REPORT on

Solar Fuels Workshop:
Roadmapping for Success

held on
November 17-18, 2011

In cooperation with

CTIM
Center for Technology & Innovation Management
(located in the Kellogg School of Management)

With support from
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OVERVIEW

1. Introductory Notes
Global energy needs are expected to double over the next 40 years. Initiatives focused on finding cost-effective and carbon-neutral energy sources are critically important for meeting those needs and sustaining earth’s balance. Of sustainable energy sources only solar technologies can fully address requirements, with fuels generated by making use of solar-enabled artificial photosynthesis. This will require development of efficient photovoltaic and photocatalytic systems to capture sunlight integrated with high performance catalysts for water splitting to produce hydrogen and the reduction of CO$_2$ and ultimately, liquid hydrocarbon fuels. Moreover with such achievement, minimal change in existing vehicle and distribution infrastructure might be required. But the science and engineering to establish a viable solar fuels industry remains undeveloped and is complicated by policy, production and management challenges and uncertainties.

Lacking until now has been a sustained, well-funded, coordinated and focused effort. Such an effort would leverage, align and enhance globally distributed, cross-disciplinary academic, research lab and corporate initiatives and skills. But such a sustained investment can, by and large, only be expected from private capital. The Solar Fuels Institute (SOFI) at Northwestern University is conceived to enable this result. Managing such an undertaking well will demand at the least:

- defining and maintaining focus,
- establishing and achieving performance metrics,
- monitoring changing contexts,
- laying out and communicating planning and operational steps with associated resource requirements,
- accounting for risks, obstacles, assumptions and stakeholder implications.

Making this possible demands a sophisticated, ongoing dynamic and systemic process such as roadmapping that is integrated with other such planning and monitoring tools. This process will guide the initiative going forward and ensure business-oriented information is available to current and future stakeholders and investors. It will also raise confidence that the ambitious goal can be and is being achieved. So what is “roadmapping”?

Roadmapping is a group process that provides a clear graphical framework for exploring and communicating vision and planning. Visually, it takes the form of a continually updated time-chart that links market, product and technology information and enables market opportunities as well as gaps in technology, organization and infrastructure to be identified and addressed. Alternative pathways are laid out with specified goal milestones including "stage gates “where appropriate and checkpoints that are dynamically adjusted to the operating environment. It can reveal funding, technology advance and capability requirements - when needed, who must provide and implications if not in place. Assumptions and risks are explicated and evaluated with strategies to address them.

2. The Workshop
It is with the above thinking in mind that SOFI initiated this Workshop. Collaborating in planning and putting on the event was the Center for Technology and Innovation Management
(CTIM) - part of Northwestern’s Buffett Center for International and Comparative Studies. CTIM, in turn, is an industry-academic research and practice center affiliated with, the Global Advanced Technology and Innovation Consortium (GATIC.) The Initiative for Sustainability and Energy at Northwestern (ISEN), Argonne National Laboratory, Telluride Science Research Center and Northwestern University at large also provided support for the workshop. CTIM and GATIC brought in significant experience and expertise in roadmapping integrated with scenario planning and other approaches. The Workshop took place November 17-18, 2011 at Northwestern. Attending was an impressive and deliberate mix of 42 participants: academic (19), research laboratory (6), corporate and investment community (17). In addition, 5 science and management graduate students with relevant experience and expertise assisted. Three interrelated goals were set forth:

- Deepen insights and provide immediate input into still-evolving SOFI conceptualization and planning; even to challenge plan elements.
- Demonstrate potential and launch a comprehensive roadmapping process to optimize progress while identifying hidden opportunities and addressing potential pitfalls. Supporting this preliminary stage, CTIM brought in experienced industry facilitators to create a useful structure, help raise critical less-recognized questions and stimulate discussion. The roadmappin focus and participant mix differentiated the program from the multitude of research-oriented events.
- Establish a working “community” of critical stakeholders. Active, open interaction and collective “buy-in” by participants was a key intended outcome.

Attendance was kept small to encourage discussion. Also, unlike for many such events, the workshop should not be standalone. Rather it would stimulate ongoing activity and taskforces with further involvement of workshop participants as well as potential others unable to attend. It would seek to advance for SOFI roadmapping, inform its project management and so maximize the solar fuel potential. The workshop was built on extensive pre-event discussion and work and this report incorporates that pre-event effort as well as program evaluation. Next steps are now being considered.

Reflecting recognition of need and support for SOFI objectives, participation was very active. The bulk of workshop time after the brief plenary presentations was devoted to breakout discussion. Attendees were assigned to one of three breakout groups, each deemed to be necessary to support the evolution of SOFI, a solar fuels industry and achievement of the goals:

A. Research/Technology Barriers
B. Institutional, Contextual and Sustaining Issues

Balancing group size, participants were allocated so as to stimulate discussion derived from varied disciplinary, experiential and industry-academic perspective with intentional overlap in suggested topics. The groups reported back in a wrap-up plenary session and group output is being integrated as initial input into roadmapping. Participants were assured that even as discussion continued beyond the workshop, they were not committed to remain in assigned groups.

The agenda follows. Suggested discussion topics were included for each breakout group.
AGENDA (see bios page 20 on)

Day 1

2:00pm  Welcome (Jay Walsh)
         Project Vision (Michael Wasielewski)

2:10pm  Keynote Perspectives Panel
         Chair, Introduction (Michael Radnor)
         A. Solar Fuel Science (Nathan Lewis)
         B. Industry (William McAllister)
         C. Financing Big Energy
             Projects/The Business Case (Tom O’Flynn)

3:00pm  Panel: Introduction to roadmapping
         Chair, introduction (Jeffrey Strauss)
         A. Overview of tool and implementation models (Richard Albright)
         B. GM experience (David Grossman)

3:40pm  OPEN DISCUSSION

4:10pm  Breakout group charge (Radnor)

Break, assemble in breakout groups. Participants are assigned to groups to ensure coverage and stimulating mix

Breakouts (with example considerations)

Research/Technology Barriers
(Facilitators: Albright, Strauss)
What role should and could SOFI play in guiding and enabling the applied central mission and potential spin-off research? How will its strategy, structure and research interplay? What research advances will be needed and when; what technical and non-technical challenges may arise? What capabilities throughout the entire value chain will be needed to accomplish the objectives laid out earlier? What could be metrics and investor benchmarks? How can knowledge/learning be captured?

Institutional, Contextual and Sustaining Issues (Facilitators: Radnor, Hellmann)
How to define, set up, run and sustain SOFI as activity evolves? What might be the impact of internal and external developments as SOFI matures? Institutional roles and limits? Make up of management board? Staffing? IP ownership? Community/network development and communication processes? Funding types and activities throughout institutional life?
**Business Case/Opportunities** (Facilitators: Grossman, McAllister)
What is and could become the business case for solar fuels and for SOFI. What will/could impact the business case and how will it play out over time and under differing scenarios? The potential form of returns from solar fuel and derivatives, when, and at what level? Milestones? Required investment, sources, timing, and limits on investors? What external developments could cause investors to pull back or to deepen? Interim/ alternative products and markets; commercialization strategies? Social, political issues, role of governments, infrastructure and other assumptions and implications if incorrect?

6:45pm  Brief group reports

7:15pm  Wrap up. Move to working dinner (breakout groups continue work)

**Day 2**

8:00am  Breakout groups resume

8:45am  Group reports

9:30am  DISCUSSION

10:15am  Where from here? (SOFI institutional next steps, roadmapping task forces, events, web discussion, other?)

10:45am  Wrap-up

**WORKSHOP CONTENT AND DISCUSSION**
See agenda above. Slides used by Wasielewski, Albright, McAllister and Grossman are appended.

1. **Plenary presentations**

A. Welcome and Project Vision
After a brief welcome by Jay Walsh, VP Research Northwestern, Michael Wasielewski, SOFI Director, set forth the vision for the SOFI initiative even while recognizing that the concept is still evolving. This was presented in terms of growing global energy needs: already 13TW in 2004, rising to 30TW in 2050 and 45 by 2100. Solar fuel solution challenges include addressing knowledge gaps, economic, social and policy issues and enabling a smooth transition from university focused research to industry focused commercial reality.

The overall goal of SOFI is to develop efficient, cost-effective solar energy capture and conversion technologies that are integrated with high performance catalysts to generate hydrogen from water and liquid fuels from carbon dioxide. The envisaged initial 10-year effort will also generate commercially valuable spin-off interim products justifying investment.
Conceived as a global consortium/network of university and corporate research organizations, activity will be funded by a combination (with sources varying by stage of development) of philanthropy, private investment and corporate partnerships and will leverage substantial government support already committed to participating institutions.

SOFI will identify, bridge, integrate and support selected complementary basic research efforts but also continually monitor and consider competing and non-technical impacting developments. It will have a practical focus with the intent of completely transitioning new technology to industry and/or lead to viable start-ups to develop the technology.

B. Perspectives Panel
Three presenters offered varying perspectives including science, relevant industry experiences, and financing/business case considerations.

*Michael Radnor of Kellogg, CTIM and GATIC* launched the panel by noting the overall need to define and maintain the desired focus but be agile, responding to learning and developments, accelerate progress and recognize and overcome typical as well as unexpected traps. He indicated that the workshop title, *Roadmapping for Success* was chosen deliberately to reflect the intended teaming of science and carefully planned implementation action perspectives and related understandings including accounting for “killer” risks and gaps. Radnor suggested that the workshop would introduce a roadmapping way of thinking rather than attempt to produce roadmaps or turn participants into roadmapping experts.

*Nathan Lewis of Caltech Joint Center for Artificial Photosynthesis (JCAP)* argued that solar fuel must be pursued because its evolution is driven by overwhelmingly clear needs including climate change mandated zero emission/carbon neutral energy making the solution “inevitable”. Required is an energy source that is large, high energy dense, not intermittent, and transportable which means using chemical bonds for energy storage. Successfully launching a new solar fuel industry that can compete with incumbent or alternative sources will require identifying and bringing in core competencies that fit the new dynamics. Getting investment will be difficult as clean energy historically has had a smaller return than other investments. While likely winners must be picked early, it is important to keep multiple options “alive” – a point reiterated by later speakers. Lewis cautioned that there will be a steep learning curve with strategic interaction with many players.

*William McAllister from GATIC, but formerly of Siemens- Westinghouse* presented a perspective from his nearly 40 years in the energy manufacturing industry which included R&D coordination and decision modeling applied to photovoltaics, solar heating, cooling and thermal power plants as well as wind turbine and solid oxide fuel cells among other research and products. McAllister suggested most new energy projects fail and detailed reasons and recommendations – including application of varying tools with the emphasis on the value of roadmapping throughout - for each of 5 development stages: between “concept” and “proof of principle”, between “proof of principle” and “prototype” between “prototype” and “product launch”, and after “product launch”. He posited three key stages:
First stage: failure usually results from an inability to make the science work and choosing a “solution” too quickly. He suggested the need to realistically, cold-bloodedly assess readiness and fit for all required technologies, recognize that different conditions and processes are required at this front end of innovation, where he noted SOFI is now, and later product development. In the front end, commercialization date and budget requirements (and revenue projections) are uncertain with work often chaotic awaiting needed discoveries. He agreed with Lewis that multiple concepts need to be explored at this stage, i.e. *fail fast and often*, but he went further in suggesting delaying picking winners. He also agreed with the need to identify critical competencies. At this stage, ideation is a key tool along with technology roadmapping.

Second and third stages: failures generally come with technology surprises or when performance does not meet all expectations. Often here too the technology does not scale – working on the lab bench but not in production. The inherent processes may be too costly or time consuming to do quality control as required. McAllister suggests at this stage to begin considering manufacturing full costs and processes, as many potential applications as possible and associated business models, and to begin characterizing markets. Scenario planning, risk analysis and concurrent engineering approaches can help.

McAllister gave two examples, dendritic web photovoltaics and a solid oxide fuel cell where prototyping showed promise but changing conditions including government actions and competing technologies that did not stand still coupled with a business model that did not fit narrowing market opportunities made the product infeasible. System design and manufacturing processes need to be balanced with profitable combinations of cost, yield, reliability and performance.

He concluded with the admonition to do the right R&D selection and to do R&D right - coupled with technology assessment, stage gate processes, risk analysis and business planning.

*Tom O’Flynn of the Blackstone Group* provided the final business case perspective. He described issues in the evolution of the solar energy industry, especially involving solar panels, noting the significant regional/country variations and stressing the role of government driving demand and competitiveness with other energy sources. He laid out the cyclical process of continuing R&D and implementation and noted that for SOFI, funding initially could be from retail sources such as Google, as well as philanthropy, with venture support and industry partners some years away. He stressed that capital planning must strive for basic steady support to survive ebbs and flows in development and in alternative funding. He encouraged seeking out other industries that might be models to guide selection of winners and losers.

C. Roadmapping panel

*Jeffrey Strauss (CTIM)* introduced the roadmapping panel noting that roadmapping has been used in many fields including chemistry catalysis and energy applications and at both the corporate and industry level, where SOFI roadmapping might be a blend of these two. He stressed that roadmapping as an ongoing group process is much more important than the resulting roadmaps.
Richard Albright, formerly roadmapping leader for many years at Bell Labs, described roadmapping as capturing the view of a group on how to get where they want to go and a tool to ensure capabilities and resources are in place when needed. In simplest terms, he noted the process has 4 steps:

“know why” – definition and scope developed through assessment of stakeholder and customer drivers, current and emerging markets, competitive landscape, mission and strategy;

“know what” – direction (specific challenges, desired characteristics, system architecture, metrics and objectives);

“know how”- determining most critical capabilities and technology investments as they link back to drivers and how they will be developed or acquired. Finally these lead into the

“to do” or action plan showing key activities over time, often broke into elements, when resources and capabilities are needed and how gaps will be addressed.

Albright pointed to the International Technology Roadmap for Semiconductors (ITRS) as a potential ultimate model. Updated regularly by assembled universities, companies and governments after initial development by the Semiconductor Industry Association, the roadmap presents a consensus view of the industry’s development and research state. It projects needs out to a 15 year horizon pointing to technical challenges and capability requirements and includes hundreds of parameters.

He then walked through detail of a technology roadmap he helped to develop for the Fluid Power Industry. Benefits from this process for the industry included: engaging a wide cross-section of the industry with active pre-competitive sharing of ideas, achieving consensus on key objectives and threats, and definition of high potential industry initiatives and key next steps.

David Grossman, GM described the company’s experience with roadmapping building on his 32 years there. Initially there was resistance to employing the tool until it was tied to group funding. GM made a simple graphical process using a common established data base although each group’s roadmaps varied based on different needs in terms of level of detail and breadth. Goals were to make the technology plan visible particularly to senior management and to ensure that functional groups shared the vision but the tool was also used to align technology and product plans and portfolios, to improve communication between groups, facilitate discussion with stakeholders and to test business plan-technology viability under varying conditions. Grossman concluded with the example of fuel cells where the technology developed very well along defined parameters of performance, cost, durability, etc but it failed because the business case was not well developed. The product was still too expensive particularly as the price of oil fell. Political support disappeared and the needed hydrogen infrastructure failed to materialize.

2. Break-out groups

Groups were generally charged with zeroing in on a limited number (5-7 was suggested) key tasks or activities within their assigned domains in the near term (1-3 years), mid-term (3-5 years) and long term (5-10 years) and identifying and assessing related challenges, requirements and uncertainties. They were all also asked to consider the value SOFI could bring.

Group-specific suggested topics were provided as included in the agenda above. Finally, a basic common template was given to facilitate reporting back in plenary session and consolidation. But groups were free to adapt the template and instructions to stimulate and pursue discussion as it unfolded and as they and facilitators saw fit, consistent with the indicated overall goals.
**Discussion/reporting template**

<table>
<thead>
<tr>
<th>WHAT</th>
<th>WHEN, HOW (impact, response/ contingency, how advance)</th>
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<tbody>
<tr>
<td>Advantages , Disadvantages</td>
<td>Near-term</td>
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<td>Opportunities</td>
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<tr>
<td><strong>Key Challenges</strong></td>
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<tr>
<td>Gaps, risks, uncertainties; threats</td>
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<tr>
<td>Other</td>
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<tr>
<td><strong>PLAN B?</strong></td>
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<tr>
<td><strong>NEXT STEPS</strong></td>
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What follows are summaries of discussion in the 3 groups. As would be expected, discussion went in different directions and the positive but chaotic group dynamics is not readily captured. Group output has been modified to also reflect discussion in the sharing plenary session.

*Key ideas leading up to the production of the summary template included on page 10*

**The mission, key questions, and challenges**

In a general sense, we must capture, convert, and store solar energy using stable and earth-abundant materials -- but what are the interfaces among those processes?

Ultimately, light-harvesting and fuel production must be combined in a small unit, in a way that avoids the inherent problems with the use of individual components. On a fundamental level, catalysts must be carefully interfaced with photosensitizers and electrodes, and catalysts used in an integrated system would be different from the catalysts used in electrolysis.

What is our device concept? How much do we draw from synthetic biology, solar thermal, or other models for photodriven fuel generation?

**Considerations for/role of SOFI:**

- We must perform a critical evaluation of all existing approaches and results. A comprehensive survey of the field is important. Innovation scorecards
- Industry currently invests less in basic research, and so SOFI could fill this niche so that we will be “ready to go” in the advent of a solar fuels market.
- SOFI could act as an intermediary between industry and the researchers. The perspective of end users and markets must be considered in the current plan, and we must be constantly aware of competing technologies and resources such as fossil fuels, coal, natural gas, and battery technology. The price, theoretical limits, and environmental impact of each of these players should be carefully considered.
## Research/Tech Barriers Breakout Group

<table>
<thead>
<tr>
<th>WHAT</th>
<th>WHEN</th>
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<tbody>
<tr>
<td></td>
<td>Near-term (1-5)</td>
<td>Mid-term (5-10)</td>
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<tr>
<td><strong>Key Challenges</strong></td>
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<tr>
<td>Functional; Explore multiple approaches; Acad/Ind Collab</td>
<td>Improved Performance</td>
<td>Cost competitive</td>
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<tr>
<td>Light capture</td>
<td>Explore multiple approaches</td>
<td>Identify industrially viable solutions</td>
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<tr>
<td>Light to Chemical Potential</td>
<td>Explore multiple approaches</td>
<td>Identify industrially viable solutions</td>
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<tr>
<td>Water Oxidation</td>
<td>Explore multiple approaches</td>
<td>Identify industrially viable solutions</td>
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<tr>
<td>CO2 Reduction</td>
<td>Explore multiple approaches</td>
<td>Identify industrially viable solutions.</td>
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<tr>
<td>CO2 Proton reduction</td>
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<tr>
<td><strong>Functional Integration</strong></td>
<td>Identify potential bottlenecks.</td>
<td>Begin integrating components.</td>
</tr>
<tr>
<td><strong>System Engineering</strong></td>
<td>Design concepts</td>
<td>Evaluate need for CO/H2 &amp; O2 Compartmentalization.</td>
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<tr>
<td>Scalability</td>
<td>Earth abundant for all components</td>
<td>Cost reduction for production</td>
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<tr>
<td><strong>SOFI Role</strong></td>
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<tr>
<td>– Critically assess current research (Innovation Scorecards) in the context of competitive/sufficient technologies.</td>
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<td>– Facilitate dialog between End Users and Researchers.</td>
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<td>– Create Catalysts vs. Conditions Matrix: Range of conditions</td>
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<tr>
<td>– Clearly define SOFI’s goal:</td>
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<tr>
<td>o Solar production of Hydrogen</td>
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<td>o CO2 to CO leading to Carbon based liquid fuels for existing infrastructure.</td>
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<tr>
<td>– Input for downselecting technologies (at what point?)</td>
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<tr>
<td>– Provide guidelines for what will work -- based on market, government role, and technology</td>
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<tr>
<td><strong>Risks, uncertainties, threats</strong></td>
<td>Liquid or gaseous fuels?</td>
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<tr>
<td>Threats from competitive technologies (e.g. Coal, Nat Gas): Assess</td>
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<tr>
<td><strong>Existing concept examples</strong></td>
<td>Current State of Art: PV plus electrolysis</td>
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<tr>
<td>Buried Junction</td>
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<tr>
<td>Nano scale Junction</td>
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<tr>
<td>Liquid fuel for transportation</td>
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• SOFI could downselect the projects based on cost/price projections and industrial requirements. Also, policymakers must know the various limitations should solar fuels become a national strategic goal.
• SOFI could establish experimental methods for the implementation of system components and the measurement of their performance. The cost/efficiency ratio is a critical metric in determining the economically viable routes. We must identify the intermediate benefits of each stage of solar fuels research. SOFI could study and inform research in these areas.
• SOFI could design and maintain a matrix for catalyst performance that would allow us to know the best conditions for each potential component in a solar fuels system. The matrix should consider best catalysis approach for a given condition and vice versa so as not to limit solutions through how problem is framed.

Issues:

**Water oxidation**
• Water oxidation is the only viable option for an electron source for solar fuel production. Multi-electron catalysts for water oxidation must demonstrate longevity, rapid turnover, low overpotentials, and low cost, though these requirements also apply to \( \text{H}^+ \) and \( \text{CO}_2 \) reduction catalysts. Also, the performance of catalysts on surfaces or electrodes is very difficult to predict.
• How do we screen catalysts? We should consider varying conditions that would allow the best catalysts to work under the best circumstances. Establishing a full matrix for catalyst performance would allow us to know the best conditions for each potential component in a solar fuels system. We can rule out conditions that would be industrially unrealistic, with the understanding that conditions for metal oxide materials and molecular catalysts would be distinct.
• Mechanistic studies and understanding are a traditional method that should still be pursued in order to improve catalyst design.

**H\textsubscript{2} generation**
• The current state-of-the-art involves the combined use of photovoltaics and electrolysis. Although the costs of PVs are dropping and electrolyzer technology is improving, there are major efficiency losses involved in the scaling up of electrolyzer use and the introduction of other components.
• We must develop proton reduction catalysts that are impervious to oxygen, which would pose simultaneous mechanistic and kinetic challenges.

**CO\textsubscript{2} reduction**
• There are progressive stages of approaches for CO\textsubscript{2} reduction: the first is using concentrated CO\textsubscript{2} from production sites, and the second stage is to concentrate it out of air.
• Reducing CO\textsubscript{2} with light is ideal, though its photocatalytic reduction into something directly useful is extraordinarily difficult. The simplest feedstock to
make is H₂, and it could be used to generate other carbon-based fuels sources (methanol, formate, etc.) via reductive chemistry.

- Cellulose could be used as a carbon source, but biomass is not able to solve the 13-14 TW energy need problem because there is not enough feedstock. Biomass could address niche markets, but it would have problems with scale.

**Functional integration**

3. In the achievement of light-to-chemical potential, we must conserve photon energy and achieve high quantum yields of electron and hole transfer processes. The electrons and holes provided to catalysts must efficiently drive fuel formation.

**The products**

4. How do we compartmentalize our products? It is still worth exploring whether CO₂/H₂ and O₂ could be produced in the same system. We could imagine separating products post-production, but we must still avoid back-reactions or cross-reactions on the microscopic level. What level of “distance” separation between sub-systems is necessary?

5. What are our endpoints, which industry could then take to the next step? Reduction of CO₂ to CO for generation of syngas is one good approach. Such a fuel would be useful given the current global energy infrastructure.

6. H₂ is a significant primary fuel source, and should we focus on that and consider liquid fuels as mainly a storage mechanism? The exact identify of the fuel may not be absolutely critical to our vision. Also, at which point does the effort of SOFI stop and that of industry take over? At the H₂/CO production step?

**Other conclusions**

- Spinoffs and innovations will be incredibly important to sustain the effort. These aspects will be valuable in niche markets. (Still, the best multi-electron catalysts usually lack cross-reactivity.)
- Our consortium will allow for parallel processing and the pursuit of many different avenues in the first several years. In the near term, we must explore multiple approaches in each of the basic scientific areas.
- How can industry be more integrally involved with research, who (level), when? The deliberate inclusion of industry representatives in this group clearly helped focus and inform discussion beyond typical research review.

**Business Case Group**

This group was able to capture most of their discussion in their template although the business case issues became a focus in discussion in the wrap up plenary session and much more came out then (see pages 13 & 14.) The group also began to explore a general business analysis framework with a minimum of the following elements:
### Business Case Group: General Business Analysis Framework

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<table>
<thead>
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<tbody>
<tr>
<td><strong>A. Market Need</strong></td>
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<td><strong>B.</strong></td>
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<tr>
<td><strong>C. Strategic Partners/Supply Chain</strong></td>
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<tr>
<td><strong>D.</strong></td>
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<tr>
<td><strong>E.</strong></td>
<td></td>
</tr>
<tr>
<td><strong>F. Market Size/Growth Potential</strong></td>
<td><strong>G. Assumptions</strong></td>
</tr>
<tr>
<td><strong>H. Product/Service</strong></td>
<td><strong>I. Risks</strong></td>
</tr>
<tr>
<td><strong>J. Target Customers</strong></td>
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</tr>
<tr>
<td><strong>K. Value proposition/Competitive Advantage</strong></td>
<td></td>
</tr>
<tr>
<td><strong>L. Key success factors</strong></td>
<td></td>
</tr>
<tr>
<td><strong>M. Competitive Landscape</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Financial</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Incumbents</strong></td>
</tr>
<tr>
<td></td>
<td><strong>New entrants</strong></td>
</tr>
<tr>
<td><strong>P. Barriers to entry</strong></td>
<td><strong>N. Timing</strong></td>
</tr>
<tr>
<td><strong>R. Regulatory Environment</strong></td>
<td><strong>S. Metrics/Targets</strong></td>
</tr>
<tr>
<td><strong>T. Constraints/Dependencies</strong></td>
<td><strong>U. Funding</strong></td>
</tr>
<tr>
<td><strong>V. Core Competencies Needed</strong></td>
<td><strong>W. Strategic Partners/Supply Chain</strong></td>
</tr>
<tr>
<td><strong>X. Market Need</strong></td>
<td><strong>Y. Assumptions</strong></td>
</tr>
<tr>
<td><strong>Z. Market Size/Growth Potential</strong></td>
<td></td>
</tr>
<tr>
<td>WHAT</td>
<td>WHEN, HOW (impact, response/contingency, how advance)</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>-------------------------------------------------------</td>
</tr>
<tr>
<td>Defining the vision / goal</td>
<td>Near-term: First product is hydrogen</td>
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<tr>
<td></td>
<td></td>
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<tr>
<td>Intermediate Products</td>
<td>Renewable hydrogen</td>
</tr>
<tr>
<td></td>
<td>Japan and Europe since they pay higher natural gas prices</td>
</tr>
<tr>
<td></td>
<td>Niche markets: Remote mines, military, fertilizer companies going green</td>
</tr>
<tr>
<td>Potential customers as well as markets (consider different stages of product; customers could be ultimate end users or refiners)</td>
<td>Intermediates: energy storage for PV/wind, CO₂ capture, catalysts to mining industry, ammonia, water</td>
</tr>
<tr>
<td></td>
<td>Japan and Europe since they pay higher natural gas prices</td>
</tr>
<tr>
<td></td>
<td>Niche markets: Remote mines, military, fertilizer companies going green</td>
</tr>
<tr>
<td>Marketing message</td>
<td>Importance to future; intermediate products</td>
</tr>
<tr>
<td><strong>Key Challenges:</strong></td>
<td>• Government funding, regulation changes could be a game stopper</td>
</tr>
<tr>
<td><strong>Government Policy</strong></td>
<td>• What incentives are there to switch, can government price externality</td>
</tr>
<tr>
<td></td>
<td>• How do you take the government out in terms of the business model?</td>
</tr>
<tr>
<td></td>
<td>• Won’t ever be more efficient than fossil fuels. Need real pricing mechanism for carbon.</td>
</tr>
<tr>
<td></td>
<td>• How does this stay alive and get funding from the private sector? Need national program.</td>
</tr>
<tr>
<td></td>
<td>• These new fuels don’t qualify as renewable. Only biofuels do today. How can definition of “renewable” be improved?</td>
</tr>
<tr>
<td><strong>Public Opinion</strong></td>
<td>• Environmentalism is a luxury good</td>
</tr>
<tr>
<td></td>
<td>• Have to educate the public to get them excited</td>
</tr>
<tr>
<td><strong>Structure</strong></td>
<td>• Integration, what does the system architecture look like?</td>
</tr>
<tr>
<td></td>
<td>• Billions of installed marketing and refining sites and infrastructure for gasoline. Has to be same form, structure. Also must work in existing engine environment,</td>
</tr>
<tr>
<td>Competitors</td>
<td></td>
</tr>
<tr>
<td>---------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>- Biofuels, electric, CNG, fossil fuels, hydrogen from natural gas</td>
<td></td>
</tr>
<tr>
<td>- Oil companies and alternative energy sources react with enhancements to existing technology or to could block progress (risk increases with success)</td>
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<tr>
<td>- Algae-based ethanol will also take a long time</td>
<td></td>
</tr>
<tr>
<td>- Never going to pipe hydrogen around, would only be viable if you had no other options.</td>
<td></td>
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<tr>
<td>- Nat Gas companies can currently generate hydrogen anywhere with pipeline or liquefied transport via truck that delivers natural gas</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Gaps, risks, uncertainties, threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>- We need more clarity around goal</td>
</tr>
<tr>
<td>- Making hydrogen is different from methanol; let’s define plausible products</td>
</tr>
<tr>
<td>- Solar to end fuels may be unrealistic. Getting to diesel requires huge plants / facilities. Just getting to methanol is good.</td>
</tr>
<tr>
<td>- Will supply keep up with demand for traditional fuels? Will prices rise? Will alternatives become necessary?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Where are private companies focused?</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Boeing can be the niche market for advanced technology or fuels . . . need high density liquid fuels. Willing to work with potential new technologies</td>
</tr>
<tr>
<td>- ExxonMobil invested in algae because it’s a liquid fuel in a form that is similar to fossil fuels and uses the same infrastructure. In addition, biofuels get positive PR and renewable energy credits</td>
</tr>
<tr>
<td>- UOP working on renewable jet, seed oil</td>
</tr>
<tr>
<td>- Sandia exploring other pathways, but same beginning and end state</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Other Misc Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>- First define the vision, goal, end-state . . . work back to business case</td>
</tr>
<tr>
<td>- Green image could be the push for people to become involved, mining companies . . . make vision flexible to attract money</td>
</tr>
<tr>
<td>- Good to have a wide variety of possibilities, but we have only 15-20 years, so only focus on hydrogen</td>
</tr>
<tr>
<td>- Small investors won’t come in if bigger players can come in later anyway. Need models for working with government e.g. with or without incentives or complementary/competing gov supported activity.</td>
</tr>
<tr>
<td>- We are early in the technology curve</td>
</tr>
<tr>
<td>- This is not science fiction. Hydrogen powers large parts of the world, Iceland. We need to replace this with PV-enabled hydrogen. This is better than algae. Biofuels or biomass can’t solve the energy challenges. Can’t scale it big enough.</td>
</tr>
<tr>
<td>- Why can’t you just use the electricity from solar? Need higher energy density liquid fuels.</td>
</tr>
<tr>
<td>- 3 credit scenarios: Don’t get credit for externalities, could substitute fuel, could get more efficient fuel.</td>
</tr>
<tr>
<td>- Substitute requires public policy. Oil companies will own this.</td>
</tr>
</tbody>
</table>
Institutional, Contextual and Sustaining Issues Group

For SOFI to achieve its stated goal will require

- designing and implementing an appropriate decision and management system,
- setting in motion the process for obtaining and then appropriately using the needed financial and organizational and personnel resources that can be obtained; and
- establishing the structures that can build and sustain SOFI though its changing and increasingly globalizing roles and demands.

Going into the group discussion the following points were indicated:

- Institutional issues: Membership; Levels and modes of fundraising and operation; management board; community building; communications and integration; management processes (e.g., roadmapping); staffing.
- Fundraising and investment; income generation.
- Particular issues: IP ownership, standards; risk & conflict management.
- Where from here?

What follows is a report on the considerable discussions that took place on some of the key points indicated above but, given the time constraints and complexity of the institutional challenge, not all could be addressed.

This group began by reviewing the core concept – a decentralized global consortium to identify and address knowledge gaps, accelerate research through coordinated funded complementary efforts by member institutions and move research to translation/commercialization achieving grand solar fuel objectives. There was discussion over the best organizational model to identify, involve and coordinate disparate research organizations, without interfering in research, and how SOFI adds value. The consensus was that SOFI contributes:

- Knowledge (continually updated) of what key competencies are required and exist and where, as well as where promising and complementary (or contradictory) research could be found
- A knowledge repository and sharing/communication mechanism and processes that avoid creating silos
- Enabling seamless integration of research output and, importantly, corporate involvement – at different levels as activity advances
- Fundraising, particularly from the private sector, and their allocation
- Development, maintenance and “ownership” of the evolving roadmaps.

The group then considered key functions and tasks in some detail. These were captured on a basic level in the following adapted template:
<table>
<thead>
<tr>
<th>What (SOFI roles, functions)</th>
<th>Near Term &lt; 1 Yr</th>
<th>Medium Term 2 – 5 years</th>
<th>Long Term &gt;5 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fund Raising (gradually builds)</td>
<td>Identify donors - philanthropy Develop pitch(es) Sell options?</td>
<td>Seek first level funding Refine pitch(es) Identify other funding sources</td>
<td>Seek later/larger and sustaining investment Government? DOE? Industry?</td>
</tr>
<tr>
<td>Organization/Governance/Board</td>
<td>Define membership; affiliation modes (include corp.) Model – network with central org. structure generate “Do’s”</td>
<td>Manage network Consider and develop a PLAN B (indicated as needed but not elaborated upon)</td>
<td>Implement Plan B if necessary</td>
</tr>
<tr>
<td>Location(s)</td>
<td>Northwestern for administration; Telluride for meetings – CO and worldwide.</td>
<td>Add sub-hubs/remove as necessary Move people/ideas fluidly = education/training</td>
<td>Add or remove sub-hubs. Move people/ideas fluidly = education/training -&gt; jobs</td>
</tr>
<tr>
<td>Scientific Membership/Network; varying objectives</td>
<td>Identify initial hubs Identify initial companies</td>
<td>Add sub-hubs/remove as necessary Move people/ideas fluidly = education/training</td>
<td>Add or remove sub-hubs. Move people/ideas fluidly = education/training -&gt; jobs</td>
</tr>
<tr>
<td>Fund Allocation (gradually builds) /Defining Scientific Goals</td>
<td>Models of how to determine allocations</td>
<td>Start to allocate funds Monitor progress</td>
<td>Continue to allocate funds Monitor progress</td>
</tr>
<tr>
<td>Communication</td>
<td>Develop structure/protocol</td>
<td>Refine/manage structure</td>
<td></td>
</tr>
<tr>
<td>Strategy Differentiation, visibility</td>
<td>Explicate goals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IP/Tech Transfer</td>
<td>Determine models for ownership</td>
<td>License/sell/start ups/options Intermediate and mature technologies</td>
<td></td>
</tr>
<tr>
<td>Market Research</td>
<td></td>
<td>Customer id Policy – global governments Developing World</td>
<td></td>
</tr>
</tbody>
</table>
While recognizing the priority need for SOFI fundraising, the group also saw the need to give attention to a variety of other foundational aspects as well as the value to learn from and seek cooperation with other models (JCAP, etc.) Thus it was suggested that success in getting SOFI up and running in a sustainable manner could be maximized with multiple, parallel complimentary models - which need to be identified. Most specifically, discussion ensued regarding the obvious beneficial logic of collaboration between the decentralized ("open") SOFI network of collaborating research centers making use of the to-be -raised complementary private funding and the centralized hub that would emerge at Caltech under the leadership of Nathan Lewis and with the DOE funding.

Indicated Issues and challenges in collaboration include:

- How to pursue this using centralized/decentralized strategic models: how to optimize collaboration?
- Identification of common goals, common capabilities (political, social, economic) between players; get the best people to work together leading to the question of how to organize these people and work effectively together (research, capital, corporate)
- Must be done in a pre-competitive model avoiding potential IP fights, etc.
- Build model off of existing consortia, pick and choose strengths, identify expectations for buy-in/get out (IP): who and how selected the board members would be will be an important success determinant (see below).

Broader questions included the levels, timing and kind of funding/investment that will be needed (and possible) at different points? What investment levels could be established? When would it be critical to have attracted different types of sponsors/investors recognizing the danger implicit in the “Valley of Death” phenomenon? It was suggested that early success was critical before large investments could be expected. Initially having many smaller investments might be the best strategy. Investors might be persuaded that they can’t afford to sit out. A key SOFI strength would be the value and power of the network it would attain and sustain. Related IP ownership and sharing issues for both investors and players were raised. Membership and funding allocation and related structure was also discussed with the following questions and concepts offered:

- Who gets to be in SOFI? Who decides who should be funded and at what levels and with what conditions? Will need to get cooperation through players accepting terms upon joining SOFI, need key institutions to sign up for this early on. Would related current and evolving industry want competitive allocation of funding? (Likely yes).
- Could SOFI identify income producing/sustaining programs (using the SEMATECH/ITRS model)?
- An independent board accepted by all would be needed that could decide which research institutions could be involved and how and in what to become involved; give consideration to a need to identify differing levels of activity and of involvement? It was suggested to establish an initial Operations Committee to address these topics, possibly designating a CTO. Interdependent issues are: structure/board/membership)?

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• Modes and protocols of relations between groups will need to be established.
• The roles of Northwestern and Telluride and how these may play out need further clarification.
• The need to keep numbers of collaborating institutions modest (20-25 groups) was Regular and perhaps in the beginning frequent e-evaluation of consortium structure may be needed (e.g., every 6 months.)
• Another issue that received some considerable mention was that of SOFI having an Educational role. This was agreed to be important, but the subject could not be pursued in the available time.

In terms of where from here”, the immediate and central institutional imperative was to move rapidly ahead in the coming months with a vigorous first stage fundraising effort to ensure next steps. Michael Wasielewski indicated this to be his major priority, starting immediately. As this succeeds, attention to the issues raised as indicated in the table above, and others, will be addressed.

3. Wrap up plenary session
Each breakout group presented extensively on their deliberations and there was lively discussion and challenging of ideas. Much of this has been incorporated into the above summaries. Particular focus centered on the commercial and investment challenges SOFI and liquid fuel will face. We asked Bill McAllister (who, along with Dave Grossman, also facilitated the Business case group) to summarize concerns. The following is extracted from his comments.

SOFI will need to consider:
➢ A thorough analysis of the existing markets for hydrogen methanol
  • Who makes it now?
  • How do they make it?
  • Where?
  • How much does a typical plant make?
  • Who buys it?
  • What do they use it for?
  • How much do they buy?
  • What quality or supply reliability requirements do they have?
  • Are there high value regional/niche markets?

This need not be a major study. Start with Sandia, etc.; look at already done studies.

➢ A conceptual plant design:
  Assume you have a working integrated photocatalytic system and that you are ready to build your first plant making hydrogen methanol, …
  • Where would you build it? What’s the best geographic location? Where couldn’t you build it? What are the siting requirements?
  • How big would it be?
  • What raw materials does it require as process inputs?
  • How is production affected by seasonal variations in insulation, temperature, etc?
  • What are the waste products? Is there any significant environmental impact?
Describe conceptually the “business idea”:
- Who owns it?
- Who operates it?
- Who does it sell to?
- How does it make money?

For example, in the residential PV market there are several alternative business ideas including private ownership, utility ownership, 3rd party ownership, etc.

Question: How well do the conceptual “business idea” and plant design fit with the realities of the existing and emerging markets?

A comparison with the competition exploring the relative strengths and weaknesses of the technologies to be developed by SOFI vis-à-vis competing technologies

Remember that competitors will also advance. It was stated in the workshop that SOFI will deliver the “first molecule” in 5 years and may be commercial in 10. Batteries and electromechanical drives are commercially viable now. With 10 years of additional development in real markets, the entry barriers they raise to SOFI’s technology will face will be substantially higher.

4. Evaluations

The workshop was clearly very well received and achieved objectives. This was evident from informal discussions and from evaluations. A number of participants who were already actively involved in the workshop design, and will certainly continue to be involved in SOFI, did not complete evaluations. Twenty participants did, and the average score (1-7 with 7 being high) for overall value was 6.15, and for design, structure and methodology (including roadmapping) was 5.95. 60% are definitely interested in participation in further activities with others waiting to see how this unfolds. There were both suggestions of specific individuals that should be invited to future events and categories including government policy makers at both the Federal and state level, broader solar industry representatives including photovoltaics and solar related manufacturing, and pension fund investors as examples of long term investment thinking.

Broader comments on workshop design included several complaints about lack of time with the desire for more time for sharing between groups and for further breakout group time after plenary sharing/challenge sessions.

Several participants would have liked more economic analysis of SOFI and of competing technologies and explication of needed return on investments and ways to measure cost and performance to attract investment. This had been suggested as a potential ongoing service for SOFI. Some participants would have liked inclusion in topics of public perceptions and more discussion of varied models from other industries and countries.

Breakout discussion, presentations and evaluations all confirmed that a foundation for ongoing impactful roadmapping and the desired community was successfully laid. Next steps beyond what was indicated above remain to be determined.
ATTENDEES

Attendees were selected from a variety of affiliations and backgrounds relevant to, and sharing common interest in solar fuel.

Participant Institutions breakdown

<table>
<thead>
<tr>
<th>University (19 reps)</th>
<th>Research Institute (6 reps)</th>
<th>Corporate (17 reps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arizona State University</td>
<td>Argonne National Laboratory</td>
<td>Blackstone Group</td>
</tr>
<tr>
<td>California Institute of Technology</td>
<td>Brookhaven National Laboratory</td>
<td>Boeing</td>
</tr>
<tr>
<td>Emory University</td>
<td>CEA-Grenoble</td>
<td>Praxair</td>
</tr>
<tr>
<td>Japan Advanced Institute of Science &amp; Technology</td>
<td>National Renewable Energy Laboratory (NREL)</td>
<td>ConocoPhillips</td>
</tr>
<tr>
<td>Michigan State University</td>
<td>Sandia National Laboratories</td>
<td>ExxonMobil</td>
</tr>
<tr>
<td>Northwestern University</td>
<td>Telluride Science Research Center</td>
<td>Geocapital Securities</td>
</tr>
<tr>
<td>Rutgers University</td>
<td>GATIC reps - previous careers in: Siemens, Bell Labs, Motorola</td>
<td>UOP</td>
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<tr>
<td>University of Colorado</td>
<td></td>
<td>GM</td>
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<tr>
<td>U. of Illinois Chicago</td>
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<tr>
<td>University of North Carolina at Chapel Hill</td>
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<tr>
<td>University of Pittsburgh</td>
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<td></td>
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<tr>
<td>Uppsala University (Sweden)</td>
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<tr>
<td>Zhejiang University (China)</td>
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</tbody>
</table>

Attendees by Category

1. Academic attendees:

**Millard Alexander: University of Maryland:** Distinguished University Professor, Department of Chemistry and Biochemistry and Institute for Physical Science and Technology. Specialist in the simulation of molecular collisions in combustion environments. Member Board of Directors and President-elect Telluride Science Research Organization.

**Rodica Baranescu: University of Illinois, Chicago:** Professor, Mechanical and Industrial Engineering; Retired from Navistar Inc. after 31 years of Engineering Management & R&D of low emission diesel engines, simulation/modeling, alternative fuels; former Chair Fluids Group
(Fuels, Lubricants, Alternative Fuels, and Coolants) in Engine Manufacturers Association; currently Chair SAE Fuel Standards Committee; first woman president of SAE International; member National Academy of Engineering; currently launching Renewable Fuels Center at UIC.

**G. Charles Dismukes: Rutgers University;** Professor of Chemistry and Chemical Biology, research interests focus on biological and chemical methods for renewable solar-based fuel production, photosynthesis, metals in biological systems and tools for investigating these systems.

**Jian Du: Zhejiang University, China;** (visiting Northwestern University), Associate Professor focuses on globalization strategy and on manufacturing for a technology innovating economy. A member of the Chinese National Institute for Innovation Management, studying technological spillovers and outward foreign direct investment of Chinese firms.

**Torsten Fiebig: Northwestern University;** Director of Operations, Argonne-Northwestern Solar Energy Research (ANSER) Center, Research Associate Professor of Chemistry, has lead research groups in Germany and in the USA. Research is focused on characterizing functional molecular assemblies using time-resolved spectroscopic methods.

**Devens Gust: Arizona State University;** Regents’ Professor of Chemistry and Director of the Center for Bio-inspired Solar Fuel Production, Energy Frontier Research Center, research interests center around artificial photosynthesis. His group applies the techniques of synthetic and physical organic chemistry, photochemistry, laser spectroscopy and electrochemistry to mimicry of important aspects of photosynthetic energy conversion.

**Leif Hammarström: Uppsala University;** Professor of Chemistry, and Director of the Swedish Consortium for Artificial Photosynthesis. Currently Chair of Chemical Physics and Head of the new department for Photochemistry and Molecular Science. Research interest concern electron transfer, time-resolved laser spectroscopy and artificial photosynthesis.

**Craig Hill: Emory University;** Goodrich C. White Professor of Chemistry, at, conducts research in inorganic, catalytic, and nanomaterials chemistry and related areas.

**Ken Jordan: University of Pittsburgh;** Distinguished Professor of Computational Chemistry, and Co-Director Center for Simulation and Modeling, President, Telluride Research Center; Senior Editor, Journal of Physical Chemistry; Faculty Fellow, National Energy Technology Laboratory – Regional University Alliance.

**Saori Kawasaki: Japan Advanced Institute of Science and Technology;** Research Associate Professor, specializes in issues of working professionals, knowledge science and machine learning in computer science. Current project is capacity-building education program on negotiation skills in the global environment.

**Nathan Lewis: California Institute of Technology;** George L. Argyros Professor of Chemistry; Principal Investigator of the Beckman Institute Molecular Materials Resource Center at Caltech; Director of the Joint Center for Artificial Photosynthesis (JCAP), the Energy Innovation Hub in Fuels from Sunlight. Research interests include artificial photosynthesis and electronic noses.
James McCusker: Michigan State University; Professor of Chemistry, Research interests involve the physical and photophysical properties of transition metal complexes. Research approach relies on a confluence of synthetic chemistry, a host of physical techniques ranging from magnetism to femtosecond time-resolved spectroscopy, and high-level theory.

Meg McDonald: Northwestern University; Senior Executive Director of the Office for Research Planning, Finance and Communication and the Office for Research Information Systems.

Thomas Meyer: University of North Carolina Chapel Hill; Arey Professor of Chemistry and Director of the UNC Energy Frontier Research Center in Solar Fuels and Next Generation Photovoltaics. Associate Director for Strategic Research at the Los Alamos National Laboratory (LANL) in New Mexico.

Michael Radnor: Kellogg School of Management, Northwestern; Professor, Management & Organization, Director, Center for Technology & Innovation Management; Co-founder & President of GATIC. Worked for Westinghouse, Lucas Industries, Israel Aircraft Industries, (GATIC/CTIM.)

Jeffrey Strauss: Northwestern University CTIM Associate Director industry-academic consortia formation, training, simulations (the latest focusing on solar energy.) 35 years in technology management, innovation, strategic planning with particular expertise in scenario planning. (GATIC/CTIM.)

Jay Walsh: Northwestern University; Vice President Research, previously Senior Associate Dean of McCormick School of Engineering and Applied Science, Professor of Biomedical Engineering. Was president of the American Society for Lasers in Medicine and Surgery.

Michael R. Wasielewski: Northwestern University; Clare Hamilton Hall Professor of Chemistry, Director, Argonne -Northwestern Solar Energy Research (ANSER), and Director, Solar Fuels Institute; Senior Scientist, Center for Nanoscale Materials, Argonne. Heads $25 million in funded energy research projects.

Fruma Yehiely: Northwestern University; Director of the Office of Research Development; oversees strategic and operational functions, including accelerating and supporting large, multi-investigator proposals in all areas of research across Northwestern and advising faculty on research grants.

2. Research Institutes

Vincent Artero: CEA-Grenoble; Research Scientist, Laboratory of Chemistry and Biology of Metals in Grenoble in 2001, current research interests are in the structural and functional hydrogenase models for the design of artificial systems for the photo- and electrochemical production of hydrogen.

Nana Naisbitt: Telluride Science Research Center; Executive Director of TSRC, founder of Pinhead Institute, a Smithsonian Affiliate and science education non-profit in Telluride Colorado, and co-author of High Tech High Touch (Broadway Books, 1999.)
Michael Pellin: Argonne National Laboratory; Argonne Distinguished Fellow, Deputy Director, Argonne-Northwestern Solar Energy Research (ANSER) Center, Pellin directs research in understanding the surface chemistry of materials; includes operation of the world’s most sensitive trace analysis facility.

Dmitry E. Polyansky: Brookhaven National Laboratory; Assistant Chemist, Polyansky’s research interests include Photochemistry and radiation chemistry relevant to catalysis and solar energy conversion, electron transfer reactions, and fast and ultrafast transient spectroscopy.

Garry Rumbles: National Renewable Energy Laboratory; Research Fellow, Adjunct Professor of Chemistry, at University of Colorado Boulder, Fellow CU/NREL Renewable and Sustainable Energy Institute (RASEI). Current research in solar energy with focus on basic science of solar photoconversion processes and photoinduced electron transfer in polymer-based nanostructured interfaces. Primary research expertise in photochemistry & photophysics, specialty in kinetics.

Ellen Stechel: Sandia National Laboratories; Manager Concentrated Solar Technologies and National Solar Thermal Test Facility. Program Manager, Sunshine to Petrol., joining ASU as Professor of Practice & Deputy Director of LightWorks. Expertise in managing large multi-disciplinary R&D efforts in National Labs and industry. Worked at both SNL and Ford and between science and research management.

3. Corporate

Oil/transportation industry

Alessandro Faldi: ExxonMobil; Section Head, Emerging Energy Sciences, Corporate Strategic Research, Research and Engineering Company and is responsible for biosciences, environmental sciences and emerging energy systems capabilities as well as interface with the external science community.

Doug Galloway: UOP; Manager for Renewable Energy and Chemicals Research. Has had a significant role on many refining and petrochemical technology delivery project teams. Along with directing internal research using various renewable feedstocks, currently serves as the technical lead for the Catalytic Fast Pyrolysis Team that is part of the National Advanced Biofuels Consortium.

David Grossman: (GM), President, Dynamic Strategy Group; Director Global Technology Strategy, General Motors (32 years in planning, engineering and international executive positions); Roadmapping and other tools specialist and consultant. Trained small businesses in mapping tools (GATIC/CTIM)

Neal McDaniel: ConocoPhillips; Associate Scientist. Research experience in Chemistry from Princeton University and California Institute of Technology.

Liam Pingree: Boeing; Engineer, Research and Technology in thin-film coatings and energy related materials; examining nanostructure of organic light emitting diodes using conductive atomic force microscopy techniques. As post-doctoral fellow studied organic photovoltaics using similar methods.
Sharon Rynders: BP; Energy Biosciences Institute Commercial Manager, Group Technology. Responsible for financial planning and program coordination/connectivity across the Institute. Held several technical and commercial roles within BP, Amoco, Albermarle and Ethyl Corp. Most recently, in London for BP's Chief Scientist, leading a global cross-discipline project team to refresh long-term technology strategy.

Investment

Jim DeNaut: Nomura Holdings; Head of Investment Banking in the Americas, WCAS 1984, Head of Investment Banking in the Americas, Nomura Holdings, Inc. (Greenwich); NU Trustee. DeNaut, a senior oil and gas banker joined Nomura Holdings in 2011 from Deutsche Bank.

George Fink: Geocapital Securities, Inc., a venture capital, corporate finance and investment banking company, CEO. Organized & managed ventures in renewable energy, health care & IT. Structured and financed over two billion dollars of business for corporate partners and investors. He served as general partner, director and officer of many partnerships and venture companies.

Tom O’Flynn: The Blackstone Group; Senior Advisor with over 25 years of experience in the power and utility industry, assists the firm in the power and utility sector. Chief Financial Officer PSEG, a New Jersey-based merchant power and utility company and President of PSEG Energy Holdings ;previously in the Global Power and Utility Group of Morgan Stanley. Currently on Director of BrightSource Energy.

Other industries and experts

Rich Albright: Albright Strategy Group. President., Roadmapping Consultant with 25 years in strategy development, systems engineering and product development. Headed technology planning at AT&T; Directed roadmaping application and training at Lucent/Bell Labs. (GATIC/CTIM.)

Niels Damrauer: Sun Catalytix (on sabbatical); Associate Professor, University of Colorado (Boulder), working on photoelectrochemical water splitting reactions and implementation. Academic research interest in solar energy conversion and photochemical control of electron transfer using state of the art time-resolved spectroscopic techniques, synthetic methodologies and computational tools.

Gary DeGregorio: Decision Innovation CEO, co-founder., Inc. Focus includes systems engineering, decision management, knowledge foundation and architectures, strategic roadmapping; Was Distinguished Member of Technical Staff, Motorola Labs. Over 30 years with Motorola.,(GATIC/CTIM.)

Janice Gordon Ginsberg: SMI, President, strategic planning/marketing firm; operates in nine countries and across many industries. It uses proprietary research and business models in identifying, implementing and integrating stages of strategic alignment and strategy. Has held executive and new product development positions at G.D. Searle, Telemedia and Wilson Sporting Goods. (GATIC/CTIM.)

Mark Hellmann: Tripod; An internationally known legal authority at on intellectual property law, with over 25 years of experience in copyright matters spanning print media, electronic
media, computer software, computer hardware, internet, video media, and design. Head of two
two firms (GATIC/CTIM).

**William McAlister:** *(previously) Siemens Energy* 39 years of experience in operations research,
management science, R&D, financial modeling and decision analysis. Applications included
new energy technology development, nuclear reactor safety, business strategy, acquisition
valuation and innovation management. Headed Siemens business process engineering Fossil
Power Generation (GATIC/CTIM).

**Jeff Wallace: Praxair;** Technology Manager, Intellectual Property Consultant. Specializing in
Technology Assessment and Valuation, In-Licensing and Creative Problem Solving Techniques.
Over 20 years experience in developing technologies for the BioPharma, Electronics, Surface
Coating, Food and Beverage, Environmental, and Metals Processing industries.

**Gerry Zajac: Ineos;** Senior Research Associate. Previously worked for BP Chemicals, Amoco,
and Argonne National Laboratory. Research interests include new technology, advanced
materials characterization, nanophased materials & catalysts.

**Graduate Student Support**

1. **Kellogg School of Management (MBA students)**
   
   **Hando Choi:** was Global Project leader, General Motors managed international project teams of
   45 engineers from, identified and implemented new technology, headed training programs,
developed standards, architecture and procurement strategies for Asian regions. Was also process
engineering specialist for Hyundai Motors, controls engineer with Boston Consulting Group.

   **Ananth Narayan Krishna:** was Associate and Stakeholder in National Energy Service
   Company, an efficient energy new venture. Was also with Mercer where he carried out strategy
   reviews, developed 3 year visions for clients and portfolio plans for 8 Mercer business lines.
   Previously, he was Senior Business Analyst for Dun & Bradstreet and Business Analyst for

2. **Department of Chemistry, Weinberg College of Arts and Sciences (Ph.D. students)**

   **Erica “Rikki” DeMarco:** 4th-year Chemistry student jointly advised by Prof. Joseph Hupp and
   Prof. Michael Pellin at Northwestern University. As part of the Argonne-Northwestern Solar
   Energy Research Center, she is currently working on incorporating plasmonic nanoarchitectures
   into photovoltaic and photoelectrochemical devices.

   **Michael Vagnini:** 5th-year Chemistry candidate advised by Prof. Michael Wasielewski at
   Northwestern University. As part of the Argonne-Northwestern Solar Energy Research Center,
   he is currently working to drive the activity of molecular water oxidation catalysts using light.

   **Venessa Williams:** 4th-year Chemistry Candidate jointly advised by Professors Michael Pellin
   and Joseph Hupp. As part of the Argonne-Northwestern Solar Energy Research Center, she
   currently researches new photoanode architectures in dye-sensitized solar cells.
Collaborating Workshop Organizers

**SOFI (Solar Fuels Institute)** is being organized as a global consortium of research and development organizations headquartered at Northwestern University that will develop the technology required to establish a solar fuels industry using largely private capital. SOFI’s overarching goal is the development of efficient, cost-effective photovoltaic and photocatalytic systems to capture sunlight that are integrated with high performance catalysts for water splitting and reduction of CO$_2$ to liquid fuels. The Institute will focus on the following objectives:

- Develop high performance photovoltaic and photocatalytic systems designed specifically to integrate with fuel-forming catalysts.
- Develop new catalysts for water splitting and CO$_2$ reduction with a tailored spectrum of products for incorporation into a fuels supply stream.
- Develop the tools necessary to characterize the performance and properties of the materials and mechanisms of solar fuels formation.
- Develop process engineering strategies to scale these technologies to the pilot stage, so that industry partners can integrate them with current fuels processing technologies.
- Develop the systems integration tools specific to the unique challenges of solar fuels technologies at all levels of the development process.
- Produce economic analyses of technical approaches at each stage of solar fuels production to obtain realistic estimates near-term economic technical advances viability.
- Carefully assess the public policy implications of developing and utilizing solar fuels, as well as public acceptance.
- Leverage complementary private sector capabilities in industry to achieve Institute goals.

**CTIM (Center for Technology & Innovation Management)** is based in the Buffett Center for International and Comparative Studies at Northwestern University but located in the university’s Kellogg School of Management. It was launched as a National Science Foundation University-Industry Cooperative Research Center at the initiative of industry (including such firms as Baxter, Coca-Cola, DuPont, Ford, General Motors, IBM, Intel, Kodak, Kraft, Lockheed Martin, Lucent, Material Sciences, McDonalds, Motorola, Rockwell Automation, Roche, Siemens Westinghouse, and United Technologies.) It carries out funded research and consulting projects for companies, US and International government agencies and various foundations across the country and worldwide. CTIM works closely with the Global Advanced Technology & Innovation Consortium (GATIC) which CTIM co-founded with ETH-Zurich and the Japan Advanced Institute of Science & Technology. GATIC now includes many other globally distributed universities and over a hundred firms. With GATIC, CTIM’s focus is on the development and adaptation of tools such as roadmapping to highly complex and dynamic problems and domains (including energy) and related analysis, training and strategic planning support.
APPENDIX

1. Briefing Document

Workshop Goal: To help establish a viable global solar fuels industry in the next 10-15 years, approximately 45 stakeholders from academia, industry, national laboratories and the investment community will assemble to launch a comprehensive roadmapping process to optimize progress while identifying hidden opportunities and addressing potential pitfalls.

OVERVIEW: The Need for Solar Fuels, the Potential and Challenges

With their potential to provide liquid fuels that take full economic advantage of existing infrastructure, while delivering a clear path toward new fuels for the future, solar fuels could furnish the needed carbon-neutral energy to satisfy the expected doubling of global energy requirements over the next 40 years. The major challenge is that the science and engineering to establish a viable industry remains undeveloped.

The global Solar Fuels Institute (SOFI) will develop the technology required to establish a solar fuels industry using largely private capital is in development. SOFI’s overarching goal is the development of efficient, cost-effective photovoltaic and photocatalytic systems to capture sunlight that are integrated with high performance catalysts for water splitting and reduction of CO₂ to liquid fuels. Meeting this grand challenge will require: 1) development of systems integration tools specific to the unique technology challenges at all levels of the development process; 2) economic analyses of the technical approaches at each production stage to obtain realistic estimates of near-term economic viability of the technical advances; 3) assessments of public policy implications of developing and utilizing solar fuels; and 4) optimizing ways to leverage complementary private sector capabilities in industry to achieve SOFI’s goals. The focus and issues are detailed further below.

Produced cost-effectively, solar fuels used with current engine technology and distributed through existing supply systems could open up exciting global, national and business potential. But solving and implementing the technical, policy and commercial development challenges over the 10-15 years of the envisaged program poses challenging planning and management requirements. Scientific knowledge gaps need to be filled and systemic trade-off decisions will be required - on costs (materials, processes, vehicle modification and distribution), scalability, capture and conversion efficiency, development and deployment time, ease of use and more. Externalities include uncertain government funding, policy and incentives, which, even if SOFI is fully privately funded, may drive development of alternative energy technologies in other directions. Fluctuating oil prices and shifting environmental pressures, competing technology breakthroughs and economic conditions impacting sustained investment add to the risks. Further complex planning and communication requirements derive from the fact that SOFI will be a widely-distributed global program with collaborations among a plethora of international research sites, face challenges in monitoring widespread competing initiatives, and deal with difficulties in coordinating and aligning many stakeholders including automotive and oil industries and systems, NGOs, investors and industry partners - with varying agendas, time horizons and technical understanding.
Taken together, a systematic process is needed to effectively focus on, layout, monitor, assess and communicate steps toward the desired outcome, with associated resources, risks, obstacles, assumptions and stakeholder implications. Roadmapping, particularly when integrated with other tools has become increasingly recognized in industry as effective and powerful in delivering such outcomes under highly complex and uncertain conditions, as here. The Center for Technology and Innovation Management (CTIM) in Northwestern’s Buffet Center for International and Comparative Studies, in association with the Global Advanced Technology & Innovation Consortium (GATIC) which CTIM co-founded with such universities as ETH-Zurich, the Japan Advanced Institute of Science & Technology and which includes a score of other globally distributed universities and over a hundred firms, is a leader in such roadmapping.

**Roadmapping (Integrated with Other Tools):** Roadmapping is a group process that provides a clear graphical framework for exploring and communicating vision and planning. Visually, it takes the form of a continually updated time chart that links market, product and technology information and enables market opportunities as well as technology, organizational and infrastructural gaps to be identified and addressed. Alternative pathways are laid out with specified goal milestones/“stage gates” and checkpoints dynamically adjusted to the operating environment. Roadmapping can reveal funding, technology advances and capabilities requirements - when needed, who must provide and implications if not in place. Assumptions/risks are explicated and evaluated with strategies to address them.

The CTIM integrated roadmapping approach incorporates other established tools, including scenario planning, particularly relevant to highly dynamic areas such as renewable energy. This process can richly and comprehensively present a range of possible future contexts to describe technical, political, economic and social considerations which challenge planning and bring out the implications of unaddressed assumptions. Mindmapping and causal mapping to assess complex interrelationships between drivers and factors, domain mapping which pushes perceived limitations defining parameters of emerging areas, as well as risk analysis and portfolio management to explore tradeoffs (particularly) from an investment perspective, are also used. These tools add practicality and insight from multiple perspectives easily missed by specialists and support communication with stakeholders.

The “Solar Fuels Workshop: Roadmapping for Success” will take full advantage of these tools and techniques to guide the SOFI initiative and provide the business-oriented information to give both current stakeholders and future investors’ confidence to move toward achieving this critical renewable energy goal. Unlike many programs, this workshop will not be standalone. Rather, it is intended to stimulate ongoing activity and taskforces to refine and advance the roadmapping, inform project management and maximize solar fuel potential.

**SOFI APPROACHES AND DIRECTIONS**

SOFI will implement a tiered and aggressive strategy to develop fully-integrated devices that will incorporate both state-of-the-art photovoltaic (PV) and catalytic functions to generate fuel from a single device. These solar fuel cells will be capable of wide use in remote locations and will target liquid fuels, such as alcohols from CO2, which can use currently available
infrastructure for storage and use. SOFI has unmatched expertise in the broad interdisciplinary fields supporting the development of advanced materials for photovoltaic energy conversion that will serve as the foundation for a next generation solar fuels technology. This aspect of the program will develop diverse new materials - molecular and polymeric systems, inorganic nanoscale materials and their assemblies, functional hybrid composites - and strive to implement them as suitable disruptive replacements for the inorganic semiconductor systems.

**Liquid fuels from Solar-driven CO₂ Reduction.** Currently there are no known molecular or heterogeneous catalysts for the reduction of CO₂ to methanol that have the combination of rates, overpotentials, selectivities, cost, and lifetimes that are needed solar fuels production. We propose a phased parallel approach that will allow us to immediately address issues associated with the integration of CO₂ reduction catalysts with light-harvesting PV components, while allowing the simultaneous development of better catalysts for CO₂ reduction. Initial efforts will focus on developing catalysts for two-electron reduction reactions to produce CO, formate, and H₂.

In parallel, catalysts capable of reducing CO₂ beyond CO and formate will be studied. This will involve development of homogeneous and heterogeneous catalysts that are capable of four- and six-electron reductions or combinations of two-electron catalysts that are optimized for sequential reduction of CO₂ to CO and CO to methanol or CO₂ to formate and formate to methanol. Such routes can also lead to the formation of high-energy-density fuels containing C-C bonds as well as C-H bonds. Ultimately CO₂ should be recovered directly from the atmosphere to achieve a fully closed CO₂ cycle, as observed in photosynthesis. However, the knowledge or technology to do this efficiently currently does not exist.

Our initial efforts to achieve an integrated solar/CO₂ reduction system will use concentrated CO₂, such as that derived from point sources such as power plants. This will allow carbon to be used at least twice before being released as CO₂ into the atmosphere. The present state of the art for capturing CO₂ from flue gases is the use of an inefficient liquid amine based system. New approaches will include *Thermal Swing Adsorption* (TSA) using tailored solid sorbents for CO₂ capture, which would not waste energy on heating water as required for regeneration of the liquid-amine systems. In the long term, electrochemically-driven CO₂ carriers capable of removing CO₂ directly from the atmosphere will be developed and integrated with the light-harvesting modules and catalysts to achieve fuels formation.

**Water Splitting and Proton (H⁺) Reduction for H₂.** Ultimately the source of electrons to drive CO₂ reduction to liquid fuels must come from water oxidation (splitting). A critical component of all potential solar fuels technologies will be efficient water oxidizing and proton reducing catalysts that are composed of earth-abundant, inexpensive materials. These catalysts will be photo-driven, stable, self-repairing, and efficient, thereby wasting little energy and responding to a wide range of the solar spectrum. Developing these catalysts, or optimizing the catalysts already in hand, will require breakthroughs in fundamental sciences (identifying and replicating the required mechanisms), synthetic approaches (making copious amounts of catalysts...
inexpensively), and process engineering/systems integration (connecting catalysts to the appropriate materials). SOFI partners will develop several approaches to optimized water splitting catalysts that can be fully integrated with photovoltaic and photocatalytic devices for near, intermediate, and long term solutions. For example, bio-inspired, inexpensive nickel- and cobalt-based catalysts that operate under non-alkaline conditions will be developed. SOFI will fully characterize the proton-coupled electron transfer (PCET) mechanisms by which these catalysts operate by the application of cutting-edge structural, dynamics, and computational tools.

**Materials, Device and Systems Fabrication and Evaluation.** Materials synthesis, device fabrication, mechanistic and performance characterization both in-situ and in-process as well as extensive theory, modeling and simulation of the entire solar fuels production cycle at the SOFI will make extensive use of world-class user facilities sited at international research centers, such as the Advanced Photon Source synchrotron light source at Argonne National Laboratory. The home institutions of the SOFI team members will also provide excellent in-house characterization facilities with access to specialized and high-end instrumentation, equipment, and pilot capabilities necessary to advance SOFI’s research and technology goals.

**Process Engineering.** Two solar strategies, a modular photovoltaic-electrocatalyst system and an integrated photocatalytic system, will be developed for generating hydrogen from water and CO from CO₂ needed to serve as the chemical building blocks for producing fuel. Once generated, one can exploit existing syngas process technologies such as the water-gas shift reaction coupled with existing Fischer-Tropsch or “methanol-to-gasoline” processes to produce a liquid fuel. Alternatively, new chemistries and processing technologies for producing fuels will be explored, such as those based on bio-inspired processes, which could prove to be more viable than existing syngas-based technologies. One can envision these processes occurring on different length scales – from micro-scale technologies that integrate multiple process steps into a single device that produces the fuel in a highly-dispersed fashion at the site of the light harvesting using microreactor systems to macro-scale technologies that collect the products of the harvested light, either electrons or chemical reactants, and then process them into a fuel at a central location. Each strategy has its own set of challenges: Processes that exploit existing syngas production technologies will require significant improvements in carbon, water, hydrogen, and energy utilization to produce more infrastructure-compatible fuels than are realized with current process technologies. Processes based on new chemistries and process technologies will require significant development to fully evaluate their potential viability at engineering scales. The distributed production of the fuel at the light harvesting site requires new micro-scale reactor and process technologies.

**Systems Integration.** A conceptual framework for solar fuels production is shown in Figure 1. In general photovoltaics (or photosensitizers in photocatalytic systems) provide electron and holes (and usable heat). The conversion “box” takes in water, carbon dioxide, and energy, and has the potential to produce purified water, hydrogen, and hydrocarbons that might include alcohols. Processes must capture and separate the useful end products from the chemical processing stream, then deliver them for end use. The overall concept is supported by materials development, characterization, modeling, and simulation. Guidance is needed from systems
engineering, economic analysis, public policy activities, and from the development of relationships and technology transfer with industry partners. Since the system can also produce electricity, tradeoffs between electricity production and chemical production must be evaluated, and even subjected to dynamic control as a system operates.

System integration must address three sets of challenges. First, diverse components that include catalytic reactors, reduction cells, feedstock management, and product separation must be designed to work together and integrate into a complete conversion box. Second, operating tradeoffs, system control, and external technical aspects must be studied. Third, comprehensive system integration involves the full feedstock stream and access to carbon, integration of end products into the transportation system, cost analysis of electricity and fuel production, integration of photovoltaic methods and electric power conversion, interconnection to the electricity grid, and other technical, economic, and policy aspects.

**Economics and Public Policy Impacts.** SOFI will take a holistic, systemic approach that will not only compute capital, fixed O&M, and variable costs, but also measure other metrics including the impacts on overall global macroeconomics and implications on energy reliability and security. Economic externalities throughout the fuel chain such as land, air, and water impacts will be quantified. Tools, models, and methodologies will emphasize transitional challenges, institutional and technical barriers, and integration issues to quantify intended and unintended consequences of sunlight-to-fuels technologies. Approaches will identify and simulate policies, both stick and carrot approaches, that will foster the development and adoption these technologies. SOFI partners will have decades of experience in both developing and applying numerous operational, economic, and financial models to solve diverse energy and environmental systems problems. Modeling methodologies include conventional techniques such as optimization, simulation, general equilibrium, decision and uncertainty analyses, and advanced heuristics along with emerging methodologies such as Agent Based Modeling Systems (ABMS) and Complex Adaptive Systems (CAS). The transition to sunlight produced fuels will directly affect virtually all economic and energy sectors. By utilizing a wide range of modeling and simulation tools that include physical, business, and regulatory layers in an integrated modeling framework, the energy, economic, and environmental implications of producing fuels from sunlight will be analyzed from a systemic viewpoint. These tools will serve as an “electronic laboratory” to learn and discover the advantages and disadvantages of solar fuels. Through this process SOFI will be able to avoid some of the potential pitfalls associated with the technology and enhance its value before it is deployed. Lessons learned through the application of these tools will help steer the development of the technology to maximize its full economic and financial potential.

2. **Powerpoint presentations from:**
   - Wasielewski
   - McAllister
   - Albright
   - Grossman
Project Vision

Michael R. Wasielewski

Northwestern University, Evanston, IL
Renewable Global Energy
Global Energy: the Need and the Solution

**THE NEED:**
- 13 TW in 2004
- 30 TW in 2050
- 45 TW in 2100

**THE SOLUTION:**
- SOLAR ENERGY UTILIZATION
  - $1.2 \times 10^5$ TW on Earth’s surface
  - 36,000 TW on land (world)
  - 2,200 TW on land (US)
The Solar Fuels Challenge

• Solar fuels are important because they can provide a method for storing solar energy using existing infrastructure.

• Knowledge gaps need to be filled.

• Define targets: e.g. water splitting to produce $\text{H}_2$, reduction of $\text{CO}_2$ to CO and/or methanol.

• Support technologies, e.g. solar photovoltaics needed.

• Economics, social and public policy input needed.

• Industrial interactions are critical to translate research discoveries into commercial reality.

• Currently, there is no solar fuels industry.
Primary Goal:
The development of efficient, cost-effective photovoltaic and photocatalytic systems to capture sunlight that are integrated with high performance catalysts for water splitting to generate $\text{H}_2$ and reduction of $\text{CO}_2$ to liquid fuels.
The vision of the Solar Fuels Institute is to develop the technology required to establish a global solar fuels industry.

The Institute’s overarching goal is the development of efficient, cost-effective photovoltaic and photocatalytic systems to capture sunlight that are integrated with high performance catalysts for water splitting to generate H₂ and reduction of CO₂ to liquid fuels.

The Solar Fuels Institute will focus on complementary technologies:

Develop photoconversion technologies in parallel with catalytic systems for H₂O splitting to generate H₂ and CO₂ reduction to fuels. This approach will provide a solar fuels technology in which the photoconversion and fuels formation technologies can be physically separated.

Develop a photocatalytic fuel cell that will produce fuels directly from sunlight in an integrated device.
What is it?
It is a global consortium of university and corporate research organizations that will develop the technology needed to establish a solar fuels industry.

Who pays for it?
The Institute’s funding will be raised from a combination of philanthropy, private investment capital, and corporate partners and comprise largely private monies. The intent is to leverage existing governmental support that has become available in the past several years.

What is its value?
The Institute’s transformative “added value” lies in its unique integration of solar-to-electrical energy conversion with solar-to-chemical energy conversion as well as its focus on the economics and public policy issues connected to establishing a viable global solar fuels industry.
Ten-Year Scenario for Solar Fuels

Years 1-5:

• Carry out research that targets the significant knowledge gaps:

  1) Develop high performance photovoltaic and photocatalytic systems designed specifically to integrate with fuel-forming catalysts.
  2) Develop new catalysts for water splitting to generate \( \text{H}_2 \) and \( \text{CO}_2 \) reduction with a tailored spectrum of products for incorporation into a fuels supply stream.
  3) Develop the tools necessary to characterize the performance and properties of the materials and mechanisms of solar fuels formation.

• The Solar Fuels Institute will provide a venue for organizing the overall effort and exchanging key project information among the researchers and other stakeholders.

• Establish start-up companies and/or partnerships with existing companies to identify the best technological directions to incorporate into the overall energy portfolio.
Ten-Year Scenario for Solar Fuels

Years 6-10

• Develop the process engineering strategies necessary to scale these technologies to the pilot stage, so that industry partners can integrate them with current fuels processing technologies.

• Develop the systems integration tools specific to the unique challenges of solar fuels technologies at all levels of the development process.

• Produce economic analyses of the technical approaches at each stage of solar fuels production to obtain realistic estimates of the near-term economic viability of the technical advances.

Year 10

Completely transition new technology to industry and/or negotiate acquisition of start-ups established to develop the new technology. It should be apparent whether start-ups can stand alone by this time.
The Dawn of a Promising Energy Future
Commercializing New Energy Technologies
A Perspective from Industry

Bill McAllister
November 17, 2011
Where am I coming from?

~40 years in Energy Equipment Manufacturing Industry

- ⅔rd at Westinghouse’s R&D Center
  - as a Decision/Risk Analyst modeling & evaluating product development projects
- ⅓rd working for CTO of Siemens Power Generation
  - in R&D management coordinating R&D project portfolio selection

- applications include:
  - Photovoltaics
  - Solar Heating & Cooling
  - Solar Thermal Power Plants
  - Wind Turbines
  - Solid Oxide Fuel Cells
  - Phosphoric Acid Fuel Cells
  - Battery Storage for Power Generation
  - Compressed Air Energy Storage Power Plants
  - Conventional Steam Power Plants
  - Combustion Turbine/Combined Cycle Power Plants
  - IGCC
  - Nuclear Power Plants
Fact: Most New Energy Technology Programs Fail

At what stage of development do they fail?

1. between “Concept” and “Proof of Principle”
2. between “Proof of Principle” and “Prototype”
3. between “Prototype” and “Product Launch”
4. after “Product Launch”

My experience:

- between “Concept” and “Proof of Principle”
- between “Proof of Principle” and “Prototype”
- between “Prototype” and “Product Launch”
- after “Product Launch”
“Concept” to “Proof of Principle”

Why do New Energy Technology Programs fail in this stage?

1. Can’t make the science work
2. The “solution” is chosen too quickly

Observations:

- Need a realistic assessment of the maturity or readiness of all required technologies
- Distinguish between “Front End Innovation” and “New Product/Process Development”
  - They require different management processes
- Early stage R&D is cheap — relative to the following stages
- In this stage, the key is to explore many concepts quickly
- Need to identify core and distinctive competencies
  - Core competencies are necessary for success – think broadly & identify skill gaps
  - Distinctive competencies create competitive advantage – identify & nurture

Tools:

- Ideation tools
- Idea/Opportunity Screening
- Innovation Management Stage Gate
- Technology Assessment & Screening
  … and Technology Roadmapping

Fail Fast & Often
Table 1. — Differences Between Front End of Innovation (FEI) and New Product Process Development (NPPD) Processes

<table>
<thead>
<tr>
<th></th>
<th>Front End of Innovation</th>
<th>New Product Process Development</th>
</tr>
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<tbody>
<tr>
<td>Nature of Work</td>
<td>Experimental, often chaotic</td>
<td>Structured, disciplined &amp; goal-oriented with a project plan</td>
</tr>
<tr>
<td></td>
<td>Difficult to plan, Eureka moments</td>
<td></td>
</tr>
<tr>
<td>Commercialization Date</td>
<td>Unpredictable</td>
<td>Definable</td>
</tr>
<tr>
<td>Funding</td>
<td>Variable. In the beginning phases, many projects may be</td>
<td>Budgeted</td>
</tr>
<tr>
<td></td>
<td>“bootlegged” while others will need funding to proceed.</td>
<td></td>
</tr>
<tr>
<td>Revenue Expectations</td>
<td>Often uncertain</td>
<td>Believable, increasing certainty, analysis &amp; documentation as the product release date gets closer</td>
</tr>
<tr>
<td></td>
<td>Sometimes done with a great deal of speculation</td>
<td></td>
</tr>
<tr>
<td>Activity</td>
<td>Both individual &amp; team in areas to minimize risk &amp; optimize potential</td>
<td>Multi-functional product and/or process development team</td>
</tr>
</tbody>
</table>

From *Providing Clarity And A Common Language To The “Fuzzy Front End*, Peter Koen et. al., Research Technology Management, March–April 2001
Technology Readiness Levels (NASA & others)

Focus Areas
TT - Theory of Technology
TM - Technology Management
HDE - High Level Design
RE - Requirements Engineering
RIM - Risk Management
TEV - Technology Verification
INT - Integration Tests
PLC - Project Planning and Control
DDE - Detailed Design
MAP - Manufacturing Preparation
ECM - Effort and Cost Management
CM - Configuration Management
QM - Quality Management
FIT - Final Tests
Kodak’s “Robust Technology Development Process”

Project Metrics:
- Time to Market (cycle time)
- Schedule Predictability
- Time to Profitability
- Project Goal Attainment

Portfolio Metrics:
- Revenue Growth Rate
- Revenue Pipeline
- Revenue Predictability

Comments:
- There is often an “off the books” pre-process investigation to validate the idea
  - Kodak management considers this a normal part of innovation and, within reason, “turns a blind eye to it”
- After Gate B, there should be “no more inventions”
  - The focus shifts to “prove technology robustness” — the ability to meet all technical performance spec’s
- Kodak considers “predictability” to be as important as “time to market & profit”
**UTC Innovation Methodology:**

- Thomas Edison, “Identify the opportunity first, then the path to it …”
- Recognize the differences between innovation & new product development
- Use an innovation specific stage/gate process to manage the innovation process

**Stage Gate Process to Manage the Innovation**

<table>
<thead>
<tr>
<th>Stage</th>
<th>Description</th>
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<tbody>
<tr>
<td>0</td>
<td>Opportunity Identification</td>
</tr>
<tr>
<td>1</td>
<td>Opportunity Analysis</td>
</tr>
<tr>
<td>2</td>
<td>Concept Synthesis &amp; Selection</td>
</tr>
<tr>
<td>3</td>
<td>Critical Risk Reduction</td>
</tr>
<tr>
<td>4</td>
<td>Feasibility Demonstration</td>
</tr>
<tr>
<td>5</td>
<td>Technology Readiness</td>
</tr>
<tr>
<td>6</td>
<td>Development</td>
</tr>
</tbody>
</table>

Stage 2 acts as a "reverse funnel". Its function is **not** to restrict or focus the innovation concept, but to **expand the opportunities**.

**New Product Development Stage Gate Process**

<table>
<thead>
<tr>
<th>Stage</th>
<th>Description</th>
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<tbody>
<tr>
<td>0</td>
<td>Concept Evaluation</td>
</tr>
<tr>
<td>1</td>
<td>Planning &amp; Specification</td>
</tr>
<tr>
<td>2</td>
<td>Development</td>
</tr>
<tr>
<td>3</td>
<td>Test &amp; Verify</td>
</tr>
<tr>
<td>4</td>
<td>Produce &amp; Release</td>
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</tbody>
</table>

The Innovation Process is linked into the standard New Product Development Process from Stage 4 on.

From Carl Nett, Director UTC Research Center, from August 14, 2001 MATI Meeting.
“Proof of Principle” to “Prototype”

Why do New Energy Technology Programs fail in this stage?

1. Technology surprises – performance / reliability doesn’t meet expectations
2. The technology doesn’t scale – works on the lab bench, but not in production
3. Reliable quality control too time consuming / expensive in large batches

Observations:

- Continue to assess technology readiness for all required technologies
- Start thinking about “balance of plant”, manufacturability, serviceability, …
- Don’t narrow your market focus too early
  - Identify your “distinctive competencies”
  - Identify as many potential applications as you can
  - Characterize potential markets — drivers, requirements, barriers, competitors, …
- Start thinking about business models
  - How will you make money
  - Map the “Value Chain” — Where’s the profit

Tools:

- Concurrent Engineering
- Scenario Planning
- Market Screening
- Decision/Risk Analysis
- … and Technology Roadmapping
Example: Westinghouse Dendritic Web Photovoltaics

By 1980, Westinghouse was drawing silicon ribbons 10 cm wide and meters long

- Photovoltaic cells made with this process were used on numerous space craft
- This process eliminated many manufacturing steps relative to silicon ingots
- But the technology never progressed beyond the prototype stage — why?

Many reasons:

- US government funding shifted from energy R&D to defense under the Reagan administration
- Demand-side efficiency improvements dramatically slowed the demand for new generation capacity
- Capacity additions were met with new coal fired steam and availability improvements in Nuclear
- But primarily, we were unable to scale manufacturing process from the lab

Dendritic web silicon ribbons are grown to solar-cell thickness. Progress is shown by experimental ribbons grown in 1976 and 1978 and a ribbon grown in a Westinghouse Electric Corporation pilot plant.
"Prototype” to “Launch”

Why do New Energy Technology Programs fail in this stage?
1. Don’t meet development targets
2. Can’t make it in quantity with high yield & consistent quality at a profit
3. Can make it, but can’t make a profit making it
4. The market we targeted changed during the development

Observations:
• Too few programs start thinking about manufacturability & serviceability early enough in the development cycle
• Too few programs put enough effort into developing critical “balance of plant” systems early enough in the development cycle
• Assess potential markets in detail — drivers, requirements, barriers, competitors, …
• Business model needs to consider the entire value chain
  • who makes money where?

Tools:
• Concurrent Engineering
• Scenario Planning
• Value Chain Analysis
• Decision/Risk Analysis

… and Technology Roadmapping

Unless your “time to market” is quite fast (< 3 years) you’re developing for an unknown market
Example: Siemens (Westinghouse) Solid Oxide Fuel Cell

World’s first …

1986  SOFC system operated on hydrogen at customer site – 0.4 kW
1988  SOFC system operated on hydrogen – 20 kW
1992  SOFC system fueled by NG providing CHP – 40 kW
1997  …and only fuel cell to reach 69,000 total operating hours
2000  SOFC system, grid connection, provided CHP at 3 sites – 100 kW
2001  Pressurized SOFC/GT hybrid system >53% net AC – 220 kW
2006  Pre-commercial product developed – SFC-200 – 125 kW

and was abandoned in 2011 — why?

- **Market:** the market window opened … and closed …
  - Competing technologies did not stand still — combustion turbines improved dramatically

- **Business Model:** Our focus was on SOFC technology and manufacturing, but, to succeed, we needed to make millions of cells at a very low margin — the profit was in other links in the value chain

- “**Balance of Plant**” components don’t follow the fuel cell’s learning curve, so their cost comes to dominate system cost — a very common phenomenon

- **Reliability:** fuel cells require thousands of cells to generate power on a MW scale
  - one failed cell can ruin an entire system

- **But primarily,** we never succeeded in developing a system design and manufacturing process with a profitable combination of cost, yield, reliability and performance
Scenario Planning

**Pace of Technology Change — Evolutionary / Predictable**

**Triumph of the Market**
- Passive Government
- Market Drives Change
- Predictable Technology Change
- Technology Follows the Market
- Regulation Follows Technology

**Eco-Industrial World**
- Activist Government
- Regulations Drive Change
- Predictable Technology Change
- Markets & Technology Follows Regulation

**Pace of Technology Change — Revolutionary / Unpredictable**

**Total-Energy.com**
- Passive Government
- Unpredictable Technology Change
- Market Drives Change
- Technology Makes Markets
- Regulation Follows Technology

**No-Carbon.gov**
- Activist Government
- Unpredictable Technology Change
- Regulations + Technology Drive Change & Markets
- Technology Obviates Regulation
A structured approach for evaluating complex technical–business decisions affected by uncertainty and risk

Pr(LM) = Probability of achieving Technical Success on the Late Milestones.
Pr(SF) = Probability of Strategic Fit

V = Expected NPV of Product or Service at Launch
V* = Critical Expected NPV
ΔCost = Incremental Cost

Invest I_c to Commercialize?
Invest I_{PL} in Pre-Launch?
Achieve Strategic Fit?
Fund Project for I_{LM}?
Fund Project for I_{NOW}?
 Achieve Early Technical Milestones?

Invest I_{PL} in Pre-Launch?

ΔCost = (I_{PL})
ΔCost = 0

Invest I_c to Commercialize?

ΔCost = 0
ΔCost = max [Pr(SF)F_L - I_{PL}, 0]

ΔCost = 0
ΔCost = max [Pr(LM)F_{PL} - I_{LM}, 0]

ΔCost = 0
ΔCost = max [Pr(EM)F_{LM} - I_{NOW}, 0]

Decision Tree for a New Technology
After “Launch”

Why do New Energy Technology Programs fail in this stage?
• … topic for another workshop

Observations:
• Energy Technology Programs take a long time to commercialize and are expensive
• Markets change quickly — even energy markets in the last 10 years
  • Collapse of nuclear renaissance
  • Rise and fall of LNG
  • Government funding for Renewables
• Infrastructure develops more slowly than technology
  • Railroad infrastructure in the 1850’s — ~20 years
  • Automobile infrastructure in the 1910’s — ~20 years
  • IT infrastructure in the 1980’s — ~20 years
  ➢ If your technology requires significant infrastructure development …
### Doing the Right R&D:
- Ideation tools
- Idea/Oportunity Screening
- Scenario Planning
- Business Modeling
  - Value Chain Analysis
  - Distinctive Competencies
- Decision/Risk Analysis
  - … and Technology Roadmapping

### Doing R&D Right:
- Technology Assessment & Screening
  - Technology Gap Assessment
  - Technology Readiness Levels
- Stage gate processes
  - Front end innovation
  - New Product/Process Development
- FMECA
  - … and Technology Roadmapping

### Business Cases — A Contrarian Perspective:
- Never saw a bad business case for a new energy technology (well, once)
- Nobody believes them, but you have to have one
- So make it useful to you – to model risks and guide decision making
  - Model uncertainties
  - Calculate “value of information”
  - Identify sources of risk
- Always remember its is a model, not reality
Roadmaps and Roadmapping

Solar Fuels Workshop
November 17, 2011

Richard E. Albright
realbright@albrightstrategy.com
Roadmaps and Roadmapping

A Roadmap

– is the view of a group of how to get where they want to go, or achieve their desired objective. *(Discipline)*
– helps the group make sure the capabilities to achieve their objective are in place at the time needed. *(Focus)*

Roadmapping

– is a *Learning* process for the group.
– is a *Communication* tool for the group.

The learning and communication benefits of the roadmapping process are as important as the roadmap document that results.
A roadmap covers four major topics, links them together with key drivers, and incorporates a strong sense of time:

**“Know-why”**
Understand applications, customers’ and stakeholders’ drivers. Target key segments. Identify competitors, complementors, and partners. Set strategic direction.

**“Know-what”**
What characteristics/features are most important? Link application drivers to specific challenges and evolution. Set multi-year targets. Define the services/program architecture.

**“Know-how”**
What capabilities and technologies are most important? Link drivers to capabilities/technologies and their evolution. Identify multi-generation capability and technology investments to maintain services and competitiveness.

**“To-Do”**
What resources and investments are needed? Plan projects with the highest priorities. Are capability/technology investments in the most important areas? Identify and track risk areas.
The International Technology Roadmap for Semiconductors

- Objective: “Present industry-wide consensus on the ‘best current estimate’ of the industry’s research and development needs out to a 15-year horizon.”
- “A guide to the efforts of companies, universities, governments, and other research providers or funders.”
- Process:
  - Initiated by the Semiconductor Industry Association as the National TRS in 1992
  - Became the International TRS in 1999.
  - Produced every two years (updated yearly).

- Objective: “What technical capabilities need to be developed for the industry to stay on Moore’s Law and the other trends?” Customer Drivers:
  - Smaller
  - Faster
  - Cheaper
  - More (Integration)
- A technology focus: hundreds of parameter forecasts over the 15 year horizon.

Trend | Example
--- | ---
Integration Level | Components/chip, Moore’s Law
Cost | Cost per function
Speed | Microprocessor throughput
Power | Laptop or cell phone battery life
Compactness | Small and light-weight products
Functionality | Nonvolatile memory, imager

http://www.itrs.net/
Technology Roadmap for the Fluid Power Industry

2009 Edition

• The purpose is to provide companies, universities, governments, and other research providers and funders with an industry wide consensus regarding the research and development needs of the fluid power industry.

• It charts a research and technology development agenda for the next ten years to realize industry elevating advancements in mobile hydraulics, industrial hydraulics, and pneumatics.

• These advancements will help the industry:
  – Meet the future needs of fluid power customers;
  – Expand fluid power into new customer markets; and
  – Attract the best and brightest young engineers to fluid power.

• This Roadmap also describes an action plan of research investments and technology developments needed to achieve those advancements.

Roadmapping Process

• National Center for Manufacturing Sciences (NCMS) and the Albright Strategy Group facilitated.
  – NCMS is a leader in developing collaborative partnerships to promote research & development and the advancement of manufacturing.

• Two 2 ½ day facilitated sessions at NCMS Headquarters, Ann Arbor, MI

• Participating organizations
  – 20 fluid power industry participants (NFPA members)
  – The Center for Compact and Efficient Fluid Power (CCEFP)

• Created technology roadmaps for
  – Hydraulics (Industrial & Mobile)
  – Pneumatics
Benefits from the Fluid Power roadmapping engagement:

- Participation from a wide cross-section of the industry.
- Active sharing of (pre-competitive) ideas
- Developed a shared understanding of competitive threats to the industry.
- Developed a common set of industry objectives.
- A concise communication tool to describe the industry future:
  - To industry participants
  - To suppliers
  - To customers
- Defined several potential industry initiatives:
  - New technologies
  - Standards development
- Many discussions among participants of their common interests.
Roadmapping:

Discipline & Focus

Learning & Communications
Step 1: Definition & Scope – Customer Drivers

Industry Position: Existing Fluid Power Market Size

Fluid power is energy transmitted and controlled by means of a pressurized fluid, either liquid or gas.

Fluid power includes both hydraulics and pneumatics, and the market is composed of a number of established application/industry segments including mobile and industrial applications, aerospace, energy, and infrastructure.

They also identified several niche markets with growth potential for fluid power—entertainment, human scale devices, life sciences and energy.

The Team discussed applications in each of these current and emerging markets to help direct the identification of key customer drivers.

Current and Emerging Markets

Fluid Power technology is used in a wide range of industries worldwide.

The Roadmapping Team organized dozens of specific application markets for fluid power into four key segments—mobile, industrial, aerospace and infrastructure.

There is a great degree of commonality of drivers across the market segments. Customers, to a great degree, have common key needs.

Customer Drivers

The following customer drivers—objectives fluid power customers in both established and emerging markets want to accomplish—have been identified. They form the foundation for the research and development challenges the industry should pursue.

### Hydraulic customers want to…
- Increase energy efficiency
- Increase up-time
- Derive greater value
- Increase productivity
- Improve safety
- Reduce size & weight

### Pneumatic customers want to…
- Derive greater value
- Increase environmental durability
- Increase energy efficiency
- Incorporate “smart” devices
- Incorporate “plug and play” function
- Improve safety
- Make products maintenance free
- Incorporate self-contained systems
- Incorporate “turnkey” systems

### GAP

There is a great degree of commonality of drivers across the market segments. Customers, to a great degree, have common key needs.

### Return to Roadmap framework
Step 2: Direction – R&D Challenges

Key R&D Challenges/Industry Initiatives

Key research and development challenges facing the fluid power industry:
1. Building "smart" components and systems (i.e., ones that perform self-diagnostics/prognostics and troubleshooting, integrate easily with "plug and play" functionality).
2. Increasing the energy efficiency of our components and systems.
3. Reducing the size of our components and systems while maintaining or increasing their power output.
4. Improving the reliability of our components and systems (i.e., eliminating leaks, reducing maintenance requirements, making fluid power safe and easy to use).
5. Reducing the environmental impact of our components and systems (i.e., lowering noise, increasing cleanliness).
6. Improving and applying the energy storage, recovery and redeployment capabilities of our components and systems.

Industry initiatives to support these research efforts:
1. Increasing the awareness of fluid power and its expanding capabilities in educational institutions and the marketplace.
2. Encouraging widespread adoption of new and existing international technical standards in key areas, including those associated with open architecture and communication protocols.
3. Utilizing technology advancements to better allow our customers to comply with safety regulations.

R&D Challenge #1: Increasing the energy efficiency of fluid power components and systems.

Specific metrics and 10-year development objectives have been identified for each of the R&D Challenges. Companies, universities, and funders that wish to pursue projects seeking achievement of these objectives are encouraged to advance these initiatives.

R&D Challenge #1
Increasing the energy efficiency of fluid power components and systems.

- Mobile Hydraulics
  1. Reduce energy consumption of the hydraulic system by half in 5 years for benchmark (IC driven) applications.
- Industrial Hydraulics and Pneumatics
  1. Match the efficiency of electromechanical systems (which will continue to improve over time) for standard benchmark tests.
- Pneumatics
  1. Reduce pressure loss by 40%.
  2. Improve recovery methods by 20%.
  3. Reduce power consumption by 50%.

Fluid Power Functional Architecture

This functional architecture for fluid power applications provides the framework for technology roadmaps and is seen to be robust with respect to future technological changes. Technological developments in these functional areas or combinations of these areas will achieve the 10-year objectives...

Fluid Power Functions

- CONVERT input power to fluid power
- FLUID
- MANAGE Energy (store & recover)
- CONDUCT fluid between components
- CONDITION fluid
- CONTAIN fluid
- COMMUNICATE/INTERFACE
- CONTROL the direction, pressure and rate of flow
- MONITOR performance of a fluid power system
- CONVERT fluid power to linear or rotary mechanical power.

Gap – In the future, the industry should perform benchmark tests to compare fluid power to electromechanical efficiency.

Return to Roadmap framework
Step 3: Driver Mapping & Technology Roadmaps

Hydraulics Driver Map

The driver map links key customer drivers to the R&D Challenges to the elements of the functional architecture for fluid power products, defining how the Challenges address customer needs and in which areas new technologies are needed...

Customer Drivers → R&D Challenges → Product/Platform Technologies

<table>
<thead>
<tr>
<th>Customer Drivers</th>
<th>R&amp;D Challenges</th>
<th>Product/Platform Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase energy efficiency</td>
<td>Increasing energy efficiency</td>
<td>CONVERT input power to fluid power</td>
</tr>
<tr>
<td>Increase up-time</td>
<td>Improving reliability</td>
<td>FLUID</td>
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<tr>
<td>Derive greater value</td>
<td>Increasing energy efficiency</td>
<td>MANAGE Energy (store &amp; recover)</td>
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Hydraulics Technology Roadmap (Excerpt)

Challenges & Objectives

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<td>Increasing energy efficiency</td>
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<td>Reduce energy consumption of the system by half for benchmark for IC</td>
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<td>80% Effic of Electromech systems</td>
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<td>Equal efficiency of electromechanical systems (improving over time) for standard benchmark tests</td>
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<td>Fluid Power Functions</td>
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<td>Parallel Hydrostatic Accumulator</td>
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<td>CONVERT input power to fluid power</td>
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<td>SeriesAccumulators/ Hydrostatic pump/motors</td>
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<td>MANAGE Energy (store &amp; recover)</td>
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<td>Reduce restriction w/ nano-surfaces</td>
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<td>CONDUCT fluid between components</td>
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<td>Eliminate energy consuming metering (mobile)</td>
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<td>CONTROL the direction, pressure and rate of flow</td>
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<td>High RPM, low noise pump</td>
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<td>Optimized system control/topology (e.g. TIER)</td>
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Return to Roadmap framework
### Technology Investment: Hydraulics

#### Disruptive
- Potential to change the basis of competition

#### Differentiating
- Product/Process Differentiation

#### Base
- Widespread and Shared

### Technology Source
- Acquire
- Partner
- Develop

### Competitive Impact of Technology

- **Influence**
  - Disruption
  - Differentiation
  - Base

- **Defend**
  - Acquire
  - Partner
  - Develop

### R&D Challenges
- Multi-sensor platform for integrated system and component control
- Common communication between components at application layer
- Low external leaks
- Improved seal design/surface finish to reduce leaks
- Optimized system control/topology
- Cost effective onboard system diagnostics

### Technology Advancement
- Improved component efficiency
  - Source: University
  - Status: Planned

### Resources Needed
- High

### Actions/Standards Needed
- Benchmark standards needed for measuring energy efficiency (e.g., duty cycle).

### Risk Roadmap (Hydraulics & Pneumatics)

#### Risk Categories
- Regulatory/Political
  - Standards, regulations
- Economic
  - Cost, contract, budget
- Resource
  - Organizational, execution
- Market
  - Growth, strategy, product attributes, etc.
- Technical
  - Component or system performance

#### Risk Consequence:
- Show Stopper
- Major
- Minor

#### Events and conditions that bear watching to trigger relooking at the directions set by the roadmap...
- Younger equip operators, lower skilled, want “video game” controls
- Perception: Electrical=green
- Low standards adoption in FP industry
- Smarter and more efficient electrical grid
- Greater regulation re: leaks
- Funding for green solutions favors electrical
- CO2 regulation
- Tier 4: Pressure to improve efficiency exceeds industry’s capabilities
- Electrical advantage for power mgt
- Customers shift to incremental improvements/spending
- Company R&D budgets directed to key issues
- Few engineers entering industry
- Breakthrough in electric motor technology: superconductor, supercaps

### Risk Roadmap Framework

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</thead>
<tbody>
<tr>
<td>Risk categories</td>
<td>Electrical sys perceived more efficient</td>
<td>Younger equip operators, lower skilled, want “video game” controls</td>
<td>Perception: Electrical=green</td>
<td>End customers turn to lower cost electromechanical solutions</td>
<td>Electrical advantage for power mgmt</td>
<td>Low standards adoption in FP industry</td>
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</table>

### Action Summary - Hydraulics

<table>
<thead>
<tr>
<th>Technology Advancement</th>
<th>Source &amp; Timeline</th>
<th>Current Status</th>
<th>Who?</th>
<th>Resources Needed</th>
<th>Actions/Standards Needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improved component efficiency</td>
<td>Develop 2009-14</td>
<td>Planned</td>
<td>University</td>
<td>High</td>
<td>Benchmark standards needed for measuring energy efficiency (e.g., duty cycle).</td>
</tr>
</tbody>
</table>

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Return to Roadmap framework
Implementing Roadmapping in the Global Enterprise - A case study at GM

Dave Grossman
Dynamic Strategy Group LLC
(dsgrossman@comcast.net)
November 17, 2011
Background

- **Previous Roadmapping Efforts at GM**
  - Mixed results
  - Different processes/formats
  - No common data source or update process

- **Company had started downsizing - no one was looking for additional tasks**

- **Guidelines**
  - Keep it simple - eliminate bureaucracy
  - Make it visual
    - Managing hundreds of projects as lists of lists extremely difficult
Expectations for Roadmapping

- Make technology plan visible –
  - Especially for senior management
- Align technology plan with vehicle product plan
- Ensure functional groups had technology vision
- Review global portfolio of projects
- Improve interaction/communication
  - Research
  - Marketing
  - Design
  - Engineering
  - Procurement
  - Suppliers
- Facilitate stakeholder discussions
Initial Efforts

- Decided that technology roadmapping would be implemented
- Collected examples of past roadmapping projects at GM
- Joined GATIC
  - Provided insights and shared experience with other companies
  - The member companies were very open in sharing knowledge and suggesting ways to ensure success
  - Saved considerable effort in researching roadmapping and getting the process up and running at GM
Different groups needed different maps

- Senior management - wanted overview
- Functional groups – great detail in limited scope
- Vehicle programs – great breadth, limited detail
- Cross functional projects – limited scope
- Different views of the same data
Initial Organization Reaction to Roadmapping - Positive

- Minimal effort since the information was in the technology database
- Simple, graphical way to describe future plans for funding requests
- Linkages between different projects steering were clear
- Disconnects between vehicle program timing and technology availability evident
- Redundant projects were obvious
Initial Organization Reaction to Roadmapping - Negative

- Did not see the immediate advantage to group
  - Tied to funding
- More work – already had excessive workload
  - Created Templates/Guides
- Lack of future technology vision embarrassing
  - Encouraged future planning
- Effort to keep data up to date
  - Simplified database
- Lack of automated roadmap generation
  - Created when process became stable
- Fear of budget cuts when projects compared
Roadmaps/Database Had Broad Usage

- Financial – Budgets/Capital Forecasting
- Marketing – Customer Benefits/Advertising
- Product Planning – Timing for Introduction
- Engineering
  - Especially cross functional use of technology
  - Technology enablers
  - Cost Reduction
- Purchasing
- Manufacturing
Lessons Learned

- The dialog and communication in the Roadmapping process is more important than the roadmap
- Technology Roadmapping requires effort
- Graphic representation better than detailed reports
- Creators of roadmaps must perceive value
- Ease of use accelerates acceptance
- Ease of understanding of roadmap more critical than volume of information displayed
Fuel Cell Example – The “Good News”

Phenomenal Technology Progress
• Performance
• Cost
• Durability
• Package
• ....
Fuel Cell Example – The “Bad News”

Poor Business Case
• Still too expensive
• Low cost oil
Lack of hydrogen infrastructure
Loss of political support
Summary

- Technology Roadmapping met or exceeded expectations at GM
- Technology Roadmapping must be aligned with business case and situation
- Very applicable to Solar Fuels Programs