Final Report - Trigeneration Gas Coupler

EML 4551C – Senior Design – Fall 2011 Deliverable

Team # 11

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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 biofuels, 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 is an organism with a great capacity for photosynthesis and an extremely rapid rate of growth. Being a plant, 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 and cool (if needed) the exhaust gases from a trigeneration system (Figure 1), and to introduce these gases to a photobioreactor (Figure 2) for the cultivation of algae. 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.

Figure 1

Figure 2

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. On top of that, 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 modular 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 efficiency of the trigenerator or the algae itself.

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

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. Coupling these

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

- $2000 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
- At least one additional photobioreactor chamber is needed to accommodate another project

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

Product Specification

Trigeneration System

The trigeneration system is a product from a previous senior design team, and has been modified by a subsequent team to utilize liquid propane as a fuel source. This system produces electricity, hot water and a refrigerated space. It is comprised of a 16-HP Kawasaki engine coupled with an electrical generator, an absorption refrigerator, and a helical heat exchanger. Waste heat present in the exhaust gases powers the refrigeration and heats water circulated through the heat exchanger and an insulated storage tank. At present, the trigeneraton system is in disrepair. The exhaust piping is badly corroded and much of it is missing, along with sections leading water to and from the heat exchanger. The original hot water pump has been removed but is operational, excluding a missing gasket that waterproofs the inside. Most of the pipe insulation has been damaged or removed. This system needs to be brought back to operational condition before our gas coupler can be mounted to it. We will take this opportunity to suit the exhaust piping to our needs.

Coupling System

At the heart of this project lies the coupling system. A system must be designed to extract the waste gasses, allow them to reach an appropriate temperature, and feed them to the

photobioreactor.

This is no simple task; combustion byproducts can be extremely corrosive at the temperature at which they are exiting the trigeneration unit and may be at too elevated a temperature.

Furthermore, if the pressure head of the exhaust gas increases too much as a result of the coupling system, the combustion engine will not function properly. This effect is a particularly important consideration with this project, as the exhaust gas is already routed through several pipes in the trigeneration unit. Lastly, the byproducts that are contained in the exhaust gas may be very harmful to the algae, as they are to most animals. However, some research exists that suggests that direct application of waste combustion gasses is permissible; algae may even thrive in these conditions.

The waste gasses will exit the trigeneration system at an elevated temperature. Excess heat energy could be harvested to aid in the regulation of the photobioreactors' temperatures. In any case, it is very likely that the exhaust gasses will need to be cooled before entering the bioreactors to prevent a destructive temperature increase.

Photobioreactor & Algae Growth

The existing photobioreactor unit consists of three individual growth chambers. Each chamber is individually circulated by independent water pumps and supplied with CO2 from pressurized tanks. The pH and temperature of the water medium are monitored digitally. The system must be outfitted so it may make use of the waste gasses. This may mean only modifying the gas inlets and tubing, or, depending on design complications, may result in an overhaul of the entire system.

Costs

Costs to repair the trigeneration system and construct a new bioreactor array must be weighed against the budget needs of the gas coupler itself. Reusing as much equipment as possible from the existing systems will help reduce these costs. This decision will be easier to make once monitoring and measurement equipment has been tested and a full parts list for repairs has been established.

Life Cycle Analysis

The planning stages of this project will be carried out simultaneously at two universities: Florida State University (FSU) in Tallahassee, Florida, and Federal University of Paraná (UFPR) in Curitiba, Paraná in Brazil. The team in Brazil has been assigned the task of completing a complete Life Cycle Analysis (LCA) of the much larger photobioreactor system located at UFPR. This research is used to determine the total ecological impact of creating a bioreactor system. The information and skills obtained by the team will be used to assess the viability of implementing the prototype system as a means of reducing engine emissions; if the system developed has too large a carbon footprint, it will obviously not be useful in this regard. Life Cycle analysis is going to be carried out on the prototype at FSU next semester.

Existing Technology

Attempts to reduce carbon emissions and improve system efficiency by virtue of algae photosynthesis has been attempted in select applications. The Massachusetts Institute of Technology recently implemented a rooftop algae bioreactor system that made use of industrial flue gasses. The system was a great success and was capable of both significantly reducing emissions and producing a large quantity of algae. However, the system has yet to become commercially viable.

Many bioreactor systems utilize compressed carbon dioxide to accelerate the growth process. There currently several companies attempting to make algae production in bioreactors a commercial viable means of generating biofuels. None have had great commercial success, but all are still in their infancy. Making use of combustion gasses, however, is a very new and exciting means to both reduce emissions and produce useful fuels and products. No modular product yet exists that extracts exhaust gasses from a combustion source for direct application in a bioreactor system.

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, Figure 4). Three direct and two indirect concepts were generated.

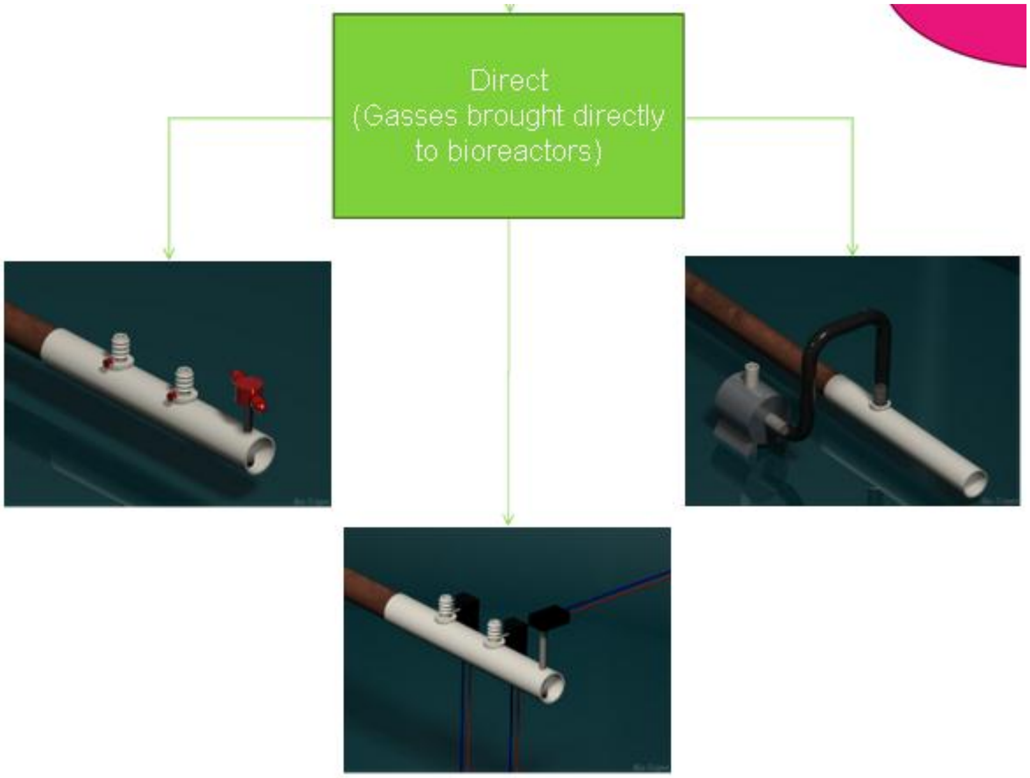


Figure 3

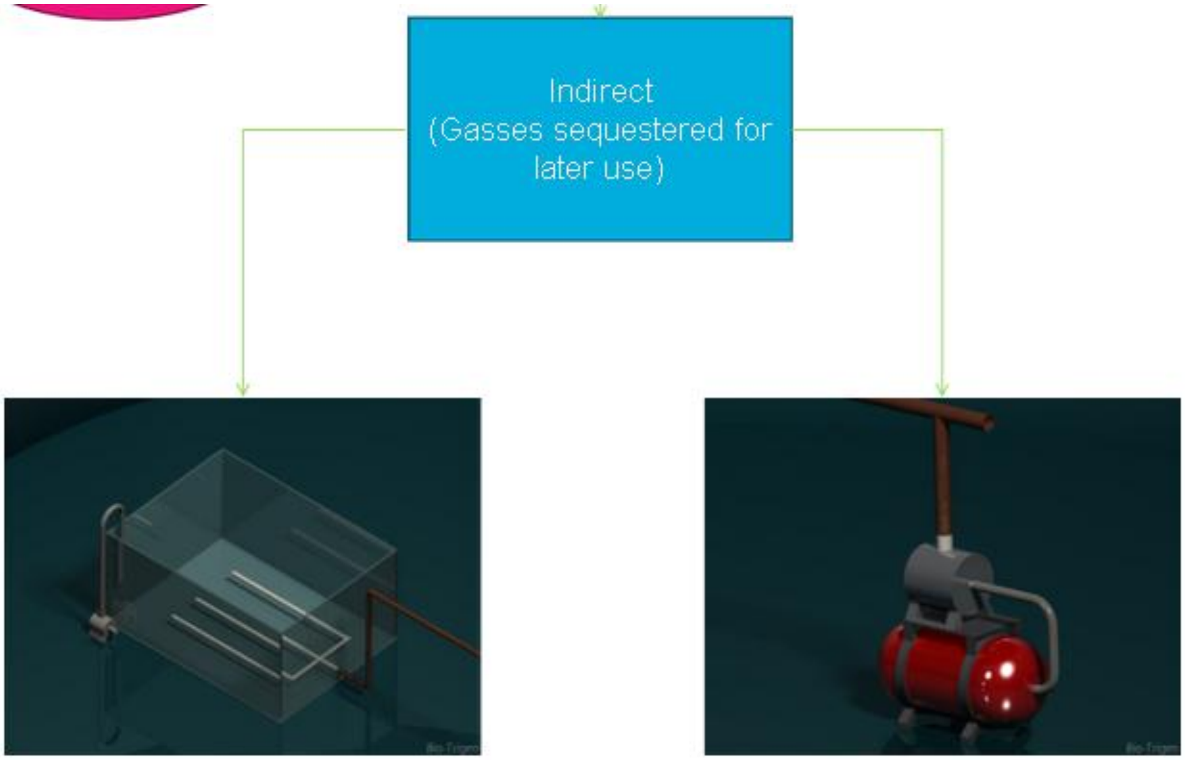


Figure 4

Concept 1: Direct Manual Pressure Vessel

Our first concept is a manually operated pressure vessel (Figure 5). 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.

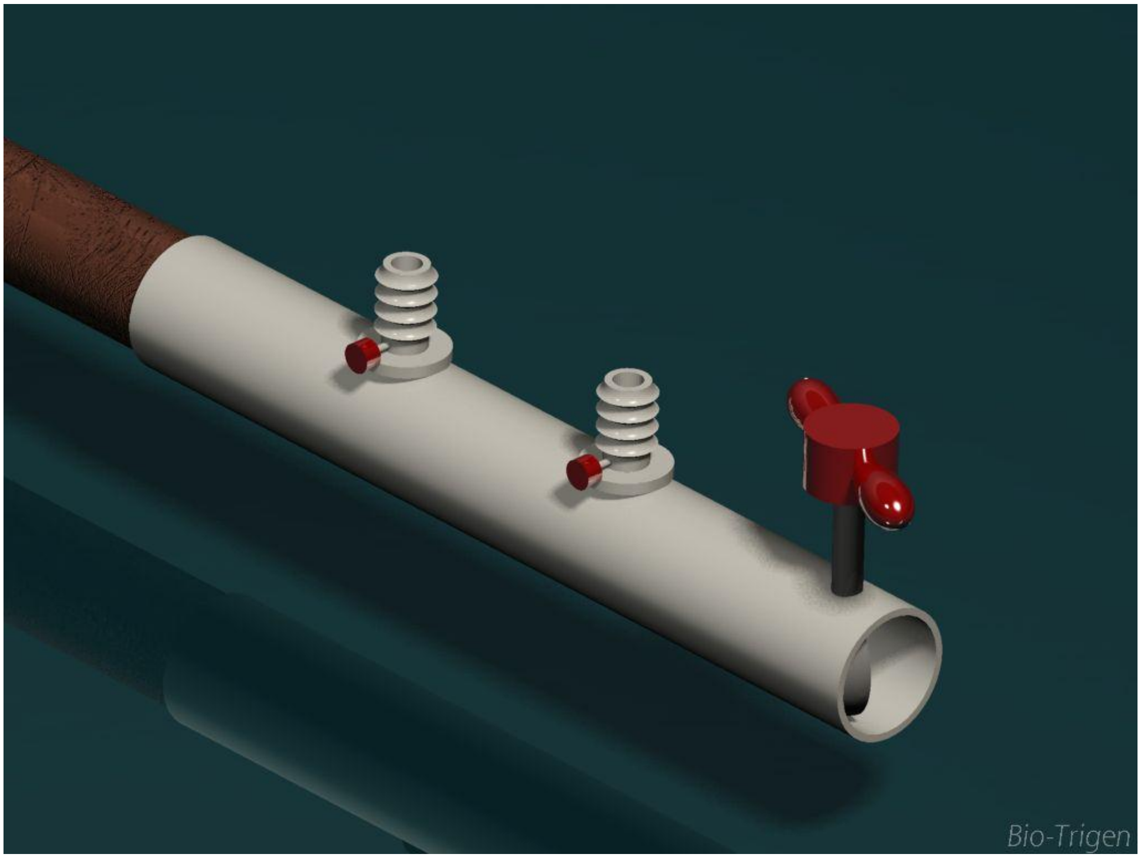


Figure 5

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 6). 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.

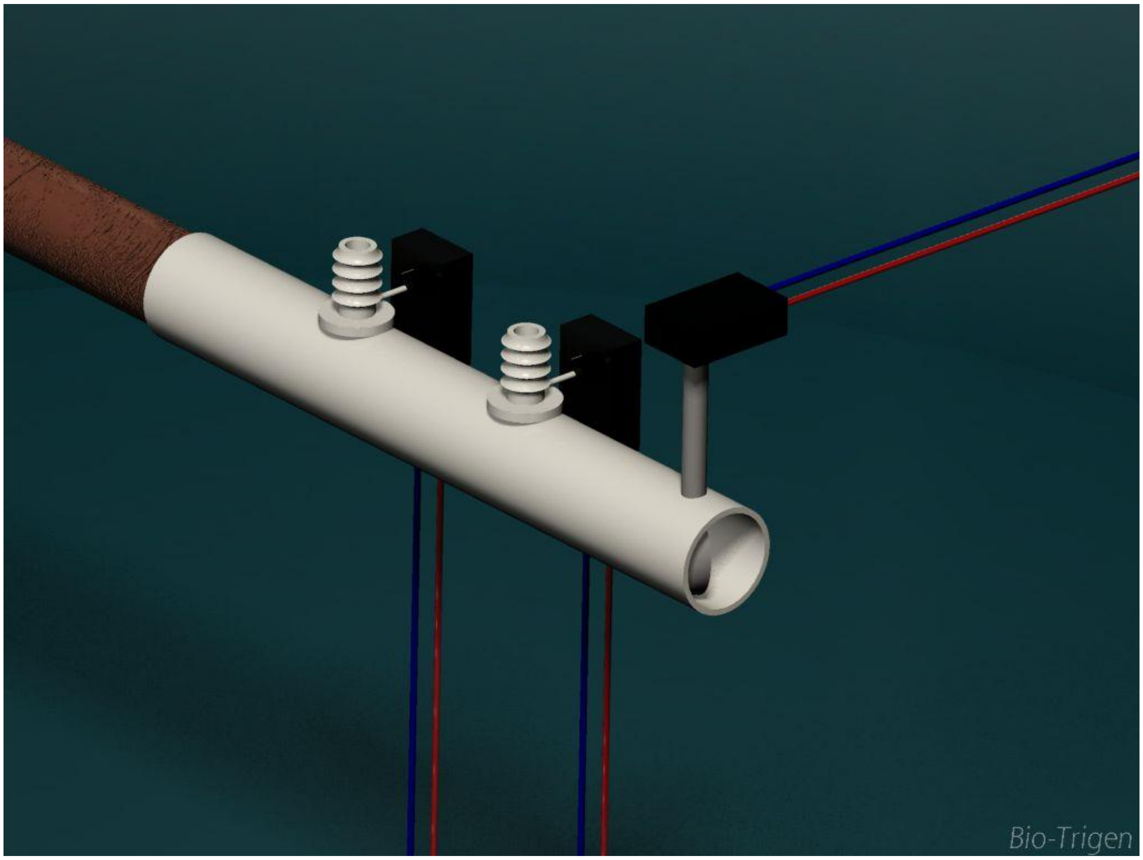


Figure 6

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 7

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 8

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.

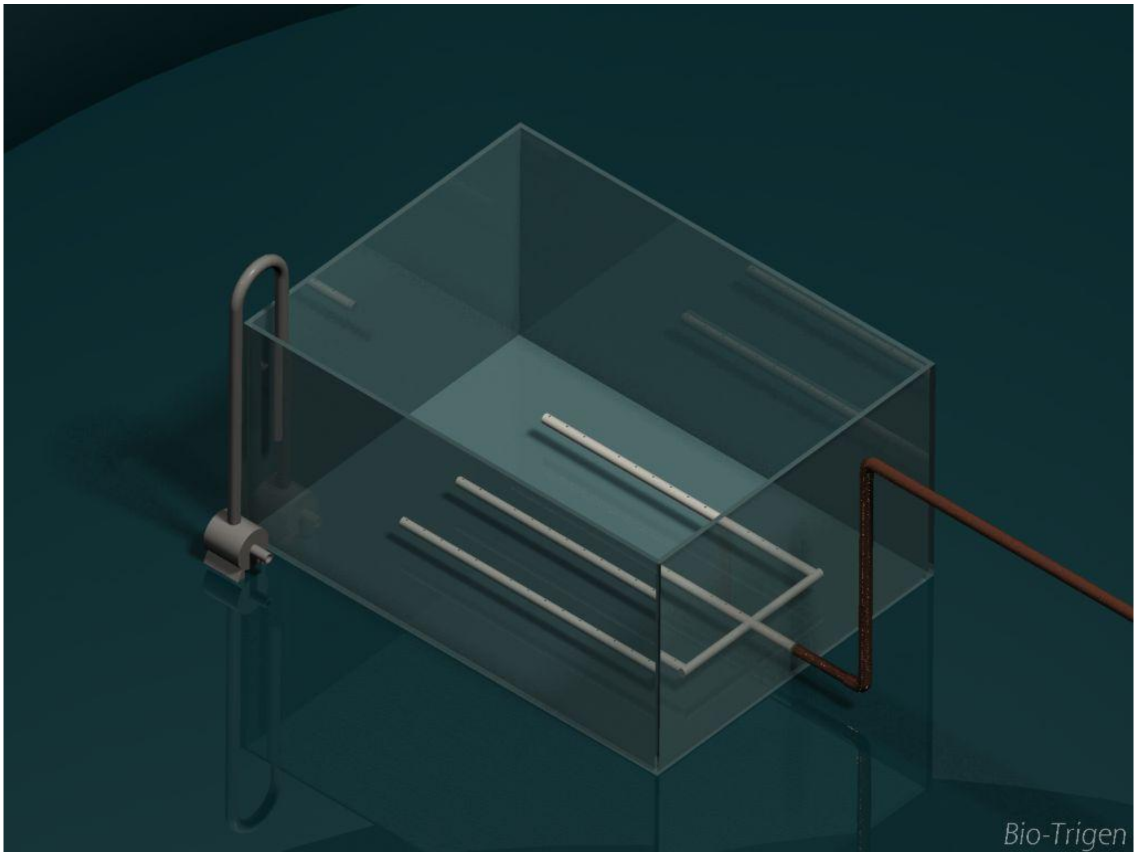


Figure 9

Interim Design Review and Selection

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.

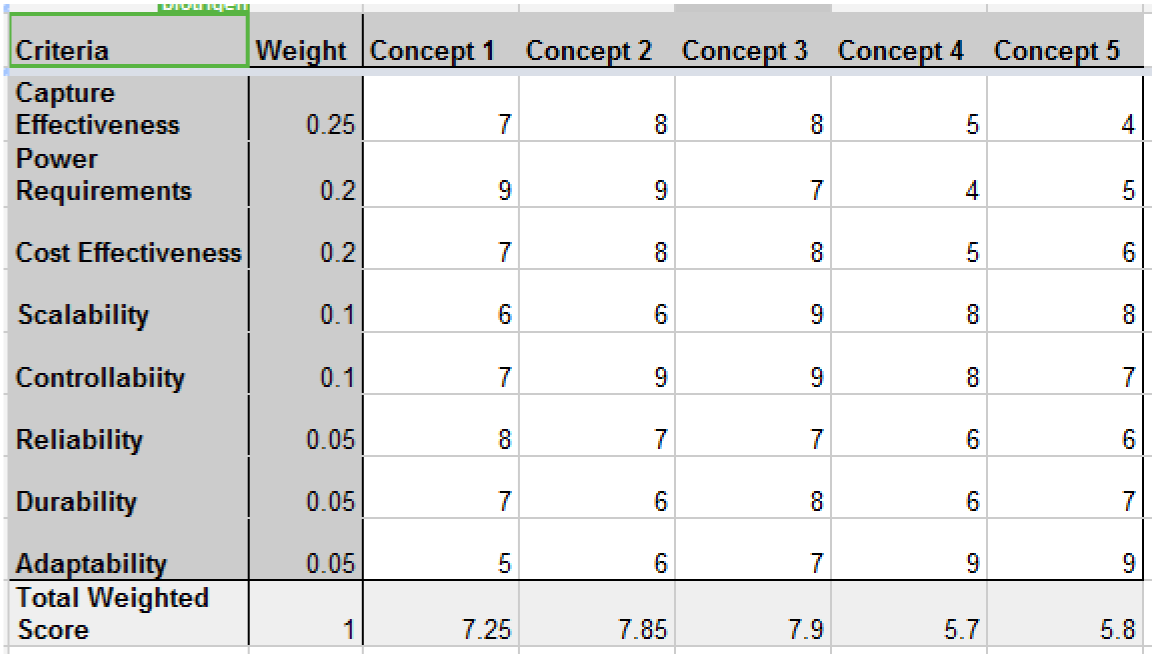
Controllability - Precision control of nutrient administration is ideal.

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 10. 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 10

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 11

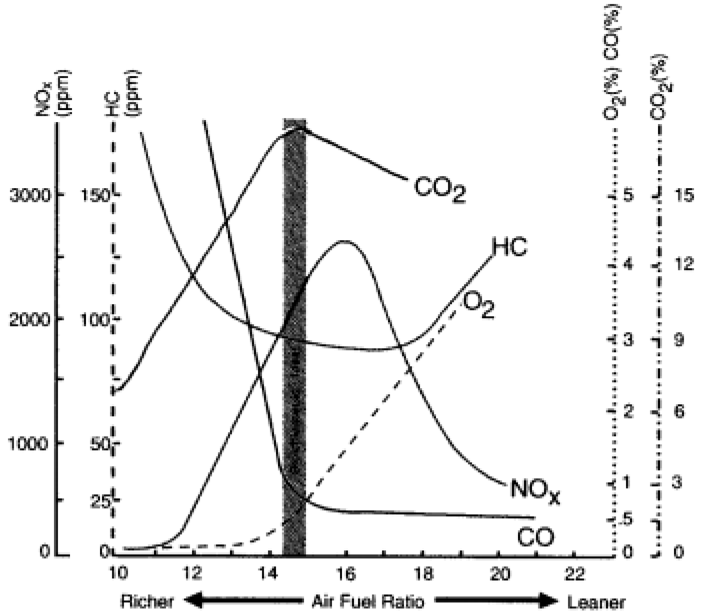


Figure 12

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 11.

Two algae species were selected for growth in our bioreactors, *Scenedesmus dimorphus* and *Chlorella sp. 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 12.

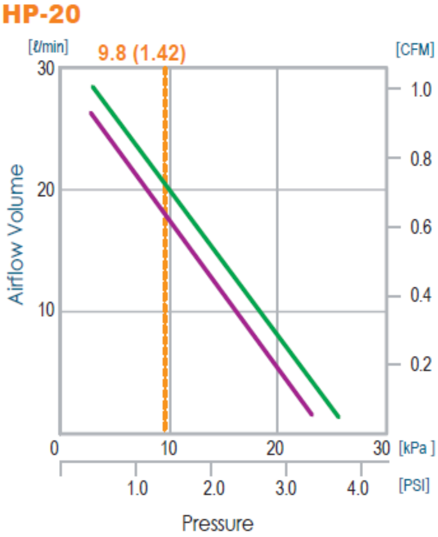
Final Design Components

Filter Medium

A particulate filter will be fabricated with fiberglass 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 should be easy to replace.

Figure 13

Figure 14



Air Pump

The amount of CO_2 that can be captured will be limited by the small size and amount of the bioreactors. The photobioreactor array will consist of two 2.5 L Aqua-Medic tubular photobioreactors. A previous experiment found an ideal CO_2 delivery rate of 13.61 μg/s. A HiBlow hp-20 will deliver more than enough flow for the two 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 14.

pH Controller

The pH controller will monitor CO_2 levels in the bioreactors. pH is an indicator of CO_2 content. When the pH level reaches a selected value, this controller will send a signal to the air pump and solenoid valve at the distribution manifold. A pH controller was used in the design of a previous photobioreactor array at FSU and the team plans on re-using this device. The pH controller is shown in

Figure 15

figure 15.

Distribution Manifold

The distribution manifold will be downstream of the air pump. This unit will be a PVC vessel with hose barb fittings directed to the photo bioreactors. This unit will also be outfitted with solenoid valves to accurately dose gases.

Photobioreactors

Our photobioreactor array consists of two Aqua-Medic tubular bioreactors. Each reactor has a 2.5 L capacity. Gas diffusers come included with the bioreactors and we also plan on re-using some tubing and fixtures from the previous bioreactor array.

Repairs to Trigenerator System

Since the trigeneration system was in disrepair, some repairs and modifications have been made. The previous exhaust lines were made of copper tubing with soldered fittings and low temperature valves. The valves and piping were so damaged by heat that it was necessary to replace them entirely (figure 16). We first attempted a similar copper exhaust line but soon found that the soldered joints would not hold up to the high exhaust temperatures (figure 17). The line was then replaced with welded steel (figure 18). The conduction circuit and refrigerator were removed for simplicity, and we are planning to replace them at a later date. This will allow us to perform tests on the exhaust stream and heat exchanger for the immediate future.

Figure 16

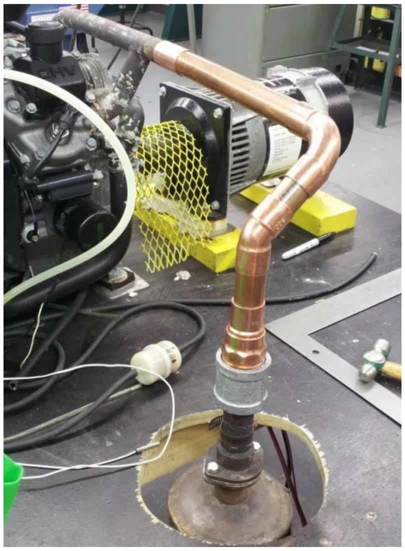
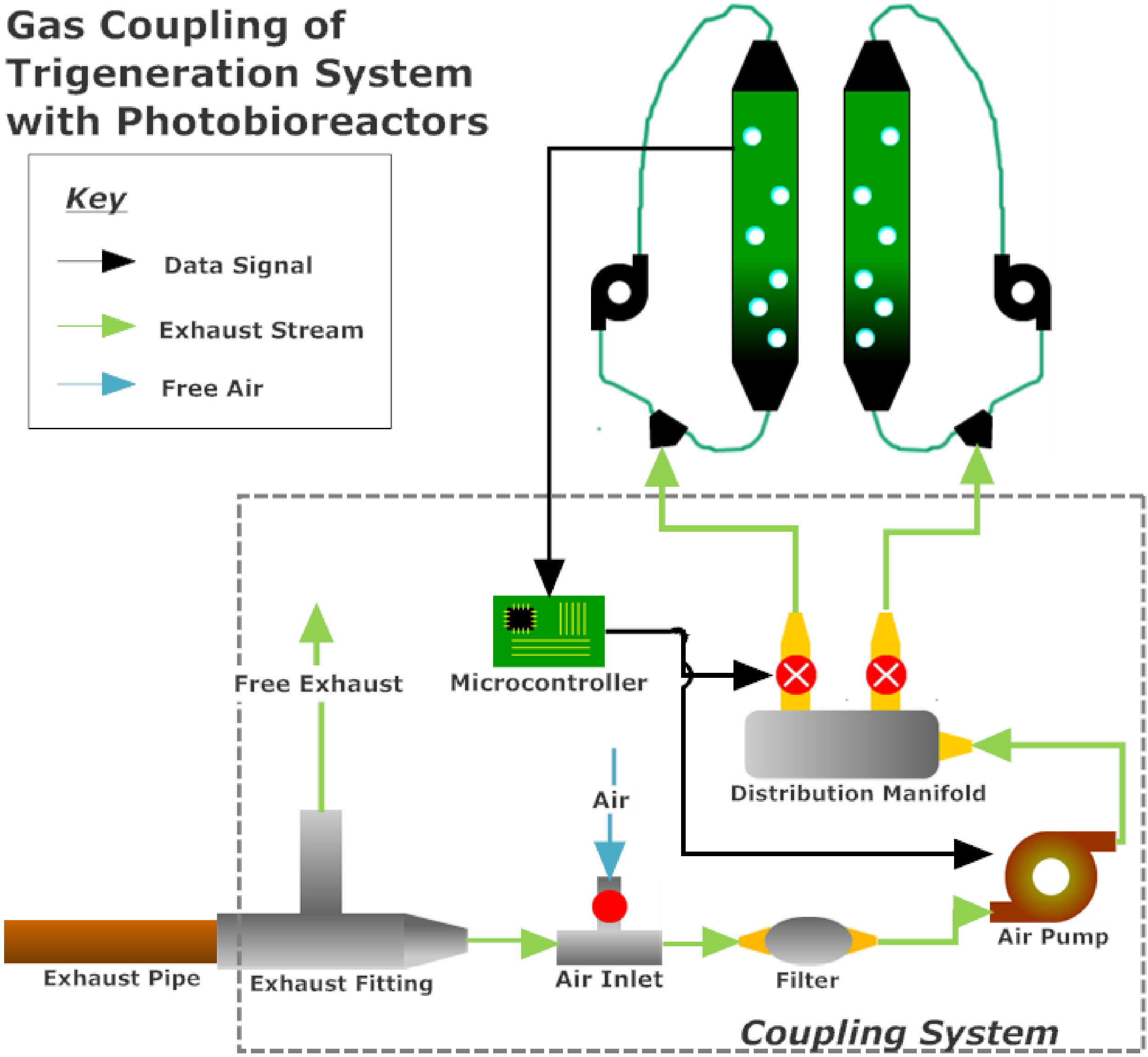


Figure 17

Figure 18

System Schematic



Environment and Safety

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 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

Updated Project Schedule

Calculations

Engine: Kawasaki FD501D

Power, Engine Speed, Displacement

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

$V_E := 26.7in^3$

Fuel consumption

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

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

Air Consumption

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

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

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

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

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

$mdot_{reqcd} := 13.61\frac{\mu g}{s}$ 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

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

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

$\eta_{eng} := .2$

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

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

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

$3bar = 300\cdot kPa$ $\quad$ $3bar = 43.511psi$

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.

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

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

$$d_{tube} := 0.5 in = 1.27 \cdot cm$$

An estimate of tube inner diameter (hydrolic 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

$$\varepsilon_{tube} := 0.0025 mm$$

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

$$f := 0.01$$

Darcy friction factor found on Moody chart. This is only a rough estimate and assumes turbulent flow!

$$L_{tube} := 3m$$

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

$$g = 9.807 \frac{m}{s^2}$$

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 esitmate 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 it's 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.

II. Life Cycle Analysis on UFPR bioreactor

1. Introduction

The increased global demand of fuel from renewable sources, motivated by tax exemptions for biofuels leveraged many initiatives in private and federal sectors, aiming the production of biofuels, particularly in Brazil, USA and Europe (Frondel and Peters, 2007; Eriksen, 2008). For example, the European production of biodiesel increased from about 1.9 billion liters in 2004 to around 4.9 billion litters in 2006, while the estimated annual production in Brazil is about 176 millions liters, which is pioneering in the use of 2% biodiesel in diesel fuel in 2009 and then 5% in 2012-2013 [see: http://www.biodiesel.gov.br]. It is interesting to highlight other advantages that result from it, such as increased jobs and useful co-products obtained during the process of this new fuel such as about 110 kg of glycerine for each ton of biodiesel (Behr et al., 2008). These initiatives require new developments in biofuel technology.

As environmental awareness increases, industries and business in general came to see how their activities affect the environment. Society had become concerned with problems of natural resources depletion and environmental degradation. Many enterprises have responded to this by providing “greener” products and using “greener” processes. Many companies have concluded that it is advantageous to explore ways to go beyond the prevention established by law using strategies of pollution prevention and environmental management systems to improve their environmental performance. This concept considers the full life cycle of a product (Curran, 1996). Among many possibilities to solve the problem of the fossil fuels dependence, microalgae has been considered promising because of its high growth rate, more photosynthetically efficient than oilseeds cultivation. In addition, tolerate high salts concentrations, allowing the use of any types of water for aquaculture and the potential production in innovate compact photobioreactors that allow better use crop area, because admit vertical growth of the culture. Table 1 lists some renewable sources to produce biodiesel, including microalgae to meet 50% of all transport fuel needs in the United States of America. Even the palm which is the largest crop culture, still required about 3 (three) times more area than a microalgae culture containing 20% oil in its dry biomass, assuming the use of cultivation pounds, which can be greatly improved with the use of vertical compact photobioreactors.

Is important to note that are few studies in the literature related to the live cycle analysis of processes using algae as a source of biomass for power generation. Among the papers found, stands out as important and informative a study of Clarens et al. (2010), which determined the impacts associated with the production of algae using a stochastic life cycle model and compared with other terrestrial crops (canola, corn and "switchgrass") and the results indicated that the crop land has lower environmental impacts than algae in energy use, emission of global warming gases, regardless of the growing site. Only in total occupation area and eutrophic potential, was algae higher according to the authors. These results bring controversy and, therefore, show the major obstacles to be overcome in the use of microalgae as a source of energy, especially on an industrial scale, as proposed in the unit of microalgae biomass production under development at the Federal University of Paraná, and also the countries that are seeking this technology. That paper analyzed only the process from growing ponds and, for terrestrial cultures, for the fields until the generation of biomass, i.e., without considering many co-generation possibilities as what is in the plant at the Center of Research and Development of Self-Sustainable Energy, NPDEAS from UFPR shown in Figure 1.

Although it is an alternative to conventional crops, cultivation of microalgae presents many challenges that must be considered with regard to sustainability, since demand a high volume of water and large amounts of chemical reagents, either in microalgae nutrition or in the processing of biomass. In an attempt to solve these problems, research is needed to test the efficiency of water reuse and residual biomass of the cultivation itself, making the process in a broader perspective, reach a sustainability status on specific parameters and testable as its efficiency. By the arguments presented and with the presence of multi-generators and environmental remediation coupled to the microalgae cultivation, the objective is to contribute through life cycle analysis to demonstrate that microalgae cultures may have better performance than terrestrial crops in all points of view and focus on making microalgae biodiesel commercially competitive with fossil diesel fuel. The results of this work will therefore be important for advancing the development of economically and ecologically sustainable technologies for industrial scale production of biodiesel from microalgae (and other products with high added value) and power generation in the near future.

Table 1 - Oil production of some sources of biodiesel. (Chisti, 2007)

Source	Oil Production (L ha^{-1})	Required Cultivation Area (M ha)*
Corn	172	1,540
Soy	446	594
Canola	1,190	223
Jatropha	1,892	140
Coconut	2,689	99
Palm	5,950	45
Microalgae [a]	70,405	7.6
Microalgae [b]	35,202	15.2

* To meet 50% of all transport fuel needs in the United States of America. [a] 40% oil in dry biomass; [b] 20 % of oil in dry biomass.

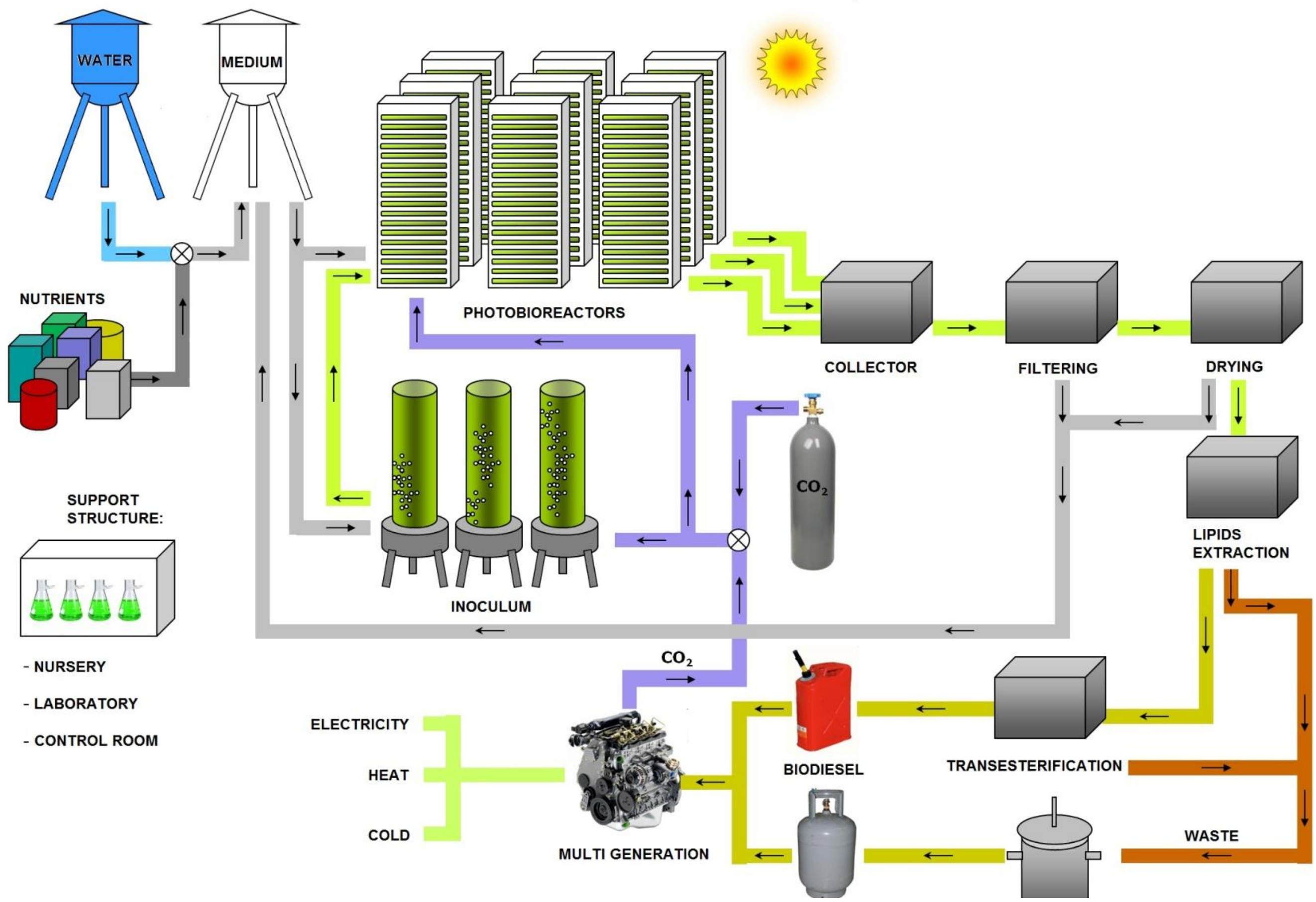


Figure 1 - Schematic diagram of the self-sustainable power generation plant under construction at UFPR for NPDEAS.

2. Methods and Materials

2.1. Infrastructure description

UFPR provides an area of 1000 m^2 which NPDEAS is in partial operation (Fig. 2). Construction is in progress and contains an area of 400 m^2 of concrete flooring (Fig. 2A) where 2 photobioreactors are built and a 300 m^2 of warehouse space containing: quality control laboratory, unit operation laboratory, support laboratory, reception, board/presentation room, high school/technical/undergraduate/graduate students and a computer laboratory (Figs. 2B and 3). 7 (seven) more photobioreactors are being built to produce microalgae biomass sufficient to result in about 200 liters of biodiesel per day, with the scope of generate 50 kW (total power demand for the complex) continuously and sustainably. A powerhouse for a tri-generation system (heat, electricity and cold), an automatic transfer framework and control (Fig. 2C) were also built on the concrete floor. So far, two of the indrustrial scale compact photobioreactors (5 m x 2 m x 8 m) are built, as shown in Fig. 2D and 4. On the concrete floor those photobioreactors receive sunlight directly for microalgae growth. The microalgae is collected and processed in the unit operations laboratory (filtration, drying and oil extraction) in sequential process as shown in Fig. 1.

The strategy for conducting all these activities was essentially multidisciplinary was to divide NPEDEAS in Research Units focused on their specific tasks. Each unit is led by an expert researcher on the project team. The defined units are:

Figure 2 - Aerial view of the infrastructure built at UFPR for NPDEAS (Google Earth, Dec 2008).

a) Cultivation and biotechnology unit

This unit aims to conduct research on the choice of algae, growing conditions, as well as all activities related to the biological part of the project. For it has a supporting laboratory. The unit also provides data for mathematical modeling of microalgae aquaculture.

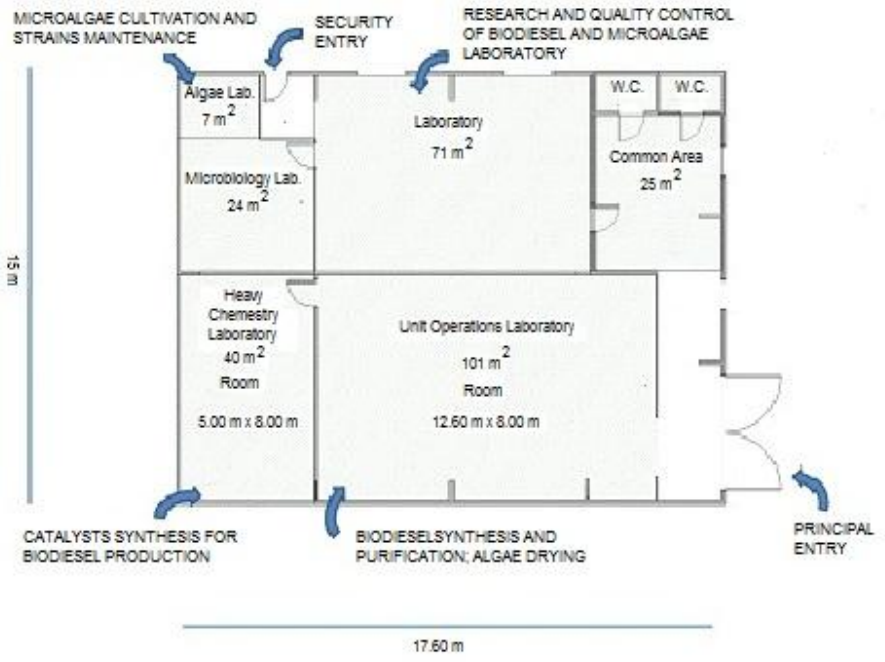


Figure 3 - Infrastructure available at UFPR for NPDEAS – Floor plan of the warehouse and its divisions.

Figure 4 - Appearance of the first industrial scale photobioreactor of NPDEAS at UFPR (5 m x 2 m x 8 m).

b) Biodiesel production unit

This unit carries out research for biodiesel production in classic mode with the use of innovative techniques planned in NPDEAS project. Another product is the provision of glycerol (a byproduct of transesterification reaction) as a nutrient for the mixotrophic microalgae cultivation.

c) Photobioreactors, filtration, algae separation and tri-generation unit

This unit is intended to perform the engineering design of all processes of NPDEAS, including equipment and infrastructure. The simulation team is part of this unit, performing mathematical modeling of all processes, procedures as well as thermodynamic optimization of project parameters and operation to maximize microalgae oil production. It also developed a mathematical model of life cycle, environmental impacts and plant processes remediation of NPDEAS from UFPR. Since this is a research unit, each photobioreactor presents peculiar features, in order to investigate different algae strains, growing in fresh or salt water, with or without auxiliary solar lighting systems, using fiber optics and other possibilities.

2.2 Life Cycle Analysis

The principles of life cycle analysis used in this body of work are recommended by the Environmental Protection Agency of the United States (EPA/600/R-06/060, 2006).

The life cycle analysis is a “cradle-to-grave” methodology 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. The analysis evaluates all of the stages of life of a product from the perspective that they are interdependent, i.e. one operation leads to the next. The analysis also allows for the estimation of the cumulative environmental impacts that result from all of the stages of the life cycle of the product, frequently including impacts that are not considered in more traditional analyses (e.g. extraction of the raw materials, transport of materials). By adding those aspects, a life cycle analysis provides a vision understandable 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 minimal content of a life cycle analysis should include three dimensions: extension, width and depth. The extension defines where to start and end the study, width defines how many and what subsystems to include and depth concerns the level of details in the analysis. These dimensions should be defined to be appropriate and sufficient to meet the goals established in the study (Lima, 2001).

For this study, the activities developed by Núcleo de Pesquisa e Desenvolvimento de Energia Auto-sustentável (NPDEAS) were taken as reference. NPDEAS possesses tubular compact photobioreactors for the cultivation of microalgae in order to produce biodiesel. More specifically, according to the diagram shown in Fig. 1, this analysis includes the upper part of the image, starting with the photobioreactor (including auxiliary systems- nutrients, inoculates, water supply, and air with CO_2) and ending in the drying process of the biomass, i.e. the final product of those stages is the microalgae biomass to be used for the extraction of oil (lipids) and possibly other products.

Therefore, all the information related to the physical infrastructure needed, nutrients used and other factors that are associated with the production of microalgae biomass were obtained from the researchers involved, with the finality of developing life cycle analysis of this process.

To obtain this data, at the NPDEAS location, during the 19th to 26th of October, and the 9th of November of 2011, technical visits and interviews were conducted with Dr.André Bellin Mariano, project manager of the programs of NPDEAS at UFPR, that provided the necessary information to develop the current study. Also, the two authors of this body of work were part of the NPDEAS research team at UFPR, daily.

3. Results

Figure 5 presents a general life cycle analysis of microalgae biomass production under development in NPDEAS

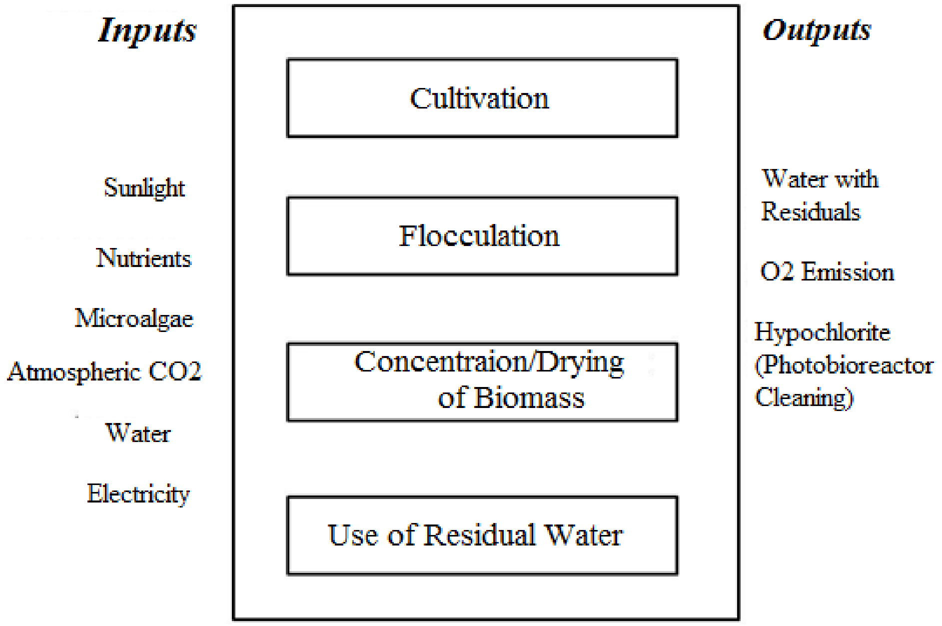


Figure 5 - Stages of Life Cycle Analysis of microalgae biomass production

In Figure 5, the factors that are involved in the production of microalgae biomass are evident. In the system inputs, special attention was paid to sunlight that is the primary source of energy for the growth of the microalgae, as well as the nutrients that are added to the water to compose the culture medium. To make the growth cultures feasible, CO_2 injection is utilized through the use of a compressor that captures atmospheric air and delivers it to the cultures, supplying a source of carbon necessary for the photosynthesis in the microalgae. The electricity is used for the operation of the compressor, as well as the hydraulic pumps responsible for the circulation of the photobioreactor.

This shows that in the cultivation and concentration process of the microalgae biomass, aspects such as the flocculation stood out. This is the process by which the microalgae is primarily concentrated through the alteration of pH in the medium, resulting in the addition of the cells and consequent precipitates, allowing for the increased thickness of the microalgae. Following that step is the concentration of the thickened microalgae that can be obtained from filtering or continuous centrifugation.

In spite of the cultivation of microalgae being promising, there are still certain difficulties of operation such as the necessity of large volumes of water. However an alternative to that elevated

Table 2 - Stages of Life Cycle Analysis of Microalgae Biomass Production

STAGES OF LIFE CYCLE ANALYSIS: MICROALGAE BIOMASS						
ENVIRONMENTAL ASPECTS		INFRASTRUCTURE	CULTIVATION	FLOCCULATION	FILTRATION	CLEANING
NATURAL RESOURCES		Steel, PVC, Plumbing, Hoses	Microalgae, Nutrients (reagents or effluent)	NaOH or $ClFe_3$	No	NaClO – sodium hypochlorite
ENERGY RESOURCES	ELECTRICAL ENERGY	Production of materials and construction of photobioreactors	Circulation and aeration	Homogenization	Filter press	Circulation
	COMBUSTIBLE	Material transport	No	No	No	No
WATER CONSUMPTION		Material production	Water for cultivation (reuse)	No	No	Cell resuspension
ATMOSPHERIC EMISSION		CO_2 related to the production and transportation of materials	O_2 and other gases resulting from the activity of the microalgae	No	No	No
EFFLUENT LIQUIDS		Production Materials	No	Clarified (water and reagents-reuse)	Remaining water	Water with dead cells
SOLID WASTE	MINERAL	Production Materials	No	No	No	No
	INDUSTRIAL	Production Materials	Packaging	Packaging	No	Packaging
	INERT	No	No	No	No	No

consumption is the reutilization of the degraded water and/or residuals for the cultivation of the microalgae, resulting in a reduced cost and in the possibility of environmental recuperation.

Within the products/outputs of the system, it is important to note the O_2 emission resulting from photosynthesis, in other words, the process itself acts to sequester carbon and attenuation of the greenhouse gas effect. Aside from the oxygen emission, the process results in a large volume of water utilized during the cultivation which contains considerable quantities of organic material as a result of the microalgae activity, such as nutrients that were not completely assimilated during the growth. An alternative to discarding this water is the reutilization subsequent cultivations, resulting in reduced costs and decreased impacts.

Another important point within the outputs of the system is the use of sodium hypochlorite in the cleaning of the tubing of the photobioreactors, resulting in a volume of water that is directly discarded in the drainage system that has a high oxidizing power that needs to be previously neutralized with the addition of sodium hyposulfite, so that it can then be safely discarded.

The process presents countless other variables; however, they are the most important points to be analyzed during the life cycle analysis of microalgae biomass production. Table 2 presents the stages of life cycle analysis of microalgae biomass production with the use of compact photobioreactors that exist at NPDEAS in UFPR.

The stage regarding the life cycle analysis of microalgae biomass production range from the fabrication process of the materials involved in the infrastructure which are the steel, PVC, pipes and hoses to the construction of the photobioreactor, and the cultivation, flocculation, filtration, and cleaning of the photobioreactor for the new cultivation.

INFRASTRUCTURE: The factors considered are the factors involved in the production of the steel used in the photobioreactor structure, the PVC pipes, plumbing and hosing for aeration, as well as the factors involved in the construction of the structure, in all, where the principal emissions are relative to the production process and transport of the materials in the form of combustibles used and gas emissions.

CULTIVATION: The resources utilized are the microalgae previously cultivated and the reagents for the composition of the cultivation medium, as well as the possibility of the reuse of the degraded water or effluents with dissolved organic material. The utilization of energy resources is represented by the use of electrical energy responsible for the circulation during cultivation and the operation of the compressor responsible for the aeration of the system. The process involves the utilization of water for cultivation that presents an alternative of reutilizing the degraded water. In this stage, the principal emission of the system is O_2 produced by the photosynthesis process, as well as the other gases that result from biological activities of the microalgae.

FLOCCULATION: The resources utilized are represented by the use of sodium hydroxide ($NaOH$) or ferric chloride ($ClFe_3$), that are responsible for the densification of the biomass suspended in a liquid medium; the process utilizes electrical energy for the homogenization and the flocculation tank. As in the other stages, the residual liquids generated could be reused in other stages of the process, provided that they are properly treated.

FILTRATION: The only resource utilized is related to the electrical energy related to the operation of the filter press that represents the last stage in the production of microalgae biomass.

CLEANING: The last stage that was considered is related to the cleaning of the photobioreactors, that implicates the use of sodium hypochlorite ($NaClO$) for the removal of the encrusted biomass in the PVC tubing. At the end of the cleaning process, it is necessary to utilize sodium hyposulfite for the neutralization of dissolved chlorine in the water. As with the other previous processes, the water could be reused, reducing the use of that resource. In all of the stages of production the discarding of the packaging of chemical products used during the process was done so that the packaging was properly conditioned and discarded in accordance to the type of material. It is possible to see in Table 2, the water constitutes as one of the principal resources utilized, such that in large parts of the stages there is a possibility of reutilizing from the system itself, as well as the use of degraded water, that allows for the process to be more sustainable and economically viable.

STOCHASTIC LIFE CYCLE ANALYSIS VIA COMPUTER SOFTWARE:

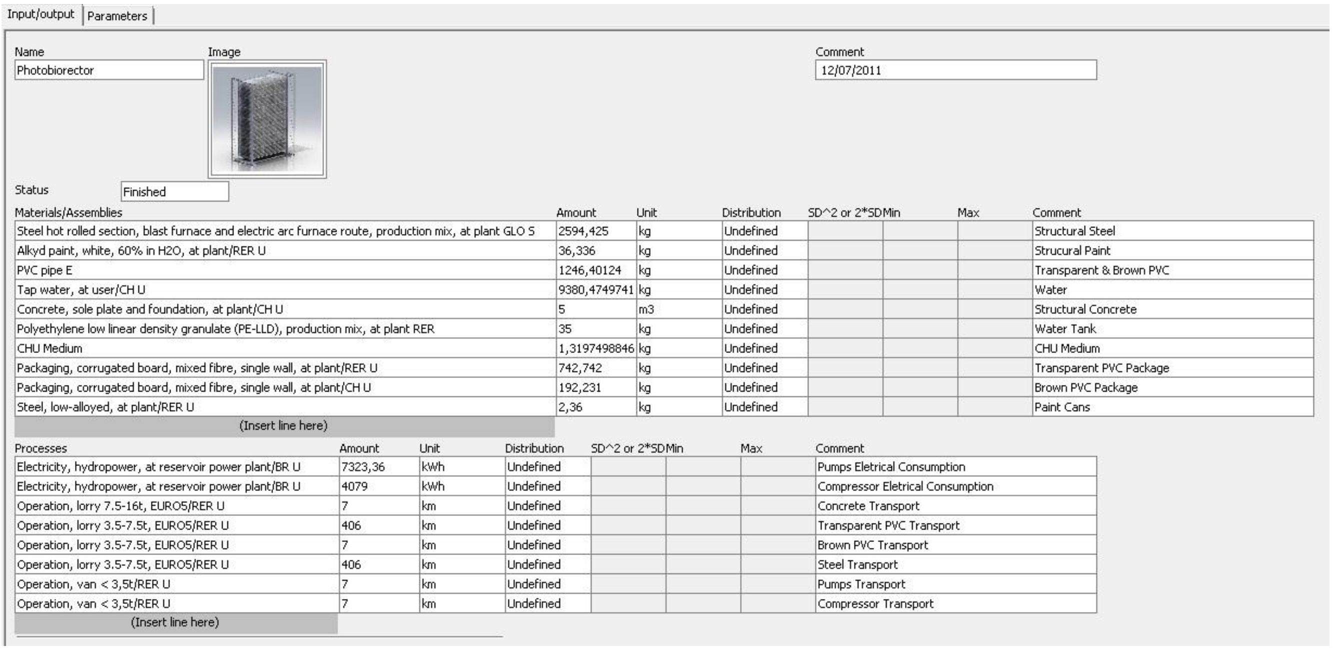
Currently there are several computer applications available for the scientific and industrial communities that utilize a stochastic model for life cycle analysis. One of these applications, available publicly on the internet is called SimaPro 7 (Goedkoop et al., 2010). The life cycle analysis model is 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 from of the NPDEAS photobioreactors at UFPR. These parameters are shown in Table 3.

Table 3 - Input data for simulations in the application SimaPro 7 (Goedkoop et al., 2010).

Materials	Volume (m^3)	Density (kg/m^3)	Weight (kg)	Energy (kWh)
Water	9.380474974	1000	9380.474974	N/A
Steel	0.3305	7850	2594.425	N/A
Paint	0.032	1198	38.336	N/A
Concrete	5	2400	12,000	N/A
Transparent PVC	0.7688366	1300	999.48758	N/A
Brown PVC	0.199154735	1300	258.9011552	N/A
Packaging (Brown PVC)	1.078	689	192.231	N/A
Packaging (Transparent PVC)	0.279	689	742.742	N/A
Paint Containers	X	X	2.36	N/A
Tank	X	X	35	N/A
Phosphorus	X	X	0.25	N/A
Magnesium	X	X	0.075	N/A
EDTA	X	X	0.05	N/A
Zinc	X	X	0.0000882	N/A
Pumps	X	X	X	7,323.36
Compressor	X	X	X	4,079

In the analysis, the following was considered: i) water in the entire system; ii) structural steel; iii) anti-corrosive paint of the structure; iv) concrete at the base of the structure; v) transparent PVC (tubing); vi) brown PVC (pipes and connections); vii) packaging for the brown PVC; viii) packing for the transparent PVC; ix) empty paint containers; x) plastic water tank; xi) phosphorus in CHU medium; xii) magnesium in CHU medium; xiii) EDTA in CHU medium; xiv) zinc in CHU medium; xv) energy consumption of the circulation pumps; xvi) energy consumption of the compressor.

Figure 6 shows an aspect of the interaction window with the user application, in which the input data and general parameters of the simulation were inserted.



Name: Photobiorector

Comment: 12/07/2011

Status: Finished

Materials/Assemblies	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Steel hot rolled section, blast furnace and electric arc furnace route, production mix, at plant GLO S	2594,425	kg	Undefined				Structural Steel
Alkyd paint, white, 60% in H2O, at plant/RER U	36,336	kg	Undefined				Strucural Paint
PVC pipe E	1246,40124	kg	Undefined				Transparent & Brown PVC
Tap water, at user/CH U	9380,4749741	kg	Undefined				Water
Concrete, sole plate and foundation, at plant/CH U	5	m3	Undefined				Structural Concrete
Polyethylene low linear density granulate (PE-LLD), production mix, at plant RER	35	kg	Undefined				Water Tank
CHU Medium	1,3197498846	kg	Undefined				CHU Medium
Packaging, corrugated board, mixed fibre, single wall, at plant/RER U	742,742	kg	Undefined				Transparent PVC Package
Packaging, corrugated board, mixed fibre, single wall, at plant/CH U	192,231	kg	Undefined				Brown PVC Package
Steel, low-alloyed, at plant/RER U	2,36	kg	Undefined				Paint Cans
(Insert line here)							

Processes	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Electricity, hydropower, at reservoir power plant/BR U	7323,36	kWh	Undefined				Pumps Eletrical Consumption
Electricity, hydropower, at reservoir power plant/BR U	4079	kWh	Undefined				Compressor Eletrical Consumption
Operation, lorry 7.5-16t, EURO5/RER U	7	km	Undefined				Concrete Transport
Operation, lorry 3.5-7.5t, EURO5/RER U	406	km	Undefined				Transparent PVC Transport
Operation, lorry 3.5-7.5t, EURO5/RER U	7	km	Undefined				Brown PVC Transport
Operation, lorry 3.5-7.5t, EURO5/RER U	406	km	Undefined				Steel Transport
Operation, van < 3,5t/RER U	7	km	Undefined				Pumps Transport
Operation, van < 3,5t/RER U	7	km	Undefined				Compressor Transport
(Insert line here)							

Figure 6 - Window user interaction with the application SimaPro 7 with photographic detail of the system photobioreactors NPDEAS UFPR in the analysis.

Figure 7 shows results that demonstrate the diverse impacts of the system, distributed amongst the sixteen components considered in the analysis through the BEES method (Goedkoop et al., 2010). The legend shows the color for each component, and on a scale from 0 to 100% the percentage impact of each component.

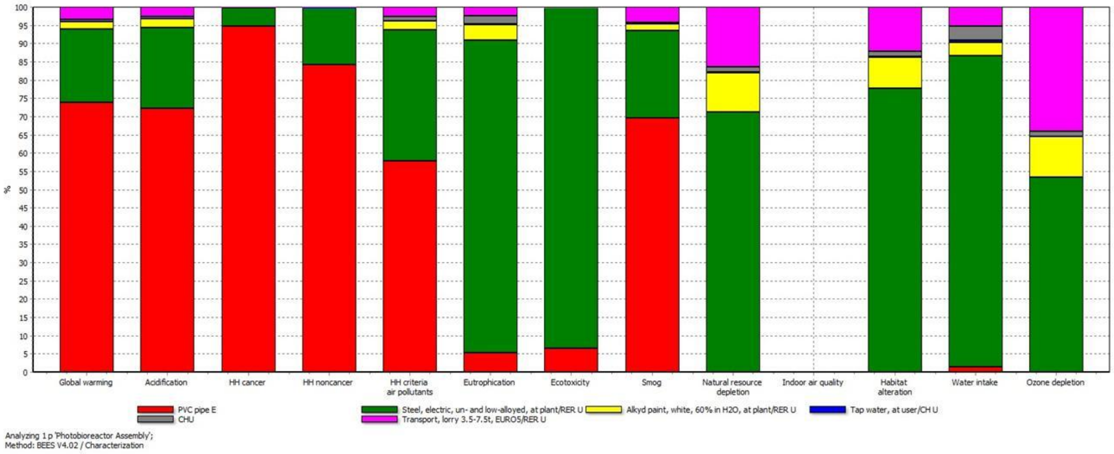


Figure 7 - Some impacts of the components considered in the analysis (method BEES).

Figure 8 shows results that demonstrate the diverse impacts of the system, distributed amongst the sixteen components considered in the analysis through the TRACI v3.03 method (Goedkoop et al., 2010). The legend shows the color for each component, and on a scale from 0 to 100% the percentage impact of each component.

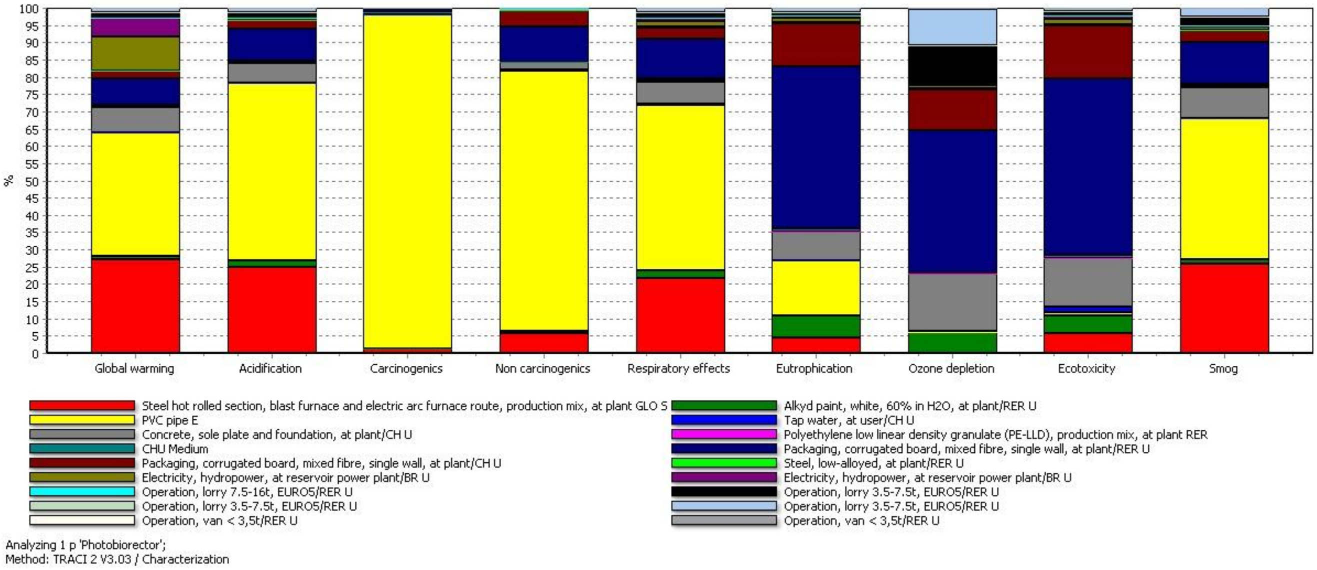


Figure 8 - Some impacts of the components considered in the analysis (using the TRACI v3.03)

Figure 9 shows results that demonstrate the diverse impacts of the system, distributed amongst the sixteen components considered in the analysis through the CML 2 Baseline 2000 / World 1995 method (Goedkoop et al., 2010). The legend shows the color for each component, and on a scale from 0 to 100% the percentage impact of each component.

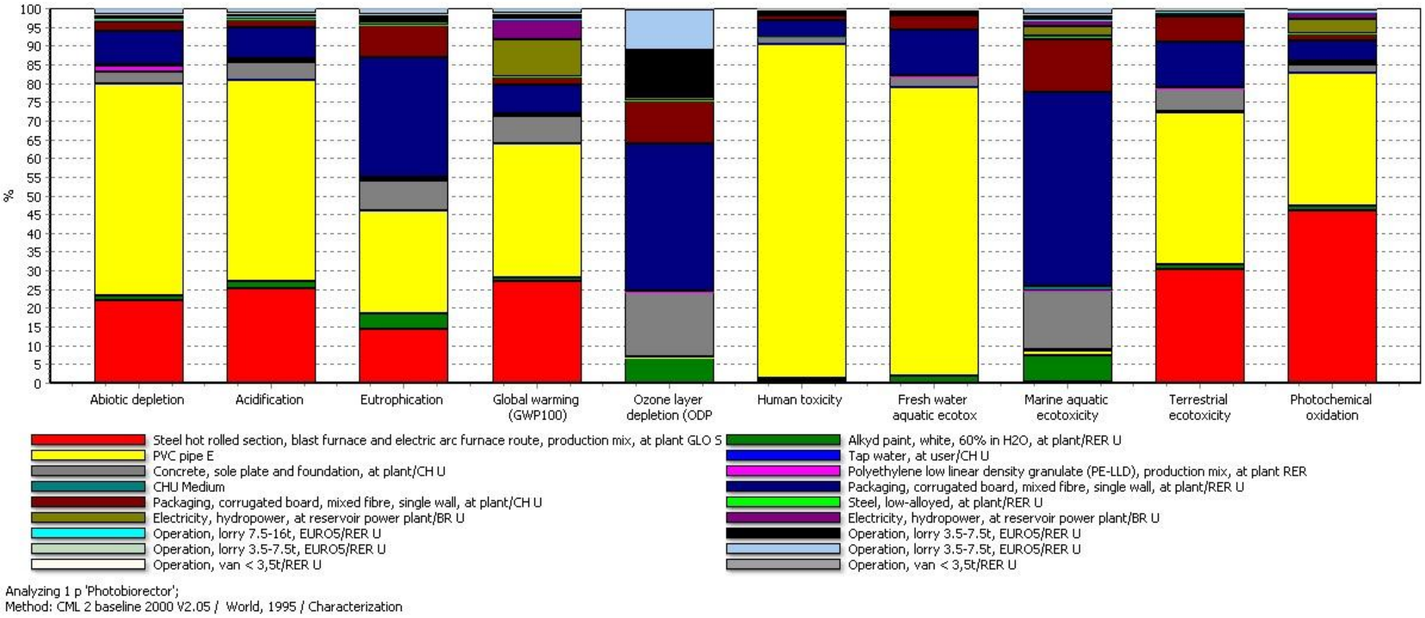


Figure 9 - Some impacts of the components considered in the analysis (method CML 2 Baseline 2000 / World 1995).

4. Discussion

Based on the life cycle stages of cultivation in compact photobioreactors shown in Table 2, the technical visits to NPDEAS at UFPR, the interview with the program manager, and the simulation results, it appears that there are still many unknowns about the degree of impact of the cultivation of microalgae for production of biofuels (e.g. biodiesel). In fact, Clarens et al. (2010) found that the so-called concept of culture in race ponds, i.e. motion caused by rotating blades, carries considerable energy to produce. Moreover, the mere contact of the atmosphere with the surface of the medium is not enough to provide CO2 necessary for photosynthesis which triggers production density (kg m^-3 day^-1) appropriate for biofuel production. For this reason, it is necessary to pump CO2 from fossil fuels in significant quantities by the use of control systems that maintain the levels of dissolved gas and near-neutral pH (~ 7.0) constant. Because of these negative aspects, the article points out that energy consumption in the cultivation of microalgae is about one order of magnitude larger than the cultivation of corn, canola and palm oil for the same purpose to produce the same final amount of bioenergy. Also, while canola, corn and palm oil have negative CO2 balance, i.e. fix CO2, microalgae have positive results due to the use of fossil CO2 in cultivation. However, even in culture ponds, the impact of the use of arable area is at least three times more favorable to the cultivation of microalgae. This article seeks to answer the question of which biomass produces a larger amount of bioenergy while simultaneously resulting in the least environmental impact. Considering the concept of race ponds for the cultivation of microalgae, this article can show that impacts of the life cycle of microalgae are sensitive to various inputs, such as the availability of renewable sources of nutrients and CO2, noting also that water and solar incidence do not contribute in the same way as you might expect. Thus, the main recommendations for improved performance of these systems are to install them next to industrial plants with abundant CO2 emissions (e.g. power plants, factories) as well as the use degraded water that already contains natural nutrients (nitrates and phosphates). Note that this adds a high degree of difficulty, because these sources are not usually close to cultivation sites, therefore, means of transport must be developed for this to occur.

The concept of the cultivation of microalgae in compact photobioreactors , with vertical growth, as shown by the description of the process in this article, as well as technical visits and an interview with the NPDEAS program manager at UFPR, is intended to address all the unfavorable points associated with growing microalgae using race ponds Clarens et al. (2010). The vertical growth greatly minimizes the impact on the use of agricultural areas. The use of photobioreactors minimizes the potential for contamination of the unwanted organisms, i.e. increasing production. Another positive aspect is that in race ponds the air is only in contact with the surface of a pond, but in tubes of small diameter (~ 50 mm), only the CO2 contained in the air that is injected through compression into the pipe in NPDEAS at UFPR has proven sufficient to maintain the same level of production as ponds that require injection of CO2 from fossil fuels. The question of nutrients is expected to be addressed with the use of degraded water for the medium, which can be available near the photobioreactors. Once the vertical growth is allowed to be installed in urban areas, the use of sewage for cultivation and other effluents can be contemplated. Finally, considering that the production of biodiesel results in a glycerol byproduct (about 10% of biodiesel produced), it can be used as a nutrient injected into the cultivation medium, causing the microalgae to have mixotrophic growth (auto and heterotrophic). At NPDEAS, it has already been shown that the biomass produced by the microalgae had an increased growth up to 80%, although this increase in biomass was reported to be up to 7 times as much Cerón Garcia et al. (2000).

The simulation results of life cycle analysis for the NPDEAS photobioreactors at UFPR presented in Figs. 7-9 show that there is an impact on CO2 emissions mainly from the production of PVC tubes used in the transparent tubes and connections as well as the steel used in the structure during its production. However, comparable effects are also expected due to the supporting infrastructure used in the production of biofuels from the cultivation of canola, corn or palm oil, for example, and not considered in the analysis of Clarens et al. (2010).

5. Final Thoughts

This work conducted a life cycle analysis of biomass production of microalgae in compact photobioreactors on an industrial scale for the primary purpose of acting as an energy source (biofuel / electricity) and new materials. Because of technical visits, the interview conducted, and the results obtained from simulation the following conclusions were made:

1. The use of compact photobioreactors for cultivation of microalgae has the potential to cause much less of an impact on the environment from a life cycle point of view than the concept of cultivation of microalgae in race ponds;
2. The entire process of cultivation of microalgae must find ways not to use CO2 from fossil fuels in order to use truly atmospheric CO2 fixation and to not contribute to the increased emissions of greenhouse gases;
3. Degraded water containing nutrients for microalgae cultivation should be used whenever possible of course, so as to reduce dependence on such reactive nitrogen originating from industrial processes such as artificial Haber-Bosch (Clarens et al., 2010);
4. The byproduct of the transesterification reaction of glycerol microalgae oil should be used as an added nutrient for the mixotrophic growth of microalgae in compact photobioreactors, and
5. As a suggestion for future work, the SimaPro 7 simulation must continue including the degassing and gasification tank present in the system, the rest of the transportation for all materials, the rest of the PVC connections, and power consumption not yet considered (compressor and recirculation pumps), to assess their impact on life cycle analysis of the compact photobioreactor system.

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