IPRO 347:

WASTE HEAT & CARBON DIOXIDE UTILIZATION
ROBBINS COMMUNITY POWER PLANT

FINAL REPORT

1. Executive Summary

The mission of IPRO 347 was to work with the leadership of the Robbins Community Power Plant to investigate the potential to recover and use as much waste heat and carbon dioxide from their power generating plant as possible. The facility is a 50 MW plant located in Robbins, Illinois at 134th and Kedzie Avenue. The plant was built in 1996 as a waste-to-energy plant, but became uneconomical to run in 2000, and was closed down. Sylvan Power Company purchased the plant and is retrofitting it to burn wood wastes, a cleaner fuel which should produce less pollution.

The IPRO team first identified locations within the plant where heat and carbon dioxide could be captured, quantified the temperature and volume of the waste stream, defined uses on side and nearby community areas, and then designed the system in which the heat and carbon dioxide would be relocated using five different streams towards a more efficient waste-to-energy plant.

2. Purpose and Objectives

IPRO 347 brings together students of diverse majors to create a solution derived from principles of various fields of engineering. We were able to suggest ideas for utilizing the plant's waste heat and increase the plant's efficiency. Since Robbins community is one of the more impoverished villages in the state of Illinois, we were able to provide benefits to the community including economic development, greater revenue for schools, reduction in regional air pollution, job creation, creation of a scholarship program, and replacement of fossil fuels.

As a team, our objectives were:

- Quantify heat to be captured with counter flow heat exchanger
- Determine the requirements and market for bio-char
- Measure the feasibility of using the heat and/or exhaust for greenhouses
- Choose a pellet mill able to increase efficiency of RCP
- Cost-benefit analysis of heat exchanger, pellet mill, and bio-char furnace
- Pursue means to secure enough green wood to continuously supply the power plant each year

3. Organization and Approach

In order to approach the overall problem, the singular team was divided into three sub-groups to work on individual tasks. The three subgroups included thermodynamics through heat exchanger, bio-char and pellets, and greenhouse and bio-oil through algae production. The thermodynamics subgroup worked most closely with Robbins Community Power to determine the availability of energy in the residual heat of the wood biomass boiler-turbine system. Using the recommendations of the thermodynamics group, the bio-char/pellet group and greenhouse/algae group were able to determine the feasibility of outlets for this energy.

The sub-teams were lead by team leaders whose responsibility was to steer the subgroup toward the given IPRO objectives and to assure that said goals will be accomplished within the semester timeline. Sub-team leaders were also responsible for encouraging and leading discussions within their research team. However, all team members took it upon themselves to share the role of research and collaboration so to make sure that everyone's interests where pursued and discovered.

We pursued several types of research methods based on the varying sub-teams; and at several points along the process, one team needed to provide their findings before the next team could continue forth.

The thermodynamic/heat exchanger team worked closely with Robbins Community Power to determine the correct temperature in which the heat would be emitted from the smoke stack. Using this information, this team relayed the correct data to the additional two teams so their research could progress forward. The thermodynamics team, using the correct temperature, could then calculate the size of a heat exchanger appropriate for RCP. Once the heat exchanger was determined, they then explored areas of the community which could benefit from the use of steam.

Using the temperature value from the thermodynamics team, the greenhouse/algae sub-team researched several techniques to utilize a portion of the waste heat. The team focused their research on types of greenhouses, ways to transport the heat, and most important the type of crops that would benefit from a high concentration of carbon dioxide. This team also researched ways to producing algae, turning it into biodiesel, and then feasibility in terms of cost.

The bio-char/pellet team took on the initiative to research several types of techniques for utilizing waste wood, and then taking any additional waste heat from the previous processes as a source of energy for these machines. This team researched the process of pryolysis, benefits to different techniques, and cost analysis for the final product. They also researched the idea of pelletizing wood and its cost benefits as a second option to creating bio-char.

4. Analysis and Findings

The focus of the thermodynamic team was to determine the type of heat exchanger that would significantly increase the efficacy of the power plant itself. If the combination of the proposed additions to RCP by this IPRO are thought of as a self-sustaining machine, then the heat exchanger is its implacable motor, incessantly facilitating heat transfer from the flue gas exiting the boiler to incoming water flow. From the water, steam can be generated that would power on-site machinery (e.g., a pellet mill) or dry wood in kilns. The newly cooled flue gas, now at a lower temperature of 200F rather than 430F, can also be pumped into greenhouses to augment plants' rates of growth or into a chamber to preheat wood for the ensuing fast or slow pryolysis for bio-char production.

The initial estimates of available energy in the various waste streams of the 50MW plant in Robbins during the summer revealed a substantial amount of energy available in the exiting flue gas that leaves the boiler and is vented into the atmosphere at the smokestack at 430F. The other two sources, the sand of the boiler and the fly ash--from the tiny particulates circulating the boiler itself--did not consistently offer enough heat to justify a system to capture the energy. The plant's overall estimated efficiency of 35% at best reveals that around 160MW of power exists in the flue gas, of which only 50MW is extracted for electricity production with an additional 5MW for the plant's parasitic loss. So, it would be quite easy to believe that 105MW of power is discarded into the atmosphere at 430F. The sentiment of the preceding statement follows naturally from hearing the facts about the conditions at RCP. Unfortunately, few share our realistic optimism that improvement is possible in this and many other power plants within the domain of the three laws of thermodynamics. What follows is not the sententious ramblings of idealists trying to forge unnecessarily new paths in power production. We have simply come across what we feel is a missed opportunity to recover and reduce otherwise discarded energy using basic thermodynamics and collected experimental studies of heat exchangers from experts in the field.

The amount of power actually available in the 105MW of the flue gas is found by first making certain assumptions. We assume that energy available to us exists in the form of a difference. We must take the flue gas from one state to the next in order to generate a heat or work output. Thus, taking the flue gas from 430F down to 200F would create two distinct states and a viable energy difference between them. Another assumption would be that the pressure at these two states is near as makes no difference to atmospheric pressure and is roughly constant. Finally, we assume that only expansion work or heat is being transferred to the system. These assumptions lead to the conclusion using the first law, that the change in potential energy and flow work from the first state to the second is equal to the heat transferred out of the system.

The heat value will be crucial to determining the characteristics of the heat exchanger because the number of tubes, flow rates, and tube diameters all play a role in the efficiency and cost of the apparatus. To determine the enthalpy, the proportions of the flue gas (by volume) were used to find the enthalpies of the gas constituents at the required temperatures. These individual enthalpies contribute proportionally to the total enthalpy value of the state. In this fashion, the enthalpies of the flue gas at 430F and 200F found. Their difference constitutes the value of heat flux possible within a heat exchanger between the two states.

Further methods were pursued in order to calculate the total area of heat exchange. (Appendix A). In brief, the process of calculation relied heavily upon the heat balance between the two fluids (flue gas and water) and observed relations from prior experiments. The total required area is around 13,500 square feet with a pressure drop of around 12 inches of water. This is greater than the current pressure drop near the stack of 4.5 inches of water, but can be remedied with a simple upgrade to the fan providing suction to the system. Using the conservation of energy relations derived by Euler for steady state conditions, the work required by the fan can be calculated (Appendix B). More importantly, the parameters of the heat exchanger designed by this group require water to exit at just under boiling temperature at atmospheric pressure. An addition of a heater just beyond the heat exchanger in the system would allow for high pressure steam to be produced according to the plant's needs.

The total revenue possible from this heat exchanger configuration with a heater can be roughly calculate using heuristics described in further detail in. The relationship of the cost of the heat exchanger to total area of heat transfer allows for a rough calculation of total expenses required of RCP. Estimating the price of steam to be around 0.3 cents per pound, around $1.1 million could be earned in the first year; the plan comes close to paying off the initial cost with the first year's revenue alone

It is in the interest of the IPRO 347 group to find methods to reduce carbon dioxide emissions in an economically feasible way. The amount of carbon dioxide is so copious in the flue gas that realistically it would be impossible to remove a large chunk of the carbon dioxide. But since the carbon dioxide emissions are not regulated in the area, there is not a mandatory amount of carbon dioxide that needs to be removed. Thus the hopes are to be able to bypass the 300ft smokestack on the RCP property and instead re-route the flue gas to structures in which the carbon and heat can be partially removed. Two proposed solutions are greenhouses and algae growth on the Cal-Sag 13.03 parcel of land which will be leased for approximately $200,000 annual minimum rental competitively bid (Location seen in Appendix C).

The main uses for the greenhouses on the RCP property would be to grow crops for market sales and to grow replacement trees. Crop selection is based on carbon sequestration abilities of individual strains of plants. Research shows that C3 plants are a better option for carbon absorption. Overall studies have shown that C3 in comparison to C4 and CAM plants absorb more CO_2 per plant mass (http://www.biologie.uni-hamburg.de/b-online/e24/24b.htm). Examples of C3 plants include wheat, rice, potatoes, cotton, barley and the list goes on. A study by Colorado University – Boulder found that on average C3 plants absorb 11.38 parts per million of carbon per minute per gram of plant mass. Taking this original research into consideration, multiple resources were used to determine amounts of carbon absorbed per year for each specific crop. (Appendix D) . As seen, five crops stand out as having exceptional carbon absorption per square meter of space used in the greenhouse. This allows us to choose the best crop per space use, instead of just best absorption in general. Tomatoes, peppers, romaine lettuce, broccoli, and cauliflower all absorb over 1300 g of CO_2 per year per square meter of greenhouse space. From the data, it is noticed that crops high in fruit weight percentage were studied. From this, it can be predicted that plants low in fruit would also be low in carbon absorption, being that additional weight is directly related to plant weight. It is also seen that of the fruits studied, they were much lower of carbon absorption values than the vegetables, due to the large amount of water that the crop consists of. Market viability in the Chicago area is also taken into consideration, meaning that obscure crop items would not be considered in the research.

As the green emerald ash beetle, with 100% mortality rate, works its way into Chicago, a large number of ash trees will need to be removed in future years. Tree farming is another option our IPRO group is looking as a viable solution to carbon sequestration for the flue gas in greenhouses as well as a replacement for the ash trees lost form the emerald beetle. Since the plant will be using trees to provide wood necessary for energy production in the RCP plant, it is imperative to us that there will be a constant supply of green wood to burn. The best way to make sure there will be wood for the plant in the future is to grow trees in the greenhouses on the property. Seeds will be planted and the trees will be allowed to grow until they are approximately five feet tall (two inch diameter). At this point in time they would leave the nursery and be planted in either public or private locations or replanted by the city in a location that a damaged or diseased tree was taken down. The main source of purchase and use for these trees, hopefully, will be from the governmental bodies. Since we will be looking to develop a relationship with the local municipalities including Chicago and surrounding suburbs and their tree removal sector for the use of this cut wood, we will also be looking toward having them use our trees for replanting. This option would allow a two way relationship with the tree removal district, allowing them to replant all the trees that they have to remove. This will shine the city in a better light and make them more respected as a sustainable group. Instead of them just being a city division that cuts down trees, they will be given the opportunity to replace certain trees to remain earth friendly.

Growing trees is not just a good solution for the possible replanting ability, but it is also a viable source for carbon sequestration. On average a 0-3 inch diameter breast height tree will sequester 2 lbs/yr. Once they increase to 9-12 in DBH they will be sequestering almost ten times as much carbon per year. Further information on carbon sequestration in trees can be seen in (Appendix E). While this may not seem significant, when there are trees in abundance, there is a much stronger impact on the carbon levels in the greenhouse. These numbers are also based on normal atmospheric conditions and 6-7 month growing period. When these trees are grown in a greenhouse, they will be exposed to an optimal carbon dioxide concentration, which enables them to absorb more carbon per year. Also greenhouses provide an environment where trees are suitable to grow 12 months out of the year. Since there is an additional 5-6 months of growing time, it can be assessed that growth of the trees in the first years of the tree's life could be increased by 75-90%.

It is the hopes of this IPRO group and of the greenhouse farmers that the heating of the greenhouses in the cold weather months is done completely by the excess heat in the flue gas coming from the power plant. The ideal greenhouse temperature for mild climate crops is between 65 and 80 degrees Fahrenheit. There are only 3-4 months out of the year where nighttime temperatures do not fall below 50 degrees (Appendix F), which is the border of the safe zone of temperatures for growing plants (http://www.rssweather.com/climate/Illinois/Chicago/temp.png). Inside of these 3-4 months, no heat will need to be added to the greenhouses during the day, for fear of overheating the crops. In the other 8-9 months of the year, flue gas will be used to heat the greenhouse. Since most of the heat that is passed through the greenhouse will be lost through the greenhouse boundary, these numbers can be used to determine approximately how much heat and energy will actually be needed to be coming from the flue gas per greenhouse.

The greenhouses would be leased by third party groups who would care for the crops. The third party greenhouse farmers would have to tend to the crops and would also sell them on the Chicagoland market without the assistance of RCP. This would mean RCP would not profit off the crop sales, but would only make money based on leasing and selling waste heat. By allowing a third party to come in and farm in the greenhouses for lease, RCP will be providing the community with job opportunities in a neighborhood in which jobs are hard to come by. Another benefit of building and utilizing the greenhouses on the RCP property is the sustainability aspect. Since the energy to heat the greenhouses are coming directly from the hot flue gas of the power plant, no natural gas is needed to heat the plants, reducing the carbon footprint of the greenhouse.

The other option for carbon dioxide sequestration is growing algae. Carbon dioxide is needed for algae to go through photosynthesis and create biomass. Instead of concentrating the carbon dioxide content in the air or purchasing concentrated carbon dioxide, flue gasses rich in carbon dioxide will be pumped into the vessel bubbling through to all the algae mass. According to one study (oakhavenpc.com) CO_2 concentration in the exhaust was significantly reduced by 82.3% (+/-12.5%) on sunny days and by 50.1% (+/- 6.5%) on cloudy days. This study was based on carbon dioxide making up 13% of the flue gases. Being that the RCP plant has a flue gas that is 12% carbon dioxide by volume, this is a realistic comparison. The NREL compared two favored strains of algae for biofuel production, chlorophyceae (green algae) and Bacillliarophy (diatom algae). Of these two, Bacilliarophy appears to be a better option for our circumstances. This is because under nutrient deficiency, the algae produce more oils per mass of algae than does the Chlorophyceae (castoroil.com). Another study by The Sierra Club (Kansas.sierraclub) found that for C. pyrenoidosa (a green algae) absorbs on average 3400 +/- 100 cc/hr of CO_2. Overall, algae will not be able to completely eliminate emissions by the power plant, but the hope is to reduce the emissions as much as possible.

Ponds are a viable source in which to grow algae. In these ponds, carbon dioxide enriched gas is pumped through the bottom and bubbled to the top. Since only about the 3-4 top inches in the algae pond can receive sunlight, it is necessary to mix the pond water, or else lower levels of algae will not gain any biomass. The bubbling of the gas provides some turbulence to the pond, agitating the water so to bring algae from the lower levels up to the surface. Bubbling gas will also be a constant agitation which will keep the algae from clumping together. Other sources of agitation in the ponds are paddle wheels or stirrers. One main design for commercial algae ponds is racetrack style. This set up is seen in Figure 1 of Appendix G. There is a motorized paddle that keeps the water flowing in a counterclockwise direction. Waste CO_2 from the power plant is also injected at some point along the path, while the entire pond surface has access to sunlight or artificial light viable for growing algae. Nutrients also have to be pumped into the pond, since algae cannot survive off CO_2 alone. Extra nutrients such as silicon or nitrogen are needed for survival. Once the algae mature, meaning they have a high enough biomass yield, it can be removed from the pond and taken to an extraction unit.

Bioreactors are also a mechanism to grow algae. They can be made out of a system of triangular clear pipes with 10-20cm diameters where carbon dioxide can be pumped in from the flue gas. The hypotenuse is set up to be facing the direction of the sun so the most surface area possible will be exposed to the light. Flue gas is to be pumped in from the base of the triangle to bubble up from the bottom and circulate the water to the top in a counterclockwise or clockwise direction. The use of the cylindrical tubes allows for less volume for reacting, due to the large surface area that is not available in the ponds. This method allows for 15-30% of the algae to be harvested each day. Figure 2 of Appendix G (http://www.oakhavenpc.org/cultivating_algae.htm) shows a set-up from GreenFuel, a licensed NASA project.

Not only is algae a great source for carbon sequestration because it uses so much of it for photosynthesis, but it also is a great source of energy. Algae absorb large amounts of carbon dioxide and convert it to biomass. A large amount of this biomass consists of bio-oils compared to most other crops (like corn) that mainly produce carbohydrates as biomass. From this bio-oil, it is possible to make 2000 gallons of biofuel per acre of algae per year in comparison to only 250 gallons per acre of corn per year (exxonmobile.com). By sequestering the carbon dioxide and reducing plant emissions, we are also producing a green fuel source. Use of this technology in just the RCP plant might seem insignificant to the national market, but if this technology was perfected and used in all power plants that emitted large quantities of excess carbon dioxide into the environment, the impact could be huge, reducing the dependence of crude oil. To make this an economically viable option for the plant to use, they must find some source of income from the project. Since bio-oil is a commodity that can be converted into biodiesel, it can be sold to refineries that are able to process the biofuel. The objective of the sales of this bio-oil is to get a return on the capital investment of the equipment.

This power plant will be primarily using wood to generate electricity. RCP will transform wood waste and green wood to generate energy. RCP is scheduled to go online in 2011. The portion of the biomass that can be efficiently burned in the boiler is greater than 1 inch and preferably 3 inches. However, there is a substantial amount of the feedstock (about 40%) that is not in the required size range ("waste" feedstock). The goal of the bio-char subgroup was to develop a base-case design for conversion of this portion of the feed into higher end products in an economical way. This base-case design involved the introduction of two unique technologies: pyrolysis and pelletizing. The portion of the feed that is between 0.25 and 1 inch is converted to useful materials (bio-oil, syngas and bio-char using a chemical reactor/pyrolyzer. Syngas is a mixture of various compounds that can be recycled for energy . Biochar is an additive that can be added to soil to help with plant growth. Bio-oils are a mixture of different organic compounds and can be used as a replacement for haeting oil #2. The really fine material (<0.25 inch) is converted to pellets using a pelletizer. In the analysis that follows, 80,000 tons of feedstock is available for processing in the pyrolyzer and the pelletizer on an annual basis.

The pyrolysis technology essentially involves the conversion of the portion of the feedstock between 0.25 and 1 inch into bio-oil, bio-char and syngas. The market value as well as the energy value of bio-oil and bio-char make them high value products. The syngas on the other hand has a low energy density value. Instead of allowing the syngas to escape into the atmosphere, it is used to dry the incoming feed to a moisture content of about 10%. This moisture content value was chosen because there seems to be a consensus in literature that beyond this moisture content value the quality of the products are not as high.

In the second technology, the “fines” in the feed were converted to pellets using a pelletizer. Depending on the size of the dye used, small pellets or big pellets can be made. The small pellets can be sold in the market while the bigger pellets can be burned in a boiler at RCP.

In what follows, literature review of the pyrolysis process and the pelletizing process is provided. An economic analysis was also done on both processes and the results obtained are presented.

In light of the current climate issues that the world currently faces combined with projections of an increase in energy demand, it is imperative to aggressively seek sustainable, economical and efficient ways to provide energy. RCP seeks to be a model for a “green campus” in south Chicago-land. This will be accomplished by burning green wood and construction in the plant and also improving process efficiency by incorporating waste heat and syngas utilization for heating.

Pyrolysis is a chemical reaction whereby biomass is heated in the absence of oxygen to temperatures around 500°C. Pyrolysis can be broken down into three main types depending on the operating conditions. There is fast, slow and intermediate pyrolysis. The main products of a pyrolysis reaction are bio-char, bio-oil and syngas. The bio-oil is a complex mixture of organic compounds and is currently being looked at as a possible replacement for heating oil #2. The bio-char has gained reputation in agricultural and farming establishments as being able to significantly improve soil quality and crop yields. The syngas consists mostly of hydrogen (50%), carbon monoxide (30%), nitrogen (15%) and methane (5%).

The different pyrolysis methods previously mentioned are able to produce more or less of certain products. As temperature is increased for example, less of the solid product (bio-char) is made and more of the liquid (bio-oil) and gaseous (syngas) products are formed. (Appendix H)

As previously mentioned, bio-oil can be used as a replacement for #2 heating oil. Bio oil is the most valuable product of pyrolysis. Other potential uses of bio-oil include: provide heating for greenhouses, district heating, stationary applications, and process heat in boilers. Bio-char can be used for agricultural purposes. Bio-char is incorporated into the soil to improve water retention and nutrient uptake. Applications of bio-char include greenroofs, greenhouses, local nurseries and also retail application (can be used instead of peat moss for plants sold at grocery stores).

At a feedstock rate of $18/ton, the cost of 80,000 tons is $1.44M. The target price for bio-char is $47/ton while that for bio-oil is $162/ton. The percent yields of different products made are shown in Table 1 for the fast pyrolysis. Based on preliminary cost analysis done, the annual cost is $5.472 million while the revenue is $10.171 million. This gives a net revenue of $4.7 million on an annual basis. The cost included in the economics included cost of feedstock, capital costs of various equipment, maintenance costs, labor costs, transportation costs and storage costs. (Appendix I)

Pelletizing is a process by which small particles of waste wood, such as sawdust, can be compressed into a pellet. The pellets can then be used as a source of energy by heating things like furnaces. This technology is very useful for multiple reasons. This process helps the environment by utilizing energy from what would otherwise be waste. Two kilograms of pellets have the same energy content as one liter of crude oil which is not bad at all for something made from sawdust. Pellets also burn much more cleanly than fossil fuels releasing less harmful chemicals into the atmosphere. As the availability of petrol decreases society will be forced to look to other sources of energy. Methods like pelletizing help us take advantage of waste products to produce energy making the best of what we have. This type of thought will be essential in the future to help avert an energy crisis.

Not only is pelletizing an investment in the future and the environment but also a fiscally sensible one at that. Our analysis shows that an investment of six million dollars will net a yearly profit of at least six million dollars in the first year. Equipment expenses are only necessary in the first year so the profit will increase every year. Maintenance and running costs are not high. The biggest cost would be transportation costs since the pellets would probably have to be sold in Europe where the market is much better for them. If the plant is unable to invest six million in the first year then they can complete the setup gradually. Our work indicates that even if only one pelletizing line is set up, compared to the three required to process all the wood available, the power plant would make over one million dollars in profit.

Another major benefit of pursuing this project would be the jobs it would afford the Robbins community. The town of Robbins is counting on this plant to provide jobs for their community and could use all the help they can get. Pelletizing will not only net the plant a positive yearly gain but also create jobs that will help the people of Robbins. Combine that with the greenness of the technology and its importance to the future and you have a definite winner.

The pelletizing process begins with all wood chips that are less than .25 inches in diameter. Usually pelletizing involves a hammer mill that grinds the particles to the same size but this will not really be required for this case since the sawdust is already the right size. The sawdust will go into the pelletizer where it will be compressed into pellets. The size of pellets can be controlled by changing the sizes of the dye in the machine. After the pellet is produced it is cooled and then dried resulting in a finished product that can be bagged and sold.

Two types of pellets will be made larger (8-18mm) which will be used for burning in the plant's own boilers and smaller pellets (6-8mm) are sold as fuel for stoves. The larger pellets are good for burning in industrial furnaces since they have a longer residence time and as such provide more energy. There is a good market for the smaller pellets in Europe that sell for around $270 per ton. In Europe, pellets are traded in bulk, not in bags as in the United States, so exporting bulk pellets to Europe is recommended. Sweden and Germany are the biggest importers of pellets. Sweden has the highest increase in pellet use over the past ten years. The energy content of pellets is relatively high. Each 2kg of pellets contain the equivalent of 1 liter of crude oil; making pellets a viable power source.

The startup costs for the program are summed up along with the projected profits in Table 3. The program can be started up gradually or all at once depending on the capital the power plant has to invest. Either way the plant should always see a profit. Another good thing about this project is after the initial equipment investment the costs go down dramatically and as such profits increase considerably. The cost of running a 5 ton facility is also very similar to the cost of running a 15 ton facility since the same number of operators are required for both. Figure 2 illustrates this. In the case of exporting pellets, transportation cost for a 35,000-ton vessel is $113/ton. To transport the pellets to Europe they will have to be loaded from lake vessels to ocean going vessels.

Implementing a pelletizing plant at the Robbins facility has many benefits. It will produce more jobs, help the environment and the company by producing a profit. By using this technology energy will be created from what is otherwise a waste product of very little utility. The major drawback is the relatively high initial investment required to initiate the program but even that isn't too big a deal since it can be done in stages to ease the financing burden. (Appendix H, Appendix I)

Bio-char is widely accepted as an effective agent for carbon capture and sequestration. It has been estimated that carbon can be stored in bio-char for about a thousand years while at the same time enriching the soil, decreasing fertilizer use and improving crop yields. The reduction in the use of fertilizer also eliminates the production of more nitrous oxides (more harmful to the environment than carbon dioxide) which results from increased fertilizer production. Furthermore, the process described in this report eliminates the need for fossil fuel that would have been burned to generate electricity. This reduced regional pollution thereby improving air quality. Thirdly, biomass pyrolysis is essentially a zero waste process. All the products from the process are utilized and nothing is wasted. The consumption of utilities is also much lower than comparable coal plants. Furthermore, this project saves landfill spaces and eliminates the generation of methane which would have resulted from wood decomposition.

In addition, the use of bio-char will decrease dependence on fossil fuels. This is an important consideration in an era of diminishing fossil fuel reserves. A Valero refining plant is located next to RCP. It might be economically attractive to get a contract with this refinery for hydrogen sale. The hydrogen can be obtained by passing the syngas through a CO catalyst which is able to remove over 99% of the CO in the syngas.

Based on preliminary cost analysis that was done, the pyrolysis technology and the pelletizer are economically feasible. The economics for the pyrolysis technology and the pelletizer are based on feedstock of 80,000 tons for each process. Based on preliminary economic analysis that was done, a profit of $4.744 million can be made from the pyrolysis technology. The pelletizer process will take waste product and convert it to energy that is clean burning. This will be done in a way that makes the plant very good profit. It can be done slowly if the financing isn't immediately available and will create jobs for the Robbins community.

5. Conclusions

In conclusion, not only will the utilization of waste heat and wood make Robbins Community power more efficient, but it will also increase its overall revenue by tapping into additional energy production sources. By introducing a heat exchanger in the Robbins Community Power system, direct steam can be generated that would power other onsite machinery including the pellet mill and algae pond. By lowering the temperature of the flue gas, this reduced heat can be pumped into greenhouses to augment plant growth along with ensuing slow pryolysis for bio-char production. Further excess heat can also be captured and sold to various industries in the area to provide a sustainable energy source for certain community technologies.

As a result of the greenhouse subgroup's research throughout the semester, it is determined that greenhouses are a great technique for reducing the heat levels of the flue gas due to the vast space; but trees and crops do not provide an efficient way to absorb carbon dioxide. It is also found that algae are great organisms that are very efficient at absorbing carbon dioxide; but raceway ponds and bioreactors would not necessarily reduce the temperature of the flue gas enough. Thus it is proposed that algae growth is used in conjunction with growing crops in greenhouses to efficiently absorb both heat and carbon dioxide from the flue gas before being released back into the environment. The most efficient and cost effective way to do this was found to be growing algae in raceway ponds inside the greenhouse in which trees are being grown.

By converting waste feedstock from RCP into more useful materials using already existing technologies, new products such as bio-oil, bio-char and syngas along with pellets can be produced. Some of the pellets can be burned in the main boiler that the power plant uses while the rest of the pellets will be sold and use in home pellet-burning stoves. The pelletizer process will take waste product and convert it to energy that is clean burning. This will be done in a way that makes the plant very good profit. It can be done slowly if the financing isn't immediately available and will create jobs for the Robbins community. Based on preliminary cost analysis, the pyrolysis technology and the pelletizer are economically feasible.

This project could have direct and indirect benefits to Robbins community. Some of these include the creation of construction jobs as well as site jobs, attraction of investment opportunities to Robbins, and scholarship program. Investment opportunities will ultimately attract more economic opportunities to the Robbins community. Also, upon commencement of this project a scholarship program will be set up for students from the village where there will also be increased revenue for local schools. Perhaps most importantly, this opportunity gives Robbins Community Power the chance to be a leader in wood to energy conservation in the United States while improving air quality for the community.

6. Appendices

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7) Mckay, Eric. "Wood Pelleting Budget Quote 4 to 5 TPH." California Pellet Mills, 2010.

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9) Mckay, Eric. "CPM Wood Pelleting." California Pellet Mills, 2010.

Appendix A

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Assume Standard Pressure throughout

$$T_{bulk} = \frac{494K - 367K}{2} = 430K \qquad \mu_{bulk} = \mu_{430K} \tag{1}$$

$$T_{H_20} = \frac{373K - 300K}{2} = 337K \qquad \mu_{H_20} = \mu_{337K} \tag{2}$$

$$\mu_{bulk,avg} = 23.68 \times 10^{-6}[\frac{N \cdot s}{m^2}] \qquad \mu_{H_20,avg} = 19.91 \times 10^{-6}[\frac{N \cdot s}{m^2}] \tag{3}$$

$$\Delta T_1 = |T_{wall,in} - T_{bulk,in}| \qquad \Delta T_2 = |T_{wall,out} - T_{bulk,out}| \tag{4}$$

$$\Delta P_{flow} = \frac{f n_p A G}{2(1.0)\rho_{bulk}\pi D_i^2} \tag{5}$$

From Table B.1 on pg 719, D_o=1.25 inches and D_i = 1.084 inches @ BWG=14. We want n_p to be even and $Re \geq 10^4$.

$$Re_{tubeside} = \frac{\rho v L}{\mu} = \frac{4\dot{m}}{\pi D_i \mu_{H_20}} \tag{6}$$

By interpolation, $\mu_{H_20,330K} = 484 \times 10^{-6}[\frac{N \cdot s}{m^2}]$ and $\dot{m}_w \approx 57[\frac{kg}{s}]$. When $n_p = 2$ and $L = 200[ft]$, $Re_{tube} \geq 8.5 \times 10^4$

We know the area of heat transfer required to be very near 13,000 square feet from enthalpy calculations.

$$n_t = \frac{Area}{\pi D_o L} = 2063 \text{ where L =20ft and} \tag{7}$$

Using Table C.6 (pg 736) (a) Shell Inner Diameter = 78 inches (b) n_{tubes}= 2068 (c) n_{passes}= 4

$$Re_{tube} = \frac{4\dot{m}\frac{n_p}{n_t}}{\pi D_i \mu_{H_20}} \approx 1.1 \times 10^4 \tag{8}$$

With this configuration, the Re_{tube} 10^4, signifying turbulent flow.

$$v_{water} = \frac{\dot{m}\frac{n_p}{n_t}}{\rho A} = \frac{57[kg/s](\frac{4}{2068})}{980[kg/m^3]\frac{\pi}{4}(0.03175[m])} \simeq 0.143[m/s] \tag{9}$$

See page 233 for verification of requirement for tube-side velocity to be less than 15 [ft/s].

$$U_{req} = \frac{q}{n_t A_s F \Delta T_{log}} \tag{10}$$

$$\Delta T_{log} = \frac{(\Delta T_1 - \Delta T_2)}{ln(\frac{\Delta T_1}{\Delta T_2})} \tag{11}$$

Using the definitions described above, $\Delta T_1 = 121K$ and $\Delta T_2 = 66K$. For a 2-4 heat exchanger, tables in the text yield $F_{2-4} = 0.93$ for the characteristics of our desired apparatus. Thus,

$$\Delta T_{log} = \frac{(121K - 66K)}{ln(\frac{121}{66})} = 90.73°C = 190.3°F$$

and the U_{req} can be calculated in both S.I. and English units using (10) as follows:

$$U_{req} = \frac{17.5[MW]}{20681254[m^2](0.93)(90.73)}$$

and

$$U_{req} = \frac{59.9 \times 10^6[Btu/hr]}{2068\pi D_o L(0.93)(190.3)[°F]} \simeq 25[Btu/(hft^2F)]$$

Now we must calculate the heat transfer coefficient for the water in the tubes. Since the Re > 10000, 160>Pr > 0.7 and L/d > 60, the Sieder-Tate correlation can be implemented to find the heat transfer coefficient of the water. It follows,

$$h_i = \frac{k_w}{D_i} \times 0.023 * Re_D^{0.8} Pr_w^{\frac{1}{3}} \frac{\mu}{\mu_{wall}}^{0.14} \quad (12)$$

For water at 330K, $k_w = 0.660[W/mK]$ and $Pr_w = 2.81$. It follows,

$$h_i = 1282[W/mK]$$

For baffle spacing:

$$B = 0.3 \cdot 78[in] = 23.4[in]$$

For flow area across the tube bundle

$$a_s = \frac{d_s C' B}{144 P_t} \quad (13)$$

Our specific situation yielded

$$a_s = \frac{78[in]0.3125[in]23.4[in]}{144[in^2/ft^2]1.563[in]} = 2.53[ft^2] = 0.2354[m^2]$$

$$G_{air} = \rho_{air} v_{avg} = \frac{\dot{m}}{a_s} = \frac{71.27[kg/s]}{0.235[m^2]} = 302.7[kg/m^2s] \quad (14)$$

$$Re_{tube} = \frac{D_e G}{\mu_b} \approx 60309 \quad (15)$$

Since the (15) is greater than 10^4, the flow in the shell is turbulent. Now we start with the calculation of the Colburn factor. The same conditions required for the Sieder-Tate relation also apply here. Since the turbulent flue gas satisfies these constraints, the Colburn j-factor can be calculated as follows.

$$j_H = 0.5(1 + \frac{B}{d_s})(0.08 Re_{shell}^{0.6821} + 0.7 Re_{shell}^{0.1772}) \quad (16)$$

$$j_H = 0.5(1 + 0.3)(0.08(60309)^{0.6821} + 0.7(60309)^{0.1772}) \approx 98$$

The heat transfer coefficient of the flue gas can be evaluated according to

$$h_o = j_H \frac{k}{D_e} Pr^{1/3} (\frac{\mu}{\mu_{wall}})^{0.14} \text{ where } \frac{\mu}{\mu_{wall}} \approx 1.0 \tag{17}$$

Using values for the flue gas,

$$h_o = 608.0 [W/m^2K]$$

$$U_c = [\frac{D_o}{h_i D_i} + \frac{D_o ln(\frac{D_o}{D_i})}{2k_{tube}} + \frac{1}{h_o}]^{-1} \tag{18}$$

In this case,

$$\frac{D_o}{D_i} = \frac{1.25[in]}{1.084[in]} = 1.153$$

or the conductivity of stainless steel. U is calculated to be 370 W/m^2K or 65.2 $BTU/hFft^2$, which is much greater than the required coefficient calculated above.

Pressure drop over the heat exchanger is depends on the Darcy-Weisbach friction factor of fully developed flue gas. For tube-side, turbulent flow

$$f = 0.4137 Re^{-0.2585} \tag{19}$$

$$f = 0.4137(60309)^{-0.2585} = 0.03778$$

The mass flux for water in the tube,

$$G_w = \frac{\dot{m}(\frac{n_p}{n_t})}{\frac{\pi}{4} D_i^2} = 185.6 \, [kg \, m^{-2} s^{-1}]$$

Now the pressure loss of water flow due to friction in fully developed flow can be determined with the Darcy-Weisbach equation

$$\Delta P_{fric} = \frac{f n_p L G^2}{2000 D_i s \theta} \tag{20}$$

where $s = \frac{\rho}{\rho_w}$ and $\theta = \frac{\mu}{\mu_w}$, which in our case are both equal to unity. Thus, the following holds true

$$\Delta P_{fric} = \frac{(0.03778)(4)(6.096)(185.6)^2}{2000(0.0275)(1.0)(1.0)} = 577.0 \, [Pa] \tag{21}$$

Also, entrance and exit losses can be estimated using the heuristic described in Ch. 5 of the text (pg. 232)

$$\alpha_r = 2n_p - 1.5 \tag{22}$$

$$\Delta P_r = 5.0 \times 10^{-4} \alpha_r \frac{G^2}{s} = 112 \, [Pa] \tag{23}$$

The pressure drop across the shell can be found through two Darcy-Weisbach friction factors f_1 and f_2

$$f_1 = (0.0076 + 0.000166(d_{s,1})) Re^{-0.125} \tag{24}$$

for $d_{s,1} = 42\,[in]$ which may be too big for the constraints of (24)

$$f_2 = (0.0016 + 5.8 \times 10^{-5} d_{s.2}) Re^{-0.157} \tag{25}$$

where $d_{s,2} = 23.25\,[in]$. So

$$f_1 = 0.00368\,[ft^2/in^2]$$

$$f_2 = 0.000524\,[ft^2/in^2]$$

$$f = 144[f_1 - 1.25(1 - \frac{B}{d_s})(f_1 - f_2)] = 0.1323 \tag{26}$$

$$n_b + 1 \approx \frac{L}{B} = \frac{6.096[m]}{0.594[m]} = 10.25 \tag{27}$$

The tube friction loss can be determined through the Darcy-Weisbach equation as well

$$\Delta P_f = \frac{f G^2 d_s (n_b + 1)}{2000 D_i s \theta} \tag{28}$$

where

$$s = \frac{\rho_{flue}}{\rho_w} = \frac{29[kg/mol]}{18[kg/mol]} 1.61$$

and $\theta = 1.0$ is assumed to be a close approximation to the real flow. Thus

$$\Delta P_f \approx 2983\,[Pa]$$

Overall, disparity between U_{req} and U_{actual} suggests the exchanger shell may be oversized and unnecessarily costly.

Source: Robert W. Serth. Process Heat Transfer: Principles and Applications. Academic Press (April 11, 2007). Note: A great resource for heat exchangers.

Appendix B

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The work required for the fan to overcome the pressure drop of the proposed heat exchanger can be determined by the first law of thermodynamics:

$$\dot{W}_s + \dot{Q}_{in} = \frac{\partial}{\partial t}\iiint_V e\rho \, dV + \iint_A e\rho \, \vec{v} \cdot d\vec{A} \tag{1}$$

where $e = (\frac{P}{\rho} + \tilde{u} + \frac{v^2}{2} + gz)$ represents specific energy of the fluid comprise of enthalpy, $h = (\frac{P}{\rho} + \tilde{u})$, kinetic energy, $\frac{v^2}{2}$, and potential energy, gz.

Assuming no heat flow occurs (adiabatic) while the fan the puts energy into a steady state flow, the shaft work necessary for required flow exit conditions can be determined. State (1) is the entrance to the fan duct and (2) is the exit. The calculation is as follows:

$$\dot{W}_s + \cancel{(\dot{Q}_{in})} = \cancel{(\frac{\partial}{\partial t}\iiint_V e\rho \, dV)} + \iint_{A_2} e_2\rho|v_2| \, dA - \iint_{A_1} e_1\rho|v_1| \, dA$$

We can further assume that the air flow is incompressible with negligible friction. Both v_1 and v_2 represent average velocities over the cross-sectional area. We can find the following:

$$\dot{W}_s = \iint_{A_2} (\frac{P_2}{\rho} + \tilde{u_2} + \frac{{v_2}^2}{2} + gz_2)\rho|v_2| \, dA - \iint_{A_1} (\frac{P_1}{\rho} + \tilde{u_1} + \frac{{v_1}^2}{2} + gz_1)\rho|v_1| \, dA$$

where $\rho_1 v_{1avg} A_1 = \rho_2 v_{2avg} A_2 = \dot{m}$ so that

$$\dot{W}_s = \dot{m}[\frac{P_2 - P_1}{\rho} + (\tilde{u_2} - \tilde{u_1}) + \frac{{v_2}^2 - {v_1}^2}{2} + g(z_2 - z_1)]$$

In our case, the fluid temperature is assumed to be constant throughout ($T_1 = T_2$). Thus,

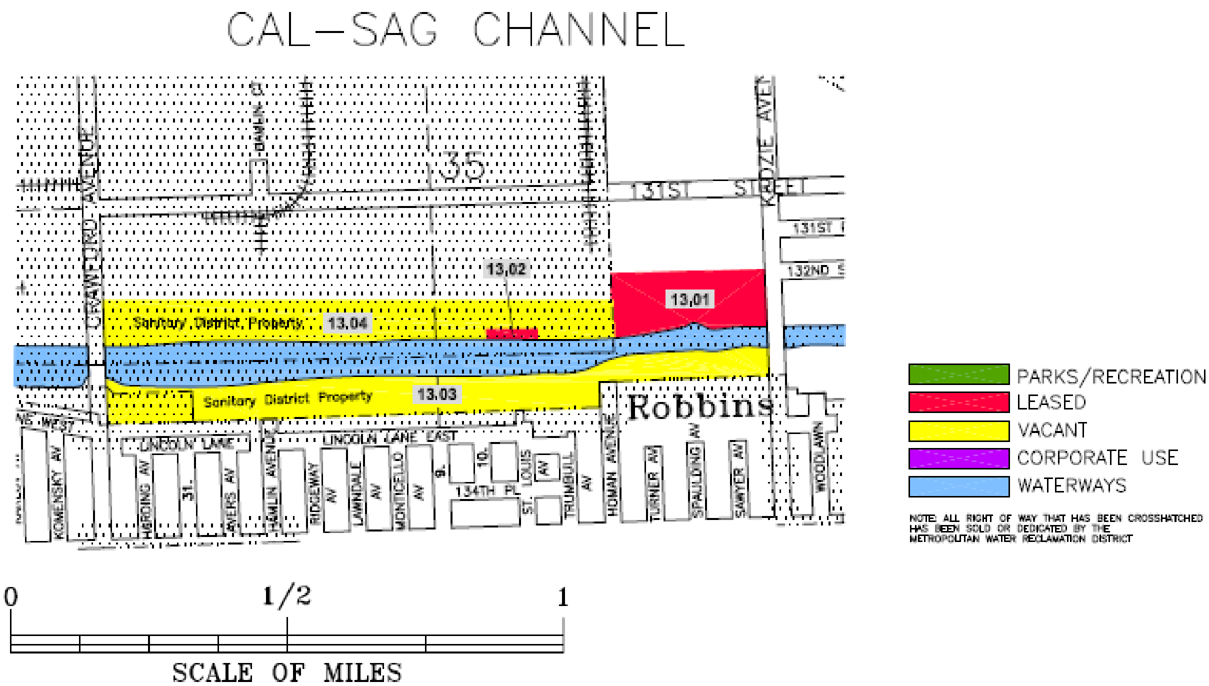
$$(\tilde{u_2} - \tilde{u_1}) = c_v(T_2 - T_1) = 0$$

The change in potential energy is negligible as well. We are left with the following

$$\dot{W}_s = \dot{m}[\frac{P_2 - P_1}{\rho} + \cancel{(\tilde{u_2} - \tilde{u_1})} + \frac{{v_2}^2 - {v_1}^2}{2} + g\cancel{(z_2 - z_1)}]$$

If the entrance and exit cross-sectional areas are equal, then $v_2 = v_2$ and the work required to pump the flue gas out of the stack is dependent only on the pressure drop from the heat exchanger. Source: Fluid Mechanics: Fundamentals and Applications, by Cengal and Cimbala, pgs 208-209

Appendix C: FMV parcel 13.03 Cal-Sag channel



This figure shows the Robbins Community Power plant location in respect to the Calumet-Sag water channel. The yellow highlighted area labeled 13.03 is the parcel of land IPRO347 is interested in leasing. The parcel totals about 30 acres. (http://www.mwrd.org/pv_obj_cache/pv_obj_id_7F89833505D70C4792FF51FAEC3782BF7F221100/filename/cal-sag1-16web.pdf)

Appendix D: Crop carbon dioxide absorption

Plant	Plant Density (plant/m2)	Carbon total (g/m2/year)	CO2 total (g/m2/year)	CO2 total (g/plant/year)
Tomato	2	867	**3208**	1604
Pepper	2.2	617	**2283**	1038
Watermelon	0.4	162	599	1499
Melon	1	219	810	810
Romaine Lettuce	6.5	691.2	**2557**	393
Broccoli	3.5	682.4	**2525**	721
Cauliflower	3.5	986	**3648**	1042
Artichoke	0.7	354	1310	1871
Oats	128	387	1432	11
Wheat	125	377.2	1396	11

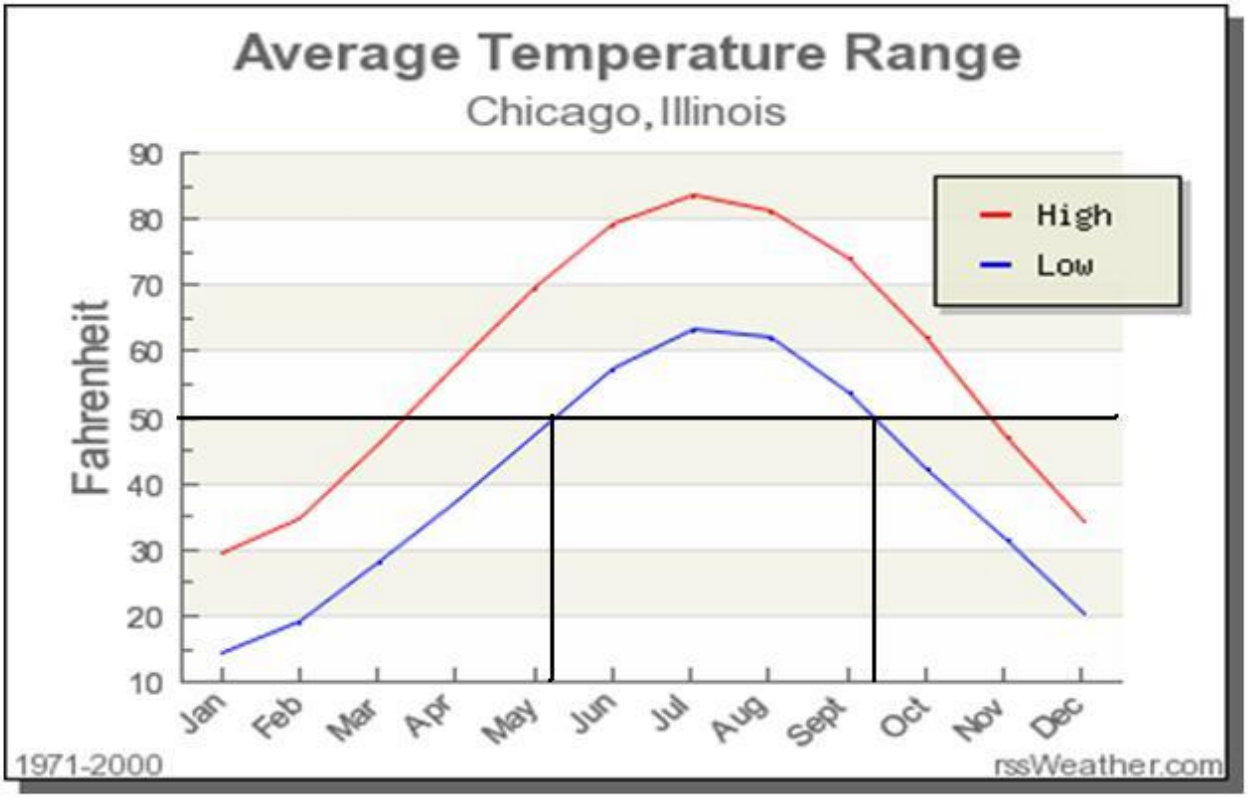
This table shows values of carbon dioxide absorption by different crops on both a plant and square meter basis. (http://www.ecorresponsabilidad.es/pdfs/lessco2/ponencia_cisc_ingles.pdf)

Appendix E: Carbon Sequestration per tree diameter

DBH Class (in)	Carbon Sequestration (lbs/yr)
0-3	2
9-12	19
18-21	43
27-30	55
39+	93

This table represents the amount of carbon dioxide that each class of tree can absorb. The tree classes are separated by diameter breast heights in inches. (http://www.oakhavenpc.org/cultivating_algae.htm)

Appendix F: Average high and low temperature ranges in Chicago, Il throughout the year



The lines on this graph show the 50 degree Fahrenheit line in which below it is dangerous as a nighttime temperature. Thus the vertical lines are drawn to show which months where minimal to no heat is needed from the flue gas (i.e. early May to early September).
(http://www.rssweather.com/climate/Illinois/Chicago/)

Appendix G: Algae growth designs

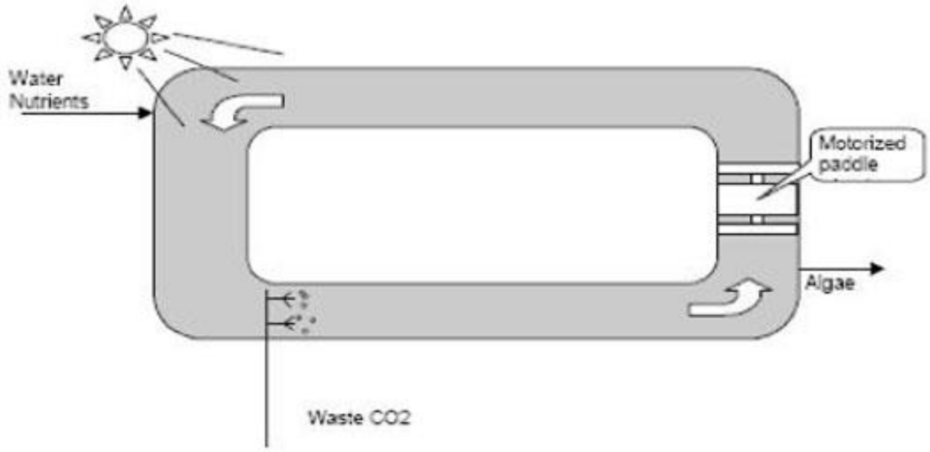


Figure 1 shows the set-up of a raceway style algae growth design with the water flowing in a counterclockwise direction around some sort of barrier in the middle. The flue gas is pumped into the algae flow and mixed in to provide turbulence and carbon dioxide. (http://www.greentechmedia.com/green-light/post/open-pond-vs.-closed-bioreactors-4012/)

Figure 2 shows the set-up of the bioreactors design for algae growth. This picture is from a study by GreenFuel Technologies in Cambridge, MA. They field tested a closed system that uses the CO_2 in power plant flue gases to feed algae, akin to the design we would be using. (http://www.oakhavenpc.org/cultivating_algae.htm)

Appendix H: Percentage yields for different pyrolysis technologies

Process	Liquid (bio-oil)	Solid (biochar)	Gas (syngas)
FAST PYROLYSIS Moderate temperature (~500 °C) Short hot vapour residence time (<2s)	75% (25% water)	12%	13%
INTERMEDIATE PYROLYSIS Low-moderate temperature, Moderate hot vapour residence time	50% (50% water)	25%	25%
SLOW PYROLYSIS Low-moderate temperature, Long residence time	30% (70% water)	35%	35%
GASIFICATION high temperature (>800 °C) Long vapour residence time	5% tar 5% water	10%	85%

Appendix I: Preliminary economic analysis of pyrolysis technology

	Annualized Cost ($ MM)	Capital Cost ($ MM)	Revenue ($ MM)
Cost of feed ($)	1.440		
Cost of dryer ($)	0.078	0.300	
Cost of steam ($)	0.080		
Cost of storage (bio-oil and bio-char) ($)	0.389	1.500	
Maintenance cost ($)	0.084		
Labor cost ($)	0.350		
Reactor cost ($)	1.556	6.000	
Miscellaneous cost ($)	0.150		
Transportation cost ($)	1.300		
Value of Bio-oil ($)			9.720
Value of Bio-char ($)			0.451
Total	5.427	7.800	10.171
Net Revenue ($)			4.744

Appendix J: Economics of pelletizer

Production (ton/ hours)	Start Cost (USD) ($x 10^6$)	Operating Cost (USD) ($x 10^6$)	Total Pellet Sales (USD) ($x 10^6$)	Total Shipping Cost (USD) ($x 10^6$)	Number of pellets produced (tons) ($x 10^6$)	Energy (kWh) ($x 10^6$)	Profit (USD) ($x 10^6$)
5	1.66	0.425	6.90	2.83	0.025	113.25	1.98
10	3.32	0.700	13.80	5.66	0.050	226.50	4.12
15	4.98	0.825	20.70	8.49	0.075	339.75	6.40