Critical National Need Idea Title: *Mobile Energy*

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ADVANCED TECHNOLOGIES FOR THE INFRASTRUCTURE:

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Energy independence is the great challenge of our time. Cheap and abundant energy has set a precarious historical precedence and expectation that underpins the fundamentals of our economy. The escalating price of oil has dramatically affected the American way of life. The impact of energy to the national economy and the looming problem of carbon emissions has instigated a "clean-tech" rhetoric, if not yet serious investment in wind, solar, clean coal and a new generation of nuclear power plants. These technologies address power generation and refocus our attention to our ingenuity and provide alternative feed-stocks of flexible fuels. They do not address the critical need of how we convert clean, alternative renewal energy feed-stocks into usable sources for transportation. Weaning ourselves from oil requires transformative energy technology for transportation. Electric and hybrid vehicles will dampen the shock of depleted oil supplies but clean sustainable energy is a matter for scientific discovery. We stand at the cusp of major scientific advances as nanotechnology manipulates matter in unprecedented ways while probing molecular structure and the very dynamic of molecular interaction. The challenge for both the public and the private sector is to mobilize mission driven objectives with high risk, high return investment in mobile energy technology.

CRITICAL NATIONAL NEED: Mobile Energy

Overcoming oil dependency requires that we develop an alternative clean and renewable energy source for transportation. Transportation consumes 30% of our national energy needs, which comprises 96% of our oil consumption. While nuclear energy may address the long term needs for centralized power generation, there is no logical solution to mobile energy. Energy drives our economy and oil has been the currency of 20th century but the 21st century ushers in a new electricity based economy with disruptive impact on society. Of all the energy technologies proposed for investment by the Office of Science & Technology Policy[1], only fuel cells and advanced charge storage technology present a viable and lasting solution that can be truly viewed as a mobile energy resource.

We need to develop a new generation of engines to power our electronic devices, machines and vehicles. Such engines must be designed to generate electricity from flexible fuels and /or recharge from the power grid. Flexible fuels can be generated independently from coal feed-stock or biofuels from cellulosics or photolysis. Advanced batteries (charge storage devices) are only part of the solution to mobile electric energy systems for our long term transportation needs. Transformative new systems will integrate advanced charge storage devices to flexible fuel reactor driven Fuel Cells (engines). Such disruptive technology will not look or feel like any battery/fuel cell systems of today but rather, integrated reactor/fuel-cell/battery micro-systems embedded into drive motor mechanisms. Nanotechnology offers us the means to design energy systems that mimic the function of biological organisms, where each cell is a functional unit of energy generation and the ensemble of cells energize the organism. When fuel cell systems are designed for heat, mass balance and charge transport management at the micro dimensional level, the macro-system design is reduced to plumbing and controls.

The need for such advanced fuel cell systems development is national because of the diverse technologies that are in play and because oil independence is a national priority. The outlook for the realization of such technology is 10 years at the very minimum. However, innovation and discovery will have immediate impact on complementary energy programs.

MAGNITUDE OF THE PROBLEM

Achieving energy independence is the fundamental challenge of our time[2]. Clean, cheap renewable energy technologies will dominate our economic horizon for some time to come. The US consumes 19.6 million barrels of oil each day. Despite DOE programs on alternative energy technology, we remain far from our goal of energy independence. The current FY'09 budget

[1] Office of Technology Policy on Energy (FY) 2009 Budget, February 4, 2008
[2] DoE Energy Frontiers Program

request of $ 25 Billion[3] by the Federal Government to develop alternative energy underscores the seriousness of our national need. Actual appropriations have fallen short of intended commitments, as we have way underinvested in securing our energy future. An early adoption of a diesel powered fuel cell/battery hybrid engine for vehicles would conservatively reduce oil consumption by 50%. The adaptation of alternative fuels would further reduce oil consumption. This argument, however, does not take into consideration the vehicle fleet replacement cycle nor the infrastructure rebuild so that even if the technology and vehicles were available today, it would take about 30 years to realize the full impact of such technology. Coincidentally, domestic oil companies[4] estimate world wide oil reserves at 30 years. It is anticipated that innovation and discovery in catalysis and fuel reactor design will allow the introduction of alternative (non oil derived) synthetic fuels.

The confluence of broad applicability and best prospects for scientific discovery make the Fuel Cell/Charge Storage system a compelling energy investment argument to meet our future needs for mobile power. However, such a program constitutes a very substantial undertaking. To solve the problem of developing a regenerative electric engine requires the collaborative commitment of several scientific and engineering disciplines, all aligned to a single purpose. The mission is to develop a fuel cell system comprising of several diverse but complementary technologies:

1] A fuel cell subsystem itself of micro-fabricated structural design and engineered with nano-structured materials for the electrodes, catalyst and separator membrane coatings[5]. Such a structure would embody the fluidic channels and electron collector channels as integral features of the micro-device.

2] A front end fuel reforming reactor that transforms the fuel intake to a Fuel Cell oxidation compatible form.

3] A back end charge storage device designed to be the energy source to drive the motors.

[3] Office of Technology Policy on Energy (FY) 2008 Budget, February 2007
[4] Exxon Corp. " July 2008 Presentation at the U. of Pennsylvania".
[5] It is assumed that the initial platform comprises of a PEM (polymer electrolyte membrane or proton exchange membrane) Fuel Cell design constructed of nanostructured materials.

4] System control electronics that monitors the charge of the storage device (i.e., battery) and controls the Fuel Cell operation. The fuel intake and Fuel Cell operation is charge demand driven to maintain a set point level of operational charge. This MEMS module monitors sensors and valves to control fuel and exhaust.

While these MEMS or perhaps NEMS components comprise the engineering test bed for the purpose of prototyping, the test bed also provides the mechanism to test innovation and discovery. A major design function for the system is compatibility of structural components for the eventual integration into a monolith. The manufacturing challenge of this technology is directly related to the integration of diverse functions.

The successful resolution of such an intricate problem will require the concerted effort by academic institutions, government and the private sector. Innovation and discovery is critical but only a small part of the desired outcome. Overcoming the "innovator paradox" requires that industry embrace risk taking with capital investment in new manufacturing technologies. The disruption caused by the technology would require massive investment in infrastructure that must be shared by the public and private sectors. Innovative reactor design breakthroughs and the manufacturing systems based on nanostructured materials will alter the energy density, efficiency and reliability necessary for robust commercial products. To be commercially successful it is desirable to derive a one design fits all objective that will apply to the entire power range of 1 milliWatt to 1 megaWatt to address the requirements of multiple applications ranging from consumer electronics to aircraft controls.[6]

The unique attribute of Fuel Cell technology when compared to competing emerging technologies is that it is the only integrated system that can be truly distributed and integrated within actuation systems.. Nanotechnology is a bottoms-up approach to systems design that allows the adaptation of NEMS into MEMS, paralleling the very nature of living organisms. The ultimate vision of a distributed energy system is for the integration of fuel cells into the actuation system (e.g.,electric motor) so that the engineering design task is reduced to simple fuel in-flow and exhaust out-flow. While the promise of nanotechnology is grand, near term commercial

[6] Boeing 787 Fuel Cell technology plans, (July, 2008 Conference Call)

goals for fuel cell micro-systems are high value enterprises with dramatic impact potential on mobile power systems.

SOCIETAL CHALLENGES

Our addiction to oil is rather confined to transportation and, as such, allows a clear definition of technical problem(s). Public awareness and sensitivity to the cost of energy somewhat alleviates the shock associated with change. America is a mobile society that embraces individual freedom of movement. It is assumed that the mass transit only approach to the transportation issue is not an option. Initial cost of an electric vehicle aside, early indication of public response to hybrid vehicles is positive and the auto industry is committed to the development of electric vehicles.

The national infrastructure pertaining to energy efficiency and communication is directly linked to commerce and economic competitiveness. Nanomanufacturing[7] for Energy Efficiency has been recognized as a critical component of our national competitiveness. The wealth and life style of our society is measured in terms of economic strength. The future of aviation has been linked to fuel cell technology that is powered by diesel fuel. There is no greater impact to commerce than energy in transportation infrastructure. Scientific and technological discovery and innovation are the major engines of increasing productivity and are indispensable to ensuring economic growth, job creation, and rising incomes for American families in the technologically driven 21st Century.[8]

Interaction of Critical National Need and Societal Challenges

One of the benefits of developing such technology is that it would provide compact energy for diverse consumer electronic products. Beyond addressing our energy needs, this is an opportunity to push commerce and economic growth. Wireless communication devices with video imaging and internet capability are ever starved for power. This technology would be applicable to powering remote sensing devices with high content data transmission for real time

[7] DOE Nanomanufacturing for Energy Efficiency Workshop, December 2007 report.
[8] 2008 Congressional Record

two way communication. The impact of infrastructure monitoring technology for the health and safety of municipalities is a direct beneficiary of such technology.

Distributed power is the likely solution to transmission loss. The ability to design fuel cell/charge storage (FC-CS) units for the residential home is another side benefit of this technology. Ultimately, the ability to design power tools and electronic devices with embedded FC-CS devices that are compatible with business and residential power sources will create seamless energy that is transparent to tools and appliances.

The widespread implementation of these sources of electrical energy generation will create a sustainable electric grid through distributed power systems that minimizes the need for long line transmission and the concomitant energy loss associated with it. This is equivalent to the replacement of central computing (mainframes) with desktop PCs, i.e., use the power where needed. One can envision solar – fuel cell hybrid generation systems for residences that are plugged into the grid for two-way transfer of power.

MAPPING TO NATIONAL OBJECTIVES

U.S. Secretary of Energy Samuel W. Bodman announced the President's $25 billion Fiscal Year (FY) 2009 budget request for the Department of Energy (DOE)[9]. This request continues the Fed's investments to meet growing energy demand with clean, safe, affordable, reliable and diverse supplies of energy. The $1B DOE budget increase (from FY08) accelerates technological breakthroughs to further the President's Advanced Energy Initiative (AEI), and scientific leadership through the American Competitiveness Initiative (ACI). The failure to appropriate ACI funding further accentuates the need. The AEI supports robust alternative energy vehicle technology based on Li battery, plug-in hybrids and critical fuel cell technology.

One DOE implementation strategy is through Energy Frontier Research Centers, which brings together the skills and talents of multiple investigators that enable research of a scope and complexity not possible with the standard individual investigator or small group awards. Catalysis and nanotechnology have been identified by the scientific community for critical

[9] DOE Energy Frontier Research Centers

Research investment by DOE Science and Technology Programs. The NSF has also identified energy science and technology for priority funding programs. Funding of these programs have not materialized and existing R&D commitments operate under a Continuing Resolution.

The DOE sponsored Workshop on Energy Efficiency (Dec.2007) highlighted the need to invest in nanomanufacturing technologies that address the issues of commercialization. Only 10% of R&D funded nanotechnology programs are in applied nanomanufacturing technology and lags the world (e.g., China commits 60%).

The workshop identifies Catalysis as a critical technology in the development of reactor technology aimed at fuel synthesis and Fuel Cell design. Catalysis also addresses the fundamental aspects of reactor design and nanostructured materials for efficient energy transfer. Nanotechnology leads the way to innovation and discovery by investigating the molecular world of chemical reactions and probing the molecule-to-molecule and atom-to-atom interactions of surface constructs that are the essence of catalytic processes. These areas of science and technology not only map to the DOE national objectives, but also constitute the centerpiece of fuel cell system innovation.

Congressional committees are focusing more attention on energy and technology and the impact on our economy and national competitiveness. The important role of basic research in developing new energy systems and conversion processes has been highlighted in two reports by the President's Council of Advisors on Science and Technology.[10] Clearly, energy technology development must be addressed with a sense of urgency and magnitude that is commesurate with the Manhattan Project. A new generation of Fuel Cell technology would qualify for such national commitment but may represent only one of a small number of projects that is worthy of intense developmental focus.

[10] "The National Nanotechnology Initiative at Five Years: Assessment and Recommendations of the National Nanotechnology Advisory Panel," May 2005, and "Improving Efficiency in the Nation's Electrical System," February 2003.

Nanostructured materials and characterization analysis corresponds directly to NISTs technical competence and measurement science. NIST's primary function is to support and promote commerce and national competitiveness through transformational research. TIP is directed to address critical technology needs that enable breakthrough manufacturing technology not addressed by DOE programs.

MEETING TIMELY NEEDS NOT MET BY OTHERS

Overview

The Fuel Cell Systems contemplated are a complex interplay of diverse technologies and scientific disciplines, most notably, chemical catalysis, electrochemistry and materials. Such technologies must be integrated into a coordinated market driven program that provides direction for discovery and a framework for technology development and commercialization. The breadth and depth of competencies and industry infrastructure are so diverse that the challenge can be most rationally addressed by broad participation and cooperation within geographic regions where essential core technology competencies and complementary industrial assets reside. A recent Brookings report [11] identified the value of regional collaborations such as the Mid-Atlantic region (Delaware, Pennsylvania and New Jersey) as a major nanotechnology/catalysis competency cluster with a high concentration of academic and industry stakeholders. It is essential that industry lead the manufacturing technology thrust by defining the mission's objectives that are aligned with commercial motivations. The skill sets are so diverse that a consortium of companies must be driven to collaborate in the restructuring of the manufacturing landscape and create an infrastructure for radical manufacturing changes and business disruption. The role of NIST and non-profits is to facilitate investment and create incentives for undertaking R&D risk.

A successful technology must be of singular design and purpose, scalable in power output to meet a range of needs (i.e., 1milliWatt to 1 megaWatt) and of scalable manufacturing capacity. Ideally, a single generic unit cell design can be replicated to accommodate application power ranging from consumer electronics to aircraft controls. The generic unit cell system design

[11] Brookings Report to Congress (2005)

simplifies manufacturing and minimizes scaling costs. The envisioned unit fuel cell system is a micro-fabricated design constructed of nanostructured materials that integrates fuel cell, charge storage device, fuel reformer reactor to balance of plant electronics. Market specific targets are defined to engineering prototype specifications that are the outcome of test bed design development. All system components (reactor, fuel cell, storage device) are developed independently and yet the designs are consistent with an integrated monolith structure. The object is to design fuel cells to manage, heat, water vapor, etc., at the micro-system level so that power is scaled to the number of such cells in a macro power system.

The vision is to create an innovation and investment environment that fosters rapid prototyping and accelerates the development and commercialization of the next generation Fuel Cell Systems and complementary technologies. A core objective is to establish a nano-catalysis program that embodies energy systems and is supported by regional academic and industrial institutions. A goal is the embodiment a scalable Fuel Cell technology platform over the milliWatt to the megaWatt power domain. The platform is a test-bed for innovative energy technologies that can energize power systems ranging from cell phones to a Boeing 787 avionics and flight control.

TIPs Role

Local and state government is empowered to enable translational research as it pertains to economic development. While energy is recognized as a critical component of economic development and an attribute of a thriving commercial environment, state government is not equipped to engage in transformational technologies. The state of Pennsylvania Energy Initiative, for example, funds translational technology that enables local industry through energy investment grants non-resource loans to assist businesses engage in energy technology. It is imperative that such state resources be leveraged to access transformational technologies via Federal Science and Technology agencies (i.e., NIST). The state of PA recognizes the need to participate in regional initiatives (e.g., Mid-Atlantic Nanotechnology Alliance or MANA) that promote regional academic and industry cluster competencies in such areas as nanotechnology and catalysis. Such regional competency clusters are ideally positioned to lead innovation thrusts in technologies of National priority. Prominent regional universities that would lead such an effort include U. of Penn, Drexel and U. of DE.

The role of NIST is to enable the commercialization of transformational technology and promote Venture Capital deal flow. Sustainable technology development is best achieved with industry participation in goal setting and commitment to the commercialization process. The ideal role for NIST is to mount a coordinated effort with NSF or DOE Energy Frontier Research Center program to develop the next generation Fuel Cell systems. NIST's critical role is to enable the manufacturing technology and to coordinate National Labs participation in the academic program.

CONCLUSIONS

Meeting the energy challenge of our time will require substantial focused investment and the concerted effort of both government and the private sector. A new generation of fuel cell systems based on nano-structured materials and catalysis science breakthroughs has the potential to generate sustainable energy for power tools, appliances and vehicles. The most effective and efficient approach to solving the mobile energy problem is for technology programs to be organized within geographic regions that define competency clusters and comprise academic and industry stakeholders. It is imperative that the project be mission driven and based on engineering platforms that deliver energy systems solutions, not only technology, and that they are prototyped and marketed by industrial partners. Manufacturing technology investment must complement program technology outcomes with risk shared by government and industry. A healthy and vibrant economy is defined by large scale commercialization of technology facilitated by venture capital deal flow and industry investment. NIST's role must be to broker the technology commercialization process and coordinate program activity with National Labs.