# BioEnergy: A Global Sustainability Effort

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## Overview: Sustainable BioEnergy is a Global but Regionally Defined Effort

BioEnergy is a global commodity expected to increase in demand as the global population rises. Renewable Fuel Standard mandates require increased domestic production of biofuel from biomass. However, while industrialized nations focus on liquid biofuel development, half of the global population continues to rely primarily on solid biomass combustion to fulfill household energy needs. Technologies enabling bioenergy use are available, but scaling-up in a sustainable manner requires a thorough, multidisciplinary approach combining elements of photosynthesis, combustion, and resource economics research. Our research foci address challenges facing the development of sustainable BioEnergy, while also highlighting these interdisciplinary overlaps (Figure 1).

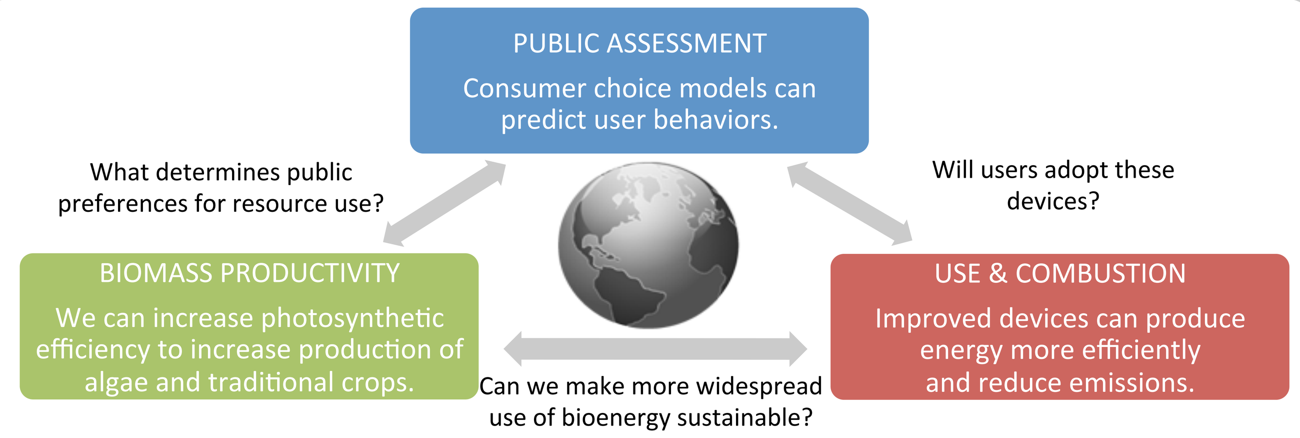



**Figure 1: Research Overview.** Interdisciplinary questions are shared between disciplines, and individual research efforts are highlighted below. These diverse efforts may inform a variety of bioenergy applications.

## Current Research Efforts

### Biomass Productivity

*Characterizing photosynthetic efficiency and carbon metabolism in model algae*

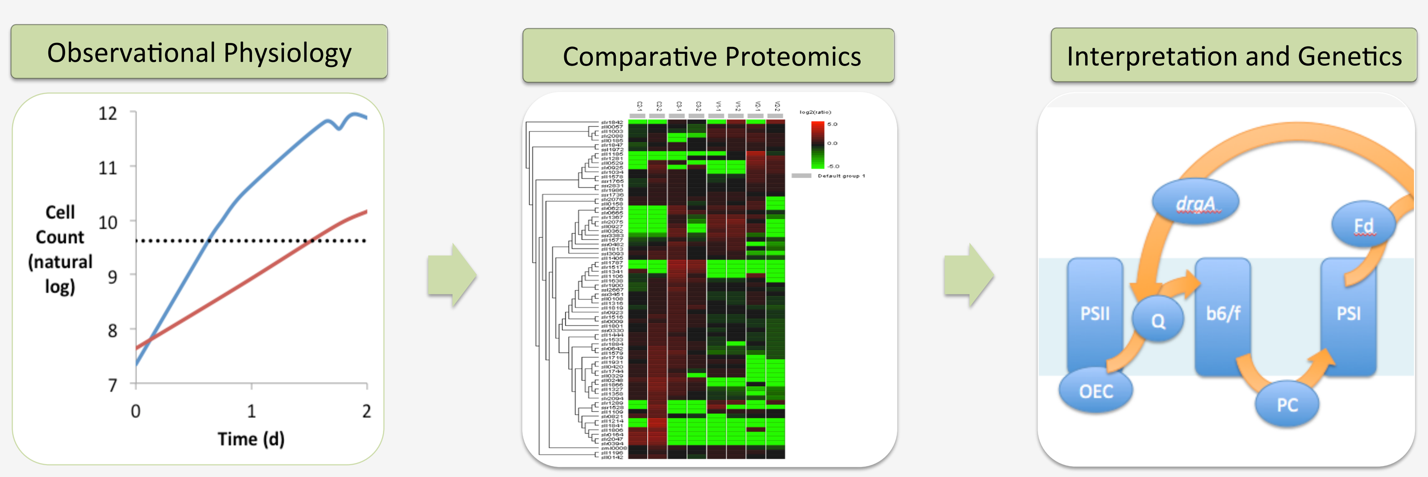



**Figure 2: Identification of divergent protein abundances between laboratory and photobioreactor-like light conditions.** Representative exponential growth curves of *Synechocystis* sp. PCC 6803 under continuous (solid blue) or rapidly-oscillating (solid red) light (A). The rapidly-oscillating light regime is a simple model for algal growth in a photobioreactor experiencing cell shading. Despite exposure to the same total light quanta, the maximal growth rate of cultures in the rapidly-oscillating light regime were nearly half that of the continuous regime. Proteins were harvested during exponential growth (dashed black) and subsequently prepared for LC/MS/MS. Label-free quantitation compares the relative intensities of peptides matched to individual proteins, generating a log2 transformed heat map for differentially abundant proteins (B, PEAKS 6.0). The original protein list (n=75) was filtered for statistical significance (student's t-test, p ≤0.05), resulting in a final list of 25 differentially abundant proteins. Many of these proteins were photosynthesis-related and oxidoreductases (C).

Algal biomass has attracted attention as a promising source for third-generation biofuels fulfilling advanced fuel requirements under the Renewable Fuel Standard. Economic and environmental costs are reduced as algae require a lower nutrient and water footprint than terrestrial crops (1). However, productivities of large-scale cultivation of algae is hindered by cell shading (2). This phenomenon is due to microalgae harvesting photons when cells are most exposed to light to the exclusion of cells deeper in the water column. Paired with physical mixing, microalgae are continuously acclimating to rapid light oscillations.

A simple model of this rapid light oscillation resulted in a major reduction in maximum growth rate (red) when compared to continuous illumination (blue) despite the same net light intensity (Fig. 2A). Profiling the proteome, many proteins that were differentially abundant between these light regimes were photosynthetic in nature, particularly oxidoreductases, which facilitate electron transfer. Two bottleneck enzymes in $CO_2$ fixation were more abundant in continuous light, including *GlpX*, which has been transformed into terrestrial crops and increased biomass phenotypes (3). Several hypothetical proteins identified from these findings inform future efforts for sustainable biomass production in algae and terrestrial crops.

### Use & Combustion

*Optimizing solid biomass cookstoves for distributed use in the developing world*

Solid biomass is used as a primary fuel source by half of the world's population (4). Improved biomass cookstoves are designed to make more efficient use of solid biomass fuel and reduce user exposure to emissions of carbon monoxide (CO) and particulate matter (PM) (5). Semi-gasifier cookstove designs have received attention recently due to their potential to achieve very low emissions (5, 6, 7). These cookstoves burn solid biomass by gasifying the solid fuel and then mixing the gases produced with additional air to create a secondary combustion zone (8).

Laboratory testing of semi-gasifier cookstoves has shown that these designs are capable of achieving low emissions, but that performance also tends to be variable, poor under transient conditions, and dependent on fuel type and use patterns (Fig. 3). Each stove was operated at high power to boil 5 L of water and emissions were collected in a fume hood. CO concentrations were measured with exhaust gas analyzers and PM emissions were collected on filters and measured gravimetrically. These experimental results have illustrated that many aspects of the combustion process taking place inside these stoves need to be understood in more detail.

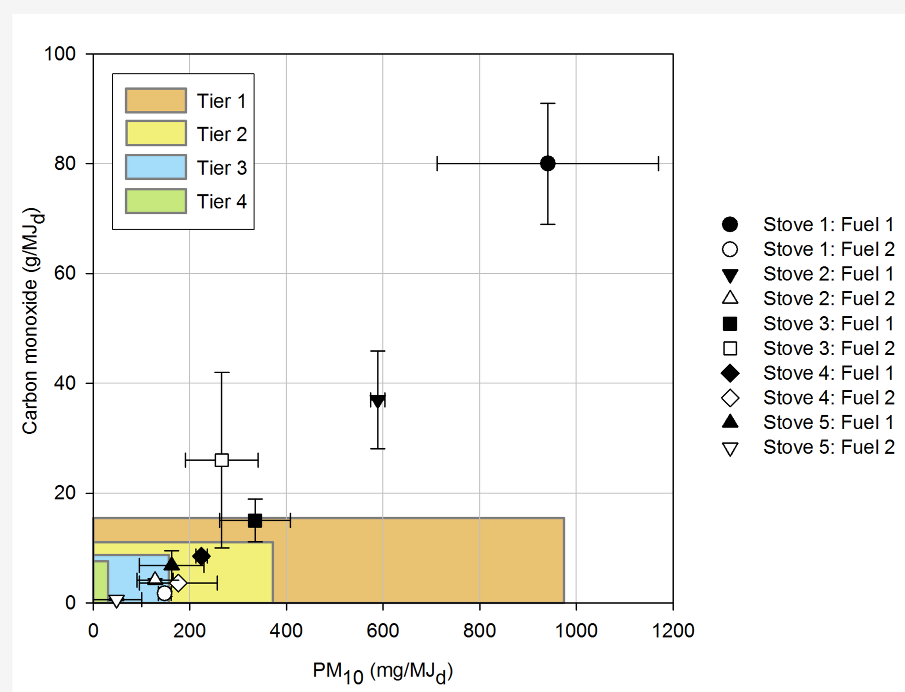
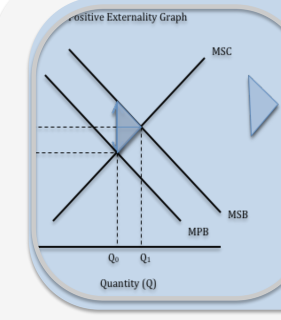



**Figure 3: High-power carbon monoxide and particulate matter emissions per megajoule of useful energy delivered compared to biomass cookstove performance tiers for several semi-gasifier cookstoves.** Emissions from semi-gasifier cookstoves were very low is some scenarios; however, performance varied widely with stove design, fuel type, and user behavior. Higher tier numbers represent better performance.

Research aimed at achieving this understanding is now beginning. As part of the project, the gases produced during the gasification process will be sampled and analyzed, high-speed planar laser induced fluorescence of the OH radical will be applied to the secondary combustion zone, and a model of semi-gasifier cookstove operation will be constructed based on theory and experimental data.



### Public Assessment

*Determining optimal use of shared resources with choice experiments*

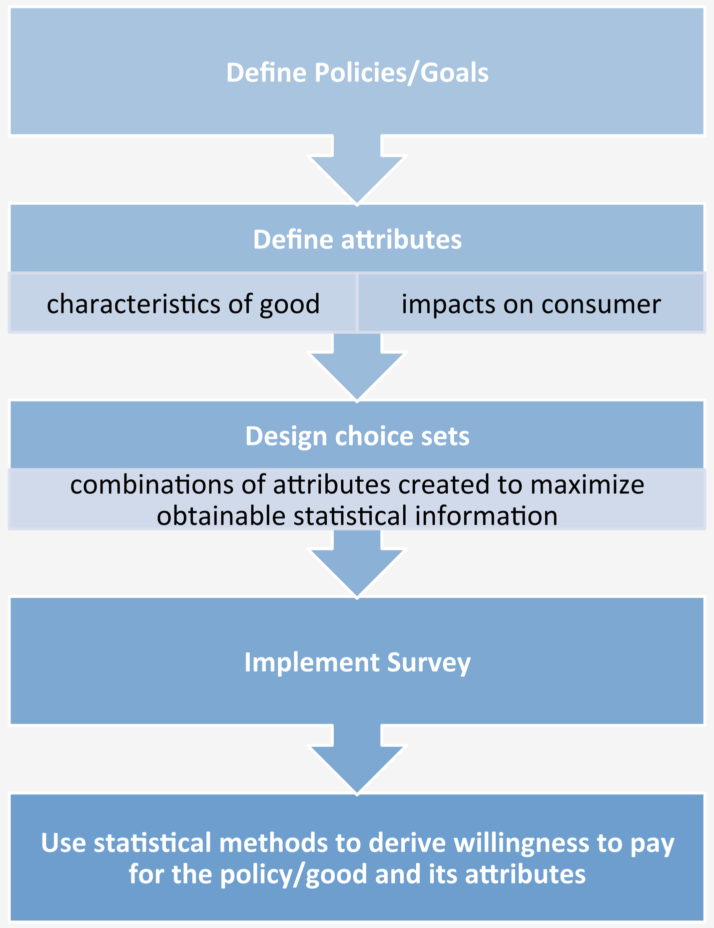



**Figure 4: Assessment Workflow.** Policy options are defined in terms of "attributes," or potential impacts and characteristics of the policy. Experimental design methods are used to bundle the attributes into choice sets. Using econometric techniques based on random utility theory, willingness to pay for attributes for a policy can be derived from a consumers decisions among attribute bundles within the choice sets.

Creating policies for sustainable resource use requires an understanding of how consumers choose to invest in "resource-conserving technologies," meaning any technology that decreases resource usage compared to the status quo. Proponents of resource-conserving technologies assume consumers' only obstacles to purchase of these devices, as long as they are cost-competitive with traditional technologies, are information and access. Historically, however, there has been a large gap between investment in these technologies and policymakers' expectations (9). For instance, many consumers delay investment in water/energy-efficient appliances and hybrid-fuel vehicles at the household level. Similarly, at the scale of the utility, managers tend to favor known, traditional supply options as opposed to bioenergy and renewable-resource portfolios. Consequently, economic and policy assessments are needed to determine the reasons for lack investment.

By generating data through both survey and laboratory-based experiments based on microeconomic consumer theory, we can better understand the reasons consumers either do or fail to adopt new technologies. For instance, simulating economic markets using computer-based experiments can be used to see what types of information and/or price-related "shocks" are needed to induce investment. Using Discrete Choice Modeling (10), we can elicit consumers' preferences for different energy and water resource portfolios as a function of attributes (cost, environmental effects, sustainability) of varying supply options. This research gives us a better understanding of consumers' preferences for resource usage and the likelihood consumers will "buy in" to the technologies developed by researchers in the laboratory sciences.

## Conclusions

**Sustainable Bioenergy faces a diversity of challenges which provide opportunities for innovation as global BioEnergy efforts expand, defined by their regional needs.**

- Algae can provide sustainable biomass, but cell shading hinders large-scale productivities.
  - Preliminary systems biology efforts have not only solidified existing molecular strategies but also identified novel targets as well.
- Half of the global population is already using a form of bioenergy as their primary energy source; however, this practice typically uses fuel inefficiently and results in adverse health effects.
  - Research focused on semi-gasifier cookstoves can enable the development of stoves that are efficient, affordable, and improve indoor air quality.
- There is uncertainty regarding whether consumers are willing support or pay a premium for bioenergy projects.
  - Non-market valuation methods like choice experiments can be used to solicit consumers' preferences for new technologies.

## Acknowledgements

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