Cal Poly's Bio Energy Vision: *Sustaining Civilization Under Cover*

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Abstract

Microalgae will be one of the most desired feedstock for biofuels production in the future. Theoretically, biodiesel produced from algae appears to be the only feasible solution today for replacing petrodiesel completely by a renewable source. No other feedstock (soybean, corn, rapeseed, or palm oil) has the oil yield high enough to be in a position to produce such large volumes of oil. High productivity levels can be reached by growing algae in transparent closed tubular systems - so called photobioreactors. Since the technology is still new, further improvements need to be done before it can be used for large-scale commercial applications. Photobioreactors have two main functions: i) producing biomass in the form of algae, and ii) taking up of carbon dioxide (CO_2) from the atmospheric environment to grow algae. CO_2 is the most emitted greenhouse gas; and therefore, it is widely responsible for global warming and its consequences. Flue gases from power plants, for instance, can be turned into valuable biomass and then converted to biofuels. Gas prices can be kept at stable levels and the dependency on foreign oil can be decreased. One of the byproducts of biofuels production from algae is a protein rich algae cake that can be used as animal feed. Photobioreactors make it possible to supply biomass without impacting the cost of agricultural land, competing with food production and harming the environment. Co-production of biofuels and animal protein makes this environment friendly and resource efficient system very attractive. Starting with the project recently funded by the Agricultural Research Initiative (ARI) Program and our industrial partners, BKS Energy LLC and Energy Alternative Solutions, Inc., Cal Poly will be one of the leading applied research institutions for the research and development of controlled environment algae production systems in the world. Currently, we are building relations with other potential industrial, and institutional partners. Our activities will include fully integrated, systems approach for the development of innovative photobioreactor system technologies for increased resource use efficiency and sustainable business opportunities at controlled environment platforms by strengthening and furthering scientific, materials, design, production, processing, and overall system knowledge. Systems will be commercially feasible, highly productive and tailored for different applications. Cal Poly's BioResource & Agricultural Engineering Department has taken the leadership, and works together in an interdisciplinary team consisting of professionals from Food & Nutrition Science, Civil & Environmental Engineering, the University of Arizona, and the private sector. We are currently putting all our efforts together to form a strong relationship to serve the common knowledge as well as the needs of industry, and society in general. Cal Poly sees the possibility for a significant reduction in greenhouse gas emissions and also hopes to contribute substantially to the energy needs of a sustainable society. This currently funded particular research shall be completed by June 2011; however, further applied research projects will be developed based on this initiative before and after 2017. The long-term objective is to help convert energy consuming farms to energy generating, locally sustainable rural communities.

Statement of the Problem

The world is faced by a huge problem: depletion of fossil fuels, the resulting dependency on fossil fuel exporting countries as well as the aspect of global warming through emission of greenhouse gases (Hinrichs and Kleinbach, 2006). Alternative, renewable, and environment friendly energy sources and energy conservation practices are key elements to solve these problems. A lot of research has been done in different fields of alternative energy such as bioethanol and biodiesel production from crops, developing hydrogen as a fuel alternative or biogas upgrades for use in gas fired vehicles. However, all of these new technologies come along with a number of disadvantages (Antoni et al., 2007). They are either not so productive, or standing in contrast with public interests, or facing lacks of resource (mainly water and land) conservation issues. Also, there are further questions to be answered. Can biomass be supplied without impacting the cost of agricultural land, competing with food production and harming the environment? Do we have sufficient land here or else where?

The answer for all these problems can be the growing of algae as a biofuel feedstock. It has emerged as a viable resource for biodiesel and bioethanol production. Algae can be grown in two different systems, in photobioreactors (PBR) (Figure 1 and 2) or in raceway ponds. Since the raceway ponds are less productive, land area extensive and uncontrollable, the PBRs will be the favorable application in the future (Chen, 1996). The technology (PBR) itself is quite new, therefore much more research and improvements need to be done to optimize and enhance the existing systems for commercial applications (NREL, 1998; Richmond, 2000; Pulz, 2001; Chisti, 2007; Huntley and Redalje, 2007). The major technical challenges are how to sustain highest photosynthesis and biomass productivity levels, reduce cell damage due to hydrodynamic stress, reduce costs in fabrication, installation and maintenance, and how to increase the capability of the system to expand to an industrial scale (Barbosa, 2003; AlgaeLink, 2007).

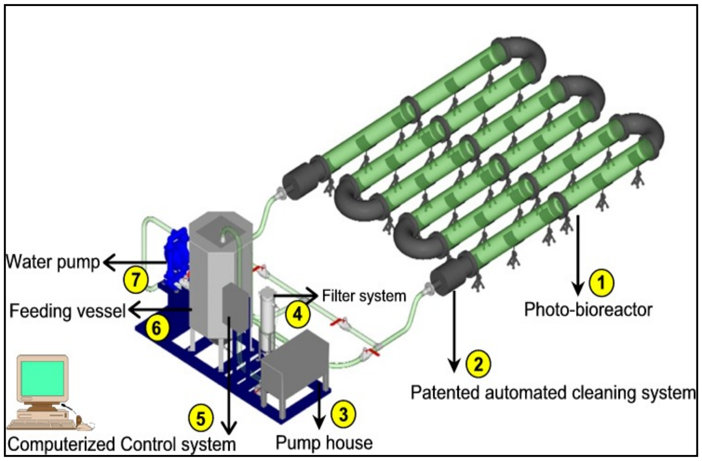


Figure 1. Schematic view of a photobioreactor system.

Unlike other crops that are currently being used for oil production such as soybean, oil palm, corn, and jatropha, some strains of algae contain as much as 70% oil. They are capable of producing more than 30-times the amount of oil (per year per unit area of land) when compared to oil seed crops (Chisti, 2007). Another advantage is that since algae use CO_2 as a carbon source to grow, it can extract the carbon dioxide from power plant exhausts or any other CO_2 emitting process when the PBR is integrated to such a plant. A yield of 200 to 400 tons of oil/hectare/year can be considered reachable with a standard PBR system (Oilgae, 2006; Huntley and Redalje, 2007).

Theoretically, biodiesel produced from algae appears to be the only feasible solution today for replacing petrodiesel completely. No other feedstock has the oil yield high enough to be in a position to produce such large volumes of oil. It has been found that about 10 million acres of land would need to be dedicated for biodiesel production in order to produce biodiesel to replace all the petrodiesel currently used in the U.S. (Oilgae, 2006). This is just 1-3% of the total land used today for farming and grazing together in the United States (about 1 billion acres). Clearly, algae biomass is a superior alternative as a feedstock for large-scale biodiesel production.

One of the byproducts of the biofuels production from algae is a protein rich algae cake that can be used as animal feed. Photobioreactors make it possible to supply biomass without impacting the cost of agricultural land, competing with food production and harming the environment.

Figure 2. Tubular photobioreactors in outdoor (left) and enclosed (right) environments.

Co-production of biofuels and animal protein makes this environment friendly and resource efficient system a very attractive alternative. Kicking-off with the newly funded project, Cal Poly will be one of the leading hands-on education and applied research institutions for the research and development of controlled environment algae production systems in the world. For this purpose, as an initial step, an interdisciplinary Controlled Environment Agriculture and Energy Working Group (www.brae.calpoly.edu/CEAE.html) was established. The activities will include fully integrated, systems approach for the development of innovative photobioreactor system technologies for increased resource use efficiency and sustainable business opportunities at controlled environment platforms by strengthening and furthering scientific, materials, design, production, processing, and overall system knowledge. Systems will be commercially feasible, highly productive and tailored for different applications. We work together in an interdisciplinary team, consisting of professionals from different academic fields, institutions, and the private sector. Our all efforts are put together to form a strong relationship and serve the common knowledge as well as the needs of industry, and society in general. We see the possibility for a significant reduction in greenhouse gas emissions and also hope to contribute substantially to the energy needs of a sustainable global society. Our long-term objective is to help convert energy consuming farms to energy generating, locally sustainable rural communities.

Statement of Methodology

A sophisticated research plan and intermediate goals are essential for this large-scale integrated project. Since the overall goal has a wide spectrum, we divided it into five subgroups:

- Microclimate requirements and economical aspects of algae growth
- Flue gas versus pure carbon dioxide
- Optimization of lighting for algae growth
- Optimization of the harvesting process
- Determination of algae strains for biofuels production

These subgroups are subject to a number of research activities at Cal Poly. Some will take only a couple of weeks or months, however some others, for instance lighting, will be investigated over the complete project period of three years. A timeline for the investigations of the sub-goals with respect to their estimated research time has been developed. The subgroups will be divided into smaller projects, accomplishable through Senior Projects, Individual Studies, Master's Thesis', and pre-Doctorial work. Our goal is to have our students working at the facility continuously.

A steady improvement of the photobioreactor system will be realized through this way. Progress steps will be published continuously. The design of experiments and the specific objectives will vary from project to project and will be specified in the corresponding individual research plan. Data will be monitored and collected with the integrated computer system. Appropriate sensors will measure the levels of oxygen, pH, CO_2, optical density, temperature, and light. The computer software will then visualize and analyze the measured values. A database will be developed to keep track of all data taken during the research period and to provide fundamental background and evidence for further optimization studies. This will be the main resource for research conclusions and further experimental designs for the past and future projects, respectively.

Various difficulties can occur while performing research with algae. Experiments can be affected by different variables (temperature, solar radiation, nutrient depletion, CO_2 supply, oxygen (O_2) poisoning). Due to the design of photobioreactors (closed system), contaminations by other algae strains or bacteria are avoided. Since the system will be operated in a controlled environment greenhouse, the temperature will be regulated as desired. A radiation sensor will keep track of the incoming solar radiation within the greenhouse. Potential differences in radiation on a day-to-day basis will be monitored in this way and counter measures will be executed as needed. Excess oxygen in the system can kill the algae. An O_2 meter will be installed to measure the O_2 concentration, and will alarm when the limit is exceeded. Daily examination of the growth media will prevent the risk of nutrient depletion and the resulting growth repression (unless intentionally desired). Just to make sure that the algae take up the injected carbon dioxide, a CO_2 sensor will be installed to monitor how much CO_2 is leftover after each cycle.

For the first research on temperature differences and design parameters, well-known algae strains will be cultivated with known growing conditions to reduce the effect of interfering variables and to concentrate on the "real" investigated variables.

Summary of the preliminary timeline:

The first and most important step is to build the photobioreactor system at Cal Poly. Due to a lead-time of up to 6 months, shipment and set-up work, the concrete starting date of research with the system is subject to change. In the meantime, initial investigations will take place on a lab-scale. All further improvements and developments of the photobioreactor system will be initially tested in an additional small bench-scale photobioreactor. A lab-scale system will save a lot of time for the experiments that will be performed in the real production system later. After the arrival and set-up of the photobioreactor system, the lab-scale investigations will still continue; however, the focus will be on the development of the "real" commercial system. The first 2-3 week period in September 2008 will be spent on the reactor with tuning and learning the system operations, and algae behavior during continuous production. Proper harvesting, drying and pressing of algae are to be understood and executed. The team will gain general knowledge of the system, before the production-scale research resumes. This particular research shall be completed by June 2011; however, further applied projects will be developed based on this initiative before and after 2017.

Microclimate requirements and economical aspects of algae growth

The first specific project will be the evaluation of temperature influences on algae cultivation in the photobioreactor. The research shall provide fundamental data for the planning of algae photobioreactors. Decision guidance for the best location and layout of algae production plants shall be given. This project will combine the effect of location, weather conditions, algae strain attributes on yield and feasibility. The study will provide valuable information to people planning a business and running systems in the field of algae production in photobioreactors. This study will answer the following questions: Where can photobioreactors be placed? Are greenhouses necessary for housing photobioreactors? How dependent is algae production on the weather? Is it a feasible practice in colder regions? How feasible is heating the system to get a better yield? At what temperatures is heating (or cooling) necessary? What is the relationship between climatic variables and yield?

A specific algae strain needs to be chosen. *Haematococcus pluvialis* proved to give good results in the past (Huntley and Redalje, 2007), and significant growing conditions were already investigated. The previous studies provide important information to our project, because all other growing parameters can be kept at optimal levels to study only the effect of temperature, for instance. Then, the photoperiod, light intensity, nutrients and substrate supply, circulation rate, and salinity have to be adjusted and kept at fixed levels.

Experiments will be conducted with different temperatures ranging from 15°C to 35°C in steps of 2°C to determine the optimum. The system will run for 3 days at every set point temperature to make sure to get the correct yield. The optimal temperature for algae growth and yield will be determined. Theoretical heating and cooling requirements of the system in different outdoor conditions will be calculated in order to perform economic feasibility studies.

Following this fundamental research project, the following sub-goals will be investigated.

Flue gas versus pure carbon dioxide

Since the photobioreactors will most probably be placed close to CO_2 emitting plants, the uptake and providing technology of CO_2 in a PBR must be developed in accordance with the contents in flue gases. Customized techniques for different flue gases have to be implemented. This is especially valuable for our industrial partners to test their flue gases on a commercial scale basis. This research topic will be divided into smaller projects, each handling an improvement of the photobioreactor with different flue gases. This phase will start after the completion of the initial project. The total investigation time will be approximately 15 months.

Optimization of lighting for algae growth

The most significant design parameter of a photobioreactor is the light quantity and distribution (Becker, 1994; Barbosa, 2003). Every alga has to get a certain amount of light to grow as fast as possible – the so-called light saturation. Photoinhibition as well as too little light supply need to be avoided. Due to the tubular design, the photobioreactor contains a photolimited central dark zone and a relatively better lighted peripheral zone. Turbulences in the tube cause light-dark cycle, simulating a night-day rhythm and providing natural and optimal growth conditions for the algae. The frequency of light-dark cycles depends on several factors such as cell concentration, turbulence intensity, optical properties, tube diameter, and external irradiance level (Grima et al., 2000). Several attempts have been made to estimate the frequency of light-dark cycling, but this problem remains unsolved. Since the productivity heavily depends on the light distribution, it will be one main research focus. This topic is very time consuming and some research in this area has already been executed by a number of researchers, however, never on a large-scale tubular photobioreactor. Tentative topics to be investigated are LED technology, reflective floor surfaces, shading, and intraday light-dark cycles. This research will start as soon as possible, and the light distribution study will be completed by June 30, 2011.

Optimization of the harvesting process

The most cost intensive process in producing biofuels from algae is the harvesting (removal of the algae from water). A centrifuge is usually used for the harvesting; however, the operational cost due to electricity consumption is extremely high. The photobioreactor system at Cal Poly will allow detailed research on this topic because the system is large enough to produce an adequate amount of biomass – one reason other institutions cannot perform this type of research. The multi-disciplinary research team will be able to find new solutions considering approaches from a broad spectrum of knowledge. A very promising approach is the harvesting by flocculation, where algae are led to flocculate, or clump together. These clumps of algae are heavier and will fall out of suspension, eventually settling at the bottom. The growth medium can be pumped off, and the remaining higher concentration algae solution can be collected from the bottom of the flocculation vessel. Flocculation is an approach used in wastewater treatment. Further investigations need to be executed to transfer this technology to algae production. The harvesting time depends on the optical density of the growth media. It can be controlled by the PLC (setting limits and controlling the harvesting bypass accordingly). However, the definition of the limits is always critical. A total depletion of algae is not required nor is excess. The optimal harvesting time for a specific algae strain therefore needs to be determined. This research shall be completed by January 2011.

Determination of algae strains for biofuels production

The simplest way to differ and test the productivity is by choosing and comparing different algae strains. Surely, this depends on the required composition, on the process, and system itself. The best strain for the given conditions needs to be determined by further research. Different algae strains will be tested throughout the research period within the scope of different projects proposed in this study. One small project at the end of the research period will summarize the overall findings.

Dissemination Plan

Events

Open Houses – Cal Poly Photobioreactor Facility
GreenSys 2009 (June 14-19, 2009, Quebec City, Canada)
National Biodiesel Conference and Expo (multiple times; locations and dates TBA)

Publications

Fact sheets (summary sheet, photos) for circulation purposes.
Interim reports.
Annual reports.
CSU Agricultural Research Initiative (ARI) website.
Articles in ASABE *Resource Magazine*.

Newsletter articles
CSU Agricultural Research Initiative (ARI) Final Report.

Publications in Peer-Reviewed Journals

Article on the economic feasibility of photobioreactors in general, comparing different systems.
Article on the first conducted research at Cal Poly, i.e. "Temperature Influence on *Haematococcus pluvialis* Cultivation in a Tubular Photobioreactor".
Article on the carbon dioxide dosing of a tubular photobioreactor.
Article on the artificial lighting of a tubular photobioreactor.

A number of other scholarly articles will be published in peer-reviewed journals, as further data become available.

Presentations

Updated Internet presentation on Cal Poly Controlled Environment Agriculture and Energy Working Group homepage (www.brae.calpoly.edu/CEAE.html).
Poster walls (summary sheet, photos, and principles) in BRAE Department, at Cal Poly Photobioreactor Facility, CAFES Display, and other places on campus as appropriate.

Impact/Industry Support Statement

Photobioreactors have two main functions: i) producing biomass in the form of algae, and ii) taking up of carbon dioxide (CO_2) from the atmospheric environment to grow algae. CO_2 is the most emitted greenhouse gas; and therefore, it is widely responsible for global warming and its consequences. About 85% of the released CO_2 in California come from fuel combustion. Other sources of CO_2 emission in California include production of ethanol, cement, lime and waste combustion (Climatechange CA, 2005).

Companies are not simply allowed to release CO_2, and they have to pay for every emitted ton of CO_2. Different scenarios estimate a CO_2 price of \$15 – \$95 per ton (Spicher, 2008) in the coming years. It is currently about \$10 per ton of CO_2. Larger systems are able to utilize about 150 tons of CO_2 to produce 100 tons of dry biomass per day. The dry biomass is pressed afterwards, and then, the end products, algae vegetable oil and algae cake are obtained. Vegetable oil can be converted to biodiesel, and the market price for vegetable oil is currently about \$3.00 per gallon. The algae cake is worth about \$3.50 per kg and highly demanded by agriculture and food industry. Algae cake is highly nutritious and used as a food supplement and feedstock for animals (AlgaeLink, 2007).

From these statements, one can easily see that the feasibility of photobioreactors is mainly dependent on the algae productivity and energy consumption during the algae production and processing. Revenue is generated simply by operating the plant; that is, from the biological sequestration of greenhouse gases, and marketing the value-added products (biodiesel, algae cake, and others).

Benefits for California and the U.S. Industries:

This project and the resulting outcome will be a major contribution to the CO_2 emitting industry (power plants, ethanol production, cement production, lime production, waste combustion, etc.) in California and elsewhere. Industrial companies will have the possibility of testing their flue gases (or other exhausts) in our system, and experience the productivity and value of photobioreactors.

Cal Poly will be able to provide business concepts and integration models for their processes. The benefits of photobioreactors shall be made visible. A new technology base will be created for a new biofuels industry within California and the U.S.

The existing companies are not the only ones, which will benefit from our applied research. One of the long-term objectives of this initiative is to support the development of an entire industry of Algae-to-Biofuels in California and the U.S. For example, supporting biodiesel or ethanol plants to change their feedstock to algae, or helping power plants in analyzing their potential are just to name a few. A photobioreactor market and distribution will be needed and accomplished in about 5 to 10 years after the trial phase has been overcome. A huge potential is to be expected – a multi-billion dollar industry can emerge. Theoretically, if all emitted CO_2 in California (360 MMT CO_2, (Climatechange CA, 2005)), for instance, were to be converted into algae biomass through photobioreactors, photobioreactors with a total sales value of $35 billion would be needed (AlgaeLink, 2007). Approximately 124 million tons of dry biomass per year could be generated in this way with the known conversion rate of algae. Algae strains for biodiesel production contain an average of 40% oil in their dry weight. Turning this 40% oil content into biodiesel, with some losses in conversion, results in 13 billion gallons of biodiesel per year. The potential is clear for both California and the U. S. in general even though this is just a theoretical approximation.

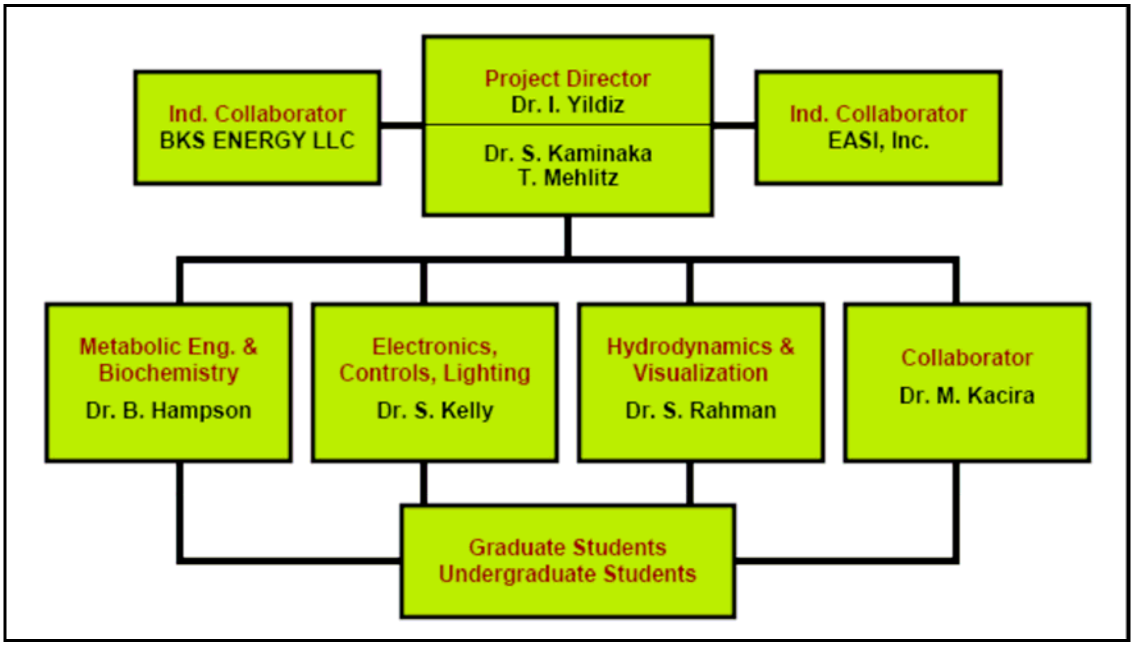
Benefits for California and the U.S. Agriculture:

Photobioreactors make it possible to supply biomass without impacting the cost of agricultural land, competing with food production and harming the environment. Co-production of biofuels and animal protein (algae cake) makes this environment friendly and resource efficient system a very attractive alternative. Algae can be grown in photobioreactors in the desert or on any other marginal land. Irrigation is not needed; water use efficiency, therefore, is much higher. The water (may even be wastewater) in the photobioreactor can be reused over and over again, conserving the water resources, and essentially making the water losses zero. Mass production of algae will also reduce the global warming potential due to reduced CO_2 emissions, hence this will help conserve our already scarce water resources, and make California and the U.S. agriculture more resource efficient. As a result, the Nation will be able to sustain its production activities while the supermarkets and residents keep enjoying locally grown produce and sustained food prices.

Benefits for California and the U.S. Residents:

This technology reduces greenhouse gases significantly by the uptake of CO_2. This is a major step to reduce global warming and enhance a cleaner environment. All the residents will benefit from a much cleaner and sustained environment. Since the feedstock (corn, soybean, etc.) prices for bioenergy (ethanol and biodiesel) is rising and will rise more in the coming years due to the increased demand, algae production is one way of meeting the demand by producing a cheap alternative feedstock for biodiesel, ethanol, and even biogas production. Algae feedstock will help replacing fossil fuel based transportation fuels and also keeping fuel prices low. Furthermore, the growing demand for biofuels will create thousands of new jobs nationwide since new companies will need to be established, and the existing ones to be expanded to cope with the demand. New manufacturing, consulting, installation and maintenance companies will emerge not only generating new employment opportunities, but also more money in circulation. Algae grown in photobioreactors will probably be the one and only major source of feedstock for feasible biofuels production in the years to come. Also, the Nation will be able to sustain its food production activities while the residents keep enjoying locally grown produce and sustained food prices.

Staffing



Dr. Ilhami Yildiz is a faculty member in BioResource and Agricultural Engineering Department, California Polytechnic State University. He is a Controlled Environment Agriculture and energy systems engineer. Dr. Yildiz, the Project Director, is responsible for supervising all project activities and ensuring that the objectives are completed within the project period and budget.

Dr. Stephen Kaminaka is a faculty member (half-time) in BioResource and Agricultural Engineering Department, California Polytechnic State University. He is responsible for coordinating and facilitating project activities and aiding in evaluating project progress, meeting agency requirements, and dissemination.

Mr. Thomas Mehlitz is a graduate (M.S.) student in BioResource and Agricultural Engineering Department, California Polytechnic State University. He is working closely with Dr. Yildiz and Dr. Kaminaka for coordinating and facilitating project activities and aiding in evaluating project progress, meeting agency requirements, and dissemination.

Dr. Shaun Kelly is a faculty member in BioResource and Agricultural Engineering Department, California Polytechnic State University. He is in charge of electronics, controls, and lighting.

Dr. Brian Hampson is a faculty member in Food Science and Nutrition Department, California Polytechnic State University. He is responsible for algae microbiology and biochemistry.

Dr. Shikha Rahman is a faculty member in Civil and Environmental Engineering Department, California Polytechnic State University. She is in charge of hydrodynamics and visualization.

Dr. Murat Kacira is a faculty member in Agricultural and Biosystems Engineering Department, University of Arizona. He is collaborating with the Cal Poly team by serving as a bridge between the two institutions. This collaboration will potentially lead to a joint graduate program.

Cal Poly Graduate and Undergraduate Students will execute specific research activities, and be responsible for data analyses, and preparing reports.

BKS Energy LLC and ***Energy Alternative Solutions, Inc.*** are the industrial collaborators of this initiative. Both are California based companies practicing business in the biofuels industry. They provide cash and in-kind contributions to the project.

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