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TITLE: ALGAL BIOFUELS AND THE ENERGY-WATER-ENVIRONMENT NEXUS

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Title: Algal Biofuels and the Energy-Water-Environment Nexus

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Background (1 page)

The economic well-being of the modern world is closely tied to reliable sources of affordable energy. Volatility in the petroleum markets and energy security concerns have motivated renewed federal investment in renewable energy R&D. The U.S. Energy Independence and Security Act of 2007 established a production target of 36 billion gallons of advanced biofuels by 2022 with separate volume requirements for each category of renewable fuel. To be classified as an renewable fuel, life cycle analyses (LCA) must be used to insure that fewer greenhouse gases are emitted compared to the petroleum a renewable fuel replaces. Finally, sustainable production of bio-based fuels can not compete with food production for fresh water, nutrients, or land. These considerations define and constrain renewable energy production within the nexus of energy, water and environmental sustainability.

One appropriate vehicle integrating the energy-water-environment nexus is microalgae-based production of renewable electricity, transportation fuels and novel biochemical feedstocks. We envision a cradle to cradle approach in which industrial wastes are seen as valuable resources and commodities which present economical solutions to environmental problems (Braungart, 2002). The integrated solution will produce beneficial products out of both the liquid and the solid waste streams. NM investigators have developed individual technologies (both patented and non-patented) that address algal production processes to maximize the beneficial return from waste management. From a logistical standpoint we argue that renewable energy production can best evolve in a local production/local use context that minimizes transportation inputs into LCA equations. The integrated solution will produce beneficial products out of both the liquid and the solid waste streams. NM investigators have developed individual technologies (both patented and non-patented) that an be integrated with algal production processes to maximize the beneficial return from waste management. Significant knowledge gaps to be addressed include:

a) assessment of N.M. water resource availability and suitability for algae production to include fresh, brackish, saline, produced waters plus agricultural and municipal waste waters,
b) solar-driven desalination to reduce consumptive use of fresh water in algae cultivation
c) assessment of geothermal waters for improved cold-weather algae cultivation
d) development, testing and risk assessment for efficient nutrient recovery from agricultural and municipal waste steams
e) creation of stable, sustainable and evolvable agronomic systems for cultivation of microalgae with efficient monitoring and crop-protection schemes
f) development of efficient extraction and conversion processes for fuels and high value commodities compatible with local production and use logistics
g) techno-economic modeling in support of process integration
h) development of strategies for addressing socio-economic and regulatory hurdles

Compared to first-generation biofuels, feedstocks derived from microalgae are characterized by higher solar energy yield, the potential for year-round cultivation in arid and semi-arid climates on non-arable land and the ability to grow in brackish, saline and produced water sources (Brown & Zeiler, 1993; Dismukes et al., 2008; Li et al., 2008; Posten & Schaub, 2009; Raja et al., 2008; Williams et al., 2009). Algal oil can be refined into transportation fuels for cars, trucks, tanks, helicopters and jet airplanes. Critically, microalgae feedstock cultivation can be coupled with waste streams to sequester CO_2 from point sources such as coal fired power plants or natural gas amine-based CO2 stripping plants, while utilizing nutrients from wastewater sources (Chisti, 2008; Li et al., 2008; Schenk et al., 2008; Sheehan et al., 1998; Wijffels & Barbosa, 2010). Furthermore, microalgae have much higher areal productivities than oil seed crops. The theoretical maximum production of oil from microalgae has been calculated at 354,000 $L \cdot ha^{-1} \cdot a^{-1}$ (38,000 $gal \cdot acre^{-1} \cdot a^{-1}$) (Weyer et al., 2009), but experimental data have suggested a near-term realizable production of 46,000 $liters \cdot hectare^{-1} \cdot a^{-1}$ (5000 $gal \cdot acre^{-1} \cdot a^{-1}$), compared to 2,533 $liters \cdot hectare^{-1} \cdot a^{-1}$ (271 $gal \cdot acre^{-1} \cdot a^{-1}$) of ethanol from corn or 584 $liters \cdot hectare^{-1} \cdot a^{-1}$ (62.5 $gal \cdot acre^{-1} \cdot a^{-1}$) of biodiesel from soybeans (Chisti, 2007; Pimentel, 2005; Pradhan et al., 2008). These observations support two important conclusions a) there is much room for improvement in algal productivity and b) there is little concern about resource competition between food and renewable fuel production.

Research Questions (2-3 pages)

We propose to develop compatible technologies for producing electricity, biodiesel fuel, new sources of animal feed and high-value biochemicals while recycling waste water and associated nutrients that cause environmental degradation (see Figure 1). The algal biofuel plan is specifically designed to contribute to the profitability of large agricultural enterprises (e.g. dairies and dairy collectives) with significant waste disposal problems. The overall scheme is designed for maximum recycling of materials with energy upgrades provided by photosynthesis. New Mexico is the 9th largest dairy producing state in the U.S. but dairy operations are under tight watch by the NM Environment Department for groundwater and EPA Region-6 for surface water. Texas, New Mexico and Arizona combine to form the third largest milkshed in the US with the highest production per cow and largest herd size in the nation.

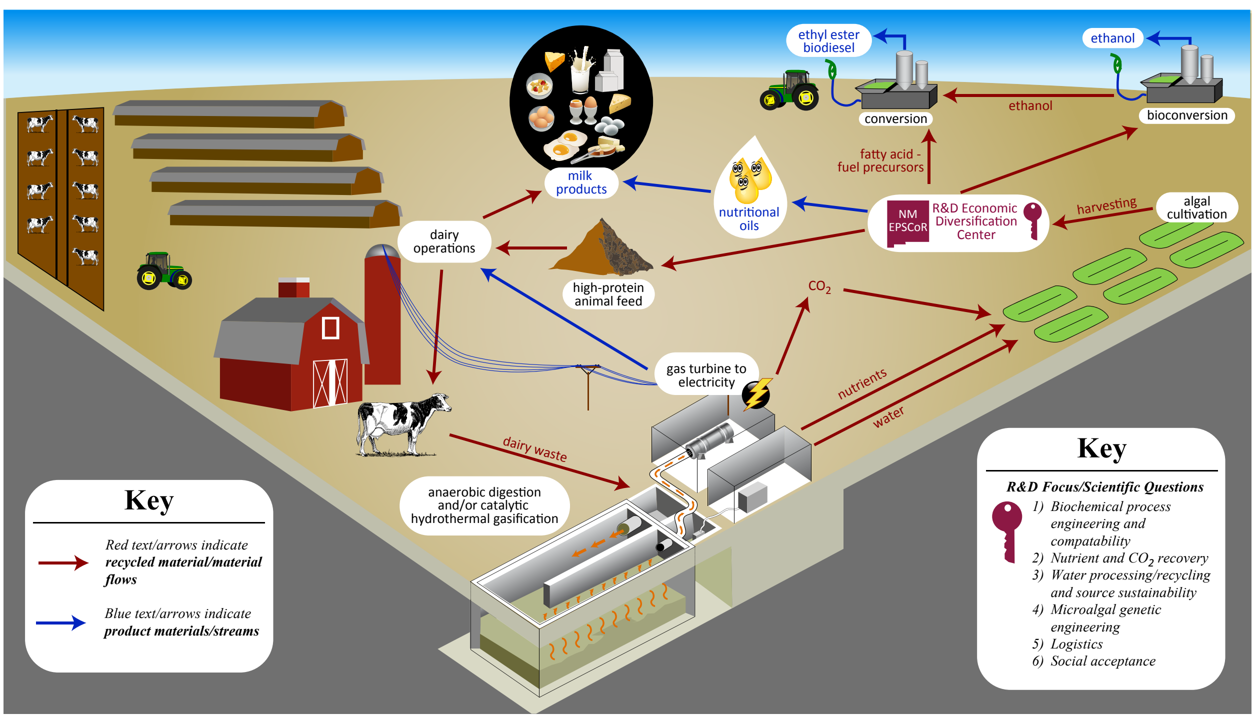

Figure 1. Scheme for linking waste treatment to renewable energy and co-product production from microalgae. *Red arrows indicate recycled material flows and blue arrows indicate product streams. Key decision points revolve around process compatibility and overall techno-economic viability – bold text. Only a few of dozens of examples of biobased products are shown in the upper portion of the diagram.*

The basic scheme in Figure 1 is an example of on-farm resource integration with wide application to feedlots, swine and poultry production and aquaculture enterprises. This integration is not typical of alternative energy projects today. Local production-and-use logistics would minimize environmental impacts and carbon lifecycle effects. The technology will directly benefit existing industries, promote rural economic development and environmental sustainability.

Process Development	1. Improve photosynthetic efficiencies, cultivation practices and crop protection; harvesting and extraction; gasification/liquefaction; fuel conversion (Sayre Lammers, Van Voorhies, Schaub, Deng, D. Hanson, Boeing, Schuler, Yan) 2. Water, CO2 and nutrient logistics and modeling (Hagevoort, Schuler, Bowles, Starbuck, Khandan, Samani, Steele) 3. Geothermal water utilization in support of algae cultivation (Crossey, Chermak & Karlstrom, UNM; Person, Wilson, NMT; Caiti Steele, NMSU 4. Chemical and biological ecology of stable algae cultivation systems including assessments of health risks posed by the use of waste water nutrients (Ivey, Schuler, Unc, Hanson, Bixby, Boeing, Lammers, Schaub) 5. Process control: metabolite analysis supporting algae harvest, extraction and conversion; fuel analysis and quality control; sensor technology support for #3 (Schaub, Sayre, Deng). 6. Techno-economics of products and co-products as a function of scale (Hagevoort, Ivey, Starbuck, Deng, Lammers)
Water, Waste, Sustainability	1. Land, water sustainability analysis for various energy product and co-product models for algal biofuels and associated workforce development needs. (Starbuck, others) 2. Identify and manage any process-related environmental risks to air, water, soil (TBD). 3. Address regulatory and resource constraints to advanced algal agronomic practices including GMO use, animal feed, co-products. (Hagevoort, Unc, Ivey, Sayre, Lammers) 4. Evaluate non-algal fuel feedstocks from range, agriculture and forestry practices with respect to CO2 flux, water use, environment and associated workforce development needs (J. Mexal, Z. Samani, A. Hanson)
Scaling and Integration	1. Scale up barriers facing advanced algal agronomic practice development, minimizing fresh water use with alternatives; produced, brackish, and solar-driven desalinated water supply logistics and techno-economics (Steele, Rosenthal, Schaub) 2. Process Integration: Cultivation, Harvesting, Extraction, Gasification, Fuel Conversion (Khandan, Deng, Durvasula 3. Technology Integration: Biodiesel/methane/ethanol/RDF for generation of energy, fuels, and beneficial by-products, such as nutrients/compost/animal feeds, while minimizing the impact on the limited water supply and the environment. (A. Hanson, Samani) 4. Workforce development, extension and outreach (agriculture and engineering, social acceptance issues, TBD)

Table 1. Technical and socioeconomic gaps and scientific questions are organized into three categories. Investigators identified thus far with each question/topic are listed in parentheses.

Next steps are for the teams identified in Table 1 to prepare statements of scientific goals and objectives, define their approach to problem solving, develop metrics for measuring outcomes, and seriously address the scientific and technical scope in light of budget resource allocation to produce winning overall proposal.

Relevance to Energy-Water-Environment Nexus

The critical requirements for algae cultivation are sunlight, water for cultivation and processing, inorganic nutrients and carbon dioxide. New Mexico's greatest asset for biomass production is its exceptionally high annual solar radiation density (9 $kWH/m^2/day$). Annual solar fluxes in New Mexico are nearly four times the average solar fluxes in the northeast US. With high solar flux come negative trade offs: low precipitation and cloud cover, high evaporation rates and winter time radiant heat losses. Non-potable water sources will be critical to growing an algal biofuel industry in the state while avoiding competition for scarce fresh water. The use of marine algae will facilitate a beneficial economic use of brackish and produced waters available in the state for production of algae. Robust, high lipid producing algae have been successfully grown at NMSU in 20-35 ppt salinities. Nevertheless, evaporative water loss in algae production ponds must be made up from some source. Pan evaporation rates in excess of 6-7 feet per year are not unusual in the southern part of the state. Furthermore, up to ten thousand acres of flat land will be required for complete recycling of the carbon and inorganic nutrients from the dairy herds of New Mexico. Expected algae oil yields range from 2,500 to 5,000 gallons per acre per year. Improved estimates for land and water requirements will be developed as additional data emerges. Options for replacing water lost to evaporation are the precious fresh water or desalinated water preferable driven by renewable solar power. Finally, the energy-environment link for this project link is through combustion of gasified animal wastes coupled with nutrient and CO2 recovery as shown in Figure 1. Electricity, liquid fuels algae-derived biochemical feedstocks will be the economic drivers will local production and use logistics proposed to minimize the overall carbon footprint and maximize sustainability.

Enhancing Competitiveness for NSF Funding

Significant infrastructure improvements will be proposed to address the enhanced competiveness goal of the NSF EPSCoR program. The existing algae cultivation facility located at the NMSU Fabian Garcia Agricultural Science Center in Las Cruces provides an advanced starting point with a 4000 L outdoor photobioreactor and four 1,000 L raceway ponds for cultivating algae and a high-speed centrifuge for harvesting biomass. Additional cultivation capacity is needed along with alternative, low-energy harvesting systems based on advanced filtration systems (ceramics, PVC), dissolved air floatation, or flocculation systems. We will investigate both wet and dry oil extraction methods as there are advantages and disadvantages of both. Additional infrastructure requirements will emerge as this white paper evolves into a full proposal balancing project scope and budget.

Identification of other Partners

We anticipate that private sector partners may play a key role in full development of this proposal. Solix Biosystems (Fort Collins, CO) produced the 4,000 L photobioreactor at NMSU and may be interested in providing additional systems and services at lower than market costs in return for licensing opportunities or joint development projects. Sapphire Energy has already made significant investment here in the form of two algae production facilities in the state (Las Cruces and Columbus New Mexico). Other partners in the academic community remain to be identified to fill gaps in Table 1. Efforts to recruit qualified researchers to fill those gaps are ongoing.

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