Energy Manufacturing

Matthew Realff and Steven Danyluk
Georgia Institute of Technology

This white paper summarizes the outcome of a workshop sponsored by the CMMI Division of the National Science Foundation and held in Arlington VA, on March 24-25, 2009 on Energy Manufacturing. The workshop attendees participated in discussions and presented their views on energy manufacturing and the presentations are available at the following website: http://www.marc.gatech.edu/events/NSFEnergyManufacturingWorkshop2009/.

Contributing Authors: Dr. Wayne Curtis, Pennsylvania State University, Dr. Placid Ferreira, University of Illinois at Urbana-Champaign, Dr. Kornel Ehmann, Northwestern University, Mr. Juris Kalejs, American Capital Energy, Dr. Emilio Molina Grima, University of Almeria, Spain, Dr. Steve Danyluk, Dr. Michael Filler, Dr. Rhett Mayor, Dr. Shreyes Melkote, Dr. Matthew J. Realff, Georgia Institute of Technology.

The high energy density of fossil fuels has dictated the nature of energy manufacturing for the past century. Large centralized chemical plants for processing and inter-conversion of energy take advantage of economics-of-scale to minimize the contribution of capital investment and processing costs to the final total cost to consumers. As we necessarily transition to energy forms that are less dense, the paradigm for energy manufacturing will have to change dramatically: we will need transformative, multi-disciplinary research programs to support it.

Solar radiation represents both a solution to nearly limitless energy, and presents a significant engineering challenge to manufacture systems that can collect this diffuse source. Assuming 30% transmission of the 'solar constant' radiation hitting the rotating earth's surface, that energy equivalent would correspond to 625 gallons of gas equivalent per acre per annum (GGEA) of the world's surface day (or over 8 inches of gasoline covering the earth's surface each year). By comparison the roughly 15 teraWatts of world energy consumption is less than 0.1 GGEA. Even when one considers the disproportionate 25% world energy use in the United States, the solar energy equivalent of that energy consumption is only just over 1 gal of gas equivalent per acre per year (See Table 1).

This paper specifically explores the challenges of using this distributed solar radiation and a dramatic shift in manufacturing paradigm from centralized to distributed energy processing. It focuses on two conversion routes that were the subject of a recent NSF workshop (Energy Manufacturing 2009), photovoltaics and liquid fuels from algae that are surface limited. However, several of the highlighted challenges are common to any conversion route that connects diffuse sources of energy, to more concentrated forms. Table 1 depicts 'ideal' cases of capturing energy via photo-voltaics, photocatalysis and photosynthesis. The photovoltaic calculations are based on a 20% efficiency which is higher than current installations, but within reach technically, and which could be substantially exceeded by transformative approaches based on multiple layers of materials. The photocatalysis is based on very recent reports of highly successful photoconversion of CO_2 to methane based on TiO_2 nanotube arrays doped with N and Cu to facilitate both water splitting and carbon reduction (Oomman et al., 2009). The advantage of such a technology is the ability to take the absorbed energy of photon capture and store it in chemical bonds of methane. This also represents a form of artificial photosynthesis whereby carbon can be utilized as an energy carrier without contributing to greenhouse gases. The production of methane, or a synthesis gas of carbon monoxide and hydrogen, serves as a precursor for liquid fuels. Chemical processes such as Fischer Tropsch synthesis can make methanol and higher alcohols from syngas, but cost effective conversion of methane to liquids is still challenging. Similar to this technology is the production of hydrogen and oxygen by water splitting with solar energy which is also carbon neutral and has the potential for similar energy production capacity (and energy manufacturing requirements). The photosynthesis calculations are based on technically achievable areal productivities of 50 grams/day/m^2/day biomass production from algae culture with 25 g/L oil content. While this is of the same order as the best energy crops (e.g. miscanthus, sugarcane) it represents largely deoxygenated hydrocarbon storage and not carbohydrate energy that will need to be fermented, for example, to alcohols.

Table 1: Analysis of solar energy capture options.

	GGEA$^{\alpha}$	Sq. mi. available or required
Insolation at Earth's surface	635	2,960,000
Photovoltaic $^{\beta}$	125	27,000
Photocatalytic $^{\delta}$	30	180,000
Photosynthesis $^{\zeta}$	10	305,000
Current burn $^{\gamma}$	1	- na -

$^{\alpha}$ Gallons of gasoline equivalent per acre per year.
$^{\beta}$ assuming 20% efficiency photo-voltaic.
$^{\delta}$ Current performance of CO_2 to CH_4 (Oomman et al., 2009).
$^{\zeta}$ Based on high density algae $^{\gamma}$ Current total average energy consumption.

An important aspect of Table 1 is the large area of land use that will be needed to be dedicated to energy capture and production. Not surprisingly, these areas start to rival the land use areas of agriculture, particularly when the method relies on photosynthesis. Analogously, the harvesting of sunlight will require a similar distributed network of energy manufacturing that resembles agricultural practices. The manufacturing of facilities and their subsequent operation and technical support will also have to take on a highly distributed nature for which there is no modern precedent. Another important requirement of this manufacturing challenge is to deliver these facilities at an absolute minimum cost due to the nature of fuels production where the volume of production is very high, but the economic margins are very small.

Research Challenges in Energy Manufacturing by Photovoltaic and Photothermal Systems

The harvesting of solar energy by photovoltaic or photothermal systems will require the development of ***manufacturing processes to create highly functional surfaces on a massive scale***. Crystalline photovoltaics require the production of large areas of silicon which is either grown into monolithic structures (Cz boules or cast bricks) and then cut into wafers, or grown directly into sheet form by for example, the edge-defined film growth (EFG) method. The cut wafers are handled, (sometimes) etched, cleaned and stacked, and handled again to position them for further processing. The completed solar cells are then assembled into large area modules. Thin film and organic photovoltaic devices require a prepared (flexible) substrate that is inspected for thickness, and these films are deposited and processed and eventually inspected. Wind and solar thermal systems require large low drag surfaces that are aerodynamically shaped or have surfaces with large area optics built-in to concentrate the sunlight.

The surfaces must be economical to manufacture and contain specific functionalities spanning large length scales e.g. feature sizes in the range of 10 to 100nm to improve light trapping (for photovoltaics) or to reduce drag losses and provide functions such as hydrophobicity, yet fabricated into structures with dimensions of tens or hundreds of meters. The creation of engineered surfaces will have broad impact and are critical to improved efficiencies in micro-channel, microfluidic based systems and specific functionality such as that needed for growing algae, for reduced flow resistance and 'algae-phobicity' to prevent fouling. These requirements necessitate research encompassing several grand challenges:

Challenge #1. Low cost, high throughput, next generation manufacturing systems are needed to produce engineered surfaces ranging from the micro scale to the macro scale. Processes, such as embossing, imprinting, deposition or laser processing need to be integrated into large-area manufacturing facilities for the creation of a wide variety of products; textured silicon for light trapping, textured tubes and pipes for heat transfer functions, and blades with specialized aerodynamic properties. New understanding of fundamental properties of the surfaces will have to be developed such as surface energy, friction, adhesion, and aerodynamic resistance. New metrology techniques will be needed for high throughput inspection of large, complex, textured surfaces.

Challenge #2. Manufacturing systems that include the fixturing and handling of very thin (50 μm) larger area crystalline silicon, and the handling of thin flexible polymeric and polymer/metal substrates for roll-to-roll processing are needed. The development of new substrate production methods such as the combination of polymer injection molding and polymer injection compression forming need to be developed. Automated, rapid inspection systems for thickness and uniformity and defects over large areas will be necessary in large area manufacturing. The handling of thin, large area crystalline silicon PV cells by touchless handling by air-flow, acoustic or electrostatic means serves as one example of how new manufacturing processes need to be developed for large throughput processes.

Challenge #3. Achieving ultrahigh efficiency (>30%), scalable photovoltaic (PV) devices at costs comparable to current thin film technologies is a key challenge in renewable energy manufacturing. Although low cost methods of PV production have been demonstrated, the light absorbing layers that exhibit sharply decreased crystal quality and devices are usually more inefficient when compared to their crystalline counterparts. Conversely, devices with efficiencies exceeding 40% are possible with III-V tandem multi-junction devices. Rather than a single semiconductor material, tandem multi-junction devices rely on a stack of semiconducting layers (e.g. Ge, GaAs, and GaInP) that each absorb a different portion of the solar spectrum. This approach of "parsing" the solar spectrum mitigates key energy loss mechanisms in traditional solar cells and limiting efficiencies in excess of 86% are theoretically possible for an infinite number of layers.

Unfortunately, the total number of single crystal layers is severely limited because current planar technologies suffer from substantial interfacial strain build-up. To circumvent barriers and enable large-scale terrestrial power production, novel methods of assembling and electrically connecting stacks (4-7 layers) of single crystal light absorbers are needed. Novel approaches that can minimize or relax the strain inherent in a materials stack will be essential and structures such as micro or nanowires with radial length scales between 100 and 1000 nm are promising candidates. While this is important for increasing the number of layers possible in a single stack, it will also afford production on flexible substrates that impart stresses on the device as it progresses through a roll-to-roll fabrication line. The key will be manufacturing of these multi junction devices on a massive scale. For defects that do develop during production processes, in-situ or ex-situ surface and bulk passivation techniques will be necessary. Handling and inline metrology tools to assess the real-time crystallinity and detect bulk defects in a non-destructive manner must also be developed.

Research Challenges in Energy Manufacturing from Algae

In theory, algae represent an extremely attractive option for producing biofuels, based on their productivity, but there are many research challenges to be addressed at different levels of the system.

Challenge #1. ***There are fundamental challenges in improving the traits of algae through genetic manipulation, and system challenges in understanding which traits are the most important for engineering effective production systems***. For example, understanding and improving algal photosynthesis, certain phenomena have been identified as playing crucial roles in this such as light saturation, photoinhibition, and light penetration. There are strategies that are being developed to reduce light harvesting antenna size to enhance photon capture efficiency under high light. We will need deeper understanding and tailoring of the biochemistry of oil synthesis to manipulate the oil content of biomass. There are still many uncertainties about the mechanisms and the constellation of enzymes involved in lipid metabolism (elongases, desaturases, etc). The investigation at the cellular and molecular level of the mechanisms that cause bioadhesion of cells will support advances in photosynthetic efficiency, biomass yield by decreasing fouling, or enabling molecular switches to activate self-flocculation for harvesting. Genetic engineering strategies could also improve temperature tolerance of microalgae, this will allow a broader range of locations to be used, and reduce the infrastructure required to manage heat during peak sunlight periods.

Challenge #2. Unlike crops or trees, algae are typically suspended in large volumes of water and hence ***creating low cost infrastructure for growing algae is a critical research challenge***. The infrastructure to grow the algae must be extremely cheap. For example, assume we want diesel at $2.00 per gallon, algae can be grown to contain 30% oils and the cost of the ponds is 20% of the overall cost of producing and distributing the diesel. Given these assumptions, the annualized cost per m2 of pond has to be around 5 cents. This means roughly $0.50 capital cost per m2 is tenable. Current photobioreactors are estimated to have a capital cost of $1000 per m2 of area (Grima 2009), and ***hence we need substantially different ways of manufacturing this infrastructure if we are to meet this challenge***. We will also need extremely low cost, but highly functional, materials. Given the above estimate of $0.5 per m2 of capital investment, estimates of polyethylene prices of $1.60 per kg, we can use approximately 0.36mm thick polyethylene sheet to cover the production area.

Challenge #3. Once the algae have been grown, ***a critical challenge is to separate algae from large volumes of water***. There could be significant innovation in this arena, such as self-flocculating algae, the design of carriers on which algae are grown and then separated, or new applications of process technologies such as membrane separation. For example, utilizing microporous membrane separation techniques to reject the Algal biomass from the water/algal mixture would require meeting specific research challenges: the design of low cost materials that can reject algae without biofouling, have high permeate flows, and which are easily produced in large area finding the optimal trade-offs between porosity, bulk strength, flexibility, biofouling resistance, and other material parameters. The design of manufacturing processes required to produce large area membranes, and to assemble these membranes into low cost effective modules. The construction of predictive performance models for separation versus pore size and morphology, to predict pressure drop and membrane loading as a function of mass flow rate of algal-water mixtures. These models would support the optimization of material properties and module costs.

Other Technical Considerations for Energy Manufacturing:

An important aspect of photosynthetic capture is the potential for integrating CO_2 capture technologies. For both photo-catalysis, and high intensity algae production processes, there is a tremendous advantage to interfacing to technologies that concentrate CO_2. In addition to existing technologies amine and ionic liquids, most recently high-capacity nano-confined ‘molecular baskets’ have been shown to have higher capacity, and reduced energy requirements for desorption (Ma et al., 2009). In addition, molecular baskets can be designed to absorb NO_X which can be used for algae fertilization while improving air quality. Combined with the CO_2 photocatalysis work noted above, these illustrate an important need for energy manufacturing: the scale-up of energy related nano-technologies. Due to the huge investment that has been made in nano-technologies, it is not surprising that applications are surfacing with the application to energy technologies. However, most of these technologies rely on laboratory-scale methods (electrochemistry, vapor deposition, etc.) that will require tremendous effort to adapt to high-throughput manufacturing technologies.

Because the capture of photosynthesis energy will require the fabrication of man-made structures over unprecedented areas, transportation of materials will become prohibitive and dictate ‘on site’ fabrication, much like massive concrete construction projects, but the handling of high technology materials. In supporting the development of technologies, a priority must be given to those technologies that are amenable to such implementation. For example, algae-based systems will require new methods for fabrication of massive man-made structures.

The interfacing of wastewater technology with photocatalysis is another example of examining energy production as part of a more integrated and sustainable society as a energy production system. Technologies such as membranes to separate nutrients from waste water for introduction to algae culture would facilitate elimination of the major costs fertilization of biological photosynthetic capture while improving emission water quality.

Emerging and Key Research Questions

- What research breakthroughs would lead to completely artificial photosynthesis, “leaf on a chip,” technology?
- How do we manufacture multiple thousands of hectares of infrastructure to capture sunlight and convert it to liquid fuels? How do we decide what part of the infrastructure will be manufactured and shipped to the harvesting location versus that which is produced and assembled on site?
- What systems could be realized that have a low capital investment and are highly distributed to make liquid fuels as opposed to the highly centralized refinery infrastructure that is currently used?
- How do we best integrate emerging sunlight harvesting technology with existing infrastructure?
- What is the right balance between the aggregation of biomass for processing versus the distribution of the resulting liquid fuel?
- What systems have the appropriate scale to meet significant fractions of energy demands without themselves have substantial negative impacts on the environment, such as land use change, fertilizer and water consumption, potential for toxic release, and other impacts?
- How are fixturing and handling systems to be designed and built for the production of kilometers square areas of highly functional surfaces?
- What sort of scale-up is necessary for the production of highly functional surfaces?
- What new manufacturing processes are needed to produce surfaces with specific functionality such as texture for light trapping, heat transfer, aerodynamics and anti-fouling?

Summary Recommendation:

We currently do not know precisely what technologies need to be scaled to facilitate progress in the use of diffuse solar energy. Nonetheless, the need to deal with green house gases has resulted in a flourishing of both academic and entrepreneurial / startup companies developing technologies to utilize solar energy. Most of these technologies have only superficially considered the ramifications of the scale at which they must be implemented to achieve their goals of significantly impacting the supply of energy. At this time investment should focus on supporting the science and engineering that will establish the best performance and cost effectiveness of these developing technologies. It is critical that the most promising technologies be identified so that the necessary manufacturing technologies can be developed to permit rapid implementation.

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