# A White Paper on

# Energy and Fuels:
# Strengths and Voids in the
# Viterbi School of Engineering

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## *A. Background and Issues*

The abundance of oil supply and the attendant low prices have been the main reasons behind past policies that did not pay close attention to the serious problems that the world is facing at present. During the last 20 years or so, various administrations felt that energy and related issues were not to attract as much interest compared to the emerging “info”, “bio”, and “nano” technologies. Research and potential advancements towards new technologies that could result in, for example:

- energy conservation;
- reduction of emissions of hazardous pollutants;
- reduction of carbon dioxide emissions;
- more efficient oil recovery;
- production and utilization of alternative fuels;
- oil-independence;
- improvements of nuclear energy production and waste treatment;
- advancements in solar and wind energy technologies;
- improved energy storage and management;
- alternative (to the combustion engine) energy conversion devices;

have not been at the top of the priority list of government budgets. This is supported by the fact that funding in these areas was notably-to-severely cut or entirely eliminated towards the end of last century in agencies like DoE, NASA, DoD, and EPA to name a few. It is surprising that administrations did not consider what would be the near- and long-term effects of:

- the instability in the Middle-East;
- the economic growth of China and India, who do and will need the same oil that the rest of world needs;
- air pollution;
- the serious, by all measures, indications that global warming is happening.

The reduced funding in energy-related disciplines had a major impact on academic research. Several researchers realigned their activities in different directions. As a result, much expertise was lost and the interest from graduate students to pursue such careers was diminished. Within this funding environment, however, a number of leading US Universities have already identified the role that energy will play during the 21st century and have established initiatives even before the current crisis became apparent to the world. This proactive approach was based on the accurate assessment that and energy (fuel) crisis is about to occur and will be here to stay regardless of the fluctuations in oil prices and availability. Additional factors were the environmental impacts of energy conversion processes, mainly combustion. For example, MIT has notable activities in energy economics since the 1970’s and in environmental economics since the 1990’s. Stanford established a Global Climate and Energy Project in 2002 and has already attracted major funding from Exxon-Mobil, General Electric, Schlumberger, and Toyota. Other academic institutions followed. For example, Chevron-Texaco is supporting “green” energy technologies at UC Davis. Only few weeks ago, a "strategic partnership" was announced between British Petroleum (BP), U. C. Berkeley, the University of Illinois at Urbana-Champaign, and the Lawrence Berkeley National Laboratory for biofuel research, with a total commitment by BP of half a billion dollars!

In 2005 USC established the Future Fuels and Energy Initiative (FFEI) aiming at reducing the reliance on fossil fuels. At this point, it appears that most major energy-related companies have committed to other academic institutions that have started this process earlier. USC needs to capitalize on its strength and focus on niche areas that one hand will be unique and on the other will be able to attract the attention of major foundations, industry, and the government both at the state and federal levels.

Among all USC academic units, the Viterbi School of Engineering (VSoE) can play a central role towards the success of the University’s initiative in the area of energy. This is because the VSoE can bridge the gap between pure science and applications by advancing and implementing the science that is required to solve the very difficult problems that the world is facing, namely to conserve, to notably increase the efficiency of energy conversion processes, to produce “green” energy from renewable sources, and to achieve energy independence. These ideas have been around for the best part of last century but it is clear that scientists have not been able to break certain barriers and result in breakthroughs. One can only recall the efforts in the area of nuclear fusion that despite the excitement and enormous potential has been a disappointment. Similar comments can be made regarding the failure to achieve breakthroughs in solar and wind energy utilization, both being the most “green” and environmentally benign types of energy.

## *B. How Do non-VsoE USC Academic Units Position in the Energy Area?*

USC has established activities in the area of energy. Such activities can be found mainly in the College of Letters, Arts, and Sciences (College), the Viterbi School of Engineering (VSoE), and the School of Policy, Planning, and Development (SPPD). Energy-related activities may be also found in the Keck School of Medicine, the Marshall School of Business, and the School of Architecture.

The contributions of the College are mainly on fundamental chemical and biological processes that could be used in energy production. For example, there are major activities on fuel cells based on methanol (Olah and Prakash), microbial fuel cells (Nealson) that could utilize biomass and waste. There are also notable research activities in carbon-based fuels and new energy resources (e.g., Haw, Jung, Olah, Periana, Prakash) as well as in solar energy (e.g., Thompson).

SPPD (e.g., Giuliano) contributes to the energy field through METRANS, the National Center for Transportation Research. The center conducts interdisciplinary research and its mission is to solve transportation problems of major metropolitan areas through an integrated approach that draws on the disciplines of engineering, policy, planning, public administration, science and business.

The School of Architecture activities include research and realized projects in solar, zero-fossil-energy, passive, low-energy, and plus-energy buildings, sustainable urban re-development, and experimental solar architecture (e.g. Spiegelhalter).

The Keck School of Medicine activities are focused mainly on the health effects produced by energy conversion processes, such as internal combustion engines (e.g., Gauderman and coworkers).

The Marshall School of Business has the expertise to address a variety of issues related to the economics, marketing, and management of energy.

## *C. How Does VSoE Position in the Energy Area?*

Among all USC academic units, the VSoE appears to play a more profound role in the energy discipline by promoting both science and technology development. There is large number of faculty that is involved with notable research funding from both the industry and the government. While the VSoE has specific strengths, as it will be outline below, there are also voids that need to be filled. It is also apparent that the research activities are largely of single- or two-PI type and that no larger research teams have been successful in pursuing major energy-related funding through multidisciplinary proposals across engineering or across the University. A notable exception to this is the recently awarded MURI on microbial fuel cells that involves several faculty members from the VSoE. However, the MURI is lead by the College. Additionally, it does not appear that any effort has been made to involve non-traditional (in terms of energy) disciplines that exist in ISI, EE, and CS in energy-related efforts. And those disciplines involve faculty and centers of very high national and international visibility.

### *C1. VSoE's Existing Strengths*

Based on faculty's expertise, research interests, and funding that has been generated over a period of time, the strengths of VSoE in the area of energy can be grouped under the following six areas:

1. Air Pollution and Environment
2. Combustion Physics and Chemistry
3. Fuel Processing
4. Large-Scale Simulations of Energy-Related Problems
5. Oil and Gas Recovery
6. Power Production and Utilization

Descriptions of the ongoing research activities in each area are summarized below:

## *C1.1 Air Pollution and Environment*

Research in this area is mainly performed in:

- The Department of Aerospace and Mechanical Engineering (AME)
- The Department of Civil and Environmental Engineering (CEE)
- The Mork Family Department of Chemical Engineering and Materials Science (ChEMS)
- The Daniel J. Epstein Department of Industrial and Systems Engineering (ISE)

Current ongoing research is supported by:

1. California Air Resources Board (CARB)
2. Environmental Protection Agency (EPA)
3. METRANS Transportation Center
4. National Institute of Health (NIH)
5. South Coast Air Quality Management District (AQMD)
6. Strategic Environmental Research and Development Program (SERDP)

*Health Effects of Air Pollutants* (C. Sioutas/CEE)

Within CEE, one of our major thrust areas in the area of energy-related research is the field of air pollution. The major objective is to investigate the underlying mechanisms that produce the health effects associated with exposure to air pollutants generated by a variety of sources, such as traffic (including light and heavy duty vehicles, natural gas buses, and biodiesel vehicles), harbor and airport operations, power plants, and photo-chemically induced atmospheric reactions. The focus is on particulate matter (PM) and its gaseous precursors in the atmosphere and the goal is to understand how toxic mechanisms and resulting health effects attributable to these air pollutants vary with their source, chemical composition and physical characteristics. This work has been motivated by the emerging scientific literature liking mortality and morbidity to exposure to PM. These efforts are funded by EPA, NIH, CARB, and AQMD.

*Heterogeneous Chemistry (Including Mercury) and Dynamics of Particles and Aerosols* (D. Phares, H. Wang/AME).

USC’s existing expertise in this area applied to focus on the specific compounds of relevance to air pollution. Sophisticated instrumentation is available to determine the size and chemical composition of particles in real-time. This instrumentation involves sampling aerosols using inertial or electrostatic separation and measuring the composition using mass spectrometry, ion mobility spectrometry or both in series. Heterogeneous chemistry can be monitored using a flow reactor, following the evolution of specific compounds. This approach is commonly employed to determine particle formation rates from organic compounds and gas-phase reaction rates. The aerosol mobility/mass spectrometer can be used to determine chemical composition at a specific source. This feature may be relevant to determining the phase and oxidation state of mercury or other compounds emitted at a specific source. Also, the reaction kinetics of ambient aerosols (e.g., NaCl, $Na_2CO_3$, soot) with trace gaseous air pollutants (OH and $HNO_3$) can be studied using ESEM/EDX and FTIR techniques. Surface reaction probabilities can be obtained by detailed analysis of diffusion-kinetic coupling using analytical techniques as well as the Monte Carlo approach. Moreover, in addition to the chemistry of particles, understanding the dynamics of aerosols (including adhesion, resuspension and transport) is critical to developing inlets for aerosol analyzers, whereby particles must be stripped from a gas for subsequent chemical analysis. Tools available for such studies include optical particle counters, condensation particle counters, aerosol generation equipment, an atomic force microscope and a variety of computational tools. Unified theories are currently being developed for particle mass, energy and momentum accommodation. This work is supported by CARB and SERDP.

*$CO_2$ Sequestration in Saline Aquifers* (K. Jessen/ChEMS)

Within ChEMS, start-up government funding has been provided to investigate the sequestration of $CO_2$ in saline aquifers. Saline aquifers provide significant storage volume for reducing emissions of anthropologically generated $CO_2$ (from fossil fuel). In the context of geological sequestration, it is important to understand the time scales associated with the mechanisms that aid the immobilization of injected $CO_2$. In this research project, the time scales for capillary entrapment of $CO_2$ in saline aquifers are investigated and the goal is to develop new and accurate models for predicting amounts and rates of entrapment of $CO_2$ in brine systems under counter-current conditions.

*Life-Cycle Environmental Impacts of Fuel Production and Distribution Systems* (M. Rahimi/ISE)

Within ISE, ongoing research work involves the modeling and measurement of the life-cycle environmental impacts of fuel production and distribution systems for a number of alternative technologies. Data on bio-based fuels, hydrogen from a number of sources, wind, solar and natural gas are collected and integrated. The final goal is to identify the alternative fuels and new energy technologies that are affordable and effective in solving the problem that has been created by the life-cycle environmental impacts of traditional (fossil-fuel based) energy sources. This work is funded through METRANS.

### *Reducing Life-Cycle Energy, Waste, and Pollution in Construction Industry Using Contour Crafting* (B. Khoshnevis/ISE, M. Rahimi/ISE)

Unlike in manufacturing, the growth of automation in construction has been slow. A promising new automation approach is *Contour Crafting (CC)*. Developed at USC, Contour Crafting is a mega-scale fabrication process aiming at automated construction of whole structures as well as subcomponents. Using this technology, a single house or a colony of houses may be constructed automatically in a single run with all plumbing and electrical utilities imbedded in each house; yet each could be a different design. The immediate implication is especially profound for emergency shelter and low income housing construction.

The energy used in built structures is 40% of total US energy consumption and an average American home generates 4-7 tons of construction waste. CC has the potential for significantly reducing this energy usage by revolutionizing the way structures are built. This research attempts to document that in addition to much reduced energy cost of construction, a structure build with CC could have a significantly less energy demand, material waste, transportation demand, and better recycling potential in its entire life cycle than comparable structures build with traditional methods. Life-cycle energy use models will be designed to capture the CC equipment manufacturing, transport, and on site use of energy. These models will be extended to include the utilization phase of the structure throughout its useful life. We will include the demolition and recycling of the CC material and compare the entire life-cycle energy use with the traditional construction methods. The same analysis will include the amount of material waste in different phases and will include multiple material compositions and cement additives currently under investigation. Any reduction in these variables will translate to its correspondent reductions in energy generation, GHG, criteria pollutants, hazardous materials, and resource depletion potential.

## *C1.2 Combustion Physics and Chemistry*

Research in this area is mainly performed in:

- The Department of Aerospace and Mechanical Engineering (AME)
- The Mork Family Department of Chemical Engineering and Materials Science (ChEMS)

Current ongoing research is supported by:

1. Air Force Office of Scientific Research (AFOSR)
2. California Energy Commission (CEC)
3. Department of Defense (DoD)
4. Department of Energy (DoE)
5. National Aeronautics and Space Administration (NASA)
6. USC's FFEI

The utilization of fossil fuels in combustion engines accounts roughly for the 85-90% production of the world power. Reducing that percentage by, say, 10 or 20% points is not a feasible proposition for the immediate or foreseeable future. This does not only stem from where science and technology is today to handle it but also from the fact that economies cannot afford such rapid transitions and would collapse. One of the main reasons for this is the clear advantage of the internal combustion engine (ICE) over other alternatives based on: (1) the power output per unit weight or unit volume of the engine, (2) the energy per unit weight or unit volume of liquid hydrocarbon fuels, (3) the distribution and handling convenience of liquids, and (4) the relative safety of hydrocarbons compared to, say, hydrogen or nuclear energy. At the same time ICEs operate at an efficiency level anywhere from 25-35% and they produce emissions that can have devastating effects on the environment, humans, animals, and plants. Advancements in combustion science and technology are key towards the improvement of the efficiency and the reduction of the pollutant emissions of fossil fuel burning for the foreseeable future. Additionally, the discipline of combustion is central in assessing the performance and environmental effects of using alternative fuels in ICEs.

Within AME (F.N. Egolfopoulos, P.D. Ronney, H. Wang), the combustion processes of conventional and alternative fuels are studied at the fundamental level. The main goal is to provide understanding into the physical and chemical mechanisms that control the oxidation of fuels, as well as the interactions between physical and chemical mechanisms.

*Experiments and Reaction Models of Fundamental Combustion Properties* (F.N. Egolfopoulos, H. Wang/AME)
This research aims to provide insight into the physico-chemical processes that control the burning behavior of practical fuels that are of relevance to high-speed air-breathing propulsion. This is achieved through combined experimental and detailed numerical studies of a number of fundamental combustion properties. Experimentally, the phenomena of flame ignition, propagation, and extinction as well as flame structures of systematically chosen fuel/oxidizer mixtures are considered and characterized. The studies consider both small (gaseous) and large (liquid) hydrocarbon molecules in view of their importance towards the accurate description of the combustion behavior of practical fuels. These studies notably expand the parameter space of existing archival fundamental combustion data, and are supported by AFOSR.

*Development of Detailed and Reduced Kinetic Mechanisms for Surrogates of Petroleum-Derived and Synthetic Jet Fuels* (F.N. Egolfopoulos, H. Wang/AME)
The main goal of this research is to improve our ability to simulate fuel combustion in air-breathing propulsion devices. The immediate problems that need to be solved can be grouped into two categories: (1) understanding and quantifying the combustion properties of practical fuels used in air-breathing propulsion systems and selection of appropriate surrogate fuels; and (2) developing reliable detailed reaction models and strategies for model reduction for use in large-scale simulations. These models could then be used for large-scale, high fidelity combustion simulations critical to the design and optimization of propulsion devices. The research concerns two types of jet fuels. The first are conventional petroleum-derived “reference” JP-8 fuels. The second are non petroleum-derived or synthetic jet fuels. By considering these two types of fuels, both short-term (current fuels and systems) and potential long-term (fuel-flexible energy conversion and design) needs of air-breathing propulsion are addressed. This work is supported by AFOSR.

*Kinetic Mechanisms for Computational Fluid Dynamics* (F.N. Egolfopoulos, H. Wang/AME)
This research pertains to development of reliable kinetics models that describe the oxidation of JP-7 (a real jet fuel) and the products of its thermal cracking. This development is based on both fundamental combustion experiments and theoretical and numerical determination of rate constants for a wide range of chemical reactions. Such models will be introduced into computational fluid dynamics (CFD) codes to compute the performance of SCRAMJETS (i.e. supersonic combustors). At high flight Mach numbers, vehicles are expected to be heated and

the fuel (JP-7) will be used as coolant. As a result the JP-7 will thermally crack to smaller hydrocarbons before it enters the combustion chamber. This work is supported by STTR/DoD.

*The Development of Gas Fuel Interchangeability Criteria for Natural Gas-Fired Combustion Systems* (F.N. Egolfopoulos, H. Wang/AME)
This research is on the determination of flame properties for a wide range of conditions and the development of a combustion reaction model for alternative fuels, including synthesis gas (syngas), landfill gases, and others. The results are of importance to power generation both in terms of petroleum-independence as well as environmental benefits. Combining intelligently performed experiments and state-of-the-art modeling capabilities of the USC group, the proposed goal can be largely met and can potentially be the “industry standard” in designing combustors, addressing issues of fuel interchangeability a priori. This work is supported by CEC.

*Studies of the Combustion Characteristics of Alternative Fuels (Synthetic Fuels and Biofuels)* (F.N. Egolfopoulos/AME, T.T. Tsotsis/ChEMS)
This is a collaborative research and includes chemical kinetics, simulations of combustion processes, experimental studies of combustion processes, and reaction engineering relevant to fuel processing. Fundamental combustion experiments and kinetics modeling are performed in order to gain fundamental understanding of the chemical and transport phenomena that take place during combustion of alternative fuels used in transportation and jet propulsion. In addition to expanding a fundamental knowledge base for alternative fuels, the resulting models will be incorporated into commercially supported software to allow direct application in proprietary fuels-development and aircraft engine-research efforts. The work will generate fundamental surrogate models for combustion of jet fuels, Fischer-Tropsch fuels, and biofuels; it will result in a novel experimental methodology and fundamental flame data useful in kinetic model validation; and it will create basic understanding of fuel-molecule combustion behavior that can be used to differentiate and design new fuels. This work is supported by DoE, NASA, and the USC’s FFEI.

*Edge Flames* (P.D. Ronney/AME)
Flames subject to temporally and spatially uniform hydrodynamic strain are frequently used to model the local interactions of flame fronts with turbulent flow fields. The “laminar flamelet” concept presumes that each surface element of the flame front behaves as though it were a steady isolated front subject to uniform strain. As a step towards more realistic quantification of strain effects in turbulent

premixed flames, numerous researchers have studied “edge flames” separating burning from non-burning regions that may occur at high strain rates where portions of the flame may be locally extinguished. Experiments on both premixed and non-premixed flames are being conducted using a novel counterflow slot-jet anchored-flame burner. The importance of strain rate, heat losses, Lewis number (Le) and (in non-premixed flames) stoichiometric mixture fraction have been identified. Due to diffusive-thermal instabilities, cellular flames were observed at low Le and traveling-wave patterns were observed at high Le. Le effects also led to the formation of isolated "flame tubes" rather than continuous fronts at sufficiently low Le and high strain rates. These results indicate that "laminar flamelet" models of turbulent combustion may not be accurate at conditions approaching those where local flame quenching occurs, except possibly for single premixed flames and low-Le twin premixed flames. Improvements to existing turbulent flamelet libraries for numerical simulation of turbulent flames are being developed. This work is supported by NASA.

*Premixed-Gas Flame Propagation in Hele-Shaw Cells* (P.D. Ronney/AME)
Premixed gas flame fronts are subject to a number of instability mechanisms that affect their propagation rates and shapes via wrinkling. After the instabilities grow past the linear stage (small-amplitude), the three-dimensional, non-linear nature of the full Navier Stokes equations renders the resulting flow difficult to model even with state-of-the-art-computing resources. Consequently, we have performed experiments in a quasi-2D channel (Hele-Shaw cell) using methane and propane as fuel and $N_2$ or $CO_2$ as diluents. Upward, downward and horizontal propagation configurations were tested for varying mixture strengths and thus burning velocities. In this way the effects of buoyancy, thermal expansion, heat loss and Lewis number can be studied. Even in the absence of turbulence, flames in these confined channels propagate at about 3 times the laminar burning velocity measured in conventional laboratory experiments due to this self-generated flame wrinkling. Such behavior is observed even for downward propagating (buoyantly stable) flames have high Le (diffusive-thermally stable) due to the effects of thermal expansion and viscosity changes across the front. These results indicate that the behavior of flame propagation in narrow channels such as crevice volumes in premixed-charge internal combustion engines may be quite different from that inferred from simple laminar flame experiments. Indeed, most laboratory experiments are conducted in open geometries such as Bunsen, counterflow or V-flames, where thermal expansion can be relaxed in the transverse directions, whereas most practical applications of these experiments are in confined flames such as internal combustion engines or gas turbines where this relaxation cannot occur. A particularly noteworthy application of our studies is to crevice volumes

in internal combustion engines, because flame quenching in crevice volumes is an important source of unburned hydrocarbon emissions in these engines.  This work is supported by NASA and DoE.

### *C1.3 Fuel Processing*

Research in this area is mainly performed in:

- The Mork Family Department of Chemical Engineering and Materials Science (ChEMS)

Current ongoing research is supported by:

1. Department of Energy (DoE)
2. National Science Foundation (NSF)

*Production of Synthesis Gas and Hydrogen* (T.T. Tsotsis, M. Sahimi/ChEMS)
Within ChEMS, ongoing research involves the utilization of membrane and nanoporous materials technology to produce synthesis gas or hydrogen from a variety of fuels including coal.  Novel reactor technologies are invoked both low and high temperature.  The produced synthesis gas can be used power generation and hydrogen preferably in fuels cells.  These efforts are funded by DoE and NSF.

*Enhanced Coalbed Methane Production and $CO_2$ Sequestration* (K. Jessen/ChEMS)
Start-up government funding has also been provided to investigate the enhanced coalbed methane production and $CO_2$ sequestration.  Currently 10% of the US natural gas production, arise from depletion of unminable coal seams.  In these settings methane is primarily stored in an adsorbed state in the surface of the coal. Injection of $CO_2$ from power plants or other significant point sources can greatly improve the recovery of methane from coalbeds.  The improvement in recovery is possible due to the higher affinity of $CO_2$ to adsorb onto the coal surface that in turn allow for sequestration of significant amounts of $CO_2$.  In this research project, the dynamics of flow and sorption of multicomponent multiphase mixtures ($CO_2$/$CH_4$/$N_2$/water) in coal are investigated in order to develop accurate models for predicting the hysteretic behavior frequently observed in these systems based on experiments and molecular simulation and to investigate efficient methods to implement these models in larger scale simulations.

## *C1.4 Large-Scale Simulations of Energy-Related Problems*

Research in this area is mainly performed in:

- The Department of Aerospace and Mechanical Engineering (AME)
- The Department of Civil and Environmental Engineering (CEE)
- The Mork Family Department of Chemical Engineering and Materials Science (ChEMS)

Current ongoing research is supported by:

1. Department of Energy (DoE)

*Modeling of Stress Corrosion Cracking* (P. Vashishta, R.K. Kalia, A. Nakano/ChEMS)

To prevent corrosive effects and to predict the lifetime beyond which corrosion may compromise the safety of nuclear reactors requires that we understand the mechanisms and conditions influencing initiation, dynamics and growth rates of corrosion, i.e., all aspects of corrosion dynamics of material surfaces and interfaces. A critical technology for understanding corrosion dynamics is predictive mechanistic and atomistic simulation methods that retain chemical accuracy at macroscopic length and time scales. This project performs peta-scale type simulations with quantum-level accuracy and accelerated dynamics to study stress corrosion cracking, which will have significant impacts on safe and reliable energy and nuclear technologies. This work is supported by DoE.

*Simulations of Nanoscale Systems in Extreme Environments* (P. Vashishta, R.K. Kalia/ChEMS)

This project focuses on multiscale simulations of complex nanoparticle composite systems under extreme environments, with focuses on nanoscale coating materials in energy technologies. Specifically, the following are investigated: (1) mechanical stability and pressure-induced structural transformations in core-shell CdSe/CdS and CdSe/ZnS nanostructures, and (2) hybrid nanostructures comprising semiconductor nanocrystal quantum dot on self-assembled monolayer coated semiconductor substrates.

*Multi-Scale Modeling of Nanomaterials and Nanotechnology Processes* (R. Ghanem/CEE-AME)

It is anticipated that the next few decades will see a rapid surge in the global demand for energy. A rise in demand in the order of 15-20% has been forecasted for the coming decade alone. To this end, the oil & gas industry is firmly searching for new means to answer this growing call to deliver. The challenge involves among others adding one trillion barrels in new oil discoveries to the current world reserve, increasing the incremental recovery rates for existing fields by 20%, and adding between one and two trillions of (non-conventional) oil to the total producible global resources. A challenge of this magnitude can only be approached at new fundamental scales that are untouched before now and met by revolutionary discoveries in materials science, energy science, and engineering technology. The promise of nanotechnology provides fertile grounds for much of the needed breakthroughs. This technology (or school of technologies) allows for unprecedented control of the material world, at the nano-scale, providing the means by which systems and materials can be built and understood with exacting specifications and characteristics. This requires a rather sophisticated modeling approach given the very large range of scales that are relevant.

*Design of Large-Scale Offshore Wind Turbines* (R. Ghanem/CEE-AME, S. Masri/CEE)

Wind energy is one of the “greenest” renewable types of energy that is available. In various parts of the word (e.g. China and Europe) the efforts to developed new technologies to capture the wind energy have been intensified. Among the various options, using large-scale wind turbines at offshore locations is a desirable one. The span of such turbines can be of the order of 200-300 m, which imposes major scientific and engineering challenges. The design can be best achieved through the aid of detailed modeling of the fluid mechanics and materials behavior under extreme environmental conditions.

## *C1.5 Oil and Gas Recovery*

Research in this area is mainly performed in:

- The Mork Family Department of Chemical Engineering and Materials Science (ChEMS) as part of the Petroleum Engineering program
- The Ming Hsieh Department of Electrical Engineering (EE)
- The Information Sciences Institute (ISI)

Current ongoing research is supported by:

1. Center for Interactive Smart Oilfield Technologies (CiSoft)

Within ChEMS (I. Ershaghi), the research focuses on upstream oil and gas reservoir and production. More specifically, it involves (1) reservoir characterization with continuously recorded pressure pulsing, (2) integrated asset modeling, (3) decision support systems, (4) fracturing optimization, and (5) wellbore productivity improvement. Furthermore, research is also conducted (P. Vashishta, R. K. Kalia, A. Nakano) on the integration of high performance computing into novel history matching and simulation methods to enable a paradigm shift in oil reservoir management. These efforts are funded by the Chevron–USC Center for Interactive Smart Oilfield Technologies (CiSoft).

Within EE, CiSoft-related research includes integrated asset management for smart oil fields (V. Prasanna, R. Raghavendra). The main goal of this project is to assess service-oriented architectures, grid services and web technologies to develop software architectures for asset management.

The contributions of ISI in CiSoft include sensor networks, robotics/learning, hardware, personal safety, and data mining.

USC faculty members that also contribute to various extents to the CiSoft efforts, include V. Prasanna, J. Mendel, C. Shahbi, U. Neumann, J. Heidemann, B. Khoshnevis, and K. Jessen.

Additional input from faculty of the Department of Computer Science (CS) in the CiSoft program could be in the area of robotics.

Finally, there is ongoing research on in-situ combustion for enhanced oil recovery (T.T. Tsotsis, K. Jessen). It is largely anticipated that unconventional techniques for enhancing domestic oil and gas production will attract substantial interest over the next few years.

## *C1.6 Power Production and Utilization*

Research in this area is the broadest one and is performed mainly in:

- The Department of Aerospace and Mechanical Engineering (AME)
- The Department of Computer Science (CS).
- The Ming Hsieh Department of Electrical Engineering (EE)
- The Mork Family Department of Chemical Engineering and Materials Science (ChEMS)

In this area, the following 5 sub-areas have been identified:

1. Clean Renewable Energy Generation
2. Efficient Energy Utilization
3. Fuel Cells
4. Internal Combustion Engines, Control Systems, and Pulsed Power
5. Micro-scale power generation and propulsion

Current ongoing research is supported by:

1. Air Force Office of Scientific Research (AFOSR)
2. CalTrans
3. Center for Interactive Smart Oilfield Technologies (CiSoft)
4. Defense Advanced Research Projects Agency (DARPA)
5. Department of Defense (DoD)
6. Department of Energy (DoE)
7. METRANS Transportation Center
8. National Aeronautics and Space Administration (NASA)
9. National Science Foundation (NSF)
10. Nissan Corporation
11. NOCO Energy Corporation (NOCO)
12. Office of Naval Research (ONR)
13. Southern California Edison
14. USC’s FFEI

### *C1.6.1 Clean Renewable Energy Generation*

Solar energy is ultimate source of much of the energy currently used. At present we mostly use solar energy by burning the fossil fuels it has created over many millennia. The resultant pollution and political and economic dependencies created by this approach have caused the impending crisis the world faces in energy generation and utilization. Direct conversion of solar energy to electricity is the cleanest form of energy generation currently known. Owing to the distributed nature of solar energy solar photovoltaic technology affords the possibility of creating a distributed energy source that is more immune to interruption by terrorists and natural disaster. Its widespread utilization is currently inhibited by the cost of photovoltaic cells and the low density of solar energy. For solar photovoltaic cells to play an important role in our energy future, there is a need for a low cost, high efficiency solar cell technology. Currently, the dominant technology for terrestrial solar cells is multicrystalline Si solar cells with and efficiency of 12-15%. Single crystal cells are available that have efficiencies greater than 20%. Solar cells used for satellite applications are often made from GaAs and related materials. A local company has recently demonstrated efficiencies as high as 40% in multijunction cells based on GaAs. All of these technologies are too expensive for deployment without subsidization. On the other hand, low cost thin film technologies have been developed as a possible answer to this challenge. At present these approaches are too inefficient for economical use.

*Nanowire Solar Cells* (P.D. Dapkus, C. Zhou, G. Lu/EE)
Research is underway at USC to explore new approaches to energy generation that is based on emerging nanotechnology. It has the potential for efficient photovoltaic conversion because it utilizes multiple junction cells designs that more efficiently utilize the solar spectrum. It has the potential to be inexpensive because it is based on low temperature processes and can be implemented on inexpensive substrates. Preliminary research is underway to realize this potential and a proposal has been submitted to the DoE for funds to support the work.

*Organic Solar Cells* (C. Zhou/EE, M.E. Thompson/Chem)
Organic photovoltaic cells that utilize heterojunctions between crystalline organic compounds are thin film devices with the potential for low cost fabrication. Research is underway at USC to perfect and develop solar cells in this technology. Thompson has funding from both DoE and DoD to develop these cells. Zhou is developing new electrodes for the devices using sheets of carbon nanotubes. Funding for this work is provided by the USC's FFEI.

*Photovoltaic Solar Cells* (A. Konkar/EE)
This research is focused on photovoltaic solar cells that employ semiconductor nanocrystals for the absorption of the solar radiation. These nanocrystal quantum dots act as broadband antenna which results in their electronic excitation. The nanocrystals subsequently de-excite or relax by the emission of light over a extremely narrow wavelength range. The emitted nanocrystal radiation is captured within an optical cavity. The radiation is absorbed within a silicon p-n junction where it is converted into a photovoltage. The use of an optical cavity will allow for the employment of Si p-n junctions that are <1/5th the thickness of that used in conventional Si photovoltaics. The nanocrystals are prepared in the laboratory using wet chemistry and their structure is analyzed via TEM in CEMMA. The Si p-n junction and the optical cavity fabrication is being done in the Clean-Room.

*Nanotechnology Applied to Catalysis for Hydrogen Production* (S. Cronin/EE)
The objective is to study new chemical pathways produced by plasmonic metal nanostructures on active and non-active catalytic supports by exploiting the high temperatures, intense electric fields, and enhanced catalytic activity provided by the surface plasmon resonance. The specific goals are: (1) to demonstrate improved efficiencies in the photochemical generation of hydrogen from water using Au nanoparticles on metal oxide catalytic films and (2) to demonstrate the production of synthetic hydrocarbons ($C_nH_{2n+2}$) from $H_2$ and CO by driving a Fischer-Tropsch reaction using Au nanoparticles irradiated with visible light.

### *C1.6.2 Efficient Energy Utilization*

Efficient use of energy must be part of future policy and technology choices for the US and the world. EE is involved in several independent efforts to better utilize energy in various aspects of human endeavor.

*Energy Efficiency in Electronic Systems* (M. Pedram/EE)
The goal of this research is to improve energy efficiency of VLSI circuits and systems. This is important from an economic point of view because about 20% of the total electric power consumption in the US (which stood at 3.1 quadrillion BTU in the month of March 2006 alone) is due to the energy requirements of various consumer electronics, computer systems, monitors, etc. (excludes energy consumption due to appliances, heating/cooling, and lighting). It is also important because power density and the resulting heat in integrated circuits tend to limit the density, performance, and reliability of these circuits. A mere 50% reduction is energy consumption of various consumer electronics and computer systems will have significant economic and technological implications. The work has focused on system-level power management and efficient power distribution in high-end

computing systems. Examples of power management work include dynamic backlight scaling for LCD’s, dynamic voltage and frequency scaling for CPU’s, power/clock gating, and intelligent shutdown and wakeup policies. Examples of power distribution work include design of high-efficiency on-chip power regulation and distribution network, secondary battery modeling and extending battery lifetime by utilizing battery relaxation techniques. This research is supported by NSF.

*Solid-State Lighting* (P.D. Dapkus/EE, C. Zhou/EE, M.E. Thompson/Chem)
Lighting represents a major use of energy in the world. In the US, about 30% of the energy is used for lighting. At the same time, the most widely used light source in modern societies is the incandescent bulb that is very inefficient. There is a growing belief that solid state lighting using light emitting diodes (LEDs) can alleviate a great deal of the waste in this area. A technological revolution occured in the 1990's in this area. Blue and green LED's that had not been very efficient previously were made with a material that resulted in very high efficiency devices and permitted the manufacture of white light emitting diodes and RGB LEDs that can produce white light. Stoplights, taillights, score boards and backlights for LCD displays are now all made with LEDs or shortly will be. Semiconductor LEDs made by the same materials technology - metalorganic chemical vapor deposition (MOCVD)- are now the most efficient sources of light known to man. The key challenge to replacing more conventional light sources is cost reduction. Right now UCSB is the leading university in solid-state lighting research based on LEDs. The research in EE in solid-state lighting has involved the development of MOCVD for the growth of GaN materials used for blue and green LEDs. More recently, it has explored the use of nanowires for visible LEDs. Many of the same ideas that make them interesting for solar cells also make nanowires compelling for a low cost visible LED technology. The possibility to build low cost white LEDs using engineered nanowire structures is the objective. A proposal has been submitted to NSF to begin research in this area. Proposals will be submitted to DoE in the near future. In addition there is emerging an LED technology based on organic LEDs that will also play a role in future lighting. Professor Mark Thompson is a world leader in the development of organic LED technology. A group of active researchers at USC have begun informal discussions of this area of research towards the goal of establishing a greater visibility in the area.

*Power Transmission and Security* (T.C. Cheng/EE, S. Nutt/ChEMS)
Research to mitigate the effects of natural disasters and terrorism on the electrical power infrastructure in the US is underway at USC (T.C. Cheng). Four programs are underway with funding from NSF, Southern California Edison, and CEC.

There are also research efforts on the durability of high-temperature low-sag conductors, which is of relevance to energy distribution with power lines (S. Nutt). This work is supported by the Composite Technologies Corporation. The focus is on long-term durability, and the motivation is to increase the ampacity of the nation's grid and upgrade the infrastructure for power distribution. An often-overlooked fact is that the capacity for generating power has grown at a much greater rate in recent decades than our capacity for DISTRIBUTING power, which is aging and near capacity. Thus, even if we invent inexpensive, clean energy tomorrow, we will have a major problem distributing that energy. Adding more towers is costly, and acquiring rights of way is just not possible in many locations, so we need to be more innovative in how we transmit power. The major limiting factor today is operating temperature and the sag associated with high currents and temperatures. The technology that is developed involves composite supported conductors, which exhibit negligible sag at high temperatures and thus carry more current. More important, however, is that existing lattice towers can support them.

*Sensors and Wireless Networks for Monitoring and Control of Energy Systems* (R. Govindan, J. Heidemann, B. Krishnamachari, U. Mitra, G. Sukhatme, W. Ye)
Dense sensing and actuation can greatly increase the spatio-temporal accuracy of energy utilization monitoring and control, both in the distribution system as well as at the end-user. *Wireless* sensor/actuator systems are increasingly becoming a reality, and energy conservation applications are often cited as being the killer application for this technology. For example, this technology will enable smart buildings that intelligently control lighting and heating, significantly reducing the operational cost of large industrial structures.

USC has a strong presence in this area. Our faculty are involved in developing and analyzing theory and models for sensing and communication (Krishnamachari, Mitra), developing sensor systems and related software technology (Govindan, Heidemann, Ye), and designing actuation systems (Sukhatme). Our faculty is also involved in collaborations exploring the application of this technology to a variety of areas: marine and environmental monitoring (Sukhatme), underwater sensing (Heidemann, Mitra, Ye), oilfield monitoring (Heidemann, Ye), structural and geophysical monitoring (Govindan, Krishnamachari, Sukhatme), and so on. These efforts are funded by NSF and CiSoft.

### *C1.6.3 Fuel Cells*

*Micro Solid-Oxide Fuel Cells* (P.D. Ronney/AME)

High-energy efficiency and energy density, together with rapid re-fuelling capability, render fuel cells highly attractive for portable power generation. Accordingly, polymer-electrolyte Direct Methanol Fuel Cells are of increasing interest as possible alternatives to Li ion batteries. However, such fuel cells face several design challenges and cannot operate with hydrocarbon fuels of higher energy density. Solid-Oxide Fuel Cells (SOFCs) enable direct use of higher hydrocarbons, but have not been seriously considered for portable applications because of thermal management difficulties at small scales, slow start-up and poor thermal cyclability. A thermally self-sustaining micro-SOFC stack with high power output and rapid start-up by using single chamber operation (which greatly reduces thermal cycling issues) using propane fuel has been demonstrated. A spiral counterflow "Swiss roll" heat exchanger and reactor maintains the fuel cells at the required 500–600 $^{o}$C using thermal energy produced by the oxidation reactions. Power densities of over 400 mW/cm$^2$ have been obtained. This research is supported by DARPA.

*Microbial Fuel Cells* (K. Nealson/GeoBio, S. Finkel/MolCompBio, F. Mansfeld/ChEMS, S. Prakash/Chem, P.D. Ronney/AME, H. Wang/AME)

The development of microbial fuel cells (MFCs) represents an area of immense potential – the conversion of *complex and impure organic fuel sources* electrical energy. The potential of MFCs remains unrealized, because of their historically low power densities. This Multi-University Research Initiative (MURI) project tackles the problem of low power density by addressing the following fundamental problems: (1) understanding the microbial mechanisms whereby electron transport to solid electrode surfaces occurs, (2) interfacing these microbial catalysts with proper MFC design to optimize power production under widely varying conditions, (3) understanding, manipulating, and improving the microbial communities to obtain those most capable of converting complex and variable organic carbon sources into electrical energy. The solutions to these problems require constant interfaces with electrochemistry, engineering, physics, and modeling. A challenge to the group that focuses the efforts is a self-propelled MFC. This MURI effort is funded by AFOSR.

*Blood Fuel Cells* (F. Mansfeld/ChEMS)

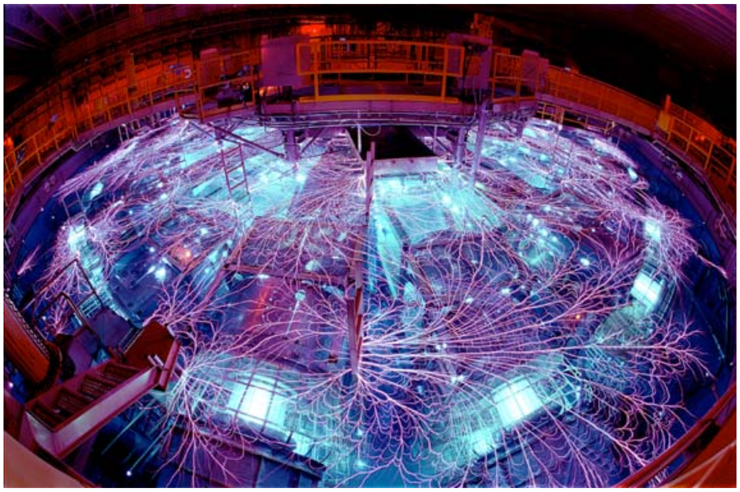
The main goal of this research is the development of a low-power implantable energy source that uses glucose in the human blood as the fuel, resulting thus in a blood fuel cell (BFC) that is also a low-power source. This work is supported by NOCO.

### *C1.6.4 Internal Combustion Engines, Control Systems, and Pulsed Power*

*Throttleless Premixed-Charge Engines* (P.D. Ronney/AME)

Conventional premixed-charge spark-ignition engines employ a throttle to reduce power and torque when demand is low by reducing the pressure of the combustible mixture drawn into the cylinder.  This results in the well-known "throttling loss." Under typical highway cruising conditions, this loss is typically 15% or more of the otherwise available power output of the engine.  This loss leads to reduced fuel economy and increased pollutant emissions.  An engine control concept has been developed, called the Throttleless Premixed Charge Engine (TPCE), which provides the necessary range of power and torque adjustment without throttling by using a combination of lean mixture and intake air preheat to adjust torque.  Higher intake temperatures reduce the air density and thus power and torque. Leaner mixtures also reduce power and torque, and the intake air-preheat substantially reduces the lean misfire limit.  Thus, in the TPCE concept the synergistic use of preheating and lean mixtures is essential; neither technique individually provides a sufficient range of power and torque adjustment for use in practical motor vehicles. The TPCE concept is ideal for vehicle applications because vehicles are constantly changing load and speed, and are only infrequently operated at wide-open throttle. In this sense the TPCE concept provides many of the best aspects of premixed-charge, spark-ignition engines (fast response time, high power to weight ratio, and negligible particulate emissions) with the best aspect of nonpremixed-charge compression-ignition (Diesel-type) engines (higher part-load thermal efficiency due to lean operation without a pressure-reducing throttle).  For these reasons the TPCE concept is equally applicable to light-duty vehicles as well as heavy-duty trucks and buses.  This work is supported by the AQMD and CalTrans.

*Pulsed Power for Fusion Research* (M.A. Gundersen/EE)



Pulsed power is an area primarily in the DoD and DoE sectors, and has numerous applications to energy. Fusion research has critical issues for switching and energy storage, for example, which require basic pulsed power innovation. For example, in the best-known picture from pulsed power (a photograph of water-based energy storage and switching technology in the Sandia Z Machine for fusion research), the size and some of the issues related to practical implementations are apparent in the photograph. In comparison to the pulsed power, the fusion part is about the size of a human forearm. USC's program in pulsed power is a leading effort in the US and the world.

*Energy, and Ignition, Combustion and Pollution Research Utilizing Pulsed Power* (M.A. Gundersen/EE, P.D. Ronney/AME)

Pulsed Power is basic to energy projects in most national laboratories for applications including fusion research and high-energy physics. Gundersen has conducted research that is energy related since the 1970s, beginning with laser isotope separation programs in collaboration with Los Alamos National Laboratory. As indicated in the graphic above (of the Sandia Z machine), pulsed power issues are very important for practical implementation. Transient plasmas, which occur in nanoseconds, are being investigated for *detonation and flame ignition*. For example, recently reductions up to factors of 10 in delays to detonation for pulse detonation engines, and other effects, have been achieved with low energy transient plasma ignition. Validation includes testing at the Naval Postgraduate School Rocket Propulsion Laboratory, Caltech, Stanford and Wright-Patterson Air Force Research Laboratory. Experiments have been now conducted for applications of this technology to internal combustion engines, working with Nissan to use this technology with the main goal being to reduce emissions. Transient plasma processes, enabled by pulsed power engineering, will have significant impact on engine and emissions technologies, and it is expected that the systems engineered approach, based in pulsed power engineering, will allow to achieve this goal. Pollution emissions reduction of particulates and $NO_x$ targets include jet turbine engines, diesel engines, HCCI internal combustion engines, and others. This research is funded by ONR, AFOSR/SBIR, AFOSR/STTR, METRANS, AFOSR, and Nissan.

### *C1.6.5 Micro-Scale Power Generation and Propulsion* **(**P.D. Ronney/AME**)**

It is known that the use of combustion processes for electrical power generation provides enormous advantages over batteries in terms of energy storage per unit mass and in terms of power generation per unit volume, even when the conversion efficiency in the combustion process from thermal energy to electrical energy is taken into account. For example, hydrocarbon fuels provide an energy storage density between 40 and 50 MJ/kg, whereas even modern lithium ion batteries commonly used in laptop computers provide only 0.4 MJ/kg. Thus, even at only 5% conversion efficiency from thermal to electrical energy, hydrocarbon fuels provide about 5 times higher energy storage density than batteries. Recently much attention has been focused on the application of MEMS devices to the production of electrical power, so-called "Power MEMS" devices, typically in applications where batteries are currently used. Many groups involved in Power MEMS are investigating scaled-down versions of well-established macro-scale combustion devices (internal combustion engines, gas turbines, pulsed combustors, etc.) but because of heat losses, friction losses and manufacturing limitations such devices have not yet proved practical. At USC two Power MEMS system concepts based on devices having no moving parts, specifically (1) thermoelectric elements and (2) solid oxide fuel cells, are being developed. Also, catalytic combustion driven thermal transpiration pumps are being used to provide pumping of reactants in power generators as well as the core of microscale propulsion systems, in both cases with no moving parts. This research is supported by DARPA and NASA.

## *C2. VSoE's Voids*

Many important disciplines within the general area of energy are satisfactorily covered by existing VSoE activities and faculty. However, there are some notable voids that could be considered as potential targets of growth and which could enhance the role of VSoE's in energy, as shown below:

### *C2.1 Nuclear Energy and Related Materials*

It is anticipated that nuclear energy will be back given that it does not contribute to global warming and does not emit pollutants, as for example do combustion processes. At the same time there are many issues associated with its use, with the main ones being safety and nuclear waste disposal. While it is unrealistic to assume that a nuclear reactor would be part of the on-campus activities, there are many topics of research that could be addressed. Those include nuclear engineering, materials, and explosions that could occur in nuclear facilities. While nuclear engineering expertise does not exist in VSoE, the areas of materials and reacting flows (explosions) could be involved in such initiatives.

### *C2.2 $CO_2$ Sequestration*

In the other end of the spectrum, compared to nuclear energy, the burning of fossil fuels and biofuels for that matter, are a reality and will be around for a long time. Thus, $CO_2$ will be emitted and its presence in the atmosphere will be one of the major factors contributing towards global warming. Although there are some activities in ChEMS and also outside VSoE (Department of Marine Biology), more needs to be done towards this very important goal of trapping $CO_2$ downstream of combustion processes. This will require intensified efforts based on existing expertise in AME and ChEMS.

### *C2.3 Energy Storage and Management*

This is also a very important topic given that enhancing the capabilities in energy storage and management could have major impact on the energy production and utilization. This could reduce the cost of energy as well as its environmental effects. Energy storage is mainly considered to be an issue for electrical energy, which is typically used at the same rate that is produced. Batteries are key in this area and it is known that existing technologies are not yet as advanced to partially solve the energy problem. Batteries can be viewed from a large- or small-scale point of view. While large-scale is of relevance to energy storage for buildings and communities, small-scale relates to electric cars. While, the future of electric car at present is debatable because the electricity is largely "non-green," future advances in solar, wind, and nuclear technologies could make the use of electric car mostly advantageous.

An additional component to energy storage that is typically not mentioned is the ability to effectively store hydrogen, whose significance will be discussed next. Hydrogen is the lightest of all elements and its storage poses a major problem. VSoE can encourage activities in the area of materials, as it is known that under certain conditions solids can adsorb hydrogen, forming thus the so-called hydrides that constitute a very effective means of storage. Then, under a different set of conditions the hydrogen could be desorbed from the solid and used in a variety of applications.

### *C2.4 Hydrogen Production and Utilization*

The last several years, there have been significant initiatives towards the so-called hydrogen economy. The US Government has also presented this as a very important target. While this appears to be a logical direction to follow given the excellent properties of hydrogen as fuel (best efficiency and least pollutant emissions), no too many appear to consider hydrogen as nearly equivalent to electricity. Hydrogen is rather expensive to produce and isolate, and very hard to store. It has to be also realized that in order for its production to be environmentally benign, it must be produced through electrolysis using electrical energy produced by utilizing solar, wind, or nuclear energies. In anticipation of advances in these areas, the technologies associated with the subsequent utilization and use of hydrogen need to be researched. Most likely hydrogen will be used in fuel cells rather than internal combustion engines as some suggest.

### *C2.5 Utilization of Renewable Energy*

Most of the world’s energy needs are currently met through the combustion of fossil fuels. With projected increases in global energy needs, more sustainable methods for energy production will need to be developed, and production of greenhouse gases will need to be reduced. Thus, there will be research opportunities in types of energy that are environmentally friendly and renewable. Renewable energy can be largely derived from sunlight, wind, and biomass. Hydrogen and alcohols are potential energy carriers that can be derived from renewable sources.

Wind power is a source of electrical energy that appears to grow. There are issues associated with wind energy utilization, such as for example the fundamental knowledge of the interaction of wind with the blade structure that could affect the turbine efficiency.

Photovoltaic devices have the potential to supply a significant electrical energy. Although silicon-based materials have been most widely used, other semiconducting materials and titanium dioxide also have potential.

Biomass is available from agricultural crops and residues, forest products, aquatic plants, and municipal wastes. Biomass can be a source of liquid, solid, and gaseous fuels including biofuels such as ethanol. However, converting biomass to either liquid or gaseous fuels that subsequently burn requires energy. In these early stages of such assessments, it is essential that all possibilities are rigorously explored and weighted. Among them is the direct utilization of biomass burning without conversion to other fuel forms. Such approach is of relevance in two important areas. The first is the advancement of technologies that will allow for the efficient and environmentally acceptable utilization of biomass for power generation in developed countries. The second, and most important, is to provide the understanding that is necessary to significantly improve the biomass utilization in under-developed countries, which on one hand will benefit the environment and on the other will aid the development of those poor economies. It is essential to note that nearly 3.4 billion, chiefly rural, people live in poverty and burn largely biomass to meet their energy needs (e.g., South East Asia and sub-Sahara). This is because burning is a simple method of energy production and there is no access to any alternative technology that could chemically process biomass to other fuel types. Biomass burning under such conditions is neither optimum nor benign to the environment at both local and global scales. Advancing technologies that could improve the direct utilization of biomass could attract the interest of foundations that deal with poverty in third world countries. Federal or state agencies could follow.

## *C3. Funding Sources*

Based on existing research activities are provided by:

1. Air Force Office of Scientific Research (AFOSR)
2. California Air Resources Board (CARB)
3. California Energy Commission (CEC)
4. CalTrans
5. Center for Interactive Smart Oilfield Technologies (CiSoft)
6. Defense Advanced Research Projects Agency (DARPA)
7. Department of Defense (DoD)
8. Department of Energy (DoE)
9. Environmental Protection Agency (EPA)
10. METRANS Transportation Center
11. National Aeronautics and Space Administration (NASA)
12. National Institute of Health (NIH)
13. National Science Foundation (NSF)
14. Nissan Corporation
15. NOCO Energy Corporation (NOCO)
16. Office of Naval Research (ONR)
17. South Coast Air Quality Management District (AQMD)
18. Southern California Edison
19. Strategic Environmental Research and Development Program (SERDP)
20. USC's FFEI

It is apparent that the funding largely originates from federal and state agencies and much less from industry. The VSoE is positioned very well within DoD, especially with AFOSR and to lesser extent with ONR. Interestingly enough there is no funding from the Army Research Office (ARO). Additionally, the DoE and EPA funding could be augmented.

Potential industrial targets are the fuel, engine, transportation, and power generation sectors. Examples are:

1. Airbus
2. Boeing
3. British Petroleum
4. Chevron Texaco
5. Chrysler
6. Coal Industry
7. Exxon Mobil
8. Ford

9. General Atomics
10. General Dynamics
11. General Electric
12. General Motors
13. Mazda
14. Nissan
15. Solar Turbines
16. Pratt and Whitney
17. Rolls Royce
18. Toyota

A complete list of energy companies can be also found at:

http://www.globalenergyconnection.ca.gov/tep/jsp/energyDirectory.jsp

Additional funding sources are foundations, such as for example the Bill and Melinda Gates Foundation, which do not appear to have been effectively targeted so far in the context of energy.