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Transformative research issues and opportunities in alternative energy generation and storage

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ABSTRACT

This article presents a summary of research issues and opportunities in alternative energy source research identified by panels of experts assembled by the Engineering Directorate of the US National Science Foundation. The objective was to identify transformative research issues and opportunities to make alternative energy sources viable. The article presents motivations for energy research, grand challenges, and specific challenges in the research areas covered. The grand challenges identified for the United States include supplying 30% of US electricity from photovoltaics by 2030, supplying 25% of US electricity from wind by 2025, displacing 30% of US hydrocarbon use by 2030 with bio-based products, and providing a practical 250–300 W h/kg energy storage system by 2025. Similar challenges could be outlined along the same lines for the remainder of the world. Examples of specific areas of research focus identified as promising include high performance p-type transparent conductors, multijunction thin-film photovoltaic devices, defects in chalcogenide semiconductors, experimental study and numerical modeling of the fluid mechanics of airflow as applied to wind turbines, improved materials for wind turbines, methods for creating high energy density transportable biological feedstocks, biorefinery processes yielding infrastructure-compatible biofuels and biochemicals directly, and improved electrodes and electrolytes for Li ion batteries. Arguments for each of these as research priorities are given.

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1. Introduction

Several panels of experts were convened by the Engineering Directorate of the US National Science Foundation to discuss research issues and opportunities in alternative energy source research. This article presents a summary of the results of that discussion. The study and therefore the article are restricted to three primary areas of alternative energy generation – photovoltaics, wind, and biofuels, and one form of energy storage – batteries. While these topics do not represent even the majority of key topics in alternative energy generation and storage, these were considered the most promising medium-term renewable and carbon-free energy sources (excluding nuclear) that are currently available. We leave nuclear, carbon-based, and longer-term energy generation concepts for other authors.

Discussions were conducted in two meetings, one held in June 2009 in Honolulu Hawaii, USA in conjunction with the NSF Civil, Mechanical, Manufacturing Innovation Grantee Conference, and a second follow-up session held in November, 2009, in Evanston, IL, USA. Several experts in each renewable energy technology and in battery technology were invited and presented many of the concepts summarized here. The study also included discussions of energy efficiency, especially related to buildings and transportation. Those will be described in a companion article to be published separately.

2. Motivation

The United States and the world face an unprecedented series of challenges related to the continuing dependence on fossil fuels and

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energy sources [1]. The interrelationship of energy, security, economics, the environment, and climate change begs for sea changes in the ways that society produces, distributes, stores, and uses energy. Our sustainable future depends on strong investment in basic, crosscutting, and applied research to develop energy efficiency and renewable energy technologies.

We use fossil fuels for transportation, industrial processes, buildings, and residences. Renewable energy and energy efficiency have the potential to address all of these sectors [2]. With adequate storage technologies, wind, solar (photovoltaic and solar thermal), geothermal, hydro, and nuclear could meet 100% of our domestic power demands. Biofuels and bio-based products could displace a significant fraction of our current fossil fuel utilization for transportation, chemicals, and materials [3,4]. With the implementation of plug-in hybrid vehicles and biofuels, we could end our dependence on fossil fuels for transportation. Taken together, renewable energy and energy efficiency are the leading pathways to a sustainable, carbon-free society.

The US currently consumes nearly 3 TWyr per year in total energy [5]. Even with aggressive energy efficiency and conservation practices, we will continue to consume huge amounts of energy for the foreseeable future. Transition to renewable energy technologies would create a high technology industry with high-quality, high-paying, domestic jobs.

The motivation for investing in research in renewables is compelling. We make an argument here with reference to the US government sponsored research, but similar arguments can be made for many countries around the globe. Consider only one US photovoltaic company, First Solar; their manufacturing capacity is expanding and projected in 2011 to be 1.8 GW. In 2009, First Solar had revenue of $2.066 billion, a net income of $640 million, and reported having an annual tax rate of 6.7%, suggesting that they paid ~$43 million in taxes [6]. This suggests that First Solar's taxes alone account for roughly 2% of the US Department of Energy, Energy Efficiency and Renewable Energy (EERE) program and its total revenue is roughly 90% of the total EERE budget. Therefore, the proposed US renewable energy research budget still represents only a fraction of the support that should be provided based on the impact to the economy of renewable energy. Similar arguments can be made based on the scale and profits of wind, biofuels and bio-based products, and battery industries. Recent developments have largely been supported by venture capital. However, venture capital is not the correct avenue to support the core basic research necessary to spur development of new technologies.

The renewable energy industry is growing rapidly worldwide, many technologies at over 40% per year [2,7]. If this growth rate is maintained, renewables could become the dominant US energy source by 2030. The economic benefits alone argue for support of the technology. The role of world governments is to provide the fundamental research backbone that underlies the engineering and science of these industries, which in turn could provide energy security for the 21st century and beyond, to train the engineers and scientists who will solve the problems we will face in the future, and address the challenges of climate change and sustainable development.

3. Grand challenges

The grand challenges identified at the meeting of the study group refer to goals for the US. Similar challenges could be developed on a worldwide scale. The overarching grand challenge of energy production, efficient utilization, and storage technologies is to sustainably meet global energy needs without harming the environment.

The grand challenges for the next 15–20 years by technology with reference to US applications are:

- *Photovoltaics*: to supply at least 30% of US electricity needs by 2030.
- *Wind*: to supply at least 25% of the US electricity needs by 2025.
- *Biofuels and bio-based products:* to displace 30% of the US hydrocarbon use by 2030.
- *Batteries*: to provide a practical 250–300 W h/kg energy storage system by 2025.

It would be reasonable to extend the above values to the entire world. However, if the above can be achieved in the US then it is likely that they will also be achieved globally within five years of achievement in the US. These are challenging goals. It will be necessary to provide an effective environment for research and learning to meet these challenges.

4. Specific challenges

For any of the technologies discussed here, it is asserted that solutions should strive *to provide energy without raising costs above current values* and should spawn a domestic manufacturing industry in addition to supply chain, installation and maintenance industries. The magnitude of global energy demand and the cost of shipping renewable energy technologies also argue for local production near the point of consumption. All cost and environment analyses should be based on a complete life cycle analysis. For all technologies, engineers and scientists need to work closely such that a commercially viable product will result.

The following list represents hallmarks of major successes in each of the areas covered in this report:

- In photovoltaics, a competitive marketplace should be one with established manufacturing of modules for under $0.75/W and ultimately more than doubling the current device efficiencies, yielding low-cost products with efficiencies over 20%. Photovoltaics would also benefit from a reliable microinverter technology that can make the modules "plug-and-play" so that they can be installed as easily as an outdoor lighting fixture and be practically installed by handy home owners.
- For wind, reliable turbines operating for more than 20 years without major repairs, in conjunction with a comprehensive set of models forecasting array output sufficient to effectively manage stored and alternate energy sources, providing practical warning of conditions that could damage a turbine array, and clearly demonstrate the interaction of proposed turbine arrays with the local topography and climate prior to their installation and operation.
- In biofuels and bio-based products, an efficient non-fossil-fuel-based method for reducing molecules, providing a mechanism to control global greenhouse gases, to provide infrastructure-compatible transportation fuels at low cost and with energies per unit weight equivalent to existing hydrocarbon fuels.
- In batteries, a safe and practical lithium–air battery that will meet or exceed the performance requirements of the United States Advanced Battery Consortium (USABC) for hybrid- and all-electric vehicles.

5. Photovoltaics

The research recommended in photovoltaics (PV) can be divided roughly into first, second, and third-generation topics [8]. Current Si technology is considered a first-generation technology, but with research support, has the potential to be competitive over the long term [9–11]. Second-generation PV is the current thin-film technology and anticipated extensions of its concepts [12–14]. Third-generation PV constitutes novel concepts currently

proposed and any new concepts that arise that do not extend current approaches. Thus, multijunction solar cells based on II–VI semiconductors constitute an extension of the current II–VI technology. When it encompasses novel materials, this technology can double the performance of the devices. Third-generation PV includes approaches based on organic materials, photoelectrochemical cells, nanoparticle and quantum dot cells, etc. [15].

Any applied research program should emphasize primarily first- and second-generation topics because the current technologies require significant scientific and engineering support to achieve their potential. Lack of support for these technologies could lead to failure of the industry in general or, more likely, failure of the industry to thrive and grow at rates anticipated in earlier sections. Third-generation topics should be explored in science-oriented programs although a path to commercial technologies is not as clear, and viability of the concepts to be studied is far less obvious, especially in the face of competition from existing technologies.

5.1. Cross-cutting PV research

Numerous topics are in common across PV technologies. These include:

- Development of high performance p-type transparent conductors and improved performance in n-type transparent conductors.
- Effective device models that are user-friendly, based on fundamental materials parameters and device physics, and provide a direct connection between detailed materials properties and specific device or processing conditions.
- Understanding, controlling and mitigating the effects of defects in the active layers.
- Improved processing methods and device designs that provide greater throughput, reduced energy consumption or improved material utilization or device efficiencies.
- Advanced materials that improve performance of the devices or that reduce the use of toxic or limited-availability elements. For example, new and improved transparent conductors that replace rare elements such as In with common elements such as Zn are needed.
- Multijunction approaches that increase device efficiency.
- Lateral multijunction geometries (where light is split spatially by wavelength and junctions to absorb that light are placed side by side rather than requiring light to pass through all higher gap junctions to reach a lower gap device.
- Improved performance in flexible PV technologies.
- New basic physics results such as electronic structure calculations that can provide a deeper understanding of the principles upon which the materials and devices operate and yield insights for design of new materials and devices.
- Improved encapsulation technologies, especially for thin-film and organic devices.
- Semitransparent device technologies for building integrated applications.
- Technologies for cell and materials recycling.
- Advanced inverter technologies that provide improved reliability and are integrated into individual modules to make them more "plug-and-play", requiring less expertise to install, thus reducing installation cost.

5.2. First-generation PV research

First-generation PV includes the classic Si bulk single crystal solar cell and related devices such as multicrystalline Si cells. Key research issues that are still valuable to pursue to drive forward this technology include:

- Thin and single crystal ribbon growth of Si (to eliminate sawing time and associated material waste).
- Improved production methods of electronic grade Si to reduce cost, energy input, and increase production volume.
- Advanced surface passivation and contact technologies.

5.3. Second-generation PV research

Current PV technologies include those based on thin films such as CdTe and related II–VI semiconductors, $Cu(In,Ga)Se_2$ (CIGS) and related chalcopyrite materials, III–V based devices (especially high-performance multijunction cells and III-nitride devices), and amorphous Si-based devices. Basic research should include the following in addition to topics that fall under the cross-cutting issues listed above.

CdTe:

- Improved back contact approaches.
- Methods for enhancing the voltage of the devices or reduced defect densities.
- Alternate heterojunctions, including new window layers and transparent buffer materials.
- Novel approaches to reducing cell thickness.
- Alloys suitable for tandem cell applications.

CIGS:

- Alternate buffer layers.
- Higher efficiency wide-gap devices.
- Approaches to reducing cell thickness.
- Improved processes and manufacturing methods that improve performance uniformity, yield, and device efficiency.

Amorphous Si:

- Increased utilization of source gases.
- Improved stability under sunlight.

III–V devices:

- Nitride multijunctions.
- Technologies to transfer finished devices off of expensive III–V single crystals onto substrates less expensive materials.

5.4. Third-generation PV research

We include in this category photoelectrochemical and organic devices that are significantly farther from a competitive product than the above as well as the common third-generation technologies, all of which are more revolutionary than evolutionary. For all third-generation technologies, basic research is needed to understand the operation of the proposed and fabricated devices and in particular the processes that take place at surfaces and interfaces.

Photoelectrochemical cells:

- Improved electrolytes.
- Increased conductivity in the TiO_2 layer.
- Reduced corrosion in the contacts.

Organic based devices:

- Improved stability of materials and improved performance.
- Materials with reduced exciton binding energy/increased dielectric constant.

- Higher carrier mobility materials.
- Manufacturing methods to reduce cost of precursor chemicals.

Photocatalytic devices:

- Improved conversion efficiency.
- Novel reaction chemistries.
- Improved catalysts.

Nanoparticle/quantum dot, intermediate band, and multiexciton devices require basic research to demonstrate proof of the concept as a viable alternative to existing technologies followed by transition to a manufacturable design. While there is much good science to do related to these ideas, the benefits are longer range, so we do not list specific research needs.

6. Biofuels and bio-based products

It is important to recognize at the start that bio-based renewable technologies encompass much more than just fuels [3,4]. Therefore, herein we consider the full range of biological feedstock conversions (specialty chemicals, chemical intermediates, biomaterials, and fuels) in a biorefinery context aimed at displacing fossil fuels and reducing greenhouse gas emissions.

Bio-based technologies can be divided by generation as for photovoltaics with first generation encompassing high energy value plant oils and plant sugars, extracted from corn and sugarcane and converted into ethanol, biodiesel, or used directly in the synthesis of bio-based products [16]. Second-generation systems are based on cellulosic feedstocks that do not directly siphon off the food supply, although they may compete for land use, and generally have a smaller greenhouse gas footprint [17]. Third-generation systems are based on algae and other high-density feedstocks and significantly reduce potential land use issues [18–20]. Third-generation biotechnologies yield bio-alcohols, "green gasoline", and renewable diesel directly or via relatively straightforward chemical modification, and also provide chemical feedstocks. Ultimately, all of these technologies will be self-sufficient in terms of energy input (or would use other potentially renewable inputs such as electricity) and therefore should be greenhouse gas neutral or nearly so, thus providing a substantial reduction in carbon-footprint compared to their fossil fuel alternatives [19]. For all technology areas, systems engineering and life cycle assessments must be carried out on a consistent basis so that proper economic and carbon footprint comparisons can be made.

We recommend that research funding agencies place emphasis on second and third-generation technologies for several reasons. There are many opportunities for fundamental breakthroughs as well as science-intensive technology improvements. Many of these technology developments can have direct applicability on 1st generation systems (e.g., improved alcohol–water separations and more efficient cellulosic conversion). Continued growth of 1st generation technologies as currently deployed will have less impact on greenhouse gas emissions attributable to the transportation sector.

6.1. Cross-cutting biofuels and bioproducts research

Some of the cross-cutting research topics key to many areas of biofuels and bioproducts include the following:

Address challenges with the logistics of handling low-density feedstocks:

- Feedstock densification: transportation of biomaterial prior to conversion to fuels must be minimized, especially with low-density feedstock.
- Feedstock conversion processes such as pyrolysis that enable transport of raw materials or intermediates to centralized fuel or chemical refineries.
- Scalability of biofuel and bio-based product technologies to enable production at the community or regional level to avoid feedstock transportation.

Improve production efficiency of biofuel and bio-based products:

- Development of general approaches allowing continuous and/or consolidative biochemical, thermochemical and chemical processing of feedstocks to improve manufacturing efficiency.
- Development of general and energy-efficient approaches to separation of product chemicals from feedstocks and nutrient broths.
- Improve productivity and yield of catalysts and biocatalysts (enzymes and organisms).
- Decrease sensitivity of catalysts and biocatalysts to process stream impurities.
- Decrease fouling and other processes that limit performance.

Design products to facilitate introduction into the marketplace

- Design biofuels and bio-based products that can be utilized with minimal disruption to existing infrastructure.

6.2. First-generation biofuels and bio-based products research

First-generation biofuels include starch and sugar cane-based ethanol and edible oil-based biodiesel. While second and third generation bio-based processes more effectively achieve the goals of decreasing greenhouse gases and reducing over fossil fuel utilization, first-generation biofuels reduce dependence on petroleum and have spurred growth of the bioenergy industry. Many technologies that will improve the feedstock logistics and process efficiency will benefit first-generation biofuels. Therefore, first-generation biofuels provide a bridge to second and third-generation technologies and assure industrial viability. Many of the following also apply to second-generation technologies. Key research topics in first-generation bioenergy include:

- Ethanol processing technologies requiring little net water input or which recycle virtually all process water.
- Conversion of feedstock materials into longer-chain hydrocarbons such as butanol and gasoline/diesel replacements.
- Methods to utilize feedstock more completely and efficiently.
- Technologies to maximize recovery of food, feed, and co-product value (e.g., protein and oil in distiller's grains or glycerin) from biofuels crops.
- Efficient utilization of CO_2 generated during ethanol fermentation.

6.3. Second-generation biofuels and bio-based products research

Second-generation biofuels include cellulosic ethanol and biodiesel produced from non-edible oils

- Development of new organisms that efficiently convert cellulose to other biomaterials that are more effective fuels or feedstocks.
- Development of organisms that can survive higher concentrations of product chemicals such as butanol.
- Continuous/consolidative processes that reduce energy inputs in cellulosic ethanol and biodiesel production.

- Technologies to reduce clean-up and conditioning of biological feedstock syngas including removal of tar, sulfides, etc.
- Develop energy-efficient technologies to produce platform bio-based products that displace petroleum-based chemicals and materials.

6.4. Third-generation biofuels and bio-based products research

Third-generation biofuels and bio-based products avoid competition with other land uses and can completely displace fossil products (infrastructure compatible)

- Development of specialized organisms that produce longer-chain hydrocarbons (for example 8–10 carbon chains) directly.
- Methods for dealing with contamination, mostly in the form of undesirable, competing organisms. Third-generation technologies may use engineered organisms that may not compete well with native organisms and therefore are particularly vulnerable to contamination.
- Development of effective, open-pond and closed bioreactor environments that can function on non-farmable land in which bioenergy-producing organisms can grow effectively and efficiently utilize carbon dioxide.
- Development of catalysts or integrated biocatalyst/catalyst platforms to produce longer-chain hydrocarbons such as decarbonylation of lipids, or dimerization and reduction of sugars.
- Develop efficient pyrolysis technologies to produce stabilized intermediate that can be blended in crude petroleum streams and chemical biorefineries.
- Develop integrated platforms to produce end use and designer bio-based products.
- Develop biofuel and bio-based products that require no fossil fuel inputs.
- Develop feedstock systems that efficiently fix soil carbon.
- Develop feedstock systems that avoid (or significantly reduce) release of nitrogen and other fertilizers to the watershed.
- Produce biofuels and bio-based products that displace more than transportation fuels (e.g., renewable natural gas, bio-based lubricants, building heating, etc.).

7. Wind

Key research areas related to wind energy technology fall into two large groups – understanding and predicting how the atmospheric fluid behaves and interacts with turbines both individually and in arrays, and understanding and improving upon the mechanical and electrical design and component materials that make up the turbines. These issues vary somewhat depending upon whether the turbines are land- or sea-based, and each of these has some specific issues associated with it.

7.1. Atmospheric modeling

A key issue cutting across areas related to wind energy is atmospheric modeling. This has implications for turbine design, siting, matching specific turbine design to the site, protecting the turbine from extreme weather events, efficiently utilizing the turbine output, and managing the electric power grid. Such models need to bridge between the large-scale atmospheric models, which have grid sizes of kilometers, and small-scale models of individual turbines. The models need to account for local climate and terrain, both of which interact with the turbine. The models need to be temporally and spatially accurate, yielding forecasts of behavior with 98% probability and 98% confidence. The models need to predict inflow to the turbine on a time scale of minutes and must account for interactions of one turbine with another. The output of the models needs to feed back to turbine design, siting requirements and standards, and provide data to the electric power grid to manage loads.

7.2. Wind turbine design

Key research areas related to the design of wind turbines fall into three topics: reducing cost of the turbine, improving performance, and increasing reliability. The latter two generally require more robust materials and better tribological design, while the first typically requires a reduction in the amount of material or the cost of that material in the turbine. Therefore, these requirements often run counter to each other. Some significant potential research topics related to these include the following:

- Methods for reduction of fatigue and tribological failures by using materials with better mechanical and tribological performance.
- Material, manufacturing, and design changes to reduce turbine cost/weight.
- Automation applied to blade manufacture.
- Advanced blade materials to reduce panel buckling and blade mass.
- Improved tower materials and design to reduce weight and improve stiffness.
- Improved power control electronics providing medium to high voltage ac output.
- Systems for turbine structural health monitoring.

8. Batteries

Current-day batteries are severely compromised by intrinsic limitations such as energy storage capacity, lifetime, safety, low-temperature performance, and cost issues [21–25]. Within the family of aqueous, non-aqueous, and high-temperature (molten salt) systems, non-aqueous lithium batteries offer the greatest opportunity for breakthrough improvements [26,27]. In time, lithium batteries are destined to constitute a 'lithium economy' that will complement a fuel cell 'hydrogen economy', as highlighted in Table 1, which summarizes the theoretical and practical specific energy densities of today's prominent rechargeable battery systems and a futuristic lithium–air battery chemistry.

Water-based systems such as lead–acid, nickel cadmium, and nickel–metal hydride systems operate at a low cell voltage, from typically 1.2 V to 2.0 V and provide theoretical/practical energy densities of 20–80 W h/kg, whereas sodium batteries (sodium-sulfur and sodium-nickel chloride) provide a cell voltage between 1.8 and 2.6 V and practical energy densities of 80–150 W h/kg. The latter systems are compromised by their high operating temperature and the need for sophisticated heating/cooling support systems. Metallic lithium and lithium-ion batteries currently offer the highest cell voltage ($\sim$4 V) and practical energy density of all rechargeable systems, $\sim$200 W h/kg having been achieved at the cell level. A major advantage of lithium-ion systems is that they are extremely versatile – the cell voltage and the energy capacity can be tailored by the selection and design of anodes and cathodes from a wide variety of possible materials. Lithium-ion batteries therefore provide the best opportunity for larger-than-incremental advances, at least for the medium term (10–15 years). They operate by lithium insertion and extraction reactions with anode and cathode host structures; the host electrodes (H) should have the following intrinsic properties:

- Good structural stability over a wide compositional range (x):

Table 1
Selected battery systems and their theoretical electrochemical properties (based on the masses of active electrode and electrolyte components only).

System	Negative electrode	Positive electrode	Open-circuit voltage (V)	Th. charge capacity (A h/kg)	Th. energy capacity (W h/kg)	Pr. energy capacity (W h/kg)
Lead–acid	Pb	PbO_2	2.1	83	171	20–40
Ni–Cd	Cd	NiOOH	1.35	162	219	40–60
Ni-MH	MH alloy	NiOOH	1.35	~178	~240	60–80
Na-S (350 °C)	Na	S	1.78–2.1 (2.0)	377	754	120–150
Na-MCl_2 (300 °C)	Na	$NiCl_2$	2.58	305	787	80–100
Li ion	Li_xC_6	$Li_{1-x}CoO_2$	3.0–4.2 (3.6)	~160 (x = 1)	~576	150–200
Li-polymer	Li	VO_x	2.0–3.3 (2.6)	~340	~884	~150
Li–air	Li	O_2	2.9–3.1	1169 (Li_2O_2)	3624	Not yet
				1795 (Li_2O)	5205	Practical

$$x\mathrm{Li} + \mathrm{H} \rightarrow \mathrm{Li}_x\mathrm{H}$$

Note: the higher the value of x, the higher the electrode capacity and the cell energy.

- Minimal change to unit cell parameters to maintain structural stability on cycling.
- Isotropic rather than anisotropic expansion/contraction during lithium insertion/extraction.
- Good reversibility to ensure a high cycle life.
- High (cathode) and low (anode) electrochemical potentials vs. lithium to ensure a high cell voltage and high energy.
- Good electronic and ionic conductivity to ensure high power.
- An energetically favorable interstitial space to ensure fast Li^+-ion transport (power).
- Safe operation.

Lithium–air batteries provide perhaps the ultimate longer-term opportunity and challenge. Strictly speaking, they should be regarded as a hybrid battery/fuel cell system; they have all the complexities of bi-functional oxygen electrodes. Li–air cells, if completely discharged to Li_2O, would offer a theoretical energy storage density approaching ten times that of lithium-ion cells (Table 1). Lithium- and lithium-ion battery technologies are, however, inherently unsafe; they are comprised of highly reactive anode and cathode materials that operate in flammable electrolyte solvents, and can be subject to venting, fire and explosion if the charging procedures and cell temperature are not carefully controlled.

8.1. Specific topics for research

Research opportunities in battery technology, notably lithium batteries, are related largely to the discovery of new or improved electrode and electrolytes through materials design or predictive modeling and to the understanding structure–property relationships and electrochemical behavior. Key topics include:

- Discovery of new, high-capacity anode and cathode materials that are stable at low/high potentials vs. metallic lithium, respectively, to replace the carbon (e.g., graphite) anodes and the relatively low capacity, layered $LiCoO_2$, spinel $LiMn_2O_4$, olivine $LiFePO_4$ cathodes of state-of-the-art lithium-ion batteries.
- Identification of new cost-effective electrode and electrolyte materials through theoretical, predictive design.
- Improved electrode design of metal/intermetallic/metalloid anode structures that, upon reaction with lithium, can tolerate significant volumetric expansion so as to improve cycling stability and battery life.
- Nanoscale modification of electrode materials to obtain maximum energy and power without compromising safety.
- Tailored surface compositions and structures to improve the stability of the electrode/electrolyte interface.
- Identification of additives to enhance the stability of electrode surfaces and prevent overcharging (redox shuttles).
- Discovery of new, highly conducting, non-flammable electrolytes to improve safety.
- Identification of cost-effective materials manufacturing processes.
- Overall improvement of battery safety through improved materials and designs.

9. Short-term research goals

The study highlighted the following specific topics for the reasons given below. It was considered that these are more general and cross-cutting or more specifically along the critical path to achieving the grand challenges than other valid but less general research topics.

- *High performance p-type transparent conductors*. These are enabling for many technologies such as solid-state lighting and organic optoelectronics, but in particular for photovoltaics. These would be highly valuable components for developing tunnel junctions as connections between layers in multijunction high efficiency devices.
- *Multijunction thin-film photovoltaic devices* and their required component materials (including the p-type transparent conductors listed above). Multijunctions are the most practical route to extremely high-efficiency photovoltaics. These are direct routes to low-cost, high-performance systems with reduced balance of systems costs. Multijunctions have proven their value in III–V-based epitaxial structures and amorphous Si, but remain to be made manufacturable with high efficiencies in large areas at low costs (a-Si has shown large, scalable manufacturing but not high efficiency, while III–V devices have proven high efficiencies to be possible but are, as yet, not easily manufactured in large areas). The remaining thin-film technologies, especially chalcogenide-based systems, have shown the ability to be manufactured in large areas with good efficiencies as single junctions but not as multijunctions with corresponding increases in performance.
- *Basic research on the defects in chalcogenide semiconductors* used in thin film polycrystalline solar cells is required. Chalcogenide photovoltaics are currently by far the lowest-cost thin-film devices. They hold the potential for further and dramatic advances if the materials were better understood. Production devices based on these materials are only approximately half the efficiency of the champion cells made thereof, and significant improvement in the champion devices is still possible. Significant resource is currently devoted to novel materials and approaches to "third generation" photovoltaic devices, but the greatest promise remains in the development of current technologies to achieve their potential. While support should be

continued toward the development of third-generation devices, more effort needs to be devoted to understanding and developing the current technologies.

Wind power is the second technology that is proving viable in its current form, but requires scientific support to achieve its ultimate potential. Top priorities for wind research were identified as:

- *Experimental data acquisition and numerical modeling of the fluid mechanics of atmospheric airflow* at the scale of wind farm and surrounding area. Significant effort has been devoted to atmospheric modeling on a large scale, and predictive capabilities for understanding general surface air currents are relatively advanced. However, models specifically describing the local conditions around and as affected by wind farms are not currently sufficient. These models are needed to improve siting decisions, layout of the farms, and to assess any local environmental impacts of the farm. Furthermore, the interaction of local atmospheric conditions with the turbines is key to improving turbine reliability and to forecasting expected power output from a large wind farm.
- *Improved materials* with high strength, high fatigue and wear resistance, low cost, and low density. The key driver for cost, weight, and mechanical/tribological performance of wind turbines is the materials of which they are constructed. While the list of properties given above would benefit nearly every engineering technology, these material properties are particularly critical to improving wind turbines.

It is particularly noted that an integrated multiscale atmospheric model suite that marries the existing large-scale models with smaller scale simulations of wind farms (and other local situations) would be of great value to understanding and predicting the impact of wind energy on a large scale. The development of such a multiscale model is a large undertaking and crosses the boundaries of several government agencies. Therefore, it is recommended that NSF partner with other agencies to support this endeavor.

Biofuels and bioproducts hold the potential to provide all of the transportation fuels and engineering feedstocks currently supplied by petrochemicals. However, revolutionary advances are required to achieve this. The top priorities for focused research in this area are:

- *Methods for creating a high energy density transportable feedstock* as input to a biorefinery. Current biofuel feedstocks are far too low in energy density to be efficient to transport to large centralized biorefineries. Therefore, these feedstocks need to be converted at the point of collection to a high energy density material such that they can be transported to a large-scale biorefinery. This may involve organisms that produce a high energy density material directly or a method to compact existing low energy density materials such as corn stover to a level practical for transport.
- *Conversion biorefinery processes yielding infrastructure-compatible biofuels/biochemicals*. Transportable biofeedstocks require conversion into infrastructure-compatible fuels and chemicals. This will require large-scale biochemical, catalytic/thermochemical, electrochemical, or photolytic processes designed to work with a biological input rather than a conventional hydrocarbon. The conversion must be accomplished with excellent energy efficiency and yield. A significant component of this may include the chemical reduction of the feedstock from an oxygen-containing form such as cellulose to a reduced form such as octane as a means of increasing the energy density and versatility of the resulting chemicals.

Finally, in the category of batteries for energy storage, the two most significant priorities for research are:

- *Improved electrodes for Li ion batteries*. The electrodes are the primary sites for degradation of the devices during charge–discharge cycles, are where the energy storage is located in the form of chemically reduced or oxidized materials that are required to provide appropriate electrochemical capacity, electrical conductivity and cell voltage. These requirements sound simple, but represent an enormous technical and materials challenge. The resulting materials need to be stable, have high storage capacity, and acceptably low cost. In addition, they need to be (1) tolerant to the volume changes normally accompanying charging and discharging and (2) resistant to runaway or parasitic reactions that can result in significant fire hazards in current battery technologies.
- *Improved electrolytes for Li ion batteries*. The two key aspects of an improved electrolyte identified in this study were improved conductivity and improved safety. Electrolytes are electronic insulators and ionic conductors. High ionic conductivity is necessary, which leads to high current and power capabilities for the resulting battery. Many electrolyte solvents are highly reactive and flammable and represent potential safety hazards. Therefore, it is also important to minimize the chances for uncontrolled reactions and thermal excursions.

While these two priorities focus primarily on Li ion batteries, other options may develop. Basic science studies looking for new alternatives would be attractive. However, the Li ion batteries represent by far the most attractive option for near-term electrochemical energy storage and are therefore the focus of the recommendations made here.

10. Conclusions

Research in support of renewable energy should include visionary science directed at long-term research without a direct connection to a clear energy technology. However, to push forward the development of practical renewable energy systems on a global scale and providing the bulk of the energy needed by the world, it will be important to focus significant resources on conventional approaches. These have dramatic promise but require supporting research.

In analogy to the microelectronics industry, the vast majority of research funded in the 1970–2000 period concerned Si devices with some exploration of closely related technologies based on Si–Ge and III–V semiconductor alloy devices. Concepts such as Josephson junction devices are analogous to the more futuristic concepts now being explored in renewable energy such as nanoparticle photovoltaics. In the same way that Josephson junctions were studied in an important but not dominant way, we recommend that research focus on practical renewable technologies primarily and that futuristic concepts be explored less intensely but not insignificantly. Finally, growth of these industries will require students to be graduated in increasing numbers with a strong understanding of the technologies being developed. Therefore, support of research in wind, photovoltaics, biofuels, and battery technologies should be an ongoing and substantial portfolio such that trained experts are available to operate and advance these new energy-related industries.

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