiled clothes. Properly dispose of contaminated leather articles including shoes, which cannot be decontaminated.

Respiratory Protection: Respiratory protection is not required under conditions of normal use. If vapor or mist is generated when the material is heated or handled, use an organic vapor respirator with a dust and mist filter. All respirators must be NIOSH certified. Do not use compressed oxygen in hydrocarbon atmospheres.

Personal Hygiene: Consumption of food and beverage should be avoided in work areas where hydrocarbons are present. Always wash hands and face with soap and water before eating, drinking, or smoking.

Engineering Controls / Work Practices

Ventilation: If vapor or mist is generated when the material is heated or handled, adequate ventilation in accordance with good engineering practice must be provided to maintain concentrations below the specified exposure or flammable limits.

Other: The OSHA permissible exposure limit (PEL) and ACGIH threshold limit value (TLV) for oil mist is 5 mg/m3. The ACGIH short-term exposure limit (STEL) for oil mist is 10 mg/m3.

---

9. PHYSICAL AND CHEMICAL PROPERTIES

Appearance: Amber to dark amber	
Odor: Hydrocarbon - mild	**Vapor Pressure:** No data available
Physical state: Liquid	**Vapor Density (air=1):** No data available
pH: No data available	**Percent Volatile by Volume:** No data available
Boiling Point: No data available	**Volatile Organic Content:** No data available
Melting Point: No data available	**Molecular Weight:** No data available
Specific Gravity: 0.88 - 0.9 @ 16 C / 60 F	**Average Carbon Number:** No data available
Pour Point: -15 F, -26.1 C	**Viscosity @ 100 F:** No data available
	Viscosity @ 40 C: No data available
Solubility in Water: Negligible in water	
Octanol / Water Coefficient: Log K_{ow} = No data available	

---

10. STABILITY AND REACTIVITY INFORMATION

Chemical Stability: Stable

Conditions to Avoid: High heat and open flames.

Incompatible Materials to Avoid: May react with strong oxidizing agents.

Other: No information available

---

11. TOXICOLOGICAL INFORMATION

Primary Eye Irritation: No information available

Primary Skin Irritation: No information available

Acute Dermal Toxicity: No information available

Subacute Dermal Toxicity: No information available

Dermal Sensitization: No information available

Inhalation Toxicity: No information available

Inhalation Sensitization: No information available

Oral Toxicity: No information available

Mutagenicity: No information available

Carcinogenicity: The International Agency for Research on Cancer (IARC) has concluded that there is inadequate data to evaluate the carcinogenicity to experimental animals of this class of product. IARC has concluded there is sufficient evidence that used gasoline-engine motor oils produce skin tumors in experimental animals. Also, IARC has determined this class of products belongs to Group 3-"not classifiable as to its carcinogenicity to humans".

Reproductive and Developmental Toxicity: No information available

Teratogenicity: No information available

Immunotoxicity: No information available

Neurotoxicity: No information available

Other: No information available

12. ECOLOGICAL INFORMATION

Aquatic Toxicity: No information available

Terrestrial Toxicity: No information available

Chemical Fate and Transport: No information available

Other: No information available

13. DISPOSAL INFORMATION

Regulatory Information: All disposals must comply with federal, state, and local regulations. The material, if spilled or discarded, may be a regulated waste. Refer to state and local regulations. Caution! If regulated solvents are used to clean up spilled material, the resulting waste mixture may be regulated. Department of Transportation (DOT) regulations may apply for transporting this material when spilled.

Waste Disposal Methods: Waste material may be landfilled or incinerated at an approved facility. Materials should be recycled if possible.

Other: No information available

14. TRANSPORTATION INFORMATION

U.S. Department of Transportation (DOT)
Highway / Rail (Bulk): Not Regulated
Highway / Rail (Non-Bulk): Not Regulated

For US shipments, US DOT law requires the shipper to determine the proper shipping description of the material that is being shipped. The shipping information and description contained in this section may not be suitable for all shipments of this material, but may help the shipper determine the proper shipping description for a particular shipment.

International Information

Vessel:	**IMDG Regulated:**	--	**IMDG Not Regulated:**	X
Air:	**ICAO Regulated:**	--	**ICAO Not Regulated:**	X

Other: No information available

15. Regulatory Information

<u>Regulatory Lists Searched</u>: **The components listed in Section 2 of this MSDS were compared to substances that appear on the following regulatory lists. Each list is numerically identified. See Regulatory Search Results below.**

Health & Safety: 10 - IARC carcinogen, 11 - NTP carcinogen, 12 - OSHA carcinogen, 15 - ACGIH TLV, 16 - OSHA PEL, 17 - NIOSH exposure limit, 20 - US DOT Appendix A, Hazardous substances, 22 - FDA 21 CFR Total food additives, 23 - NFPA 49 or 325

Environmental: 30 - CAA 1990 Hazardous air pollutants, 31 - CAA Ozone depletors, 33 - CAA HON rule, 34 - CAA Toxic substance for accidental release prevention, 35 - CAA Volatile organic compounds (VOC's) in SOCMI, 41 - CERCLA / SARA Section 302 extremely hazardous substances, 42 - CERCLA / SARA Section 313 emissions reporting, 43 - CWA Hazardous substances, 44 - CWA Priority pollutants, 45 - CWA Toxic pollutants, 46 - EPA Proposed test rule for hazardous air pollutants, 47 - RCRA Basis for listing - Appendix VII, 48 - RCRA waste, 49 - SDWA - (S)MCLs

International: 50 - Canada - WHMIS Classification of substance, 54 - Mexico - Drinking water - ecological criteria, 55 - Mexico - Wastewater discharges, 56 - US -TSCA Section (12)(b) - export notification

State Lists: 60 - CA - Proposition 65, 61 - FL - Substances, 62 - MI - Critical materials, 63 - MA - RTK, 64 - MA - Extraordinarily hazardous substances, 65 - MN - Hazardous substances, 66 - PA - RTK, 67 - NJ - RTK, 68 - NJ - Environmental hazardous substances, 69 - NJ - Special hazardous substances

Inventories: 80 - Canada - Domestic substances , 81 - European - EINECS, 82 - Japan - ENCS, 83 - Korea - Existing and evaluated chemical substances, 84 - US - TSCA , 85 - China Inventory

<u>Regulatory Search Results:</u>
HYDROTREATED HEAVY PARAFFINIC PETROLEUM DISTILLATES: 80, 81, 83, 84, 85
SOLVENT-DEWAXED HEAVY PARAFFINIC DISTILLATE: 80, 81, 83, 84, 85
VISCOSITY MODIFIER: 35, 80, 83, 84, 85

U.S. TSCA Inventory: All components of this material are on the US TSCA Inventory.

SARA Section 313: This product is not known to contain any SARA, Title III, Section 313 Reportable Chemicals at or greater than 1.0% (0.1% for carcinogens).

IARC: No information available

SARA 311 / 312 Categories

Acute: -- **Chronic:** -- **Fire:** -- **Pressure:** -- **Reactive:** --

Not Regulated: X

Canadian WHMIS Classification

Not a controlled substance under WHMIS

European Union Classification

Hazard Symbols:

No classification recommended

Risk Phrases:

No classification recommended

Safety Phrases:

No classification recommended

Other: No information available

---

16. OTHER INFORMATION

Health and Environmental Label Language

WARNING: Continuous contact with used gasoline engine oils has caused skin cancer in animal tests.
ATTENTION: Prolonged or repeated skin contact may cause oil acne or dermatitis. Repeated exposure to oil mist in excess of the OSHA limit (5mg/m3 can result in accumulation of oil droplets in pulmonary tissue.

Precautionary Measures: Avoid prolonged or repeated contact with eyes, skin and clothing. Avoid generation and inhalation of oil mists.

First Aid: Skin Contact: Wash skin with soap and water. Launder soiled clothes and discard oil-soaked shoes. If irritation persists seek medical attention. Eye Contact: Flush with water. If irritation persists seek medical attention. Ingestion: Do not induce vomiting. In general, no treatment is necessary unless large quantities of product are ingested. If discomfort persists seek medical assistance.

Instructions in Case of Fire or Spill: In case of fire, use water fog, foam, dry chemical or carbon dioxide. Water spray may be ineffective, but can be used to cool containers. Do not use a direct stream of water. Material will float and can be reignited on surface of water.

Spill or Leak: Dike and contain spill. Do not use water; soak up with absorbent material such as clay, sand or other suitable material. Place in non-leaking container and seal tightly for proper disposal.

Contains: highly refined petroleum distillate, mixture; zinc compounds, mixture; polymer additives, mixture.

KEEP OUT OF REACH OF CHILDREN. (If intended for retail also)

MSDS Revisions

Previous Version Date: 06/01/01

Previous Version Information

Revised Section 1 - Product Name

Other

No information available

Prepared By:

SOPUS Products
P.O. Box 4427
Houston, TX 77210-4453 USA

Disclaimer of Warranty: The information contained herein is based upon data and information available to us, and reflects our best professional judgment. This product may be formulated in part with components purchased from other companies. In many instances, especially when proprietary or trade secret materials are used, SOPUS Products must rely upon the hazard evaluation of such components submitted by that product's manufacturer or importer. No warranty of merchantability, fitness for any use, or any other warranty is expressed or implied regarding the accuracy of such data or information, the results to be obtained from the use thereof, or that any such use do not infringe any patent. Since the information contained herein may be applied under conditions of use beyond our control and with which we may be unfamiliar, we do not assume responsibility for the results of such application. This information is furnished upon the condition that the person receiving it shall make his own determination of the suitability of the material for his particular use.

USED OIL

MATERIAL SAFETY DATA SHEET

SECTION 1: PRODUCT AND COMPANY IDENTIFICATION

PRODUCT NAME: **USED OIL**

SYNONYMS: Waste oil; Used lubricating oil; Oil and water mixture

PRODUCT PART NUMBER(S): Not applicable.

PRODUCT USE: Oil or water mixture for re-refining or reprocessing.
If this product is used in combination with other products, refer to the Material Safety Data Sheets for those products.

These numbers are for emergency use only. If you desire non-emergency product information, please call a phone number listed below.

24-HOUR EMERGENCY PHONE NUMBERS MEDICAL AND TRANSPORTATION (SPILL):

1-800-468-1760

MANUFACTURER/ SUPPLIER: Safety-Kleen Systems, Inc.
5400 Legacy Drive
Cluster II, Building 3
Plano, Texas 75024
USA
1-800-669-5740
www.Safety-Kleen.com

TECHNICAL INFORMATION: 1-800-669-5740 Press 1 then 1 then Extension 7500

MSDS FORM NUMBER: 81451

ISSUE: September 20, 2007

ORIGINAL ISSUE: January 15, 1990

SUPERSEDES: June 11, 2007

PREPARED BY: Product MSDS Coordinator

APPROVED BY: MSDS Task Force

SECTION 2: COMPOSITION/INFORMATION ON INGREDIENTS

				OSHA PEL		ACGIH TLV®			
WT%	NAME	SYNONYM	CAS NO.	TWA	STEL	TWA	STEL	LD[a]	LC[b]
80 to 100	Lubricating oils, used	Used oil	70514-12-4	N. Av.	N. Av.	N. Av.	N. Av.	N. Av.	N. Av.
0 to 20*	Water/solids	N. Av.	N. Av.	N. Av.	N. Av.	N. Av.	N. Av.	N. Av.	N. Av.
0 to 10*	Hydrocarbon solvents. May include gasoline, diesel fuel, jet fuel, mineral spirits, etc.	N. Av.	N. Av.	N. Av.	N. Av.	N. Av.	N. Av.	N. Av.	N. Av.
0 to 1.5*	Metals. May include lead, iron, zinc, copper, chromium, arsenic, nickel, and others: each below 1.0 WT%.	N. Av.	N. Av.	N. Av.	N. Av.	N. Av.	N. Av.	N. Av.	N. Av.
0 to 1.0*	Polynuclear aromatics. May include naphthalene, fluoranthene, phenanthrene, pyrene, and others: each below 0.3 WT%.	N. Av.	N. Av.	N. Av.	N. Av.	N. Av.	N. Av.	N. Av.	N. Av.
0 to 0.5*	Chlorinated solvents.	N. Av.	N. Av.	N. Av.	N. Av.	N. Av.	N. Av.	N. Av.	N. Av.

N.Av. = Not Available

*Even though the concentration range does not fall under the ranges prescribed by WHMIS, this is the actual range which varies with each batch of the product.

[a] Oral-Rat LD_{50} (mg/kg)

[b] Inhalation-Rat LC_{50}

SECTION 3: HAZARDS IDENTIFICATION

EMERGENCY OVERVIEW

APPEARANCE

Liquid, black and viscous (thick), petroleum odor.

WARNING!

PHYSICAL HAZARDS

Combustible liquid.

HEALTH HAZARDS

May be harmful if inhaled.
May be harmful if absorbed through skin.
May be harmful or fatal if swallowed.
May irritate the respiratory tract (nose, throat, and lungs), eyes, and skin.
Suspect cancer hazard. Contains material which can cause cancer. Risk of cancer depends on duration and level of exposure.
Contains material which can cause birth defects.
Contains material which can cause central nervous system damage.

ENVIRONMENTAL HAZARDS

Product may be toxic to fish, plants, wildlife, and/or domestic animals.

POTENTIAL HEALTH EFFECTS

Effects may vary depending on material composition. Typical effects may include:

INHALATION (BREATHING): High concentrations of vapor or mist may be harmful if inhaled. High concentrations of vapor or mist may irritate the respiratory tract (nose, throat, and lungs). High concentrations of vapor or mist may cause nausea, vomiting, headaches, dizziness, loss of coordination, numbness, and other central nervous system effects. Massive acute overexposure may cause rapid central nervous system depression, sudden collapse, coma, and/or death.

EYES: May cause irritation.

SKIN: May cause irritation. Product may be absorbed through the skin and cause harm as noted under **INHALATION (BREATHING)**.

INGESTION (SWALLOWING): May be harmful or fatal if swallowed. May cause throat irritation, nausea, vomiting, and central nervous system effects as noted under **INHALATION (BREATHING)**. Breathing product into the lungs during ingestion or vomiting may cause lung injury and possible death.

MEDICAL CONDITIONS AGGRAVATED BY EXPOSURE: Individuals with pre-existing cardiovascular, liver, kidney, respiratory tract (nose, throat, and lungs), central nervous system, eye, and/or skin disorders may have increased susceptibility to the effects of exposure.

CHRONIC: Prolonged or repeated inhalation may cause oil pneumonia, lung tissue inflammation, fibrous tissue formation, and/or toxic effects as noted under **INHALATION (BREATHING)**. Prolonged or repeated eye contact may cause inflammation of the membrane lining the eyelids and covering the eyeball (conjunctivitis). Prolonged or repeated skin contact may cause drying, cracking, redness, itching, and/or swelling (dermatitis).

CANCER INFORMATION: This product contains mineral oils, untreated or mildly treated, which can cause cancer. This product may contain hydrocarbon and chlorinated solvents; metals, and polynuclear aromatics which can cause cancer. Risk of cancer depends on duration and level of exposure. For more information, see **SECTION 11: CARCINOGENICITY**.

POTENTIAL ENVIRONMENTAL EFFECTS

Product may be toxic to fish, plants, wildlife, and/or domestic animals.
Also see **SECTION 12: ECOLOGICAL INFORMATION**.

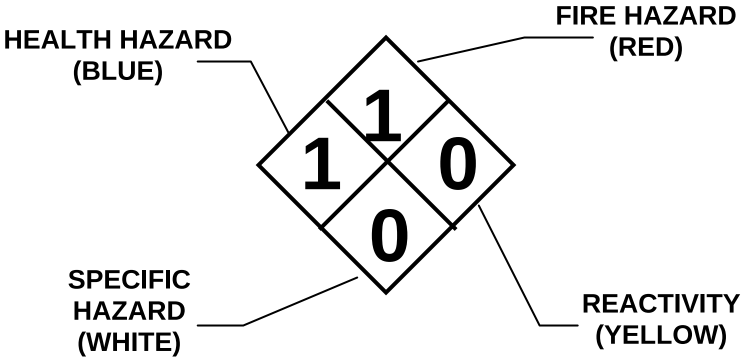
SECTION 4: FIRST AID MEASURES

INHALATION: (BREATHING)	Remove to fresh air. If not breathing, give artificial respiration. If breathing is difficult, give oxygen. Oxygen should only be administered by qualified personnel. Someone should stay with victim. Get medical attention if breathing difficulty persists.
EYES:	If irritation or redness from exposure to vapor develops, move away from exposure into fresh air. Upon contact, immediately flush eyes with plenty of lukewarm water, holding eyelids apart, for 15 minutes. Get medical attention.
SKIN:	Remove affected clothing and shoes. Wash skin thoroughly with soap and water. Get medical attention if irritation or pain develops or persists.
INGESTION: (SWALLOWING)	Do NOT induce vomiting. Immediately get medical attention. Call 1-800-468-1760 for additional information. If spontaneous vomiting occurs, keep head below hips to avoid breathing the product into the lungs. Never give anything to an unconscious person by mouth.
NOTE TO PHYSICIANS:	Treat symptomatically and supportively. Treatment may vary with condition of victim and specifics of incident. Call 1-800-468-1760 for additional information.

SECTION 5: FIRE FIGHTING MEASURES

FLASH POINT:	>200°F (93°C) (minimum) Pensky-Martens Closed Cup
FLAMMABLE LIMITS IN AIR:	Not available.
AUTOIGNITION TEMPERATURE:	Not available.
HAZARDOUS COMBUSTION PRODUCTS:	Decomposition and combustion materials may be toxic. Burning may produce phosgene gas, nitrogen oxides, carbon monoxide, and unidentified organic compounds.
CONDITIONS OF FLAMMABILITY:	Heat, sparks, or flame. Product may burn but does not ignite readily.
EXTINGUISHING MEDIA:	Use carbon dioxide, regular foam, dry chemical, water spray, or water fog.

NFPA 704 HAZARD IDENTIFICATION: This information is intended solely for the use by individuals trained in this system.



FIRE FIGHTING INSTRUCTIONS: Keep storage containers cool with water spray.
A positive-pressure, self-contained breathing apparatus (SCBA) and full-body protective equipment are required for fire emergencies.

FIRE AND EXPLOSION HAZARDS: Heated containers may rupture. “Empty” containers may retain residue and can be dangerous. Product is not sensitive to mechanical impact. Product may be sensitive to static discharge, which could result in fire or explosion.

SECTION 6: ACCIDENTAL RELEASE MEASURES

Remove all ignition sources. Do not touch or walk through spilled product. Stop leak if you can do it without risk. Wear protective equipment and provide engineering controls as specified in **SECTION 8: EXPOSURE CONTROLS/PERSONAL PROTECTION**. Isolate hazard area. Keep unnecessary and unprotected personnel from entering. Ventilate area and avoid breathing vapor or mist. A vapor suppressing foam may be used to reduce vapors. Contain spill away from surface waters and sewers. Contain spill as a liquid for possible recovery, or sorb with compatible sorbent material and shovel with a clean, sparkproof tool into a sealable container for disposal.

Additionally, for large spills: Water spray may reduce vapor, but may not prevent ignition in closed spaces. Dike far ahead of liquid spill for collection and later disposal.

There may be specific federal regulatory reporting requirements associated with spills, leaks, or releases of this product. Also see **SECTION 15: REGULATORY INFORMATION.**

SECTION 7: HANDLING AND STORAGE

HANDLING: Keep away from heat, sparks, or flame. Where flammable mixtures may be present, equipment safe for such locations should be used. Use clean, sparkproof tools and explosion-proof equipment. When transferring product, storage tanks, tanker trucks, and rail tank cars should be grounded and bonded. Do not breathe vapor or mist. Use in a well ventilated area. Avoid contact with eyes, skin, clothing, and shoes. Do not smoke while using this product.

SHIPPING AND STORING: Keep container tightly closed when not in use and during transport. Do not pressurize, cut, weld, braze, solder, drill, or grind containers. Keep containers away from heat, flame, sparks, static electricity, or other sources of ignition. Empty product containers may retain product residue and can be dangerous. See **SECTION 14: TRANSPORT INFORMATION** for Packing Group information.

SECTION 8: EXPOSURE CONTROLS/PERSONAL PROTECTION

ENGINEERING CONTROLS: Use general ventilation, process enclosures, local exhaust ventilation, or other engineering controls to control air-borne levels. Where explosive mixtures may be present, equipment safe for such locations should be used.

PERSONAL PROTECTIVE EQUIPMENT

RESPIRATORY PROTECTION: A respiratory protection program which meets USA's OSHA General Industry Standard 29 CFR 1910.134 or Canada's CSA Standard Z94.4-M1982 requirements must be followed whenever workplace conditions warrant a respirator's use. Consult a qualified Industrial Hygienist or Safety Professional for respirator selection guidance.

EYE PROTECTION: Wearing chemical goggles is recommended.
Contact lens may be worn with eye protection.

SKIN PROTECTION: Where prolonged or repeated skin contact is likely, wear neoprene, nitrile (4 mil minimum), PVC (polyvinyl chloride), or equivalent protective gloves; wearing natural rubber or equivalent gloves is not recommended.

When product is heated and skin contact is likely, wear heat-insulating gloves, boots, and other protective clothing.

To avoid prolonged or repeated contact with product where spills and splashes are likely, wear appropriate chemical-resistant faceshield, boots, apron, whole body suits, or other protective clothing.

PERSONAL HYGIENE: Wash thoroughly with soap and water after handling product and before eating, drinking, or using tobacco products. Clean affected clothing, shoes, and protective equipment before reuse. Discard affected clothing, shoes, and/or protective equipment if they cannot be thoroughly cleaned. Discard leather articles, such as shoes, saturated with the product.

OTHER PROTECTIVE EQUIPMENT: Where spills and splashes are likely, facilities storing or using this product should be equipped with an emergency eyewash and shower, both equipped with clean water, in the immediate work area.

SECTION 9: PHYSICAL AND CHEMICAL PROPERTIES

PHYSICAL STATE, APPEARANCE, AND ODOR: Liquid, black and viscous (thick), petroleum odor.

ODOR THRESHOLD: Not available.

MOLECULAR WEIGHT: Not applicable.

SPECIFIC GRAVITY: 0.8 to 1.0 at 60°F (15.6°C) (water = 1)

DENSITY: 6.7 to 8.3 LB/US gal (800 to 1000 g/l) (approximately)

VAPOR DENSITY: greater than 1 (air = 1) (based on kerosene)

VAPOR PRESSURE: Not available.

BOILING POINT: Not available.

FREEZING/MELTING POINT: Not available.

pH: Not applicable.

EVAPORATION RATE: less than 1 (butyl acetate = 1)

SOLUBILITY IN WATER: Slight.

FLASH POINT: >200°F (93°C) (minimum) Pensky-Martens Closed Cup

FLAMMABLE LIMITS IN AIR: Not available.

AUTOIGNITION TEMPERATURE: Not available.

SECTION 10: STABILITY AND REACTIVITY

STABILITY: Stable under normal temperatures and pressures. Avoid heat, sparks, or flame.

INCOMPATIBILITY: Avoid acids, alkalies, oxidizing agents, reducing agents, reactive halogens, or reactive metals.

REACTIVITY: Polymerization is not known to occur under normal temperatures and pressures. Not reactive with water.

HAZARDOUS DECOMPOSITION PRODUCTS: None under normal temperatures and pressures. Also see **SECTION 5: HAZARDOUS COMBUSTION PRODUCTS**.

SECTION 11: TOXICOLOGICAL INFORMATION

SENSITIZATION: Based on best current information, there may be known human sensitization associated with this product.

MUTAGENICITY: Based on best current information, there may be mutagenicity associated with this product.

CARCINOGENICITY: Mineral oils, untreated or mildly treated are listed by IARC as a known carcinogen. Mineral oils, untreated or mildly treated are classified by NTP as having limited evidence of carcinogenicity in humans or sufficient evidence of carcinogenicity in experimental animals.

There may be hydrocarbon and chlorinated solvents; metals, and polynuclear aromatics present in this product which are listed by OSHA as known carcinogens. There may be hydrocarbon and chlorinated solvents; metals, and polynuclear aromatics present in this product which are listed by IARC as known, probable, or possible carcinogens. There may be hydrocarbon and chlorinated solvents; metals, and polynuclear aromatics present in this product which are classified by NTP as known carcinogens or as having limited evidence of carcinogenicity in humans or sufficient evidence of carcinogenicity in experimental animals. There may be hydrocarbon and chlorinated solvents; metals, and polynuclear aromatics present in this product which are recognized by ACGIH as confirmed or suspected human carcinogens.

Also see **SECTION 3: CANCER INFORMATION**.

REPRODUCTIVE TOXICITY:	Based on best current information, there may be reproductive toxicity associated with this product.
TERATOGENICITY:	Based on best current information, there may be teratogenicity associated with this product.
TOXICOLOGICALLY SYNERGISTIC PRODUCT(S):	Based on best current information, there may be toxicologically synergistic products associated with this product.

SECTION 12: ECOLOGICAL INFORMATION

ECOTOXICITY:	Not available.
OCTANOL/WATER PARTITION COEFFICIENT:	Not available.
VOLATILE ORGANIC COMPOUNDS:	Not available. As per 40 CFR Part 51.100(s).

SECTION 13: DISPOSAL CONSIDERATIONS

Dispose in accordance with federal, state, provincial, and local regulations. Regulations may also apply to empty containers. The responsibility for proper waste disposal lies with the owner of the waste. Contact Safety-Kleen regarding proper recycling or disposal.

SECTION 14: TRANSPORT INFORMATION

DOT:	Not regulated.
TDG:	Not regulated.
EMERGENCY RESPONSE GUIDE NUMBER:	Not applicable. Reference *North American Emergency Response Guidebook*

SECTION 15: REGULATORY INFORMATION

USA REGULATIONS SARA SECTIONS 302 AND 304:	Based on the ingredient(s) listed in **SECTION 2**, this product does not contain any "extremely hazardous substances" listed pursuant to Title III of the Superfund Amendments and Reauthorization Act of 1986 (SARA) Section 302 or Section 304 as identified in 40 CFR Part 355, Appendix A and B.

SARA SECTIONS 311 AND 312: This product poses the following physical and health hazards as defined in 40 CFR Part 370 and is subject to the requirements of sections 311 and 312 of Title III of the Superfund Amendments and Reauthorization Act of 1986 (SARA):

- Immediate (Acute) Health Hazard
- Delayed (Chronic) Health Hazard

SARA SECTION 313: This product may contain "toxic" chemicals subject to the requirements of section 313 of Title III of the Superfund Amendments and Reauthorization Act of 1986 (SARA) and 40 CFR Part 372.

CERCLA: This product may contain “hazardous substances” listed pursuant to Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA) in 40 CFR Part 302, Table 302.4.

TSCA: Not available.

CALIFORNIA: This product is not for sale or use in the State of California.

CANADIAN REGULATIONS
WHMIS: Not regulated

CANADIAN ENVIRONMENTAL PROTECTION ACT (CEPA): Not available.

SECTION 16: OTHER INFORMATION

REVISION INFORMATION: Change from MSIS to MSDS.

LABEL/OTHER INFORMATION: Not available.

MATERIAL SAFETY DATA SHEET
Propylene Glycol

SECTION 1: IDENTIFICATION

Company Name:	QUALICHEM TECHNOLOGIES
Address:	885 Woodstock Rd Roswell, GA 30075
Phone No.	(800) 658-7716
Fax No.	(877) 209-1556
Emergency Phone No.	CHEM-TEL 800-255-3924
Date Prepared:	5/21/97
Date Revised:	10/11/05

SECTION 2: INGREDIENTS

Hazardous Ingredients

MATERIAL	CAS NO.	%	TLV
NONE			
Non-Hazardous Ingredients			
1-2 PROPANEDIOL		99.9	NONE ESTAB.
WATER		BAL.	NONE ESTAB.

SECTION 3: HEALTH HAZARDS

Ingestion:	IF MORE THAN SEVERAL MOUTHFULS ARE INGESTED, ABDOMINAL DISCOMFORT, NAUSEA AND DIARRHEA MAY OCCUR.
Inhalation:	NOT A LIKELY ROUTE OF EXPOSURE. INHALATION OF MIST MAY BE IRRITATING TO RESPIRATORY TRACT, HEADACHE, NAUSEA AND DROWSINESS.
Skin Contact:	NOT AN IRRITANT. PROLONGED CONTACT CAN RESULT IN DEFATTING.
Eye Contact:	CAUSES MILD IRRITATION.
Other Information:	OTHER THAN ACUTE EFFECTS LISTED ABOVE, NO LONG TERM EFFECTS KNOWN.

SECTION 4: FIRST AID

Ingestion:	DRINK SEVERAL GLASSES OF WATER TO DILUTE. NO NOT INDUCE VOMITING UNLESS DIRECTED TO DO SO BY MEDICAL PERSONNEL. NEVER GIVE ANYTHING BY MOUTH TO AN UNCONSCIOUS PERSON. GET MEDICAL ATTENTION.
Inhalation:	REMOVE VICTIM TO FRESH AIR. GET MEDICAL ATTENTION IF SYMPTOMS PERSIST.
Skin Contact:	WASH WITH PLAIN WATER OR SOAP AND WATER.
Eye Contact:	IMMEDIATELY FLUSH WITH CLEAR WATER FOR 15 MINUTES AND GET MEDICAL ATTENTION IF IRRITATION PERSISTS.
Notes to Physician:	NO ANTIDOTES KNOWN. TREAT SYMPTOMS SUPPORTIVELY.

SECTION 5: FIRE AND EXPLOSION HAZARD DATA

Flash Point/Method:	NONE
Lower Limit in Air:	N.A.
Upper Limit in Air:	N.A.
Extinguishing Media:	WATER OR ANY MEDIA SUITABLE FOR THE SURROUNDING FIRE.
Procedures:	FIREFIGHTERS SHOULD WEAR NORMAL PROTECTIVE EQUIPMENT. SELF-CONTAINED BREATHING APPARATUS SHOULD BE USED IN CONFINED AREAS.
Unusual Hazards:	NONE
Combustion Products:	IF WATER IS EVAPORATED, OXIDES OF CARBON AND NITROGEN MAY BE PRODUCED.

SECTION 6: ACCIDENTAL RELEASE MEASURES

Personal Precautions:	THE WEARING OF SAFETY GLASSES AS A MINIMUM IS RECOMMENDED.
Environmental Precautions:	THIS PRODUCT HAS A LOW HAZARD POTENTIAL IF RELEASED INTO THE ENVIRONMENT ACCIDENTLY.
Procedures for Clean Up:	SMALL SPILLS MAY BE FLUSHED WITH COPIOUS QUANTITIES OF WATER, PREFERABLY TO A SANITARY SEWER. LARGER SPILLS MAY BE DIKED TO MINIMIZE RUN-OFF. LIQUID MAY BE ABSORBED IN SAWDUST OR ANY AVAILABLE ABSORBANT AND SWEEPINGS DISPOSED OF IN A LANDFILL. OBEY ALL FEDERAL, STATE OR LOCAL REGULATIONS.
Prohibited Materials:	NONE

SECTION 7: HANDLING AND STORAGE

Handling:	NORMAL INDUSTRIAL HANDLING PRACTICES.
Storage:	KEEP OUT OF REACH OF CHILDREN. STORE IN A COOL, DRY PLACE. KEEP CONTAINERS TIGHTLY CLOSED WHEN NOT IN USE.

SECTION 8: EXPOSURE CONTROLS/PERSONAL PROTECTION

Precautionary Measures:	STANDARD INDUSTRIAL HANDLING PRECAUTIONS.
Engineering Controls:	NONE
Control Limits:	NONE.
Equipment for Personal Protection:	EYEWASH STATION AND SAFETY SHOWER IN AREA OF USE.

SECTION 9: PHYSICAL AND CHEMICAL PROPERTIES

Appearance:	CLEAR LIQUID
Odor:	CHARACTERISTIC
pH (undiluted):	<12
Specific Gravity:	1.05-1.07
Density:	8.88 lbs./gal.
Solubility in Water:	COMPLETE
Boiling Point:	212°F
Percent Volatile:	<5 (WATER)
Vapor Pressure (mmHg):	N.D.
Vapor Density:	N.D.
Evaporation Rate:	(water=1): ~1

SECTION 10: STABILITY AND REACTIVITY

Stability:	STABLE
Conditions to Avoid:	NONE
Hazardous Polymerization:	STABLE
Conditions to Avoid:	NONE
Incompatibility:	MAY REACT WITH STRONG OXIDIZING AGENTS OR ACIDS.
Hazardous Decomposition Products:	IF WATER EVAPORATED, OXIDES OF CARBON COULD BE PRODUCED BY COMBUSTION.

SECTION 11: TOXICOLOGICAL INFORMATION

Material & Tests:	NONE DETERMINED. LOW ORDER OF TOXICITY EXPECTED.
Symptoms:	N.A.
Effects:	N.A.

MATERIAL SAFETY DATA SHEET
Propylene Glycol

SECTION 12: ECOLOGICAL INFORMATION

Possible Effects:	TOXIC EFFECTS MINIMAL .
Biodegradability:	ALL ORGANIC COMPONENTS ARE BIODEGRADABLE.
Persistence:	NOT PERSISTENT.
Aquatic Toxicity:	N.D.

SECTION 13: DISPOSAL CONSIDERATIONS

General Considerations:	THIS PRODUCT IS NOT A HAZARDOUS WASTE.
Procedures:	DISPOSAL BY USE PREFERRED BUT IF THIS NOT POSSIBLE, DILUTE WITH COPIOUS QUANTITIES OF WATER AND FLUSH TO WASTE, PREFERABLY TO A SANITARY SEWER. OBEY ALL FEDERAL, STATE OR LOCAL REGULATIONS.

SECTION 14: TRANSPORT INFORMATION

Shipping Name:	COMPOUNDS, WATER TREATMENT, N.O.S.
Primary Hazard Class:	NON-HAZARDOUS PER D.O.T. REGULATIONS
Secondary Hazard Class:	N.A.
Identification No.	N.A.
Packing Group:	N.A.
1996 NAERG No.	N.A.

SECTION 15: REGULATORY INFORMATION

Regulation	Material	RQ	Max. %
CERCLA (40 CFR302.4):	NONE		
SARA 302 (Sect. 355, Appendix A):	Material	TPQ	Max. %
	NONE		
SARA 311/312 :	Categories	Hazards	
	IMMEDIATE HEALTH	EYE IRRITANT	
SARA 313 (40 CFR 372.45):	Material		Max. %
	NONE		
CWA (40 CFR 401.15):	NONE		
RCRA (40 CFR 261):	NONE		
OSHA (29 CFR 1910.1200):	ALL COMPONENTS LISTED UNDER THIS STANDARD ARE SHOWN IN SECTION 2 OF THIS MSDS.		
TSCA	ALL INGREDIENTS IN THIS PRODUCT ARE LISTED IN THE TSCA INVENTORY.		

SPECIAL STATE REGULATIONS

STATE	INGREDIENT	%	REGULATORY DESIGNATION
NONE			

SECTION 16 OTHER INFORMATION

SUGGESTED HAZARD RATINGS

NFPA*	HAZARD	HMIS*
1	HEALTH (Blue)	1
1	FIRE (Red)	1
0	REACTIVITY (Yellow)	0
	PERSONAL PROTECTION	B
	SPECIAL HAZARDS	

*Notes: 0 = Insignificant; 1 = Slight; 2 = Moderate; 3 = High; 4 = Extreme

Prepared By: Environmental Manager

The data contained in this Material Safety Data Sheet has been prepared based upon an evaluation of the ingredients in the product, their concentration in the product and potential interactions. The information is offered in good faith and is believed to be accurate. It is furnished to the customer who is urged to study it carefully to become aware of hazards, if any, in the storage, handling, use and disposal of the product; and to insure his employees are properly informed and advised of all safety precautions required. The information is furnished for compliance with the "Occupational Safety and Health Act" of 1970, the "Hazards Communication Act" of 1983 as well as various other Federal, State and Local regulations. Use or dissemination of all or part of this information for any other purpose is prohibited by law.

**** MATERIAL SAFETY DATA SHEET ****

NATURAL GAS

CHES 1728

**** SECTION 1 - CHEMICAL PRODUCT AND COMPANY IDENTIFICATION ****

MSDS Name: NATURAL GAS

Product CAS:

Product Code:

Synonyms: MARSH GAS; METHANE; NATURAL GAS; SYNTHETIC NATURAL GAS

Company Identification:

Name: WISCONSIN GAS COMPANY

Address: P.O. BOX 544

Address:

City: MILWAUKEE **State:** WI **Zip:** 53201

For information, call:

Emergency Number: 800-261-5325

Emergency Agency:

Number:

MSDS Creation Date: 03/22/2000

Supersedes Date:

Miscellaneous:

PRODUCT NAME OR CODE: NATURAL GAS

NAME AND/OR OTHER IDENTIFICATION: NATURAL GAS

GENERAL INFORMATION: A MIXTURE OF LOW MOLECULAR WEIGHT HYDROCARBON GAS, FUEL GAS DELIVERED IN PIPELINES, USED FROM COMPRESSED GAS CYLINDERS. CONSIDERED A SIMPLE ASPHYXIANT.

Return to top

**** SECTION 2 - COMPOSITION, INFORMATION ON INGREDIENTS ****

Chemical Name	CAS	MIN	MAX
METHANE	74-82-8	90.2	90.2
ETHANE	74-84-0	7.02	7.02
PROPANE	74-98-6	1.0	1.0
ISOBUTANE	75-28-5	0	0
N-BUTANE	106-97-8	0	0
ISOPENTANE	78-78-4	0	0
N-PENTANE	109-66-0	0	0
NEOPENTANE	463-82-1	0	0
OTHER ALIPHATIC HYDROCARBONS	(none)	0	0

Miscellaneous:

INGREDIENT	TLV	PEL	CARCINOGEN
METHANE	---	---	NO
ETHANE	---	---	NO
PROPANE	1000	2500	NO

OTHER TRACE MATERIALS (LT 1% BY WEIGHT) MAY INCLUDE ISOBUTANE, N-BUTANE, ISOPENTANE, N-PENTANE, NEOPENTANE, OTHER ALIPHATIC HYDROCARBONS IN CONCENTRATIONS LT 100 PPM (BY VOLUME); ODORANT (MIXTURE OF MERCAPTAN AND ALKYL SULFIDE IN CONCENTRATIONS OF LT 50 PPM).

INGREDIENTS SUBJECT TO SARA TITLE III, SECTION 313: NONE

Lbs of VOC per Gallon Coating (minus water):

Coating Density (lbs/gal):

Solvent Density (lbs/gal):

Percent Solvent (volume):

Percent Solids (volume):

Percent Water (volume):

Return to top

**** SECTION 3 - HAZARDS IDENTIFICATION ****

NFPA: Health: 1 **Fire:** 4 **Reactivity:** 0 **Other:**

HMIS: Health: 1 **Fire:** 4 **Reactivity:** 0 **Special Protection:**

Miscellaneous:

HAZARD RATINGS (CERCLA):
TOXICITY: 1
IGNITABILITY/FLAMMABILITY: 4
REACTIVITY: 0
PERSISTENCE: 0

SEE SECTION 11 FOR TOXICOLOGY INFORMATION.

POTENTIAL HEALTH EFFECTS

Target Organs:

RESPIRATORY SYSTEM, LUNGS - SIMPLE ASPHYXIANT; SKIN AND EYES

ROUTES OF ENTRY: INHALATION, SKIN AND EYE CONTACT.

Eye:

MAY CAUSE IRRITATION OF EYES IN LARGE CONCENTRATIONS

SYMPTOMS OF ACUTE EXPOSURE: SEE MISCELLANEOUS.

Skin:

MAY CAUSE IRRITATION OF SKIN IN LARGE CONCENTRATIONS

SYMPTOMS OF ACUTE EXPOSURE: SEE MISCELLANEOUS.

Ingestion:

SYMPTOMS OF ACUTE EXPOSURE: SEE MISCELLANEOUS.

Inhalation:

SYMPTOMS OF ACUTE EXPOSURE: SEE MISCELLANEOUS.

Miscellaneous:

PRE-EXISTING CONDITION: SOME PULMONARY CONDITIONS.

SEE SECTION 11 FOR MUTAGENIC AND CARCINOGENIC DATA.

SYMPTOMS OF ACUTE EXPOSURE INCLUDE RESPIRATORY ARREST, UNCONSCIOUSNESS; MAY CAUSE NAUSEA, VOMITING, DIZZINESS, DROWSINESS, STUPOR, DISCOMFORT AND REDNESS TO SKIN AND EYES.

Return to top

**** SECTION 4 - FIRST AID MEASURES ****

Eye:

N/A

Skin:

N/A

Ingestion:

N/A

Inhalation:

REMOVE FROM EXCESSIVE EXPOSURE TO FRESH AIR IMMEDIATELY. IF BREATHING HAS STOPPED, PERFORM ARTIFICIAL RESPIRATION. KEEP INDIVIDUAL WARM AND AT REST.

Notes to Physician:

Return to top

**** SECTION 5 - FIRE FIGHTING MEASURES ****

Unusual Fire and Explosion Hazards:

RE-IGNITION OR EXPLOSION MAY OCCUR IF THE FLAME IS EXTINGUISHED WITHOUT STOPPING THE FLOW OF GAS AND/OR COOLING SURROUNDINGS AND ELIMINATING IGNITION SOURCES.

Special Fire Fighting Procedures:

WEAR SCBA AND FULL PROTECTIVE GEAR. DO NOT EXTINGUISH FLAMES WHILE GAS IS FLOWING. USE WATER SPRAY TO COOL SURROUNDINGS AND EXPOSURES.

Extinguishing Media:

CARBON DIOXIDE, DRY CHEMICAL, HALON

Flash Point:

-306 F

Flammable Limits:

Lower Limit:

{LFL}: 4%

Upper Limit:

(UFL): 16%

AutoIgnition Temperature:

900 F - 1200 F

General Information:

THERMAL DECOMPOSITION PRODUCTS: CARBON MONOXIDE, CARBON DIOXIDE, SULFUR DIOXIDE, NITROGEN OXIDES.

Return to top

**** SECTION 6 - ACCIDENTAL RELEASE MEASURES ****

Disposal:

MATERIAL IS A GAS WHICH NATURALLY DISSIPATES.

Spills/Leaks:

EVACUATE AREA. PROVIDE OPTIMUM EXPLOSION-PROOF VENTILATION. SHUT OFF SUPPLY, REMOVE OR ELIMINATE IGNITION SOURCES. MINOR LEAKS CAN BE DETECTED WITH A SOAP SOLUTION APPLIED TO SUSPECTED LEAK POINTS. NEVER USE A FLAME TO DETECT LEAKS.

Return to top

**** SECTION 7 - HANDLING and STORAGE ****

Handling:

SEE "STORAGE" BELOW.

Storage:

NATURAL GAS IS CONTAINED AND DELIVERED IN PIPING AND EQUIPMENT DESIGNED FOR ELEVATED PRESSURES. USE EXPLOSION-PROOF CLASS I, GROUP D ELECTRICAL EQUIPMENT AND NON-SPARKING TOOLS.

Return to top

**** SECTION 8 - EXPOSURE CONTROLS, PERSONAL PROTECTION ****

Engineering Controls:

VENTILATION: USE EXPLOSION-PROOF, NON-SPARKING VENTILATION EQUIPMENT TO DILUTE NATURAL GAS.

Eyes:

NONE SPECIFIED.

Skin:

NONE SPECIFIED.

Clothing:

Respirators:

IN AREAS WHERE CONCENTRATIONS MAY EXCEED 10,000 PPM (1%), SUCH AS CONFINED SPACES, ENCLOSED AREAS, ADJACENT TO BLOWING NATURAL GAS, USE SELF-CONTAINED BREATHING APPARATUS (SCBA)

Return to top

**** SECTION 9 - PHYSICAL AND CHEMICAL PROPERTIES ****

Appearance/Odor:

COLORLESS FLAMMABLE GAS, ALMOST ODORLESS. ODORANTS ADDED AS A SAFETY PRECAUTION IMPART DISTINCTIVE SULFUR-LIKE ODOR.

pH:

Vapor Pressure: (@ 70 F): 760 MM HG

Vapor Density: (AIR=1): 0.6

Evaporation Rate:

Viscosity:

Boiling Point: -258 F

Freezing/Melting Point: -296 F

Decomposition Temperature:

Solubility: NEGLIGIBLE

Specific Gravity: .60

Molecular Formula:

Molecular Weight: 16

Miscellaneous:

SPECIFIC GRAVITY: 0.55 - 0.60 AT 30" HG AND 60 F.

Return to top

**** SECTION 10 - STABILITY AND REACTIVITY ****

Chemical Stability:

STABLE; AVOID CONTACT WITH FLAMES OR HEAT SOURCES. COMBINES READILY WITH AIR AND OTHER OXIDIZERS TO FORM A COMBUSTIBLE ATMOSPHERE.

Conditions to Avoid:

Incompatibilities with Other Materials:

OTHER OXIDIZERS INCLUDING CHLORINE, CHLORINE DIOXIDE, BROMINE PENTAFLUORIDE, OXYGEN, OXYGEN DIFLUORIDE, NITROGEN TRIFLUORIDE, FLUORINE MONOXIDE.

Hazardous Decomposition Products:

CARBON MONOXIDE, CARBON DIOXIDE, SULFUR DIOXIDE, NITROGEN OXIDES.

Hazardous Polymerization:

DOES NOT OCCUR.

Return to top

**** SECTION 11 - TOXICOLOGICAL INFORMATION ****

Toxicological Information:

MUTAGENIC DATA: NONE KNOWN.

CARCINOGENICITY: NO BY IARC, NTP, OSHA

TOXICOLOGY: PRACTICALLY NONTOXIC. SIMPLE ASPHYXIANT BY INHALATION - NATURAL GAS DISPLACES OXYGEN REQUIRED FOR RESPIRATION. MAY ALSO CAUSE CENTRAL NERVOUS SYSTEM DEPRESSION IN LARGE CONCENTRATIONS.

Return to top

**** SECTION 12 - ECOLOGICAL INFORMATION ****

Ecological Information:

Return to top

**** SECTION 13 - OTHER PRECAUTIONS ****

Other Precautions:

Work/Hygienic Practices:

Return to top

**** SECTION 14 - TRANSPORT INFORMATION ****

Transportation Information:

Label Information:

Return to top

**** SECTION 15 - REGULATORY INFORMATION ****

Regulatory Information:

29 CFR 1910 (OSHA GENERAL INDUSTRY):
SECTION .20 - ACCESS TO EMPLOYEE EXPOSURE AND MEDIAL RECORDS
SECTION .94 - VENTILATION
SECTION .132 - PERSONAL PROTECTIVE EQUIPMENT
SECTION .134 - RESPIRATORY PROTECTION
SECTION .151 - MEDICAL SERVICES AND FIRST AID

SECTION .1200 - HAZARD COMMUNICATION
SECTION .1450 - HAZARDOUS CHEMICALS IN LABORATORIES

49 CFR 172: REGULATED BY DOT (UN 1971, UN 1972); DOT HAZARD CLASS 2.0

STATE REGULATIONS: MASSACHUSETTS, PENNSYLVANIA, MINNESOTA, CALIFORNIA, NEW JERSEY RIGHT TO KNOW LISTS.

INTERNATIONAL REGULATIONS: AUSTRALIAN EXPOSURE STANDARDS - ASPHYXIANT AT LT 18% OXYGEN, EXPLOSION HAZARD; CANADA - BRITISH COLUMBIA AND ONTARIO TWAS - SIMPLE ASPHYXIANT; ISRAEL TWAS - SIMPLE ASPHYXIANT.

Return to top

**** SECTION 16 - ADDITIONAL INFORMATION ****

Additional Information:

MATERIAL SAFETY DATA SHEET
REVISION DATE: 3/22/00

SUPPLIER NAME AND ADDRESS:
WISCONSIN GAS COMPANY
626 EAST WISCONSIN AVENUE
MILWAUKEE, WISCONSIN 53202

THIS MSDS MEETS THE REQUIREMENTS OF OSHA 'HAZARD COMMUNICATION STANDARD" 29 CFR 1910.1200.

THE INFORMATION PRESENTED HEREIN HAS BEEN COMPILED FROM SOURCES CONSIDERED TO BE RELIABLE AND IS ACCURATE AND RELIABLE TO THE BEST OUR OUR KNOWLEDGE AND BELIEF, BUT IS NOT GUARANTEED TO BE SO.

Return to top