Design and Development of a Gas Coupling Unit for Trigeneration and Algae Photobioreactor Systems

Senior Design Final Report – April 2012

By
Angela Silva[1], Felipe Merss[2], Richard Carter[1], Robert Rantz[1], Wayne Weatherford[1]
[1]Department of Mechanical Engineering, FSU
[2]Department of Mechanical Engineering, UFPR

Project Sponsors

Dr. Jose Vargas, *Professor*
Department of Mechanical Engineering

Dr. Juan Ordonez, *Professor*
Department of Mechanical Engineering

Department of Mechanical Engineering
UFPR Centro Politécnico
Bairro Jardim das Américas, Curitiba, PR

Department of Mechanical Engineering
FAMU-FSU College of Engineering
2525 Pottsdamer St, Tallahassee, FL 32304

Table of Contents

List of Figures

Introduction

The goal of this project is to harvest the wasted energy and exhaust gases produced from an existing trigeneration unit for use in cultivating algae in a photobioreactor. The trigeneration unit operates by virtue of an internal combustion engine, and thus produces the typical waste products: carbon dioxide, carbon monoxide, and various nitrogen compounds. These products can be supplied to a photobioreactor to accelerate the algal growth, and the heat lost via the exhaust could be (further) utilized as a source of energy.

This project is a joint effort between two universities: Florida State University of the United States, and Federal University of Paraná, of Brazil. The project aims to expose students to the challenges and advantages of working on international teams.

In recent years, there has been intensive research on the production and implementation of clean and renewable fuels. Climate-changing pollution and shrinking fossil fuel supply are often cited as the main driving forces in this field of research, as well as a new-found public interest. Among the many new energy alternatives emerged biodiesel.

Biodiesel is a biodegradable fuel derived from renewable sources and can be obtained from several different raw materials. There are many conventional agricultural crops that can be used to produce bio-fuels, such as corn, soy and castor beans. However, the growth period of these crops is substantial and they require large quantities of land which could otherwise be used for food production. Biodiesel can also be produced from the fatty acids extracted from microalgae. Research shows that biodiesel production through microalgae is much more efficient both in volume of oil and in cultivation area, as algae are organisms with a great capacity for photosynthesis and an extremely rapid rate of growth. Being a photosynthetic organism, algae also consumes carbon dioxide to propel biomass production.

The search for sources of clean, renewable energy is intimately tied to research in improving the efficiency of existing energy-harnessing systems. Therefore, it is very important to efficiently utilize energy and heat when it is produced. A manifestation of this concept, coined “trigeneration,” was developed to do just this. The trigeneration system that was developed at FSU produces electricity, hot water, and a refrigerated space from one small internal combustion engine. A generator is coupled to the drive shaft of the motor to produce electricity. The energy typically wasted by expelling the hot exhaust gases into the atmosphere is “recycled” to heat water and run an absorption refrigerator.

The ultimate goal of this project is to design and build a prototype of a unit that is able to treat the exhaust gases from a trigeneration system, and to introduce these gases to a photobioreactor for the cultivation of algae (The two systems shown in Figure 1). Introducing the waste gases to the photobioreactor will help accelerate the growth of algae and the algae will in turn remove harmful greenhouse gases from the exhaust stream. A functional diagram of this process is shown in Figure 2.

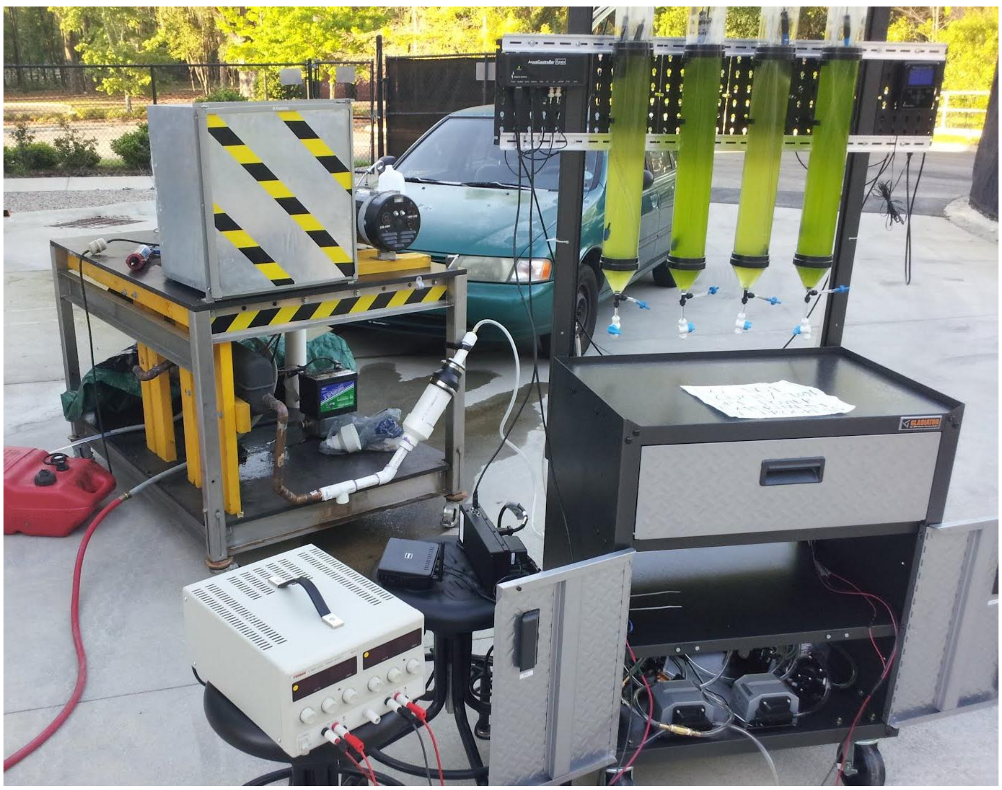


Figure 1 - Trigenerator with Coupling Device and Bioreactor Array

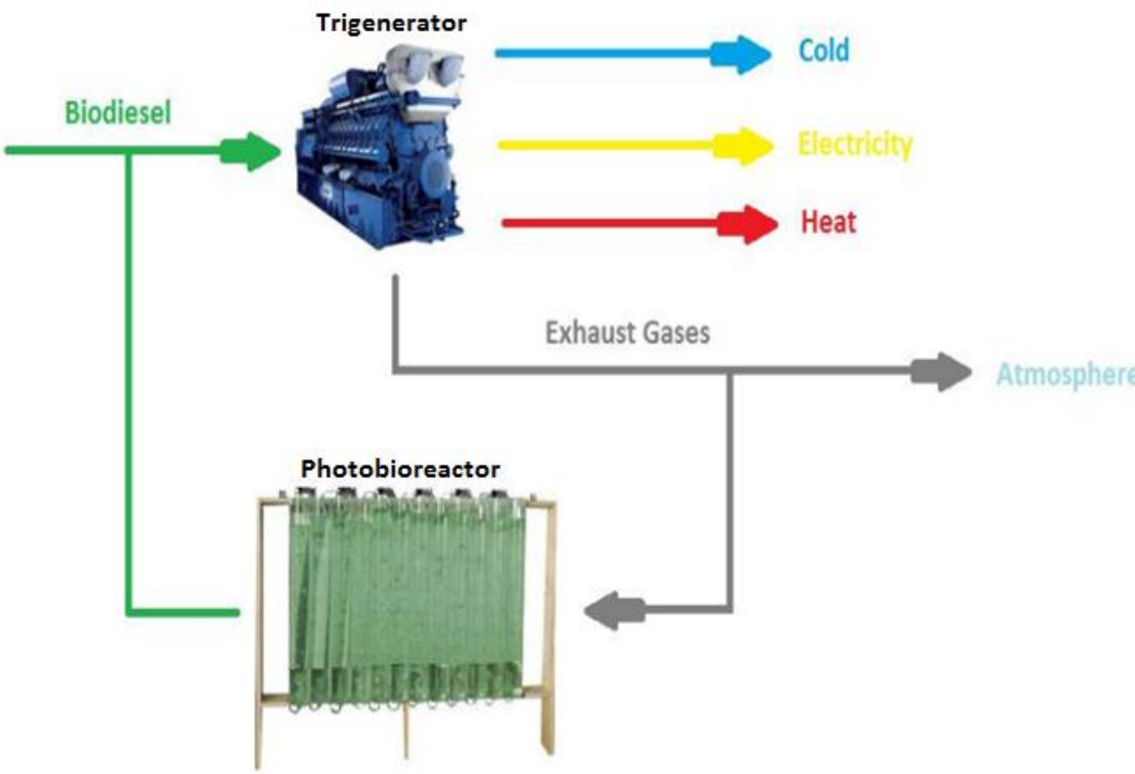


Figure 2 - Functional Diagram of Concept

Needs Assessment

Global energy production must rise to meet growing demand; along with this comes increased production of greenhouse gases like carbon dioxide, which can lead to undesirable climate change. In addition, we are facing ever-shrinking supplies of natural resources. As we move toward the future it becomes more necessary maximize the use of produced energy, cultivate renewable forms of energy, re-use waste heat, and reduce our CO_2 emissions. This project focuses on coupling a trigeneration system with a photobioreactor to increase the yield of algae grown in the bioreactor and clean exhaust gases by sequestering CO_2. This adaptable coupling device will be able to couple the two existing systems so that a portion of what was originally waste CO_2 will be sequestered through photosynthesis in the algae. The algae can then be used to produce biodiesel and biomass to help meet future energy demand and reduce our dependence on fossil fuels.

Project Scope

Problem Statement

The emphasis of this project is to create a coupling system that will bring the exhaust stream to the photobioreactor without compromising the algae or efficiency of the trigenerator.

Objective

This project has three main objectives:

- Use waste CO_2 to drive photosynthesis in a photobioreactor
- Mitigate CO_2 emission by sequestering it from the exhaust stream
- Couple trigenerator exhaust with bioreactor in an adaptable package
- Complete Life Cycle Analysis (LCA) on final product

Justification and Background

The system will be built with existing trigeneration unit and photobioreactor, both of which are in need of repair. The trigenerator contains a gasoline fed internal combustion engine, an electrical generator, an absorption refrigerator, a helical heat exchanger and various related subsystems. The photobioreactor consists of three translucent reactor tubes with aquarium monitoring equipment, pumps to circulate water, a diffuser for the introduction of gas, thermometers and pH sensors.

Methodology

Before the gas coupler is built, the existing systems it is built around must be returned to working condition. Some missing parts of the trigenerator must be replaced or re paired and all the subsystems should be operational. Some data must be obtained through previous studies or our own experiments. Knowing optimal algae growth conditions is required so that our gas coupler can be designed to maintain them. It is also necessary to know whether the presence of gases other than CO_2 in the exhaust stream could harm the growth of algae. Early research indicates that catalytic conversion is not necessary, but filtration of particulate matter is.

Constraints

- $2500 Budget
- Must maintain optimal growth conditions in photobioreactor for algae growth
- The exhaust system will be prone to corrosion
- Fuel choice will affect the composition of exhaust gases

Expected Results

- An adaptable gas coupling system that can provide the right amount of CO_2 for the bioreactor at the right temperature
- A subsystem that will monitor temperature and pH levels to prevent damage to the algae and foster growth

Concept Generation

To simplify the concept generation process, we decided that all concepts could be lumped into two broad methods: direct and indirect gas capture. Exhaust gases are brought directly from exhaust line to the bioreactor with the direct method. They are sequestered in a storage medium before being injected with the indirect case. Once these methods were defined, it became easier to generate plausible concepts. A diagram was drawn to help the brainstorming process. (Figure 3). Three direct and two indirect concepts were generated.

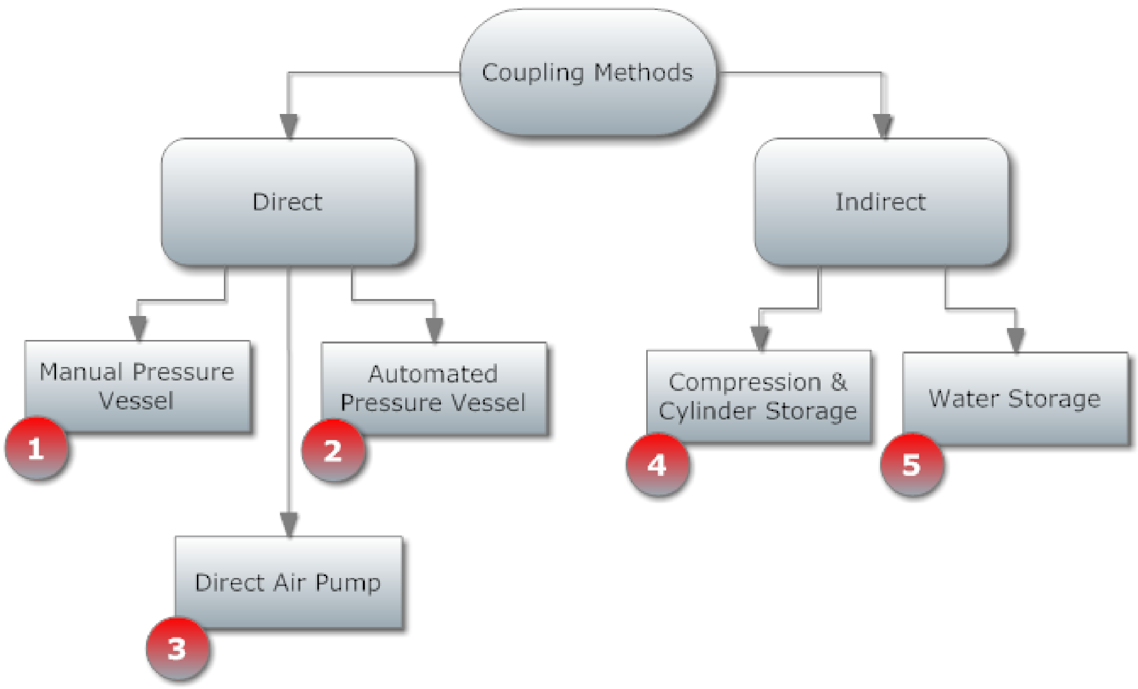


Figure 3 - Concept Generation Tree

Concept 1: Direct Manual Pressure Vessel

Our first concept is a manually operated pressure vessel (Figure 4). This is a direct method. First, the exhaust stream will be directed into a corrosion resistant pressure vessel, which is adjusted with a manual choke valve at the exit. Two barbed tube fittings allow a constant gas stream to be delivered to different photobioreactor chambers. Each connection barb will have its own independent control valve. The amount of gas delivered to the photobioreactors can be controlled with the position of the choke valve. Pressure from the engine will drive this process, which means some back-pressure toward the engine will be generated by this device. Back-pressure will decrease the efficiency of the engine, which is not desired. However, we believe that the pressure needed to force gas into the photobioreactors will be sufficiently small to keep the efficiency within an acceptable range.

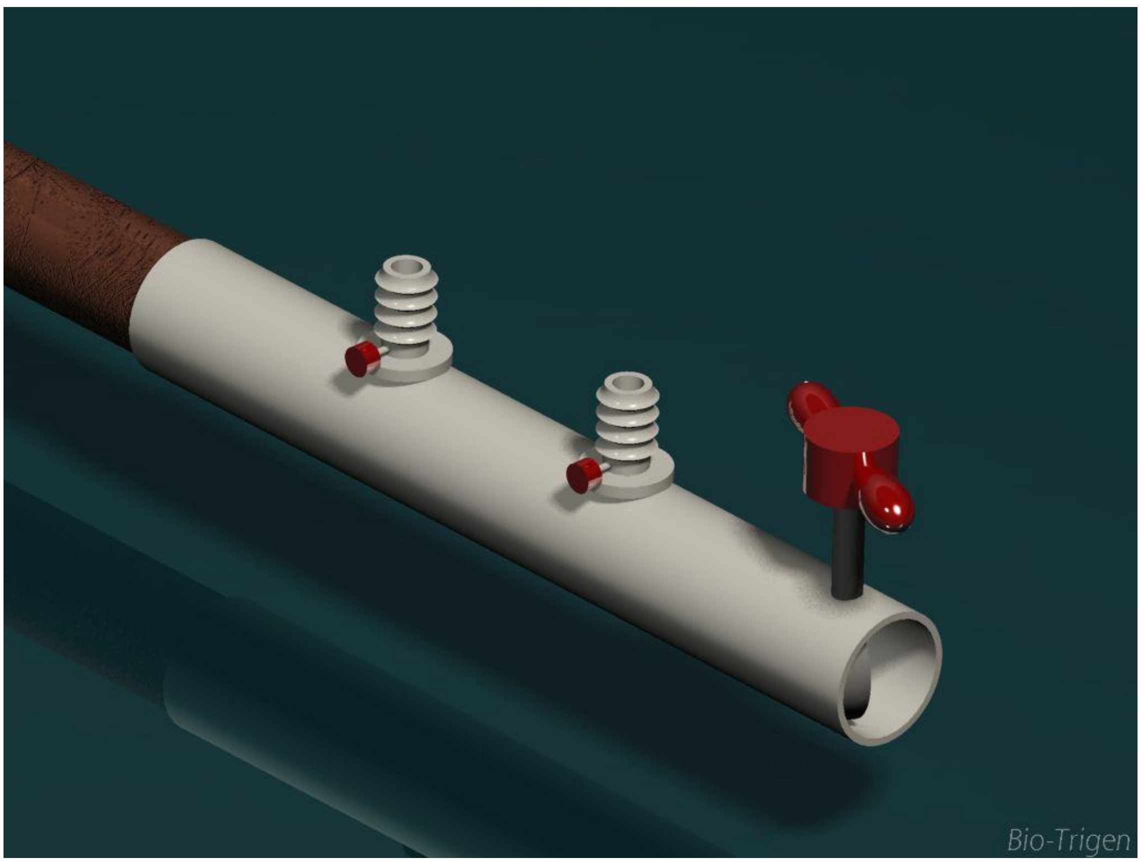


Figure 4 - Concept One - Manual Pressure Vessel

Concept 2: Direct Automated Pressure Vessel

The second direct concept follows a similar design to the first. The same pressure vessel will collect the exhaust stream, again with a choke valve at the exit (Figure 5). They differ in how the choke and two barb connections are controlled. These three valves will be solenoid or servo controlled. A micro-controller will open, close, or adjust the valves depending on pH, temperature or pressure readings. This system could be programmed to manage optimal algal growth conditions automatically.

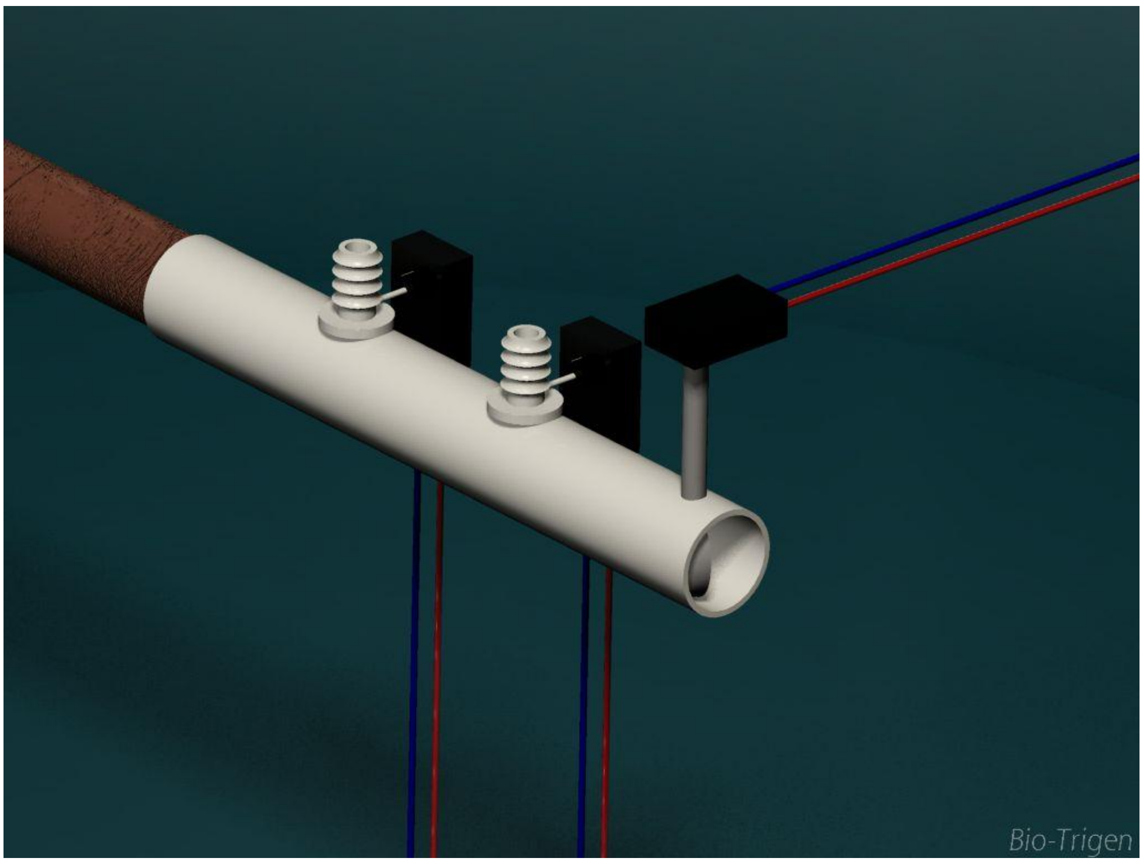


Figure 5 - Concept Two - Automated Pressure Vessel

Concept 3: Direct Air Pump

Concept 3 utilizes an air pump to draw a specific flow rate out of the exhaust stream. The air pump will couple to the exhaust line at a T-joint. One end of the joint will remain open to release excess exhaust. This simple design will reduce any extra back-pressure seen by the engine due to the gas coupling system.

Figure 6 - Concept Three - Direct Air Pump

Concept 4: Indirect Pump to Pressure Vessel

This concept utilizes a compressor to draw the exhaust gasses from the exit pipe to a pressurized vessel. It has the advantage of producing little back-pressure to the engine, as well as conveniently storing the gas for use when the engine is not running. This system is significantly more complicated than some of the direct capture systems, and will be much more expensive to produce.

Figure 7 - Concept Four - Compression and Cylinder Storage

Concept 5: Indirect Water Storage

This concept makes use of the solubility of carbon dioxide gas in water. Although not particularly soluble in water, a significant amount of carbon dioxide may be captured in water of sufficient volume, and water is a very inexpensive solvent. This method of gas sequestration involves diffusing the gas stream beneath a volume of water in a storage tank. The carbon dioxide rich water may then be pumped directly to the bioreactors using inexpensive, low flow rate water pumps when needed. Also, extra nutrients may be added to the storage tank to enhance the growth of the algae.

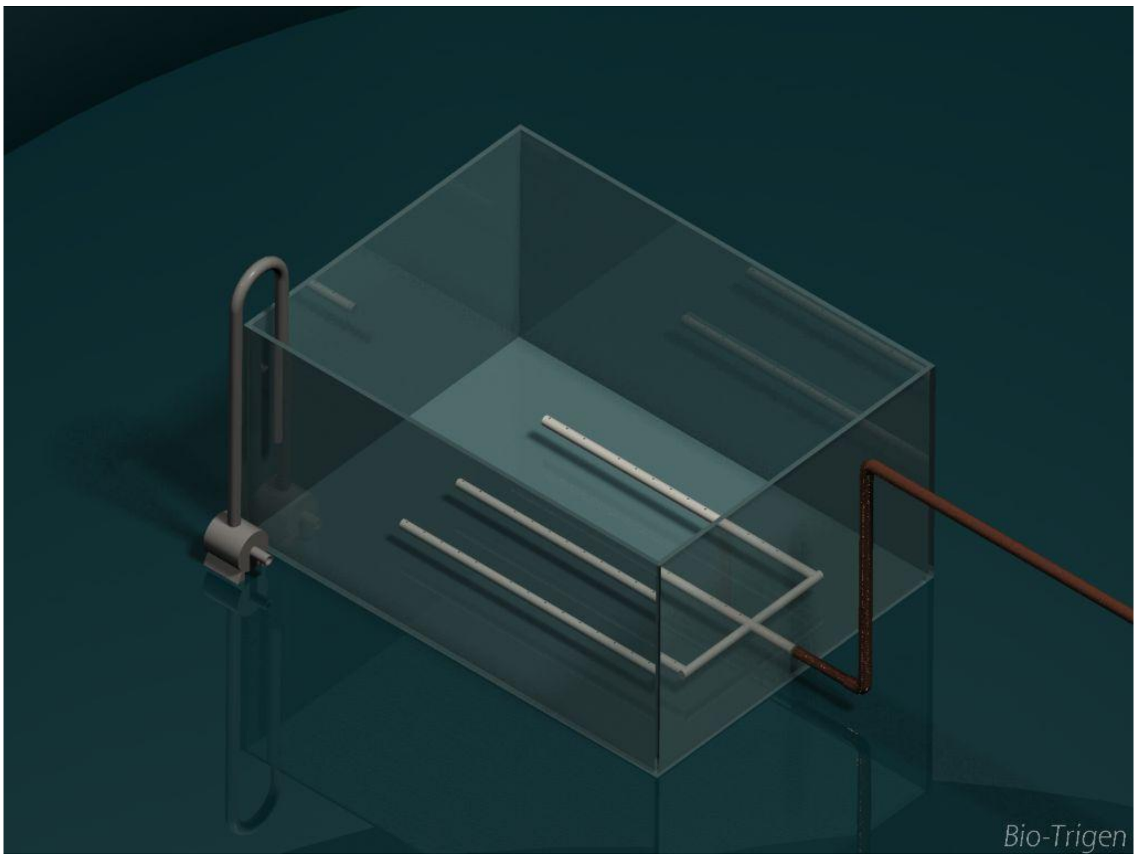


Figure 8 - Concept 5 - Water Storage

Selection Criteria

Concept selection will be the next phase in the project development plan. The following selection criteria represent the most important aspects of the final product. These criteria will be weighted and arranged into a decision matrix. Each concept will be given a score in each category, and a total score for each will be evaluated. The highest scoring concept will be selected and the design process will move into the next phase. If more than one concept scores highly, the lower scoring concepts will be discarded and refined grading criteria will be invoked.

Adaptability - The system should be modular in design for robust application and ease of manufacture.

Scalability - The product should exhibit features of scalability for implementation in a wide range of systems.

Ease of Use - The product should be easy to install, uninstall and operate.

Durability - The product should have a long operating life.

Reliability - The system's behavior should be consistent.

Cost Effectiveness - The budget should be efficiently utilized.

Controllability - Precision control of nutrient administration is ideal.

Exhaust Capture Effectiveness - The system should be able to capture a large portion of exhaust gases to reduce overall emissions.

Power Efficiency - The system should accomplish its goal while drawing as little power as possible.

Decision Matrix

The decision matrix is shown in Figure 9. There was a conference to discuss the importance of each criterion and they were weighted as seen fit by the group. Given the main goals and constraints from the existing equipment and budget, the top three concerns are capture effectiveness, power requirements, and cost-effectiveness. Since the selected design may be scaled up to fit UFPR's photobioreactor and trigeneration systems, scalability is a close fourth and was considered closely in the design process.

Criteria	Weight	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Capture Effectiveness	0.25	7	8	8	5	4
Power Requirements	0.2	9	9	7	4	5
Cost Effectiveness	0.2	7	8	8	5	6
Scalability	0.1	6	6	9	8	8
Controllabiity	0.1	7	9	9	8	7
Reliability	0.05	8	7	7	6	6
Durability	0.05	7	6	8	6	7
Adaptability	0.05	5	6	7	9	9
Total Weighted Score	1	7.25	7.85	7.9	5.7	5.8

Figure 9 - Decision Matrix

Due to restricted capture capacity and the energy cost of compression, the two indirect concepts scored poorly against the direct methods. It was estimated that the compressor in concept 4 would draw nearly 25% of the power generated by the trigeneration system. Concepts two and three scored highly, and both have desirable features. Since scalability is an issue, there is a need to calculate the feasibility of delivering the exhaust gases using only the pressure provided by the motor. Too much pressure resistance would make the engine run inefficiently or could even cause it to stall. An estimate of required pressure for the FSU bioreactor was calculated at about 10 kPa. The pressure requirement of UFPR's bioreactor was measured at about 300 kPa. These two values were used as benchmarks when considering the backpressure seen by the engine.

Research was also done on acceptable levels of backpressure for large and small generator exhaust streams. It was found that acceptable ranges for backpressure were only about 6-10 kPa and actually decreased for larger generators. At this point it became clear that pressure provided from the engine would not be sufficient or desirable for injecting gases into the bioreactor. Concept 3 features a pump that would alleviate backpressure seen by the engine, but the automated control scheme of concept 2 was also desired. The decision was made to combine concepts 2 and 3 to make a stronger system.

Other Design Considerations

Due to the nature of the internal combustion engine a particulate filter will be needed to remove soot from the exhaust that might otherwise clog important components downstream. The filter will be placed upstream of the air pump. Gases other than CO_2 are also present in the exhaust stream, like NO_x, SO_2 and CO and are not harmful to the algae in the photobioreactor. In addition to sequestering CO_2, Algae actually converts sulfur dioxide and nitrogen oxides into harmless gases.

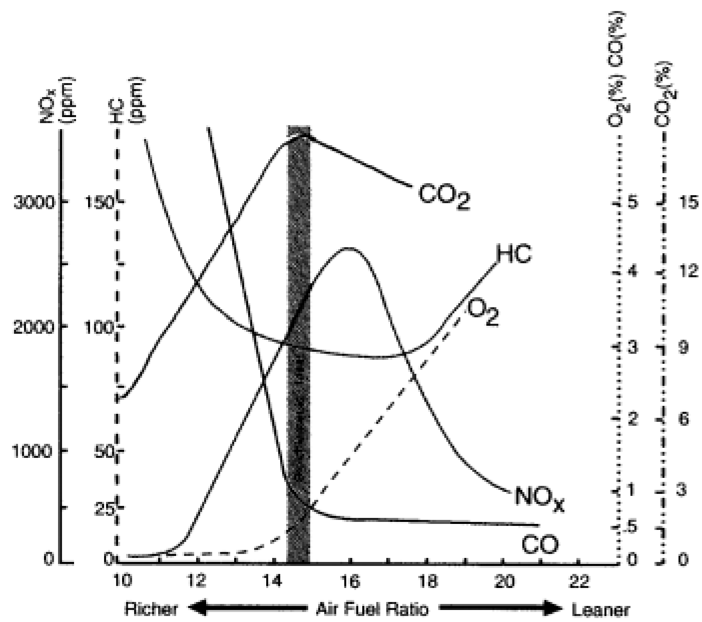


Figure 10 - Composition of Exhaust Gas as a Function of Air/Fuel Ratio

For design calculations, the estimate of 15.5% CO_2 in exhaust gas was used. This percentage is based on efficient combustion with an ideal air fuel ratio of 14.7:1. The relation of exhaust gas output with air-fuel ratio is shown in Figure 10.

Two algae species were selected for growth in our bioreactors, *Scenedesmus dimorphus* and *Chlorella vulgaris*. *Chlorella* was selected for its hardiness and adaptability to growth conditions, and *Scenedesmus* was chosen for its previous use at UFPR. The algae cultures are shown in Figure 11. Research indicates that *Scenedesmus* will digest NO_x emissions, while *Chlorella* will simply tolerate the presence of it.

Figure 11 - *Scenedesmus dimorphus* and *Chlorella vulgaris*

Final Concept

Moisture Catch

A low outlet allows excess gases and condensed moisture to escape the gas stream before entering the air pump. This system does not utilize all of the exhaust that flows out of the motor, and excess moisture will damage the pump. This is constructed of PVC and connected inline with the filter casing.

Filter Medium

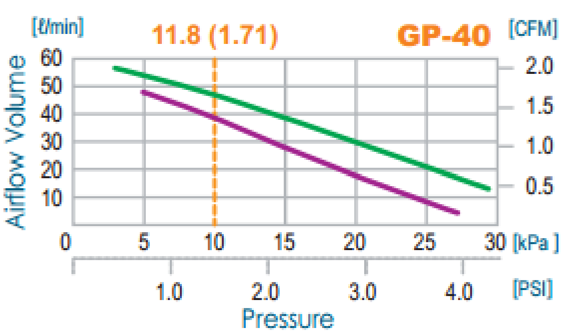
Figure 12 - Filter Medium

A particulate filter will be fabricated with synthetic filter material. This will prevent the undesired build up of soot and other particulate contaminants. This filter medium is inexpensive and easy to apply. The filter unit is easy to replace, requiring the removal of one clamp.

Air Pump

The amount of CO_2 that can be captured will be limited by the small size and number of bioreactors. The photobioreactor array will consist of four 2.5 L Aqua-Medic

Figure 13 - Air Pump Performance Curve



tubular photobioreactors. A previous experiment found an ideal CO_2 delivery rate of 13.61 µg/s. A HiBlow GP-40 will deliver more than enough flow for the bioreactors, and the rate to each bioreactor can be adjusted with the distribution manifold and pH controller. This air pump will also be able to handle the pressure requirements for our small bioreactor array. It will also allow for expansion of the bioreactor array. The performance curve for this pump is shown in Figure 13.

Neptune Systems Apex Control System

Several parameters must be monitored and some controlled in each bioreactor. The CO_2 content and the temperature of the algae growth medium must be monitored to

Figure 14 - The pH Controller

ensure that the algae will grow successfully. The pH of the algae medium is an indicator of CO_2 content. As CO_2 is injected via exhaust or ambient air into the reactors, the pH of the medium will decrease. In order to maintain the pH of the medium, the system must intelligently determine when to pump air or exhaust into the bioreactors. This is accomplished by using a control system. Based on the pH control signal, the control system actuates the pumps and solenoid valves so that each reactor's pH can be maintained. The Neptune Systems Apex control system was used in the design of a previous photobioreactor array at FSU and this design team plans on re-using this device. The control system is shown in Figure 14.

Although the temperature of the reactors cannot be controlled, it can be limited in the case that the exhaust gasses sent to the reactors is too high, resulting in a medium temperature that is lethal for the algae. The control system is designed to shut off the exhaust pumps when the temperature probes read too high of a temperature.

Photobioreactors

The photobioreactor array consists of four Aqua-Medic tubular bioreactors, most of which were inherited from a previous design team. Each reactor has a 2.5 L capacity. Tubing and fixtures from the previous bioreactor array will also be reused. These chambers are constructed of a clear plastic to allow light in and are easily cleaned. Regular cleaning is important to prevent the accumulation of stains which will reduce the amount of light entering the reactor. These are shown in Figure 15.

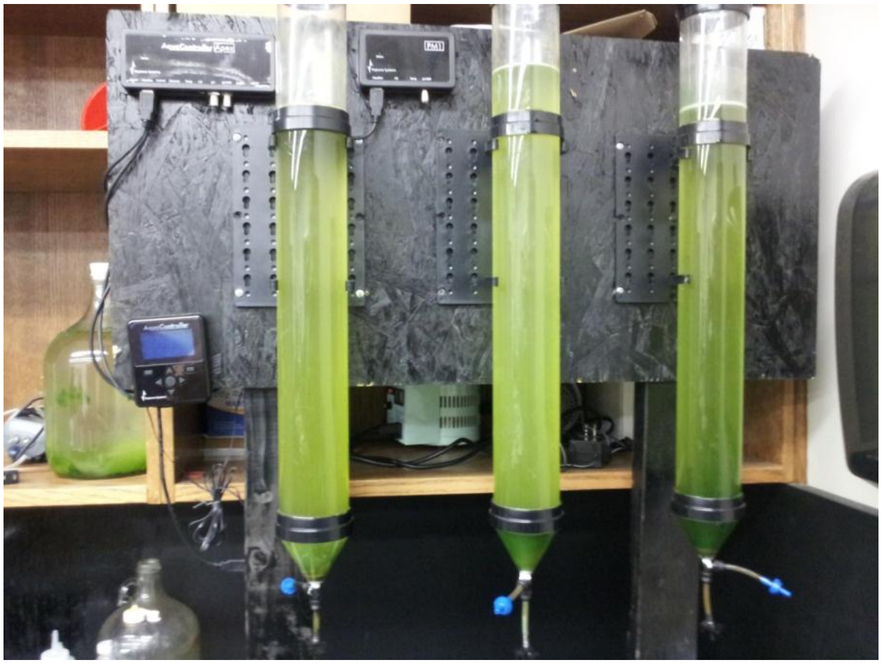
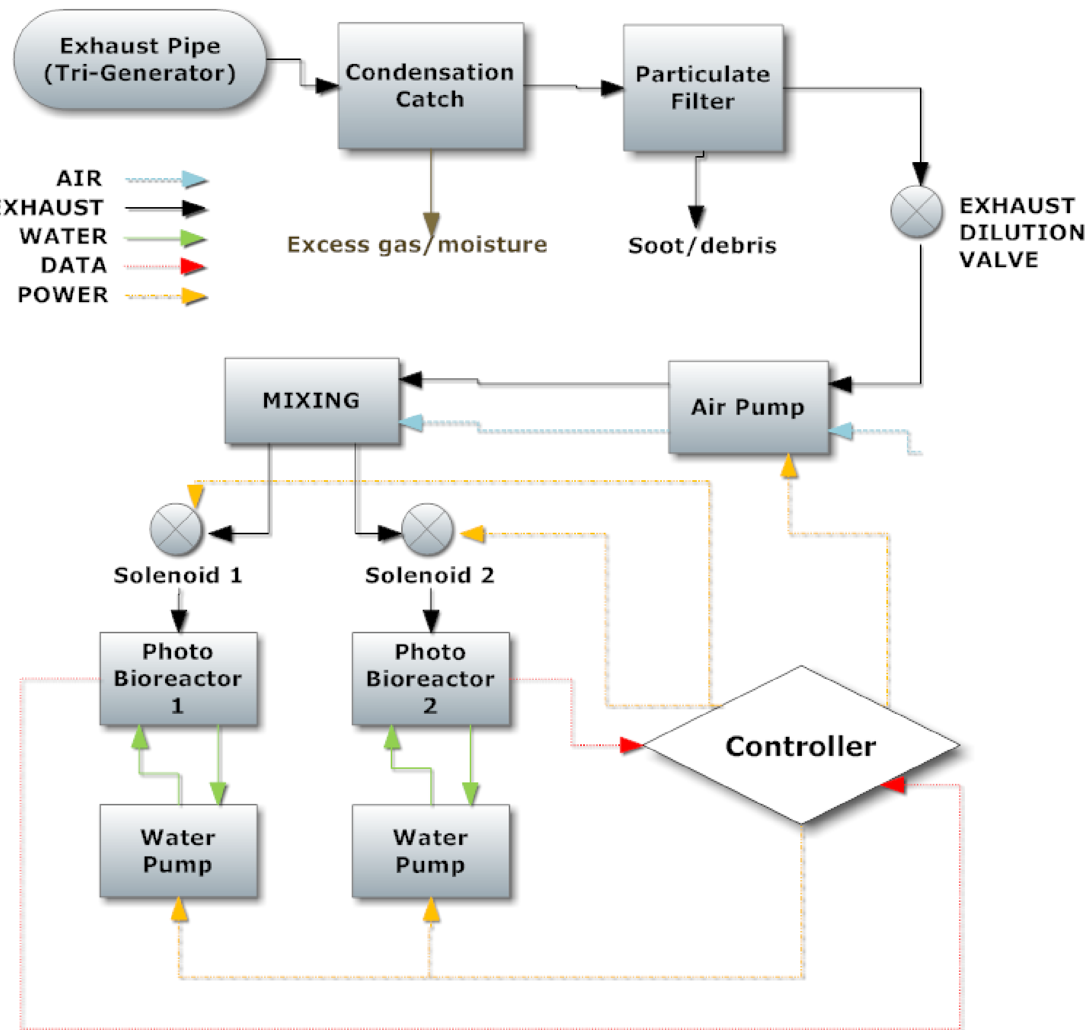


Figure 15 - The Original Photobioreactor Array

Diffusors

As an added feature, in line diffusors were added to the water return lines. Because it is not feasible to use the trigenerator as a consistent source of CO_2,

Figure 16 - Functional Diagram of the Coupling System



Results & Discussion

Control System

The control system is designed to maintain optimal growth conditions in the bioreactors. This is accomplished by actuating air pumps, water pumps, and solenoid valves in response to pH and temperature control signals. This data comes from pH and temperature probes immersed in the algae medium. pH is used as an indicator of diffused CO_2; when injected it acidifies water, lowering the pH, until the water becomes saturated. In our tests, the minimum pH at saturation was found to be approximately 6.4. This pH is not very conducive to algae growth. Algae will consume the diffused gas and will thus gradually increase the pH of the algae medium.

The controller was set up to maintain pH in the bioreactors between 7.5 and 7.9. This range was selected as it represents optimal conditions for growth of both algae species. When any one of the solenoid valves is powered, the exhaust gas pump is also powered. This enables the control of gases to many bioreactors with a single pump. Algae growth will basify the medium until a pH of 7.9 is read by the probe, at which point the controller will energize the appropriate solenoid valve. The injection of gas will then lower the pH until a value of 7.5 is read, triggering an off command to the solenoid. If all solenoids are off, then the air pump will also be turned off.

The controller also powers the water pumps at regular intervals to circulate water throughout the reactors. To protect the algae from an unexpected temperature swing as a result of critically hot exhaust gasses, the controller will also cease gas flow if the temperature in the bioreactor reaches a critical level. Gas flow to each bioreactor can be restricted with an in-line valve. Exhaust concentration can be controlled with a valve that chokes the exhaust inlet.

Overall, the implementation of the controller was successful. However there was one unexpected result of utilizing the Neptune Systems Apex controller and the proprietary probes: sensor noise reduction algorithms caused pH runaway.

In order to understand the issue, one must first understand the type of signal filtration applied to the Neptune Systems probes. When collecting data digitally, sensor noise in commonplace. In order to reduce this sensor noise, a filter based on the time rate of change (time derivative) of the data can be implemented. This filter will reject data that appears to have changed in amplitude in an unrealistic fashion. For instance, in a 200 liter fish tank (a common setting for the use of Neptune System products), it would be nearly impossible for the pH of the water within the tank to change at a rate greater than, say, 1 pH unit within 10 second's time. However, it is not uncommon for a pH sensor to produce a signal equivalent to several pH points higher than the actual system pH for a brief period of time. Such a spike can be filtered before interfering with any control algorithms by limiting the time rate of change of the probe signal. When the time rate of change of a signal appears unreasonable, the filter can hold the signal constant at the last reasonable measurement until the time rate of change of the signal is within reasonable limits. Such a derivative filter is very useful for preventing actuated components (e.g. pumps, chillers, heaters, etc.) from changing state in response to erroneous signal data.

The bioreactors used in practice, however, are of much smaller volume than 200 liters. The ones in this project have a volume of 2.5 liters. Furthermore, CO_2-rich exhaust gas and air mixtures were pumped into these small bioreactors at high volumetric flow rate. As a result, the pH of the medium changed at a rate that was filtered out by the controller's filtering algorithm. So, instead of observing the change in pH, the control system only "saw" the last "reasonable" measured value (typically above 7.5) until the time rate of change of the pH decreased to a level that would not be filtered. This decrease in the rate of change of the pH was a result of the growth medium reaching its maximum point of CO_2 saturation; this value, approximately 6.4, was mentioned earlier in this section of the document.

This issue could have been immediately remedied by choking the exhaust gas intake with an adjustable valve; in fact, this accommodation was eventually furnished. However, in the interest of conducting a consistent experiment, the system was not changed until the planned growing period of 5-7 days was elapsed. The results of this experiment were astounding.

In spite of the huge, undesirable drops in pH, the algae grown using exhaust gasses not only survived, but appeared to thrive in the conditions to which they were subjected. Both algae species supplied with exhaust grew competitively with the ambient air supplied algae. The controller automatically logs pH, temperature, and on/off status of components, so it is not difficult to evaluate the effectiveness of a chosen control scheme.

The following figures show the pH and temperature in the bioreactors as a function of time:

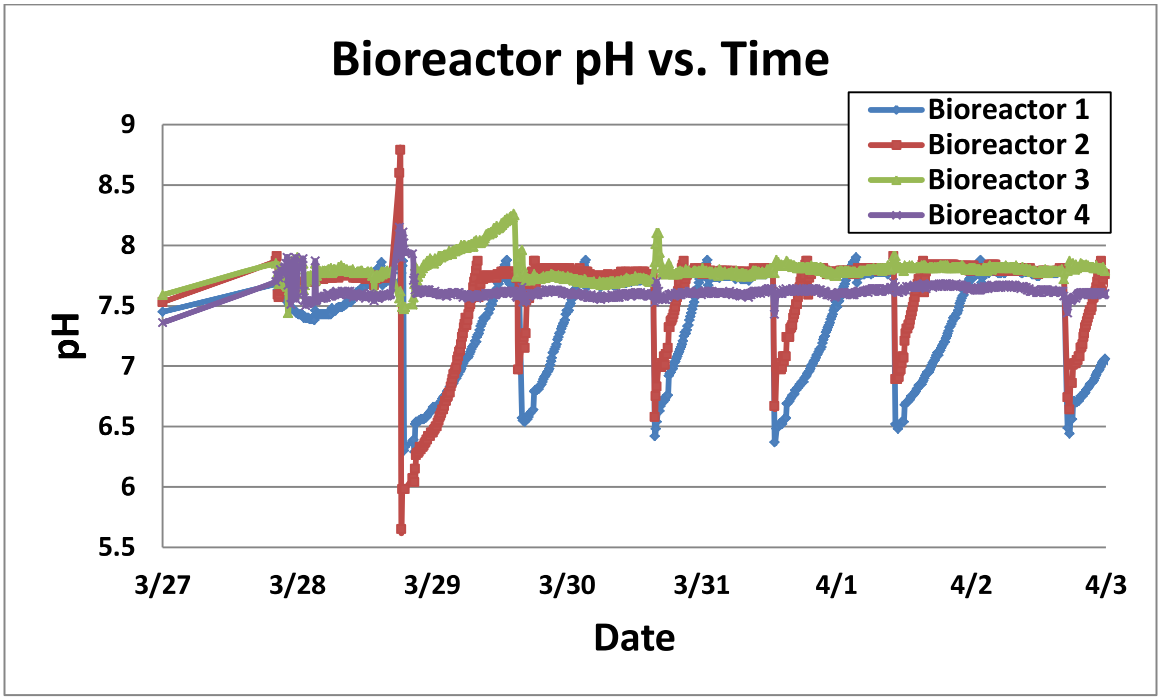


Figure 17 - Evolution of bioreactor pH during the test period

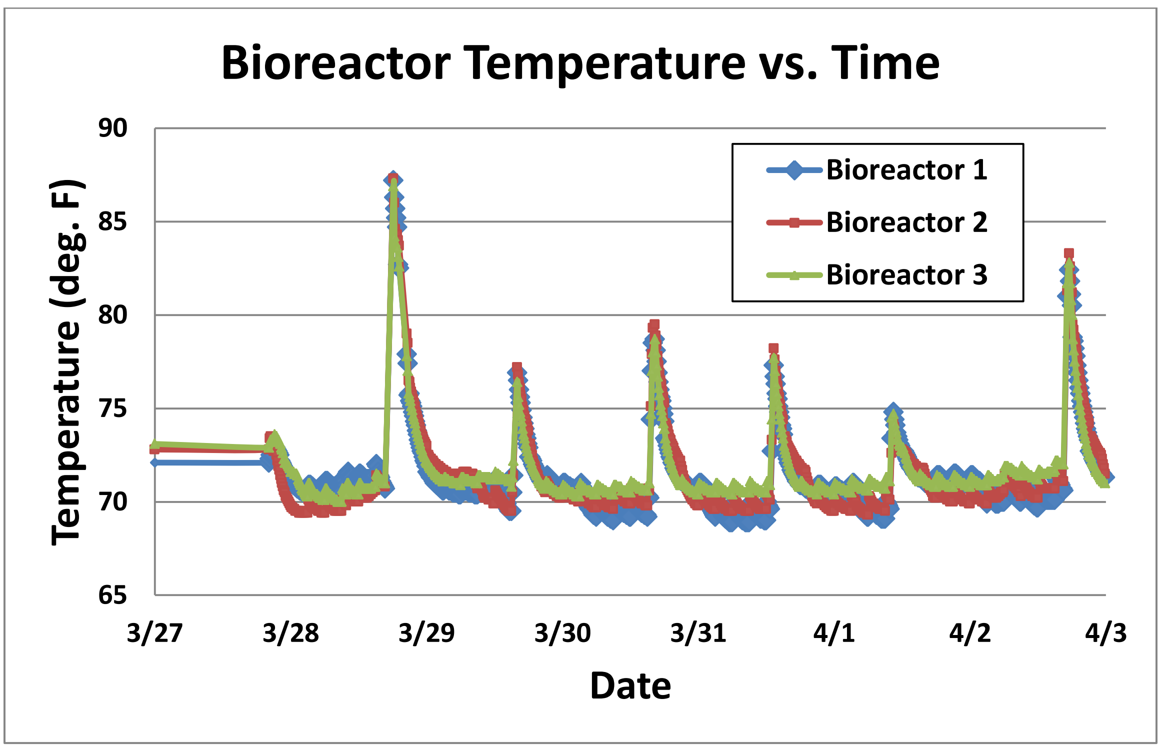


Figure 18 - Evolution of bioreactor temperature during the test period

Algae Growth

Before the algae could be inoculated and tested with exhaust, it was necessary to build volume and biomass. Algae cultures were received in test tubes as small samples smeared on agar. Volume of medium had to increase from about 20 mL to 10 L, and biomass needed to be built to a high concentration to out-compete bacteria and better survive exposure to exhaust gases. Growth ramp-up was performed by progressively scaling up the volume of nutrient medium while allowing biomass to grow over time. This process was performed in a lab with simulated full-spectrum lighting. Satisfactory volume and biomass were reached after 3 weeks.

Exhaust was diluted with ambient air (for a mix of 50% air and 50% exhaust) and administered in short pulses for testing. Our prototype allows adjusting dilution of exhaust in the stream (0-50%) to suit the algae or methods used. Control algae was injected with ambient air and maintained between 7.5 and 7.9 pH. Cell counts were performed immediately after injecting exhaust

Results from growing algae with exhaust are promising. Graphs of exhaust and control algae growth are shown on the following page. In our tests, both *Chlorella* and *Scenedesmus* grown with exhaust performed competitively with their control counter-parts. *Chlorella* seemed to tolerate exhaust better than *Scenedesmus*, possibly due to the denser biomass achieved with *Chlorella*. The rate at which the exhaust gases changed the pH in the bioreactor was an unexpected result. Dosing the algae with exhaust lowered the pH to saturation (around pH 6.2) in just a few minutes. In contrast, it takes the algae several hours to basify the medium back to the upper control pH, 7.9. A slight decrease in biomass for both experiment and control groups can be seen at the beginning of testing. This is likely due to the fact that the algae had grown indoors and was transferred outdoors for testing. The fast temperature change from moving indoors to outdoors and back again is likely kill off weak cells, effectively reducing cell count. Algae are very adaptive, and if gradually acclimated to growth conditions (outdoor temperatures and exhaust gas) these yields could be improved even further.

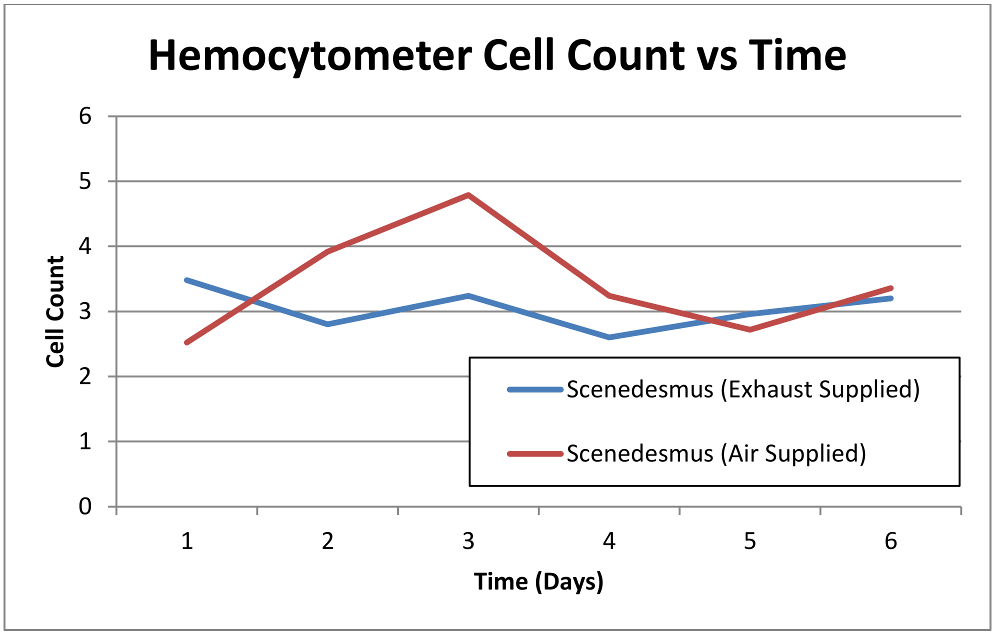


Figure 19 - Scenedesmus growth trends during experiment period

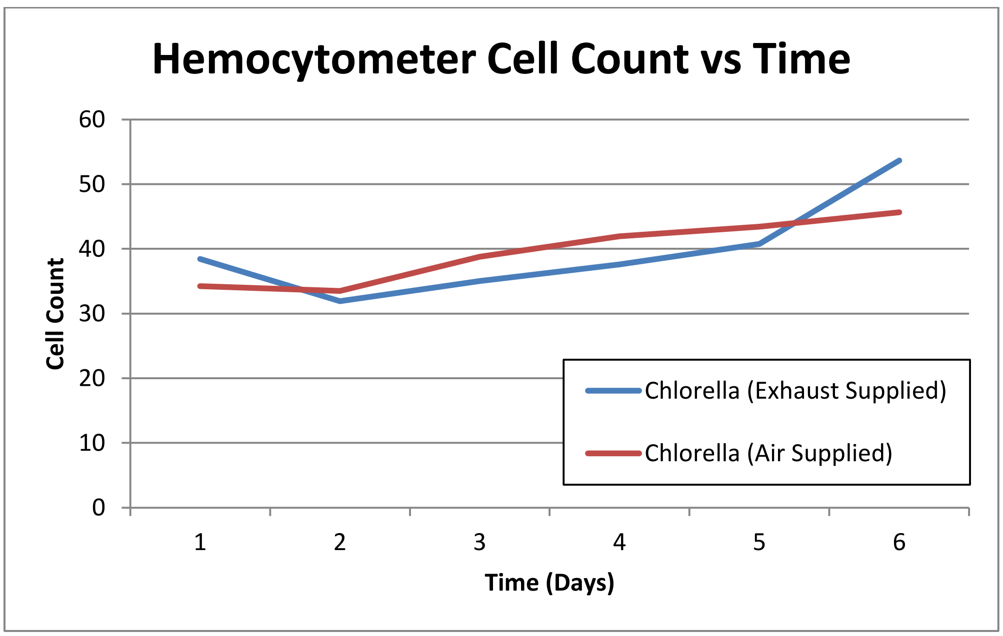


Figure 20 - Chlorella growth trends during experiment period

Life Cycle Analysis

The life cycle analysis is a "cradle-to-grave" methodology used to analyze industrial systems. It starts with the collection of raw materials from the earth to create the product and finalizes at the point where all materials are returned to the earth. A life cycle analysis provides an understandable vision of the environmental aspects of the product or process and a more precise image of the true environmental pros and cons in the selection process of a product.

The objective of performing life cycle analysis over this system is to evaluate the environmental impacts and harmful emissions for humans of all materials used to build our system and also the electricity consumed by it during a certain period of time, in this case 1 year. The aspects covered, were the electrical consumption, the coupling system and the algae cultivation structure this parts will be properly discussed and specified later in this paper.

Electrical Consumption: It was calculated the approximately energy consumption of the system (basically water pumps and air pumps) in terms of kWh per year.

Coupling System: The resources utilized in this stage are all the PVC pieces which are part of the coupling system, as well as the filter and the rubber protection.

Cultivation Structure: The stage regarding the life cycle analysis of microalgae biomass production range from the fabrication process of the materials involved in the cultivation infrastructure which are the steel cabinet, wheels of the cabinet, brass connections and valves, plastic bioreactors, diffusers and hoses (tubing), as well as all nutrients and distilled water used in the medium to grow algae.

Stochastic Life Cycle Analysis via Computer Software

Currently there are several computer applications available for the scientific and industrial communities that utilize a stochastic model for life cycle analysis. One of these applications, available is called SimaPro (PRé – Product Ecology Consultants). The life cycle analysis model is built after the analyst has chosen a theory available in the application. Statistical distributions are defined for the input parameters. The program then performs automatic sampling of the various input distributions and generates the selected output parameters. Some simulations were performed with SimaPro 7 from input data collected directly at CAPS Building (Florida State University). These parameters are shown in Figure 21.

Element	Weight (g)	Electricity (kWh/year)
Cabinet	26489	N/A
Wheels	3560	N/A
Tubing	1800	N/A
Bioreactors	1872	N/A
Coupling System (PVC)	881	N/A
Rubber Protection	350	N/A
Filter	6	N/A
Cross bars	332	N/A
Plastic Bioreactors Supports	160	N/A
Plastic Panels	576	N/A
Brass Conections	192	N/A
Valves	52	N/A
Diffusers	74	N/A
Distillate Water	521400	N/A
Water Pumps	N/A	473.04
Air Pumps	N/A	846.96
CHU Medium	1042.8	N/A

Figure 21: Input data for simulations in the application SimaPro 7

In the analysis, the following was considered: i) cabinet used to support the bioreactors, keep the pumps (water and air) and control system; ii) cabinet wheels; iii) all the tubing used to circulate the medium and pump air into the bioreactors; iv) bioreactors used to growth algae; v) coupling system (PVC pieces); vi) rubber protection (coupling system); vii) filter used to clean the exhaust gases before run it into the bioreactors ; viii) aluminum cross bars used to fix the support panels ; ix) plastic support panels; x) plastic panels used to support the control system and bioreactors; xi) brass connections used in the system; xii) PVC valves used in the system; xiii) diffusers used to diffuse the air and exhaust in the system; xiv) distillate water used during a year considering a batch procedure; xv) energy consumption of the water pumps; xvi) energy consumption of the air pump; xvii) CHU medium used to provide nutrients for a better algae growth.

SimaPro 7 software Simulation Results

Figures 22, 23 and 24 shows results that demonstrate the diverse impacts of the system, distributed amongst the sixteen components considered in the analysis through the CML 2 2000 method for the World 1995 database. The legend shows each component, and on a scale from 0 to 100% the percentage impact of each component for different categories of impacts. Through this method it can be seen that the Electricity consumption and the Steel Cabinet contribute a large percentage to ozone layer depletion, human toxicity and global warming. The reason for the large electricity contribution for those impacts categories is the fuel burned to generate it.

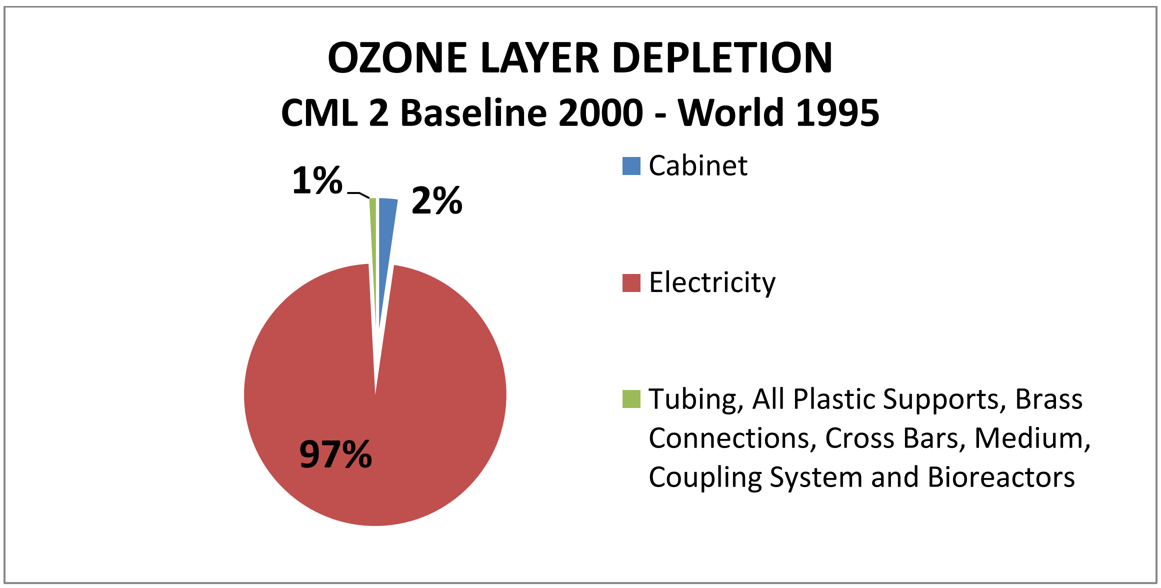


Figure 22: Ozone layer depletion impact (CML 2 Baseline 2000 method – World 1995 database)

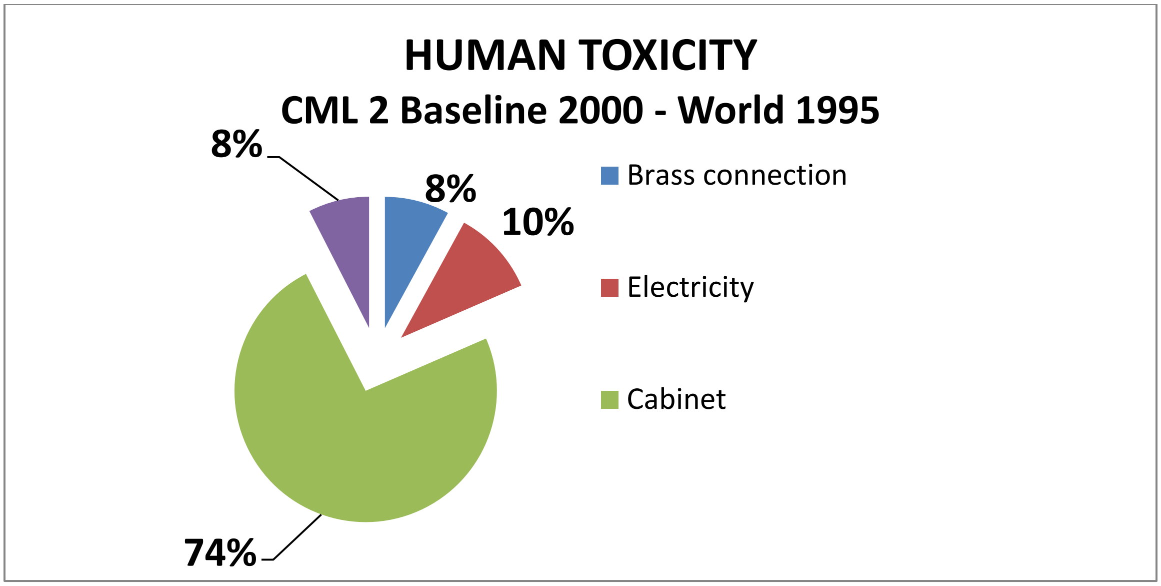


Figure 23: Human Toxicity impact (CML 2 Baseline 2000 method – World 1995 database)

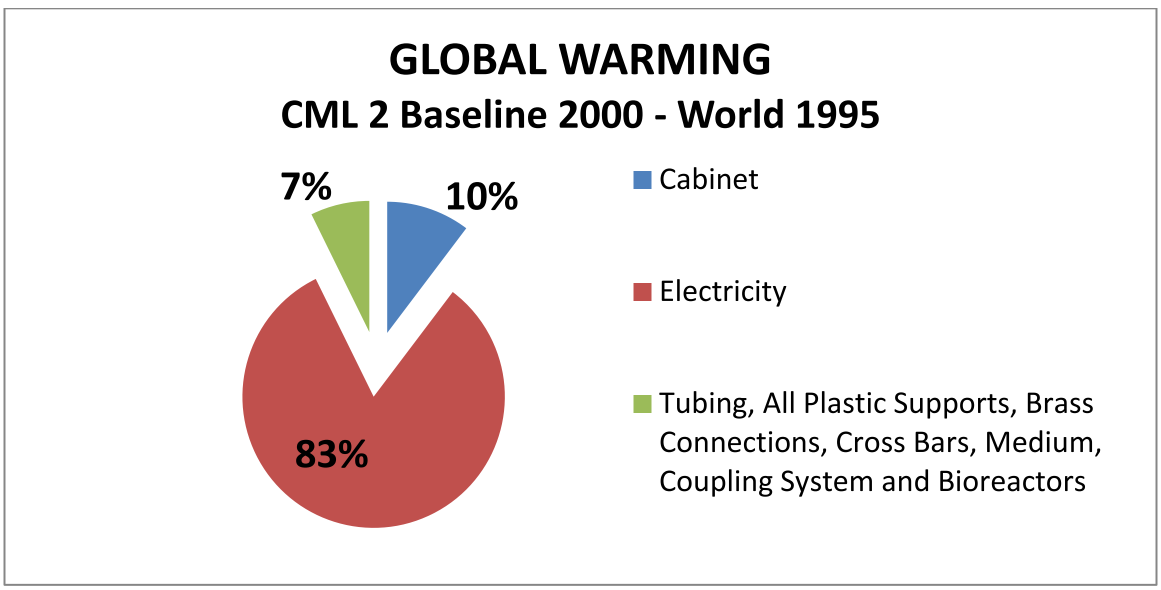


Figure 24: Global Warming impact (CML 2 Baseline 2000 method – World 1995 database)

Figure 25 shows results that demonstrate the carbon dioxide emissions of the system, considered in the analysis through the Ecological Footprint V1.01 method. The legend shows the color for each component, and on a scale from 0 to 100% the percentage impact of each component. Through this method it can be seen that most of CO_2 emissions are caused by the fuel burn to generate electricity.

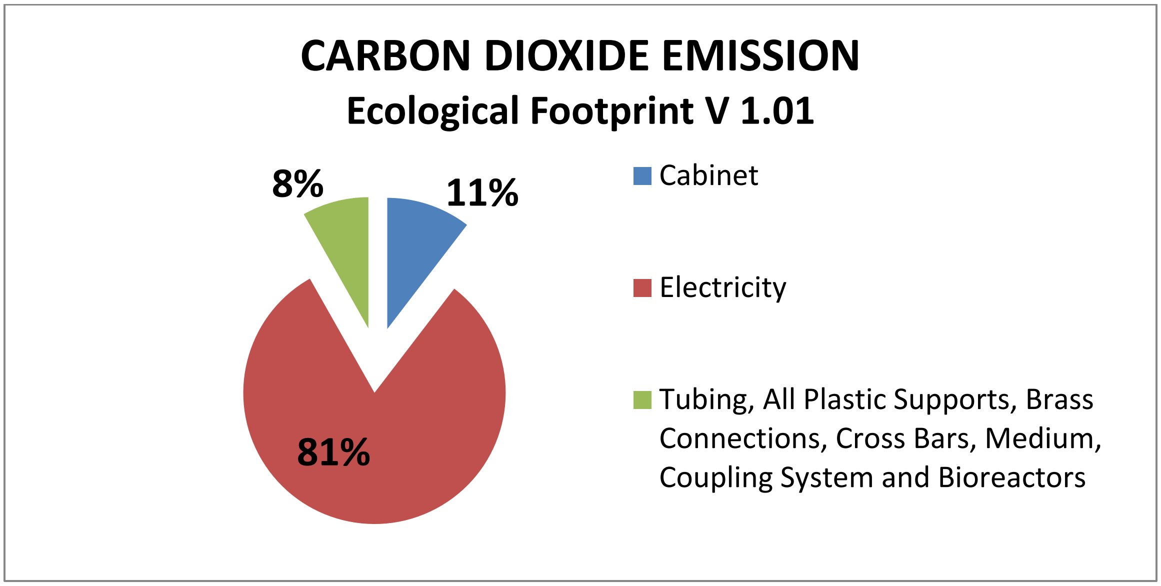


Figure 25: Carbon dioxide emissions (Ecological Footprint V1.01 Method)

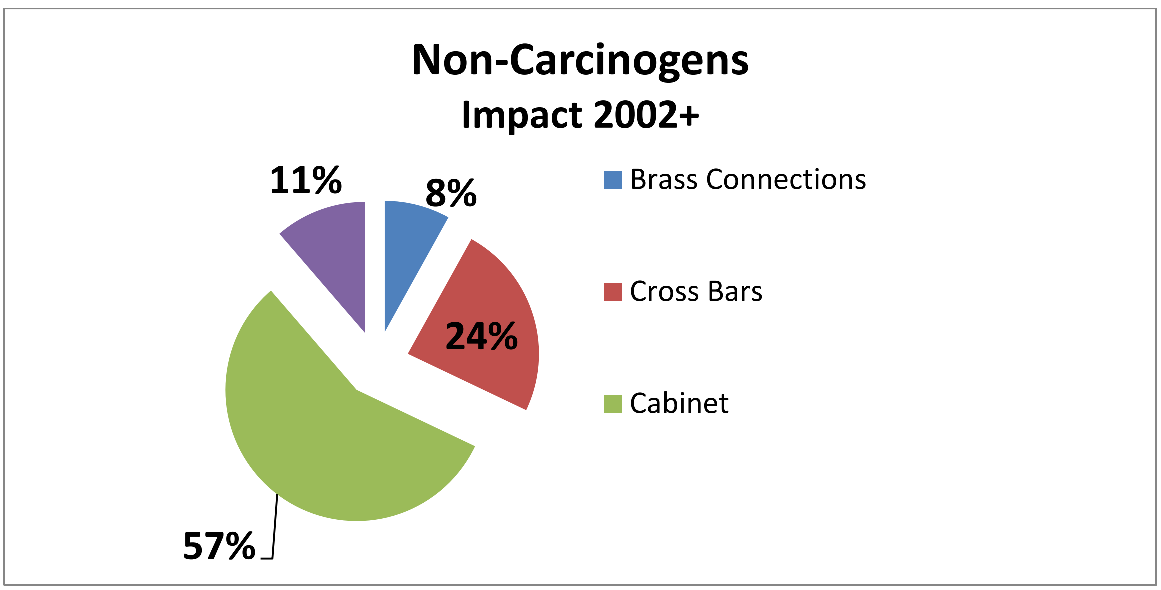


Figure 26: Non-Carcinogens emissions (Impact 2002+ Method)

Figures 26 and 27 shows results that demonstrate other impacts of the system, distributed amongst the seventeen components considered in the analysis through the Impact 2002+ method. The legend shows the color for each component and on a scale from 0 to 100% the percentage impact of each component. Through this method 2 impacts can be examined such as carcinogens emissions which are an agent directly involved in causing cancer and non-carcinogens emissions that are not responsible to cause cancer but stills to be harmful for humans. As we can see through this method the production of metal components as the cabinet, aluminum cross bars and brass connections are linked with carcinogens particles emission. In the other hand, the materials which contribute more in non-carcinogen emissions are the plastics elements, especially the coupling system made of PVC.

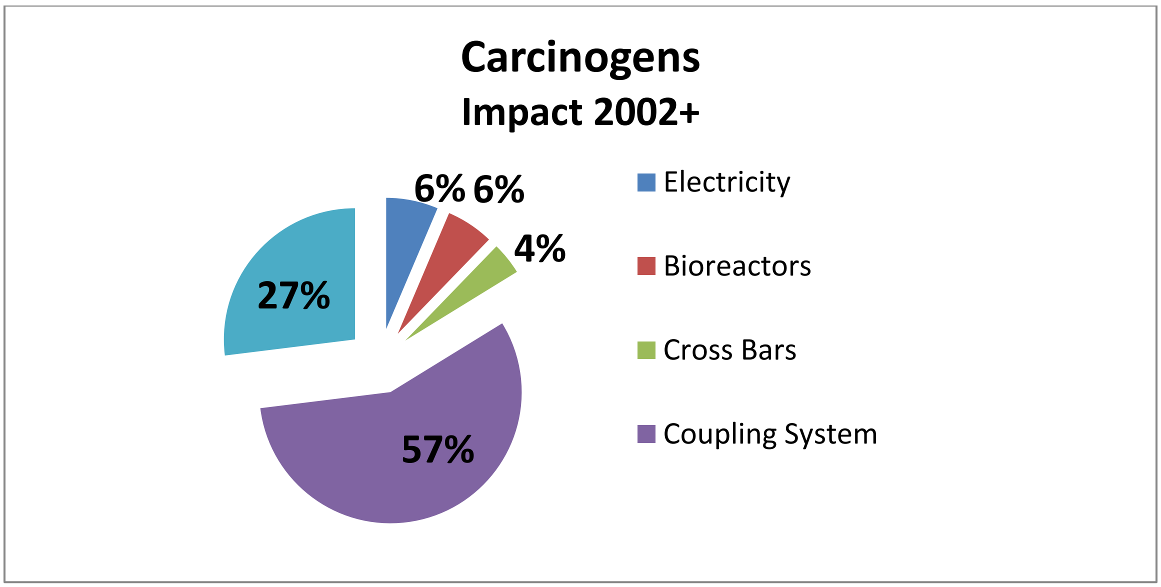


Figure 27: Carcinogens emissions (Impact 2002+ Method)

From the results of these 2 methods of life cycle analysis it can be seen that the steel cabinet and the electricity cause the greatest environmental impact when compared to the other materials necessary for the construction of the system. Also, we can conclude that plastic production is very harmful to human health.

Biodiesel Production

Making several idealistic assumptions gathered from the literature, it is possible to calculate the amount of biodiesel that this system can produce in a year. To do this, we can assume a batch-style procedure to harvest the biomass from the photobioreactors, gathering 10 liters of algae within medium (5 liters of Chlorella vulgaris and 5 liters of Scenedesmus quadricauda) per week. According to the NPDEAS (Núcleo de Pesquisa e Desenvolvimento em Energia Auto-Sustentável - UFPR) project manager Dr. André Bellin Mariano, it is possible to produce a quantity of biodiesel equivalent to 20% of the dry algae biomass collected from this medium. Calculations that it was found that 104.23kg of dry biomass is produced per year using both species, The next step is to extract the oil from the dry biomass, to do this we assumed two different realistic efficiencies for each algae specie, 20% for *Chlorella vulgaris* and 30% for *Scenedesmus quadricauda*.

It is possible to find in literature higher values of oil percentage for each particular specie, such as: 29% for *Chlorella vulgaris* and 45% for *Scenedesmus quadricauda* (Algal Oil Yields. Oilgae, 2012); but it was chosen more realistic values.

The final process is to chemically convert the algae oil into biodiesel, this process has a efficiency of approximately 95% according with Dr. Mariano. Using all this information is possible to calculate the theoretical amount of biodiesel that our system could produce per year processing both species in the same time, which is around 24kg or 27.27 liters assuming that the biodiesel density is ~0.88 kg/l.

Carbon Dioxide Sequestering

It is known that 104.23kg of dry biomass can be extracted from this particular system, with this value we can estimate the kg of CO_2 that the algae will sequester in a year. Since 1 kg of dry algae biomass has the capacity to sequester 1.8 kg of carbon dioxide from atmosphere (Global CCS Institute, 2012), the system could sequester 187.7 kg of CO_2 during 1 year.

If it’s assumed, for example, that the whole system is using grid electricity produced by a natural gas power plant, our system could sequester 32% of all CO_2 emissions necessary to run it during 1 year. Also, if we consider only the emissions to run the water pumps for a year, the system is able to consume 89% of it.

Engineering Economics

Cost-saving steps were taken whenever possible during the design and construction of the coupling system. The Neptune Systems Apex controller, two Probe Module 1 units, and three Aquamedic photobioreactors were inherited from a previous senior design team and were utilized in the final design.

However, in order to completely develop our system, several other components needed to be purchased. In the interest of compatibility and aesthetics, components of matching brand were selected even if the cost was higher for such items. For instance, Neptune Systems sensors and probe modules, which were considerably more expensive than some competitor's products, were selected in the interest of system compatibility.

The housing unit and mounting systems were some of the more expensive system components. The team advisor made it very clear that a well-constructed, attractive housing was a major requirement for the final coupling unit, and thus a considerable portion of the budget was allocated to furnishing the request.

Unfortunately, the Apex controller suddenly ceased to function immediately before the first system test. A new control unit was ordered and rush-shipped so that experimentation could move forward.

Diffusors were not used during the testing of the system. However, the diffusors were deemed a necessary purchase as it is not feasible to consistently supply CO_2 by means of the trigeneration unit. Because the system features in-line diffusors, CO_2 can be supplied via compressed gas cylinders.

A breakdown of the budget can be seen in the following table:

Item	Quantity	Price
CO_2 Diffusors	4	$150.49
Air Pumps	2	$216.69
Water Pump	1	$59.99
Algae Samples and Medium	12	$320.75
Photobioreactors	2	$202.01
Local Trigen Repair Parts	NA	$60.74
Probe Module	1	$75.00
Temperature Probles	3	$15.22
pH Probes	4	$204.00
Replacement Controller	1	$280.37
Solenoid Valves	2	$96.60
Housing Unit	1	$354.44
Tubing	70 feet	$18.90
Electrical Butt Splices	1 package	$2.46
DIN Mounting System	4	$32.24
	TOTAL	**$2120.29**
	ALLOCATED BUDGET	$2500.00

Figure 28 - A detailed breakdown of the budget

Conclusions

The coupling system as fabricated satisfies the customer requirements and appeals to the needs assessment. The project did not span a scope larger than that defined in the "Project Scope" section of this document and can be deemed a success.

The experiments using the coupling devices showed that, in spite of a minor (and temporary) control system failure, algae can thrive in an environment that is subjected to exhaust gasses. Even though the pH of the bioreactor medium dropped well below the optimal value conducive to growth, the algae thrived once an acclimation period had elapsed. These results are both surprising and promising; if the algae subjected to such a harsh environment were able to survive with ease, it is very likely that algae grown in the improved system will exhibit fast and hearty growth.

Life Cycle Analysis (LCA) was performed on the system, as required in the needs assessment. If it is assumed that the system is powered by a natural gas power plant (as much of Tallahassee, Florida is) then LCA determined that 32% of the carbon dioxide produced to power the system during a period of one year can be sequestered by virtue of the algae biomass. This is a considerable fraction, and it could be greatly improved if a greater amount biomass were employed. The pumps were selected with expansion in mind, and not much retrofitting would be necessary to support larger bioreactors.

Life Cycle Analysis also determined that the steel housing unit constituted a significant portion of the total CO_2 emissions for the entire system. Although the housing unit was used in the design for aesthetic reasons, a greener system could be achieved by selecting more eco-friendly materials for fabrication.

Because the trigenerator produces far more exhaust gasses than can be used with the current bioreactor array, CO_2 sequestration is limited by the total volume of the bioreactors in the system. The system can be significantly improved in both maximum emission reduction and biodiesel production by expanding the bioreactor array. The final design was constructed with expansion in mind, so the addition of extra bioreactors would be simple to implement.

Environment, Health & Safety Considerations

1. Operation
    a. Always operate the trigenerator in open, well ventilated areas. The exhaust gases and gasoline fumes are toxic
    b. Never touch exhaust piping, whether the system is running or not. They may still be hot from operation
    c. Secure the trigenerator table with wheel locks before operating
    d. Be aware of fuel lines and electrical wires
    e. Have a fire extinguisher nearby
    f. Do not wear long hair down or loose clothing, and keep any body part away from the crank shaft
2. Transport
    a. Do not attempt to move the trigenerator or bioreactor array by yourself
    b. Use close-toed footwear for transport. The unit is very heavy and could cause foot injury
    c. Secure electrical wires and fuel lines before transport
    d. Secure the fuel tank before transfer to avoid spills
3. Environment
    a. Avoid gasoline spills. Gasoline is corrosive and harmful to the environment
    b. Never dispose of algae by simply pouring it down the drain. Use bleach to kill the culture and prevent it from becoming an invasive organism to your local biome
    c. Correctly dispose of the battery when necessary
    d. Algae must be killed with iodine solution before dumping. Releasing live foreign algae species into the local biome may have serious environmental impacts

Appendix

Calculations

Engine: Kawasaki FD501D

Power, Engine Speed, Displacement

$P_E := 16hp$ $\omega_E := 3600rpm$

$V_E := 26.7in^3$

Fuel consumption

$mdot_{gas} := .0004\frac{kg}{s}$ $\rho_{gas} := 720\frac{kg}{m^3}$

$$Vdot_{gas} := \frac{mdot_{gas}}{\rho_{gas}} = 0.528\frac{gal}{hr}$$

Air Consumption

$Vdot_{air} := \omega_E \cdot \frac{V_E}{2} = 0.082\frac{m^3}{s}$ $v_{air} := \frac{Vdot_{air}}{.25\pi\, 1in^2} = 162.763\frac{m}{s}$ $\rho_{air} := 1.177\frac{kg}{m^3}$

$C_{cd} := 15.5\%$ ExhaustCO.2 concentration for optimal air/fuel ratio (14.7:1)

$\rho_{cd} := 1.797\frac{kg}{m^3}$ Assumed Density of CO2

$Vdot_{cd} := .155\, Vdot_{air} = 0.013\frac{m^3}{s}$ $mdot_{cd} := Vdot_{cd} \cdot \rho_{cd} = 0.023\frac{kg}{s}$

$Vdot_{air} = 4.948 \times 10^3 \cdot \frac{L}{min}$ $\mu g := 1gm \cdot 10^{-6}$

$mdot_{reqcd} := 13.61\frac{\mu g}{s}$ Optimal CO2 rate for each bioreactor

$Vdot_{reqair} := \frac{mdot_{reqcd}}{\rho_{cd} \cdot .155} = 2.932 \times 10^{-3} \cdot \frac{L}{min}$ Volumetric Flow of Exhaust Needed for Each Bioreactor

$N_{bio} := \frac{mdot_{cd}}{mdot_{reqcd}} = 1.688 \times 10^6$ Number of small bioreactors this engine could support

$2 \cdot Vdot_{reqair} = 5.864 \times 10^{-3} \cdot \frac{L}{min}$ Volumetric flow for 2 bioreactors

Engineering Analysis for Concepts

Trigenerator Stats

$P_{Gen} := 5000W$ $P_{load\_TG} := 425W$ $P_{Eng} := 16hp = 11.931kW$ $\frac{P_{Gen}}{P_{Eng}} = 0.419$

$P_{Avail} := P_{Gen} - P_{load\_TG} = 4.575kW$ $m_{fuel} := .0004\frac{kg}{s}$ $\eta_{sys} := .42$

$\eta_{eng} := .25$

Concepts 1/2/3 - Pressure Head required to move gas $\rho_w := 1000\frac{kg}{m^3}$

$\rho_w \cdot g \cdot 1m = 9.807kPa$ $\rho_w \cdot g \cdot 1m = 1.422psi$

Approximate height of FSU bioreactor ~1m

For small scale, exhaust pressure could be enough. For larger scales there would be a larger pressure drop

A fan or compressor could be used to augment these designs

Thinking of a mix of concepts 2 and 3. An automated pressure vessel with solenoid/servo valves supplied with a fan or compressor.

Concept 4 - Compression Needs / Water Depth Pressure

This system would need a compressor.

Pancake Tank Compressor

$V_{flow1} := 1.7cfm$ $P_{max1} := 150psi$

Cost : $189.75

$P_{c1} := 120V \cdot 10A = 1.2kW$ $\frac{P_{c1}}{P_{Avail}} = 26.23\%$

Percentage of available power used for compressor

Limited capacity
Draws substantial power

Scalable
Adaptable

Concept 5 - Water depth pressure requirement

$3\text{bar} = 300\cdot\text{kPa}$ $\quad$ $3\text{bar} = 43.511\text{psi}$

A vertical water height of less than 1 m (current design) does not allow enough time for gas bubbles to diffuse into water. Brazil photobioreactor has an extended vertical water tube for gas diffusion. The pressure needed to force gas into this tube is about 3 bar. A compressor would be necessary for this water height. An air blower could be used for a water height of less than 55 in. This would require a compact gas diffuser.

$P_{Reqd} \le 2.1\text{psi}$ $\quad$ $P_{b1} := .5\text{hp}$

Single Stage Blower

Cost : $610.82

$$\frac{P_{b1}}{P_{Avail}} = 8.15\%$$

Percentage of available power used for blower

For pressures greater than about 2 psi, a compressor would be required. Similar to concept 4.

$$\frac{P_{c1}}{P_{Avail}} = 26.23\%$$

Percentage of available power used for compressor

Limited capacity
Draws substantial power

Scalable

Pumping Requirements - Losses

$\mu_{air} := 2.05 \cdot 10^{-5} \frac{kg}{m \cdot s}$ At approximately 50°C

$\rho_{air} := 1.06 \frac{kg}{m^3}$ At approximately 50°C, 50% relative humidity

$d_{tube} := 0.5in = 1.27 \cdot cm$ An estimate of tube inner diameter (hydraulic diameter) based on current bioreactor setup

$V_{dot} := 2 \frac{L}{min}$ A (very high) estimate of volumetric flow necessary for bioreactors

$A_{tube} := 0.25\pi \cdot d_{tube}^{2} = 1.267 \times 10^{-4} m^2$ This is the cross-sectional area of the inside of the tube

$Vel := \frac{V_{dot}}{A_{tube}} = 0.263 \frac{m}{s}$ This is the velocity of the flow

$Re_{flow} := \frac{\rho_{air} \cdot Vel \cdot d_{tube}}{\mu_{air}} = 172.797$ Reynolds number for estimated flow parameters

$\varepsilon_{tube} := 0.0025mm$

$Roughness_{tube} := \frac{\varepsilon_{tube}}{d_{tube}} = 1.969 \times 10^{-4}$

$f := 0.015$ Darcy friction factor found on Moody chart. This is only a rough estimate and assumes turbulent flow!

$L_{tube} := 3m$

$h_f := f \cdot \frac{L_{tube}}{d_{tube}} \cdot \frac{Vel^2}{2g} = 0.013m$ $g = 9.807 \frac{m}{s^2}$

This is a pretty small estimate. It may be better to assume the pump produces laminar flow

$$f_{lam\_flow} := \frac{64}{Re_{flow}} = 0.37$$

$$h_f := f_{lam\_flow} \cdot \frac{L_{tube}}{d_{tube}} \cdot \frac{Vel^2}{2g} = 0.309m$$

This is a more reasonable estimate. Another calculation should be made to estimate the total head loss including minor losses. These losses may be significant, as several fittings and flexible tubing will be employed. If five fittings are encountered before the gas reaches the bioreactors, and the flexible tubing creates the equivalent of 2-4 long radii 90° bends, then...

$$\xi := 0.9 + 0.25 + 0.25 + 0.3 + 0.3 + 0.9 + 0.9 + 0.9 + 0.9 + 0.9 = 6.5$$

$$h_{minor} := \xi \cdot \frac{Vel^2}{2g} = 0.023m$$

$$h_{total} := h_f + h_{minor} = 0.332m$$

Still a small estimate, but the relatively miniscule diameter of the tubing and its ability to flex may still create more losses later on in fabrication. Furthermore, if the bioreactors are mounted significantly higher than the exhaust exit (a likely possibility) then it would be best to make sure that the pump is capable of handling much greater losses than calculated.

Biodiesel Production

1 year has 365 days and 52.14 weeks

our bioreactors produce 5 liters of wet chlorella and 5 liters of wet scenedesmus biomass per week

$weeks := 52.1$

$chl\_wet := 5 \qquad scen\_wet := 5$

$eff3 := 0.9 \qquad eff1 := 0.2 \qquad eff2\_chl := 0.2 \qquad eff2\_scen := 0.3$

$chl\_wet\_liter\_year := weeks \cdot chl\_wet = 260.7$

$scen\_wet\_liter\_year := weeks \cdot scen\_wet = 260.7$

$chl\_dry\_Kg\_year := weeks \cdot chl\_wet \cdot eff1 = 52.14$

$scen\_dry\_Kg\_year := weeks \cdot scen\_wet \cdot eff1 = 52.14$

$chl\_oil\_Kg\_year := weeks \cdot chl\_wet \cdot eff1 \cdot eff2\_chl = 10.428$

$scen\_oil\_Kg\_year := weeks \cdot scen\_wet \cdot eff1 \cdot eff2\_scen = 15.642$

$total\_oil\_Kg\_year := chl\_oil\_Kg\_year + scen\_oil\_Kg\_year = 26.07$

$total\_biodiesel\_Kg\_year := (total\_oil\_Kg\_year) \cdot eff3 = 24.767$

assuming a biodiesel density of 0.88kg/liter

$den := 0.8$

$$total\_biodiesel\_liter\_year := \frac{[(total\_oil\_Kg\_year) \cdot eff3]}{den} = 28.144$$

CO_2 Sequestration

$$Total\_dry\_biomass\_Kg\_year := chl\_dry\_Kg\_year + scen\_dry\_Kg\_year = 104.28$$

It is known that 1 Kg of algae dry biomass is able to sequester 1.8 Kg of CO_2 from the atmosphere. So for that amount of dry biomass our system sequester:

$$carbon\_dioxide\_sequestered\_Kg\_year := 1.8 Total\_dry\_biomass\_Kg\_year = 187.704$$

References

"Algal Oil Yields". Oilgae. Retrieved 13 March 2012

"Accelerating the uptake of CCS: Industrial use of captured carbon dioxide". Global CCS Institute. Retrieved 2012-02-25.

Behr A, Eilting J, Irawadi K, Leschinski J, Lindner F. Improved utilization of renewable resources: new important derivatives of glycerol. Green Chemistry. 2008; 10(1): 13–30, DOI: 10.1039/b710561d.

Clarens AF, Ressurreccion EP, White MA, Colosi LM. Environmental life cycle comparison of algae to other bioenergy feedstocks. Environ. Sci. Technol. 2010; 44: 1813–1819.

Cerón Garcia MC, García Camacho F, Fernández Sevilla JM, Acien Fernández FG, Molina Grima E. Mixotrophic growth of Phaeodactylum tricornutum on glycerol: growth rate and fatty acid profile. J. of Applied Phycology. 2000; 12:239-248.

Chisti Y. Biodiesel from microalgae. Biotechnology Advances. 2007; 25(3): 294–306, DOI: 10.1016/j.biotechadv.2007.02.001.

Curran MA. (ed) 1996. Environmental Life Cycle Assessment. ISBN 0-07-015063-X, McGraw-Hill.

EPA/600/R-06/060. Life cycle assessment: principles and practice. Environmental Protection Agency, EPA, USA, May 2006.

Eriksen NT. The technology of microalgal culturing. Biotechnology Letters. 2008; 30(9): 1525–1536, DOI: 10.1007/s10529-008-9740-3.

Frondel M, Peters J. Biodiesel: A new oildorado? Energy Policy. 2007; 35(3): 1675–1684, DOI: 10.1016/j.enpol.2006.04.022.

Goedkoop M, De Schryver A, Oele M, Durksz S, De Roest D. Introduction to LCA with SimaPro 7. Report version 4.4. PRé Consultants. Creative Commons, San Francisco, California, USA, 2010.

Lima AMF. Estudo da cadeia produtiva do polietileno tereftalato na região metropolitana de Salvador como subsídio para análise do ciclo de vida. Universidade Federal da Bahia: Salvador, 2001.