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# Systems-Driven Approach for Solar Applications of Energy Storage

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## List of Acronyms

Ahr, Ampere hour, a measure of capacity
BEV, battery electric vehicle
BU, backup
CAES, compressed air energy storage
CAFÉ, corporate average fuel economy
CCHP, combined cooling, heating and power
DER, distributed energy resources
DG, distributed generation
DOD, depth of discharge
ESA, Energy Storage Alliance
EV, electric vehicle
FCEV, fuel cell electric vehicle
FCV, fuel cell vehicle
HEV, hybrid electric vehicle
IC engine, internal combustion engine
kg, kilogram
kW, kiloWatt
kWh, kiloWatt-hours
l, liter
Li-ion, Lithium ion
Mg, Magnesium
M-HEV, mild hybrid electric vehicle
MW, megaWatt
NaS, Sodium-Sulphur
NiCd, Nickel-Cadmium
NiZinc, Nickel-Zinc
NiFe, Nickel-Iron
NPV, net present value
P-HEV, power assist hybrid electric vehicle
PV, photovoltaic
RPM, revolutions per minute
SMES, superconducting magnetic energy storage
SOC, state of charge
UAV, unmanned aerial vehicle
UPS, uninterruptible power supply
USABC, United States Advanced Battery Consortium
UUV, unmanned undersea vehicle
W/L, Watts per liter, a measure of power density
Wh/L, Watt-hours per liter, a measure of energy density
W/kg, Watts per kilogram, a measure of specific power
Wh/kg, Watt-hours per kilogram, a measure of specific energy
Y2K, year 2000
ZEB, zero energy building

# Workshop on Systems Driven Approach for Solar Applications of Energy Storage November 5-6, 2003

## Executive Summary

On November 5 and 6, 2003, a workshop was held at the Maritime Institute in Linthicum, Maryland, to address the Department of Energy's Systems-Driven Approach (SDA) for solar applications of energy storage. The workshop was co-sponsored by three organizations within DOE: Solar Energy Technologies, Energy Storage, and FreedomCAR Programs. Participants included representatives from the battery industry, the solar industry, universities, national laboratories, and several DOE program offices. The objectives of the workshop were to explore a new generation of energy storage solutions for potential use with solar systems. Several factors were addressed, including efficiency, reliability, cost, maintenance, manufacturability, and cross-technology applications.

The first part of the workshop involved presentations from several of the participants, providing assorted perspectives on the status of storage technology research and development; the role of storage in present and future solar markets; non-PV applications of storage, such as vehicle systems; and how the SDA will be applied to further assess the role of storage in solar PV systems.

The following key topic areas were covered during these discussions:

- An overview of the Systems-Driven Approach and how it is being developed and applied within DOE's solar program.
- Detailed tables of cost and performance targets for DOE's FreedomCAR and Vehicle Technologies programs, which serve as a good example of how analogous targets can be developed for solar PV applications.
- The large ranges of energy and power involved in stationary energy storage applications, and the potential market for such applications.
- PV applications requiring energy storage, the appropriate storage technologies, storage lifetime issues and examples. Emphasis was placed on storage applications for off-grid residential systems, but utility and other applications were also discussed.
- The three major vehicle types that rely on storage technologies: battery electric vehicles, hybrid electric vehicles, and fuel cell electric vehicles.
- Industry perspectives of markets for PV technologies on a global and U.S. basis, with the observation that traditional off-grid markets have been flat in the last couple of years, while grid-connected systems have expanded rapidly.
- Industry perspectives on markets, emerging technologies, and research priorities related specifically to battery storage components and systems. Focus was principally on lithium-ion and nickel-metal-hydride batteries.
- The types of related research being conducted at U.S. universities, funding, and management issues.

- Implications of energy storage and solar energy on overall energy surety, along with a methodology to assess and apply energy surety methods.

Following these presentations, facilitated breakout sessions were organized around three market sectors: on-grid solar, off-grid solar, and transportation. The objectives of these sessions were to discuss existing and promising storage technologies, identify and prioritize technology development pathways for promising technology developments, and to explore synergies among market sectors that can improve the application of storage in solar systems. Although the general consensus was that most battery development is geared toward the much larger vehicle market, it was also clear that consideration of solar applications among battery manufacturers could lead to advantages in both market sectors. This, in turn, could help grow the market for solar PV applications to the extent that it increases the interest of battery manufacturers – a positive feedback loop.

Participants were asked to list the most likely solar PV applications in which storage technologies can help to significantly add value. These were listed as:

1. Making utility-based solar PV dispatchable to offset late-afternoon peaks;
2. Uninterruptible power supplies (UPS's) to cover short interruptions in grid power; and
3. Off-grid systems for facilities power.

Of these three application areas, the second is included in the Multi-Year Technical Plan (MYTP) of the DOE Solar Energy Technologies Program, in the form of technical targets regarding cost and performance for grid-tied residential systems with storage. This means that, in the context of developing and implementing the Systems-Driven Approach, modeling and analysis of storage in this application will precede the others.

Possible technology-development linkages were identified and discussed in relation to the following areas:

- Specific battery technologies, with emphasis on lithium-ion and nickel-metal-hydride batteries;
- Continued improvement of inverter technology to manage battery charging regimes;
- Application of intelligent systems, including sophisticated controls; and
- Advanced communication protocols to facilitate implementing controls across networks of systems as well as at the individual system level.

Regarding battery technologies, lead-acid batteries still dominate the solar PV market due to their much lower cost and their ability to deliver large amounts of energy per volume. However, advancements in other technologies – including significant cost reductions – could lead to higher reliability, lower maintenance requirements, and lower life cycle costs of solar energy systems. A wide variety of storage technologies are discussed in the body of this report. For grid-connected solar applications, some of the larger energy storage systems could have indirect impacts on solar's potential, for example by allowing the grid to better accommodate all types of distributed generation. In other situations solar and storage technologies could either compete with each other or be deployed in combination to provide similar services, for example in peak shaving and grid support.

However, the consensus of the group was that Li-ion and NiMH batteries offer the most near-term promise. Specific focus should be on the development of new materials and manufacturing methods to increase size and reduce costs while controlling failure modes to eliminate battery damage and safety issues.

All participants agreed that further improvements in inverter technology should greatly enhance the viability of storage in fielded PV systems. Smart inverters of the future may incorporate intelligent control schemes, allowing inverters to customize energy flows based on physical properties of the specific batteries in a system. This helps to maximize overall system efficiency, reduce battery maintenance, and increase battery lifetimes.

Another promising technology development area is the application of communication protocols within solar PV systems, for the benefit of individual users and for users operating a network of PV systems, such as utilities. These intelligent communications can greatly enhance utility-scale implementation of distributed solar PV systems by matching energy production with loads, assessing performance of individual systems and the overall network, and facilitating rapid responses to operational problems. The value of solar PV and associated storage technologies would be greatly enhanced through these integrated communications schemes. For instance, to be utility friendly, the combination of storage and solar energy could reduce local demand during peak periods by 90% to 100%. To make this work, homes will need communications and controls that combine the results of energy efficiency measures, generation, storage, to respond to utility needs.

All participants agreed that further research on applications and markets is merited in order to enhance the value of new or improved storage technologies in solar markets, and bring these markets into fruition. Issues related to utility industry deregulation, tariff structures, incentive packages, and even public perception need to be taken into account as DOE considers the future of storage in solar applications.

Presently, shifting consumption and generation to avoid demand charges is a consumer problem more than it is for utilities. Thus, whom does the solar/storage system serve? If distributed generation does indeed reshape demand profile for utility power, might utilities adjust their tariffs in response to this change? All players who may benefit from or be impacted by the implementation of such a system need to be involved in the transaction.

In summary, the two-day workshop brought together technical leaders in the government, academic, and industry sectors to address the near-term possibilities for expanding markets for solar energy systems through advancement of storage technologies. Although it was clear that transportation applications, being a more dominant market for storage, would direct R&D pathways, such advancements may have direct benefits in solar energy markets. The DOE can provide leadership in several ways: through establishing technical targets for solar applications of storage; by paving the way for the development and integration of intelligent controls and communications within storage and solar energy systems; through leading continued advancement of promising storage technologies, such as Li-ion and NiMH, to improve their reliability, lifetimes, and reduce costs; and by facilitating market-based research on the impacts of the technologies in new applications.

## Introduction/Objectives

This workshop was the third in a series of Systems-Driven Approach workshops. The first was on the solar energy Systems-Driven Approach and the second on inverter research and development. Participants used a similar methodology to explore a new generation of energy storage solutions for potential use with solar (specifically photovoltaic) systems. Initially, the group met to establish a baseline understanding of current energy storage products, with an emphasis on markets. An annotated agenda for that portion of the meeting follows. The Presentations are available at http://208.230.252.233/. The group then examined factors influencing efficiency, reliability, cost, maintenance, manufacturability, and cross-technology applications, but again with an emphasis on how all of these elements relate to market potential for solar applications.

The meeting notes themselves are organized by breakout group discussion: grid-connected applications, transportation applications, and off-grid applications.

## Annotated Meeting Agenda and Presentation Highlights

**Outline of Systems-Driven Approach, Guidelines and Goals for the Workshop, Conceptual Framework Applied to Energy Storage Issues (Dr. Raymond Sutula)**
Dr. Sutula welcomed the participants to the meeting and provided an overview of the objectives and the agenda for the day. His presentation went on to explain DOE's interest in a Systems-Driven Approach in responding to OMB applied R&D investment criteria and serving the President's management agenda. He then explained the framework for the Systems-Driven Approach developed by the solar program, and went through an example of how it has been applied to research management for vehicle batteries.

**Survey of Energy Storage Applications (Dr. Imre Gyuk)**
Dr. Gyuk's presentation provided a detailed review of energy storage concepts, technologies and issues. Key points addressed the large amounts of energy and power and the substantial potential market for stationary energy storage systems. Figure 1 illustrates a framework for examining applications of energy storage. Applications are classified according to time scale (from a few cycles to days) and by beneficiary (the consumer or the utilities).

| | POWER Seconds | minutes – hours | ENERGY diurnal |
|---|---|---|---|
| LOAD | PQ, Digital Reliability | DER Support for Load Following | Peak Shaving to Avoid Demand Charges |
| GRID | Voltage Support, Transients | Dispatchability for Renewables, Village Power | Mitigation of Transmission Congestion, Arbitrage |

**Figure 1: Energy Storage Applications**

He then reviewed storage potential and benefits, using California as a case study. Extrapolation to the U.S. leads to an estimate of a 50GW market potential saving $5B per year. Figure 2 illustrates the relationship between storage time, storage capacity and applications. Figure 3 shows how discharge time at rated power and system power ratings relate to a variety of storage technologies and applications. The information on these two charts was cited extensively throughout the discussions.

Dr. Gyuk then discussed various types of applications:

- Reliability has become a necessity for the digital society. Only storage can provide the 9 nines of reliability demanded by high-tech industry.
- Voltage and frequency support are taking on added importance after the disastrous recent blackouts. Effective control devices involving storage are under development.
- Peak shaving and load shifting requires larger batteries which are becoming available. They will become an important aid for relief of transmission and distribution congestion.
- Because they are not able to respond fast enough to load changes, distributed generation applications will need to be coupled to storage devices.

Making renewables dispatchable and village power were the next major topics. Renewables such as wind and solar are inherently intermittent and can cause considerable disturbance on the grid. With storage, however, renewables can provide reliable energy when needed. Extensive examples from Alaska to Peru were presented. The presentation ended with a statement of the DOE program goal: Develop a broad portfolio of demonstrated storage technologies for a wide spectrum of applications.

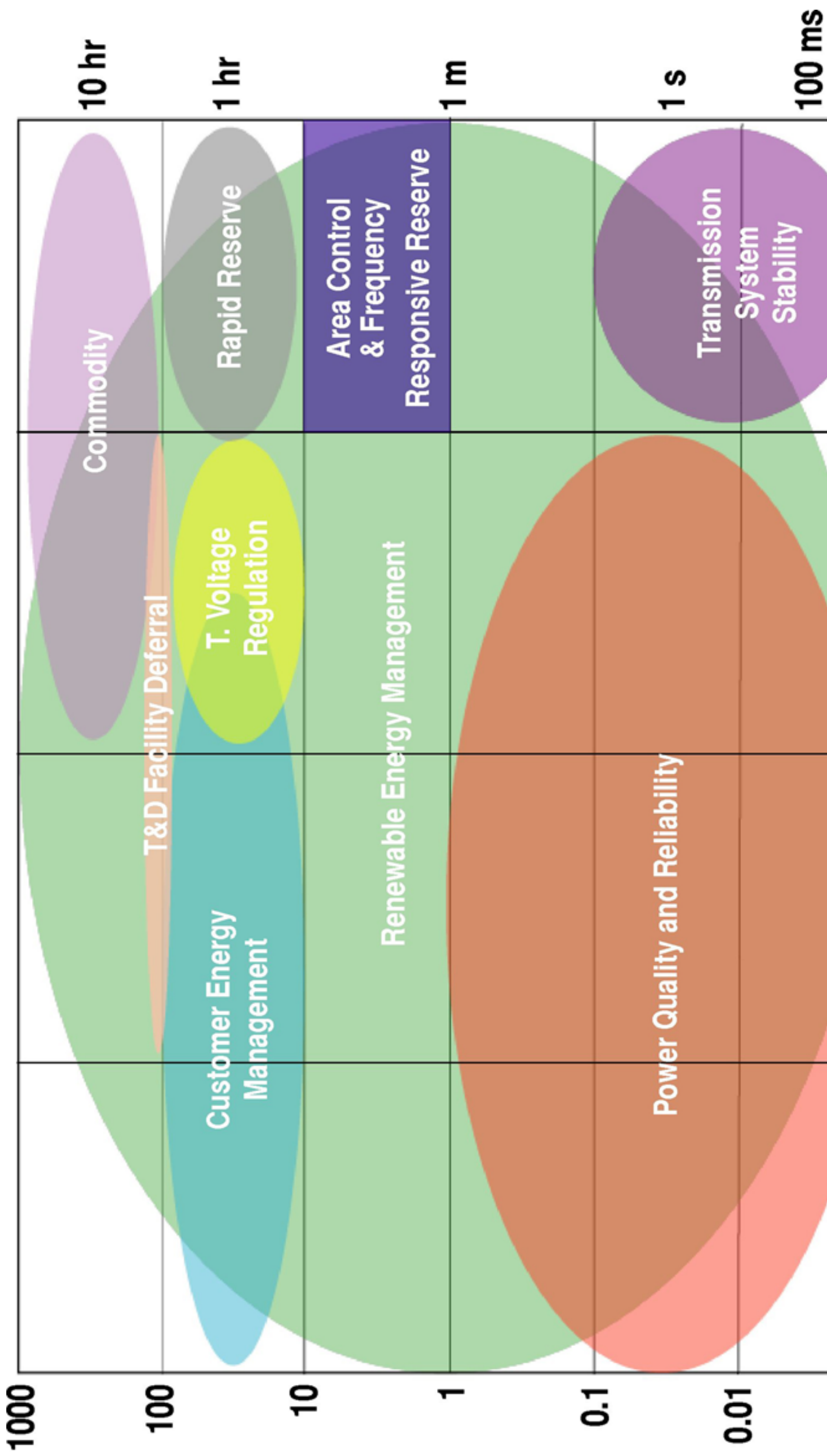


**Figure 2: Storage Time/Storage Capacity and Applications**

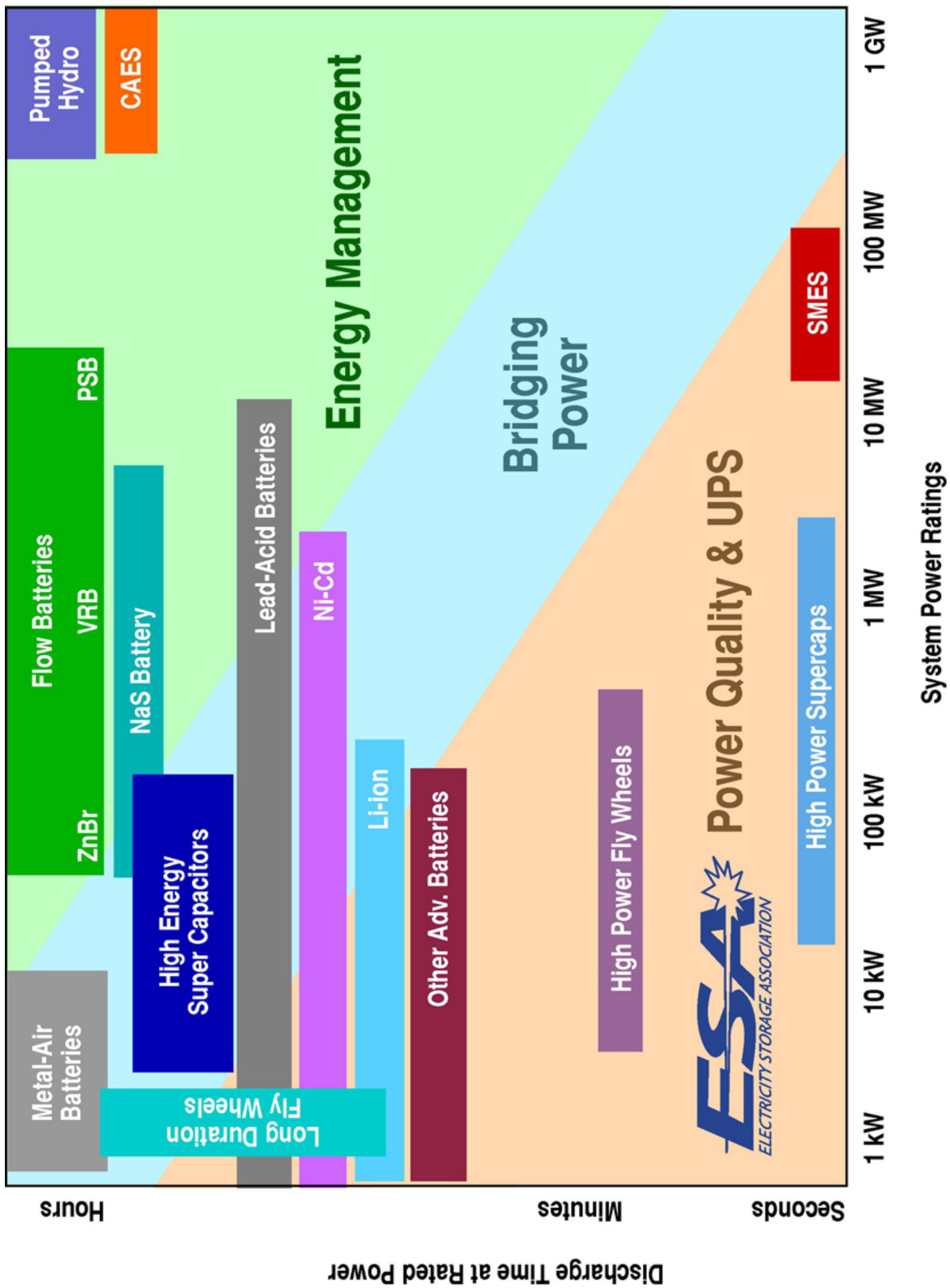


**Figure 3: Discharge Time, Power Ratings, Technologies and Applications**

**FreedomCAR Program Work on Battery and Energy Storage Systems (Tien Duong)**

Mr. Duong's presentation started with the program goals of the FreedomCAR and Vehicle Technologies program, and its energy storage effort: Conduct R&D on advanced batteries to facilitate the commercial viability of battery electric vehicles (EVs), hybrid electric vehicles (HEVs), 42 volt vehicular systems (42V), and fuel cell vehicles (FCVs). He then reviewed the program's research activities, R&D budget, and the current status and system targets for Li-ion batteries for EVs (Figure 4), batteries for HEVs (Figure 5), 42 Volt systems (Figure 6), and FCVs (Figure 7). The detailed tables of current performance, minimum requirements and goals were used as a baseline for technology assumptions by all of the breakout groups. The discussion of barriers to advanced batteries and the approach to cost, life and durability issues were also echoed in the discussions that followed.

***Performance of High-Energy Li-Ion Batteries (2003)***

| *Characteristic* | *Current Li-Ion* | *System Target* |
|---|---|---|
| **Specific Power (W/kg, 80% DOD, 30 sec.)** | **280** | **400** |
| **Power Density (W/L @ C/3)** | **155** | **300** |
| **Specific Energy (W/kg @ C/3)** | **100** | **200** |
| **Power Density (W/L)** | **440** | **600** |
| **Cycle Life (Cycles at 80% DOD)** | **1,000** | **1,000** |
| **Selling Price ($/kWh @ 100 k units/yr)** | **2 to 4 times the target** | **100** |

***Li/S Developmental System***

| *Possibilities* | *Issues* |
|---|---|
| • **Meet all USABC Performance Goals**<br>• **Meet USABC Cost Goals** | • **Poor Cycle Life**<br>• **High Capacity Loss**<br>• **Instability at Li Surface**<br>• **Isolation of Sulfur** |

**Figure 4: EV Battery Performance and Targets**

## *Performance of High-Power Li-Ion Batteries (2003)*

| *Characteristic* | *Current Li-Ion* | *System Target* |
|---|---|---|
| Specific Power (W/kg, 18 sec. pulse) | 900 | 625 |
| Power Density (W/L) | 1,450 | 780 |
| Cycle Life (25 Wh cycles) | 300,000 | 300,000 |
| Calendar Life (Years) | 15 (Projected) | 15 |
| Selling Price ($/system @ 100 k /yr) | 2 to 4 times the target | 500 |

**Figure 5: Performance and Targets for HEV Batteries**

| *Characteristic* | *USABC Commercialization Goals* | |
|---|---|---|
| | *M-HEV* | *P-HEV* |
| Discharge Pulse Power (kW) | 13 for 2 sec. | 18 for 10 sec. |
| Regenerative Pulse Power (kW) | 8 for 2 sec. | 18 for 2 sec. |
| Engine-off Accessory Load (kW) | 3 for 5 min. | 3 for 5 min. |
| Available Energy (Wh at 3 kW) | 300 | 700 |
| Recharge Rate (kW) | 2.6 | 4.5 |
| Energy Efficiency on Load Profile (%) | 90 | 90 |
| Cycle Life, Profiles/Engine Starts | 150k/450k | 150k/450k |
| Calendar Life (Years) | 15 | 15 |
| Cold Cranking Power @ -30°C | 8 (21 V minimum) | 8 (21 V minimum) |
| Maximum System Weight (kg) | 25 | 35 |
| Maximum System Volume (L) | 20 | 28 |
| Maximum Self Discharge (Wh/Day) | <20 | <20 |
| Operating Voltage, Maximum/Minimum (V dc) | 48/27 | 48/27 |
| Operating Temperature Range (°C) | -30 to 52 | -30 to 52 |
| Selling Price ($/system @ 100,000 units) | 260 | 360 |
| *M-HEV is mild hybrid electric vehicle, P-HEV is power assist hybrid electric vehicle. | | |

**Figure 6: Performance and Targets, 42 Volt Batteries**

***FreedomCAR FCV Goals***

| *Characteristic* | *Minimum* | *Maximum* |
|---|---|---|
| Pulse Discharge Power (kW) | 25 for 18 sec. | 75 for 18 sec. |
| Maximum Regenerative Pulse (kW) | 22 for 10 sec. | 65 for 10 sec. |
| Total Available Energy (kWh) | 1.5 | 5 |
| Round Trip Efficiency (%) | >90 | >90 |
| Cold-start at -30$^{o}$C (kW) | 5 | 5 |
| Cycle Life | TBD (15 year equivalent) | |
| Calendar Life (Years) | 15 | 15 |
| Maximum Weight (kg) | 40 | 100 |
| Maximum Volume (L) | 30 | 75 |
| Production Price @ 100,000 units/year ($) | 500 | 1,500 |
| Operating Voltage, Maximum/Minimum (V dc) | 440/220 | 440/220 |
| Maximum Self Discharge (Wh/Day) | 50 | 50 |
| Operating Temperature ($^{o}$C) | -30 to 52 | -30 to 52 |
| Survival Temperature ($^{o}$C) | -46 to 66 | -46 to 66 |

**Figure 7: Proposed Goals, FCVs**

**Energy Storage Technologies ( Dr. Thomas Hund, SNL)**
Dr. Hund's presentation covered four main topics: Energy storage technologies, solar PV applications requiring storage, solar PV battery life issues and solar PV energy storage examples. For storage technologies he reviewed different types of batteries; alternate storage technologies such as hydrogen, flywheels, ultracapacitors, compressed air, pumped hydro and superconducting magnetic energy storage (SMES). Figure 8 shows an illustration of how technologies and applications are related to different measures of capital costs.

He then discussed battery life-cycle costs for solar PV systems, and the substantial expense they add to solar systems – in many systems the battery is the most costly item over the life of the system. He then reviewed the main solar PV system issues that reduce battery life, and their causes. Solar PV applications that require storage can be grouped into stand alone and grid-tied applications. There are examples of each in real world applications, including a number of projects supported by the DOE energy storage program and/or the DOE Solar program. Dr. Hund's presentation ended with a summary of what is needed:

- New energy storage technologies need continued R&D, and when ready, a demonstration of their performance predictions with respect to cycle life, reliability and cost.
- Lead-acid batteries are most cost-effective at present, but they still need proper charge control, optimum design, and maintenance.

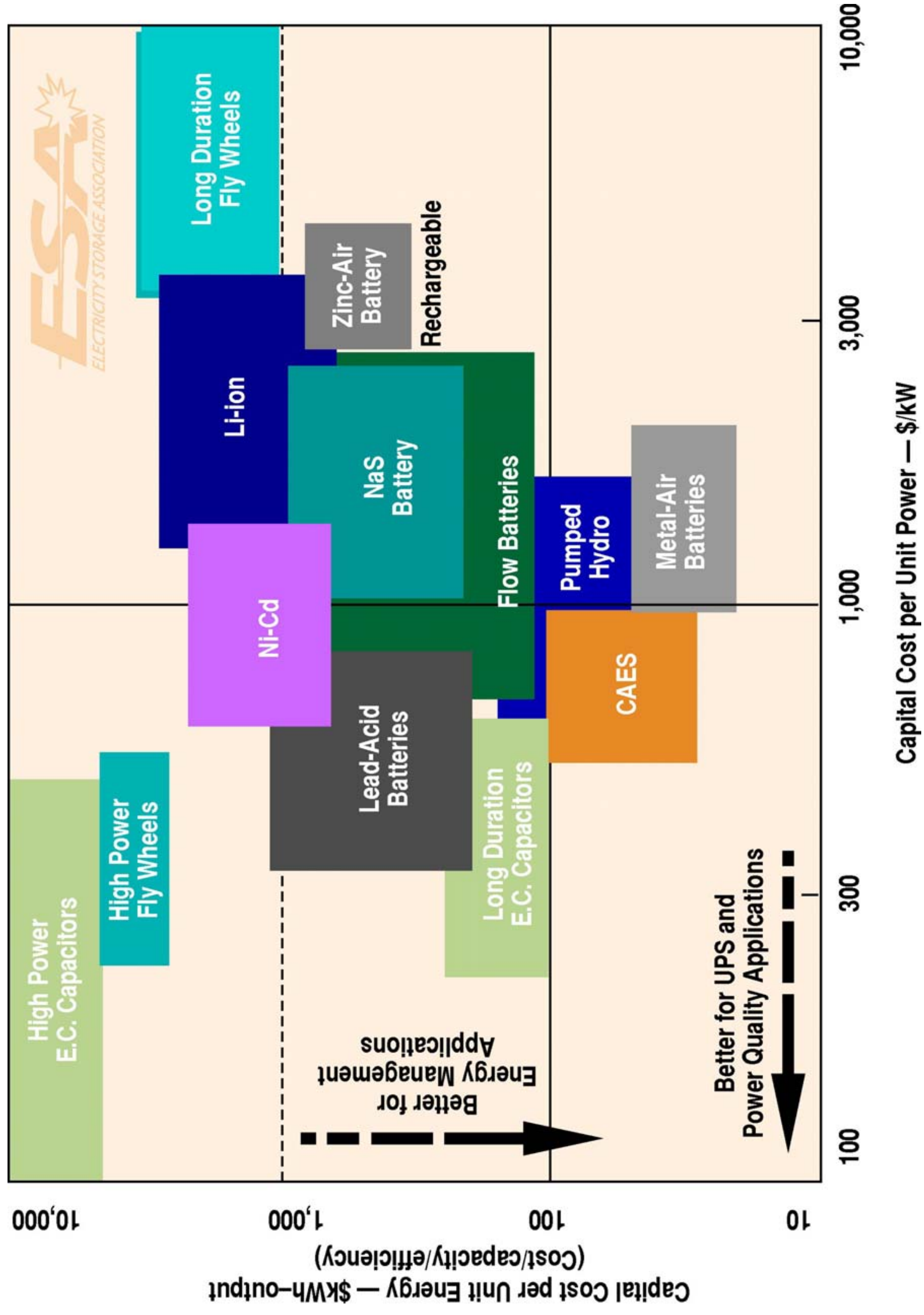


**Figure 8: Battery and Alternate Storage Technologies**

## Energy Storage User Requirements

This section of the workshop focused on storage for power markets, transportation markets and solar markets. The presentations were designed to give the participants an idea of the potential in these markets, where there are common concerns, and where there are distinct differences in performance/cost/design requirements for storage technologies.

Power Markets, General (Larry Moore, SNL)

Larry Moore presented work he had conducted with Rolland Skinner, Manager of the Northwest Rural Public Power District, on energy storage considerations among rural electric cooperatives involved in solar electric or photovoltaic (PV) markets. It started with a discussion of the size of the co-op market and the opportunities that exist for PV systems and storage because of aging infrastructure, long lines, and light loads. The information he presented showed that PV water pumping and off-grid residential systems can make economic sense for cooperatives, and represent a business opportunity. There is a strong base of O&M field experience with PV water pumps that indicates clearly where improvements are needed. There is also a track record for off-grid residential applications, with data on 62 systems installed by Pinnacle West between 1996 and 2002. Additional applications may be for grid-tied systems with storage to provide energy when the grid is down; highway construction equipment; fence charging; and temporary power sites for special events. Improvements in energy storage are still needed, but O&M costs in the form of system design, component reliability and business models still need attention. Even with current battery problems, these applications represent a here and now market.

Transportation Markets (Robert Graham, EPRI)

Dr. Graham's presentation provided a thorough review of where we have been, where we are, technology opportunities, barriers, and policy options. EPRI is currently involved in non-road EV development and plug-in HEV development for various vehicle types. The first part of the presentation reviewed the energy security, climate change, environmental, quality of life and consumer interests driving advanced vehicle development. The three major vehicle types – which all have a role in the future of advanced vehicles – include battery electric vehicles (BEVs), hybrid electric vehicles (HEVs) and fuel cell electric vehicles (FCEVs). An interesting aspect of hybrid electric vehicles is the potential for plug-in HEVs, which could make them a source of mobile distributed generation, as illustrated in Figure 9.

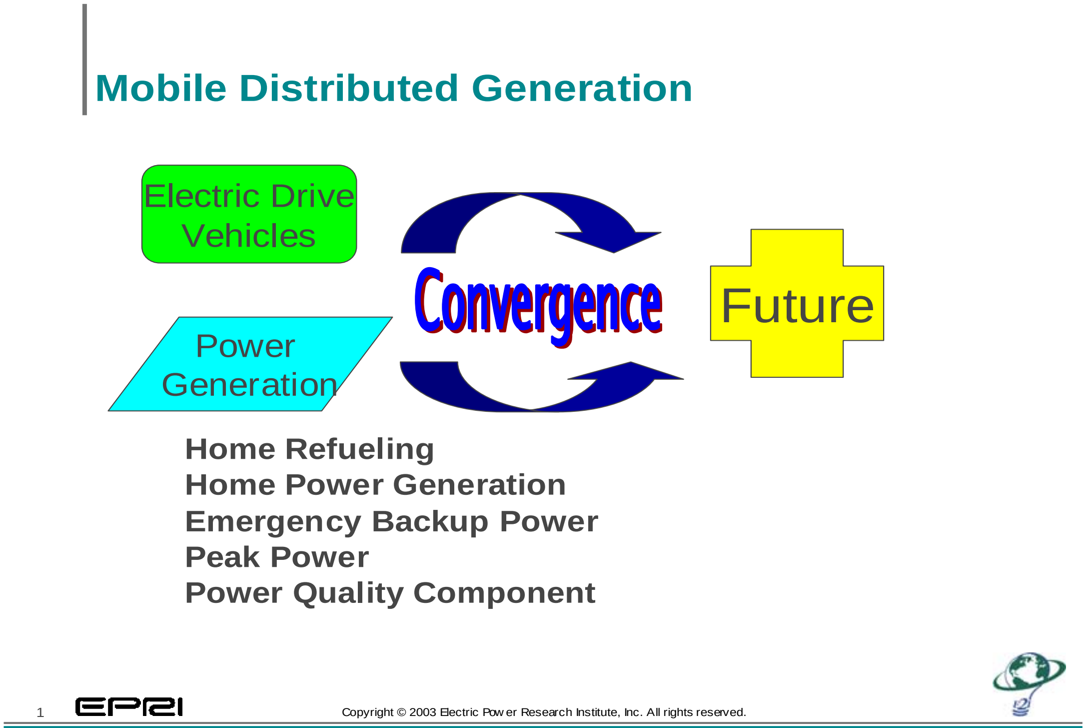


**Figure 9: Mobile Distributed Generation Concept**

Technology challenges facing all the advanced vehicles include:

- Improving the energy storage system (battery technology is new and costly);
- Energy management and control – when to use electricity or gasoline
- Electric drive systems and power electronics,
  - Cost-effective, high power motors;
  - Power electronics, electric accessories;
- Vehicle design and packaging to cope with mass and volume of battery package, and HEV performance which is highly dependent on the vehicle platform

Dr. Graham's major conclusions were that manufacturer participation is critical, and there needs to be public policy support.

<u>Solar Markets and Storage (Paul Garvison, BP Solar)</u>
Paul Garvison's presentation provided a solar PV market overview and a discussion of the implications for energy storage. Currently the global solar PV market is expected to reach approximately 575 MW in 2003. Market growth is expected to reach 30% or more. Japan is the largest solar PV market in the world, accounting for 225 MW in 2003. There has been a significant shift in applications of solar PV – grid-connected markets now dominate, accounting for over 70% of global solar PV demand. Traditional off-grid markets are flat. From a business perspective, the top 8 companies expanded their share of the overall market from 84% in 2001 to 89% in 2002.

Japan continues to grow its market, even as it has gradually reduced subsidies to residential customers, to the point where they are now less than $1/W peak. The residential program accounts for over 80% of the Japanese market. Supports have declined, but applications are still increasing at a rate of 30% to 40% per year. At the same time, system costs have declined, and even with the reduced subsidies solar PV is expected to reach lifecycle cost parity with grid electricity in the next few years for residential customers.

Germany's market share is also growing. Although 2003 is the last year of the 100,000 roof program in its current form, new feed-in tariff laws are being debated that will continue to fuel strong growth. To date Germany has installed 350 MW of solar PV.

The U.S. only accounts for about 12% of the global market, with about 1/3 of that associated with grid-connected applications in California. California's outlook is clouded by the fact that residential funding will run out in 2004 without additional approvals, although funding for commercial systems is secure through 2008. New buydown programs are starting in New Jersey, Pennsylvania, Connecticut and Massachusetts, which should help push market growth to 25% or more in 2004.

In the rest of the world there are promising developments in other European nations that will add to the grid-connected applications. Most of the remainder will be in off-grid applications split between rural homes and industrial. There are promising signs for large rural infrastructure projects, and continued development of grassroots markets where users are purchasing systems outright or accessing micro-loans or other small-scale finance tools. Rest of world market growth is expected to be approximately 15% in 2004. The presentation concluded with a review of the drivers behind the solar PV market, estimates of the value of the major market segments, and a summary of market directions for solar PV energy storage, shown in Figure 10.

## Market Directions for PV Energy Storage

- Lower lifecycle costs:
  - Longer life/higher reliability/lower maintenance
  - Lower capital cost
  - Reduced product stewardship costs
- Dispatchable power to grid
  - Requires reliable control system
  - Adds value to PV energy as a "peak shaving" method, but economics unclear with current technology
- Large scale storage – needed to achieve PV energy contribution beyond 5-10% of total electricity
- Energy security - some interest has appeared following recent grid outages in the Northeast
  - But economics of alternatives (eg. gensets) are presently considerable more attractive than PV/battery

**Figure 10: PV Energy Storage Market Directions**

**Perspectives on Energy Storage and the Systems Driven Approach (Charles Hanley, SNL)**

Charlie Hanley's presentation provided more detailed information on the Systems-Driven Approach being developed by the solar program – an example of the modeling capabilities the solar program is pursuing, progress on developing the solar version of the model, work on benchmarking and analysis, and ideas for the role of storage in solar and in the Systems-Driven Approach. The solar program's objective is to create a framework and analysis tools that will allow the program to explore alternative technology pathways and identify critical technology needs to guide planning and management of the entire solar technology portfolio. The first application of the Systems-Driven Approach was in the development of an integrated solar multi-year technical plan. The information provided a much more detailed explanation of how the Systems-Driven Approach is expected to be used, and how storage fits into the approach. An in-depth example of analyzing storage in solar thermal electric plants was presented. The presentation showed the impact a 1250 MW plant with thermal energy storage could have in meeting peak demands in Nevada. The presentation concluded with thoughts on the role of storage and solar energy in a Systems-Driven Approach, as shown in Figures 11 and 12.

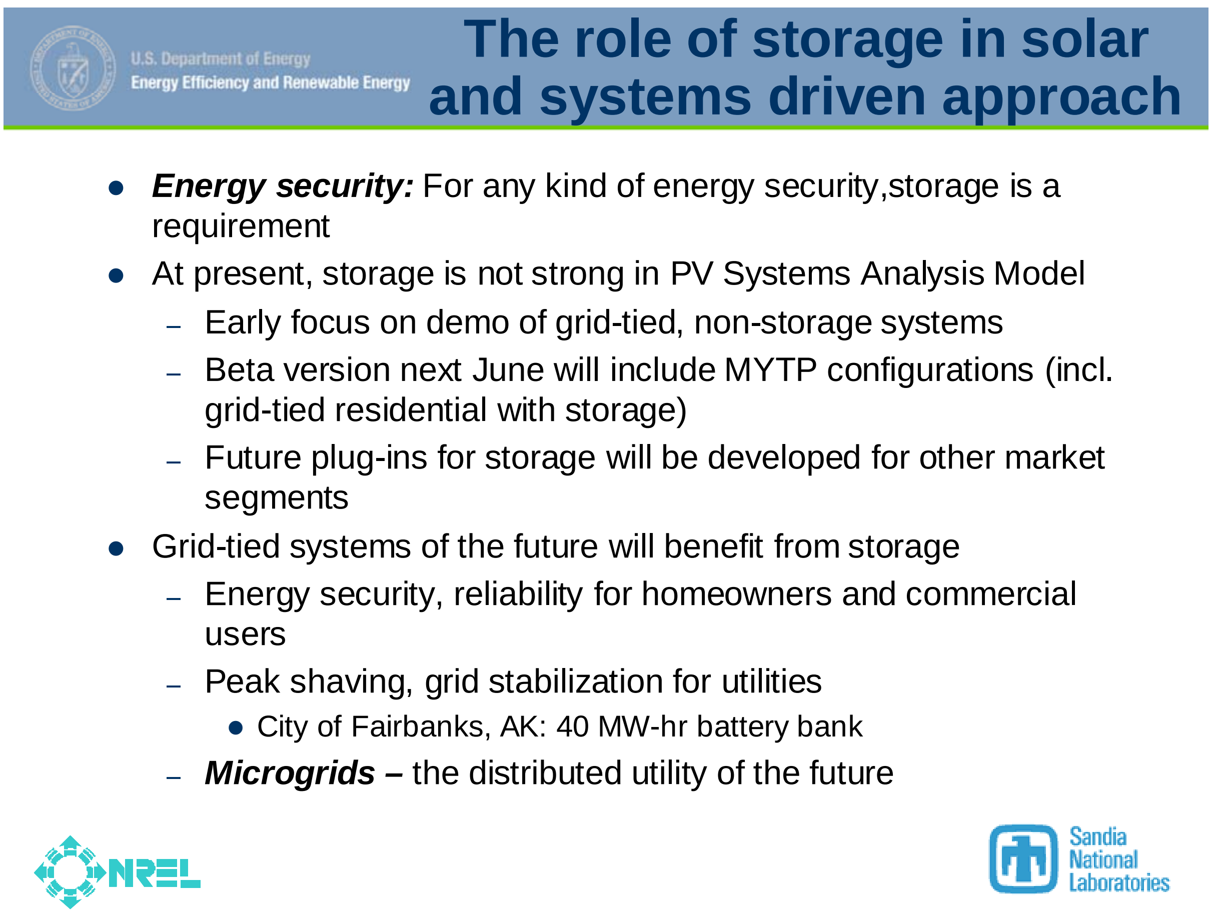


**Figure 11: Storage, Solar and the Systems-Driven Approach**

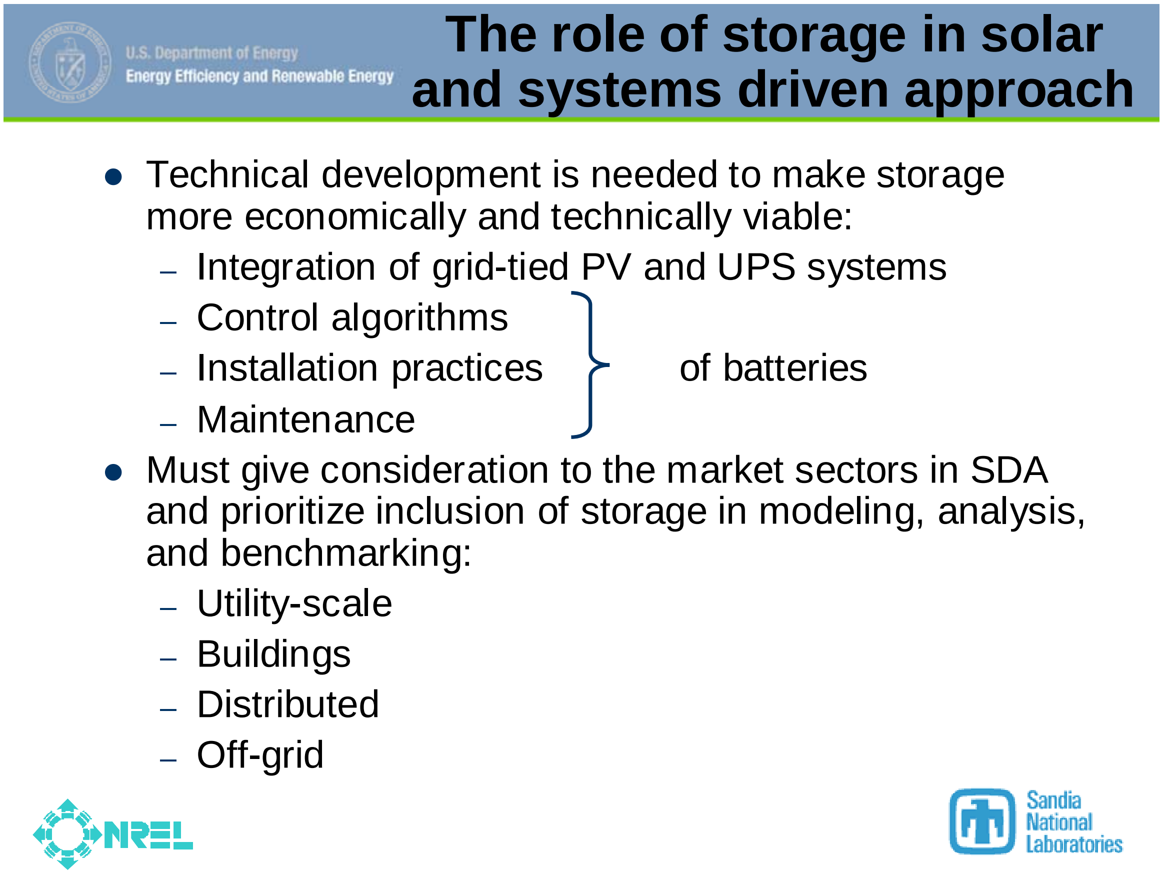


**Figure 12: Storage, Solar and the Systems-Driven Approach Continued**

**University/Lab Perspectives on Research and Markets (Dr. Michael Ropp, South Dakota State University)**

Dr. Ropp's presentation provided the audience with a comprehensive view of the types of research being pursued at universities and where it is performed. Dr. Ropp identified two distinct approaches to energy storage research – one track focused on technologies, and the other focused on chemical converters, with hydrogen as an important common element. His investigation of research included work on electrochemical batteries, flywheels, ultracapacitors, thermal energy storage and hydrogen. The only technologies excluded were pumped hydro and superconducting magnetic energy storage (SMES). There are high levels of activity in all technologies, including a number of dedicated university centers (although the definition of center varies widely). Most of the applications work is for space or transportation.

Some of the challenges facing university research include the interdisciplinary nature of the subject (although it can be overcome); accessing startup money; programs that are "hardware rich but cash poor," meaning it is difficult to get money for students and personnel; and multiple demands on the same people for research, teaching, outreach, and other responsibilities. Finally, there was universal agreement that "institutional schizophrenia" was a significant challenge. This involves a debate over whether research should be supported because it is important, or whether research should be self-sustaining, which goes back and forth and therefore complicates the sustained, long-term funding that is a critical ingredient to success.

Research efforts highlighted in the presentation included:

- Penn State's Graduate Automotive Education (GATE) Center (electrochemical)
- University of South Carolina Center for Electrochemical Engineering
- Texas A&M Center for Space Power (kinetic)
- Auburn University (kinetic)
- University of Texas-Austin, Center for Electro-mechanics (kinetic)
- University of Nebraska, Architectural Engineering (thermal)
- Florida Solar Energy Center (University of Florida system) (hydrogen)

**Industry Perspectives on Markets, Emerging Technology, Research Priorities (Dr. Salah Oweis, SAFT, Advanced Battery Systems Division)**

After presenting a brief overview of SAFT's business and capabilities in industrial batteries, rechargeable battery systems and specialty batteries, Dr. Oweis went into more detail on their applications for standby power; telecom networks; railways and mass transit; space; defense; and high-energy, high power systems for EVs and HEVs. Technical details on SAFT's high-power Li-Ion battery pack for fuel cell and power assist HEVs were provided so that the audience could understand the current state of this emerging technology and how it has progressed. SAFT also has demonstrations in progress of their battery in use for distributed generation with Southern Services Co. and American Electric Power. Details on configuration, capabilities and preliminary test results were presented. The presentation ended with a review of SAFT research priorities: manufacturing development/cost reduction; performance capability for energy storage; and integrated systems.

**Presentation on Energy Surety and Implications for Energy Storage and Solar (Charles Hanley, SNL)**

Sandia has been active in researching technologies and applications of distributed energy and storage to enhance energy surety. They have expertise in distributed generation technologies and an energy surety methodology that they have been applying to both military and civilian communities and facilities. Their experience has helped identify benefits and risks involved in energy systems and how to approach the evaluation and remediation of problems. Energy surety is a measure of power reliability. It is applied to facilities and communities to assess the vulnerability of their energy systems to terrorist attack or natural disaster. It also deals with other critical infrastructure that depends on energy, and considers methods for insuring energy surety. The distributed generation technologies considered include all of the types shown in Figure 13.

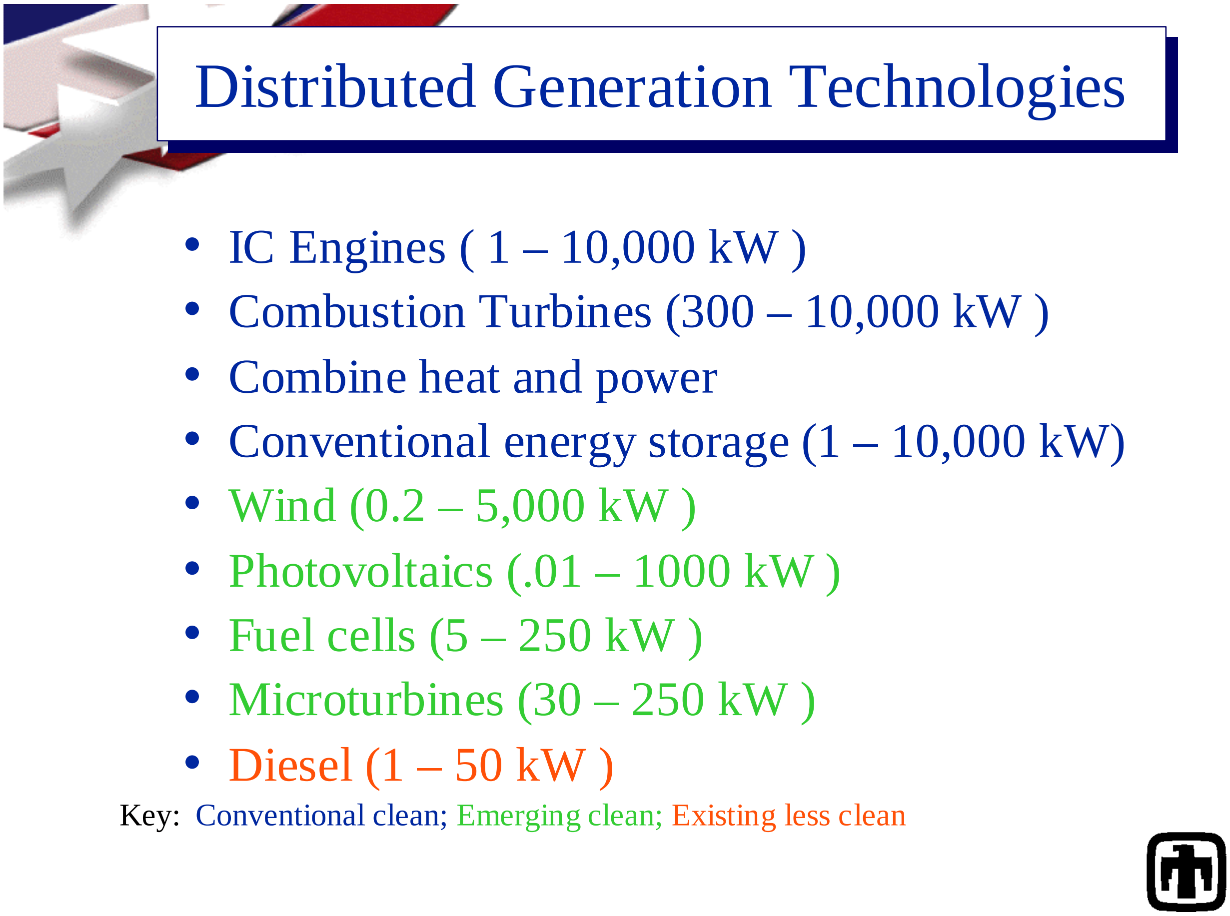


**Figure 13: Distributed Generation Technologies for Energy Surety**

He then covered methods to improve energy surety, traditional approaches, new approaches, and what is involved in an energy surety assessment. Using a cost-analysis for a hospital, Mr. Hanley showed that there is a $1.6M difference in Net Present Value (NPV) for a single 1 MW diesel system versus a single 1 MW combined cooling heating and power system, largely because the CCHP system generates energy savings even when it is not needed for an emergency. Figure 14 illustrates the basic steps in the energy surety methodology.

Energy surety is currently being applied or considered by both cities and military bases around the country. He noted that distributed energy is not always the best answer to energy surety problems, but there are situations where it is the best option if high levels of surety are needed, distributed energy is cheaper than energy from the market, and where buildings are closely clustered. For Federal facilities it is an issue because energy is often critical to their missions, they have vulnerable energy infrastructure, and terrorism has created a new threat. Federal facilities received an important wakeup call when fire took out both transmission lines serving Ft. Huachuca in Arizona, taking the base down for 16 hours, incurring $3M in costs, and forcing the potential loss of the base's ability to perform its mission. There are now resources available for Federal facility planning, as well as civilian planning. In summary distributed energy

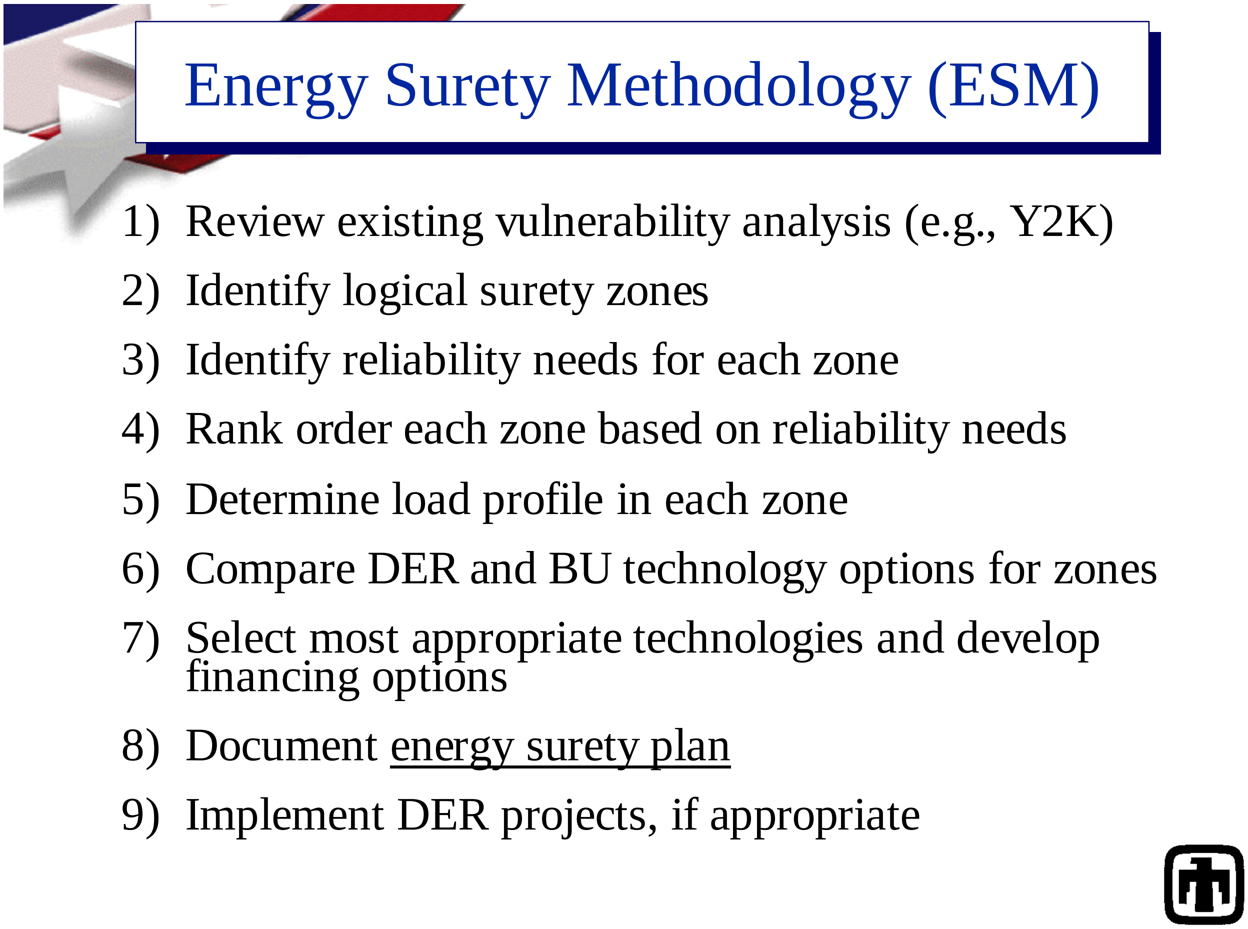


**Figure 14: Energy Surety Methodology**

technologies are proven, energy surety is a growing concern in the country, and new concepts for applying distributed energy may provide more or equivalent reliability for the same costs as backup systems, and Sandia now has a methodology to identify energy surety needs and the best technologies to address them.

**Banquet – Presentation on "Ovonic Metal Hydride Technologies for Photovoltaic Energy Storage Applications" (Dennis Corrigan, ECD Ovonics)**

Dennis Corrigan's presentation began with a discussion of the connections between Ovonics' NiMH battery technology and their emerging hydrogen storage system. Basically Ovonics is positioning itself and its technology to play an important role in both the hydrogen economy and in electricity storage. They have an extensive network of strategic alliances associated with their core businesses – energy generation (solar PV and fuel cells), energy storage (solid hydrogen storage and batteries), and information technologies (optical memory and Ovonic unified memory). They are significant players in solar PV development with the Uni-Solar 30-MW PV facility, which manufacturers their patented multijunction roll-to-roll thin amorphous silicon product, which has strong competitive advantages in its light weight, durability, flexibility and comparatively high conversion efficiency for an amorphous silicon product. Their solar PV products are selling and performing well in remote applications, rural electrification, roof-integrated systems for residential and commercial customers, and a new application in a 500 kW "solar mine" that powers oil field operations for Chevron Texaco operations in Bakersfield, CA.

Ovonic battery products are focusing on NiMH batteries. Mr. Corrigan reviewed their work in automotive and stationary applications. He then explained their metal hydride production capabilities and the work they are conducting with Texaco on hydrogen storage systems, and their attributes. Their system basically provides a hydrogen storage tank that operates at low pressures, provides for fast refueling and is compact enough to be a practical vehicle fuel system. They are also developing the same technology and canister system to provide bulk hydrogen storage for refueling stations. He finished his presentation by presenting a video that showed the innovations Ovonics is pursuing.

## Introduction to Breakout Group Sessions

This was the conclusion of day one of the meeting. The following day focused on discussions within small breakout groups focused on issues facing storage and solar technologies in transportation, off-grid and grid-connected applications.

Each group was asked first to discuss what was needed in terms of what technologies could be applied today, 5 years from now and 10 years from now. The discussion included what characteristics of storage technologies will change over these time periods, and whether these changes would create new opportunities. If advances are expected, the groups were asked to consider how much uncertainty was involved, and how dependent they might be on funding and actions by the Federal government, industry and universities.

Following these opening brainstorming sessions, participants were asked to identify the key indicators of success in addressing different applications, and which indicators should be included in modeling and scenario analysis.

In the afternoon each group was asked to focus on future directions for solar and storage technology/applications development. Specifically they were asked to address overlaps between market sectors – for example plug-in electric vehicles that could operate as distributed generation, or home generation/storage systems that could be used to refuel vehicles. Finally, each group was asked to consider what should be done next to incorporate storage into a Systems-Driven Approach, modeling, and how the three DOE programs could coordinate related work. Summary notes from each breakout session follow.

**Workshop on Systems Driven Approach**
**for Solar Applications of Energy Storage**
**Breakout Group: On-Grid Solar Applications**

## Participants

Moderator:  Kevin DeGroat (McNeil Technologies)
Notes:  Roxanne Drayton (McNeil Technologies)
Ira Bloom (Argonne National Labs)
Alec Bulawka (U.S. Department of Energy)
Chris Cameron (Sandia)
Robert Cary (Power Services Group, Inc.)
Chris Cook (E3 Energy Services)
Steve Eckroad (EPRI)
Paul Garvison (BP Solar)
Ron Judkoff (NREL)
Richard King (U.S. Department of Energy)
Robert Margolis (NREL)
John McKeever (Oak Ridge National Laboratory)
Colin Murchie (SEIA)
Lew Pratsch (U.S. Department of Energy)
Robert Rallo (Kyocera Solar)
Barry Segal (Segal's Solar Systems)
Byron Stafford (NREL)
Samuel Taylor (U.S. Department of Energy)
Irwin Weinstock (Sentech)
Herman Weigman (GE Corporate R&D)

## Background

The intent of this session was to discuss grid-connected applications of solar and storage technologies starting with their current status, and then considering where technology and markets are headed over the next 5 and 10 years.  Some of the key questions included:

- How are solar energy and storage going to work for utilities and customers?
- How will utilities change in the future?
- Where are storage technologies going?
- What are the key marketing issues to be considered?
- What applications exist today and where will the market be in the next 5 years and 10 years from now?
- Where do solar and storage enhance or compete with each other?

## Solar PV Applications

Since this group had a mix of people, many with little background in solar electric technologies, the discussion began with a review of how solar PV is currently being used on the utility grid. At the large scale there is the Hedge Substation, an on-grid central station solar PV system which is completely utility-owned and operated and consists of approximately 6 MW, but no storage capabilities.

The solar PV Pioneers program typifies another approach. These systems are also utility owned and operated and consist of multiple 1.5 kW systems installed on the roofs of utility customers who volunteer for the program. The systems do not directly displace any of the energy used in the houses that host the systems – it is all fed directly into the utility grid. Again, these systems include no storage.

Finally there are roof-mounted units for commercial (100s of kW) and residential (3 to 5 kW) customers. These systems are generally owned by the customer and displace electricity consumed by the building or facility they are connected with. In cases where they generate more power than the building can use, the power generally goes back into the grid. In some states this excess generation is regulated under net metering provisions that require utilities to pay consumers for their excess generation. Most of these systems do not involve storage; the grid is used in lieu of storage. When the grid goes down, so do these systems. A few do include storage systems, usually attached to critical circuits or loads that the customers want to keep on-line during power interruptions.

## Issues Facing Solar PV and Storage

The group quickly focused on inverters as a key issue in integrating solar and storage. The group feels there are no inverter products available that can really effectively handle the combination of a battery, the grid and solar. Some of the companies that were working on solutions, like Advanced Energy, Inc., have gone out of business. Others, like Outback, are working on products, but they are just emerging into commercialization.

If the inverters were capable, a system like those PowerLight installs could add storage for backup power and uninterruptible power supply (UPS) for big box retail stores and for net zero energy buildings. The challenge for solar is can it compete with standalone UPS systems – what is the rationale for combining the solar energy and storage? The discussion then shifted to the outlook for high-value applications of solar and storage.

**Peak Power Shaving:**

In the next 5 years peak power shaving will offer the biggest return for commercial and residential applications of solar, especially in California because of the pricing structure there. The advantage of solar PV and battery backup is the ability to shift the peak output window for solar PV up to 2 to 3 hours, so that it can cover the shoulders of evening peaks. The inverter can also charge the battery by taking power from the solar PV during off-peak periods, when the value of displacing power from the grid with solar PV is lower, or recharge from the grid at night. Taking advantage of peak shaving is highly dependent on the rate/pricing structure offered by the utility.

The value of dispatch is based on the time of day, price structure, stability, and economics of the system, which can vary widely from utility to utility. In working to maximize peak shaving value, the user should also look at their power use to reduce their load during peaks. While the group definitely saw the potential for storage to shave peaks, the value of solar PV added to storage was questioned because it is usually cheaper to recharge from the grid during off-peak hours. From the viewpoint of solar PV, peak shaving is a byproduct value of a customer installing a solar PV system, and it would be tough to justify the expense of a storage system in addition to the solar unless incentives for peak shaving were just right for the customer.

**Uninterruptible Power Supplies**

UPS is probably the next important application after peak shaving, involving larger storage and educating consumers on the decisions they must make in deciding which loads have to be maintained, how long they must be maintained, how quickly the system needs to switch over, and other features that influence price and performance.

**"Smart" Controls and Inverters**

Eventually, to maximize value, smart inverters that know when to shift from charging to serving load to exporting power to the grid will be needed. Smart controls that are flexible and programmable so that they can be adapted to different customer and utility situations are going to be important because utility peak profiles, rate structures, and customer needs vary from location to location. Right now, time-of-use rates are well defined, fixed-time periods. But at some point communication links to utilities to allow a more fine-tuned response to utility conditions like voltage sags and surges could add value, especially if large numbers of solar/storage systems are deployed. Power factor correction and reactive power control are other smart control applications for inverters.

**Customer Identification**

The inverter discussion raised the issue of whether the systems should be responsive to utility needs, to customer needs, or a combination of both. Right now shifting consumption and generation to avoid demand charges is purely a consumer problem. If a consumer exceeds certain levels of demand, even once, it triggers a change in their tariff for an entire tariff period. During this discussion it was noted that it is difficult to see who the industry is marketing with these systems – is it the utility, is it customers, or is it some combination? There is a basic problem in getting everyone who might benefit from a system to become a part of the transaction. Who will buy also determines what is being sold – grid reinforcement, protection from outages, reduced peak charges for the customer, reduced peak load for the utility?

**Major Market Applications**

After some discussion, four major market applications were offered:

- Solar with the grid as storage, which might involve smarter grids that are more capable of dealing with intermittent distributed generation
- Applications that deal with ½ to 1 hour power interruptions with storage
- Applications that shift some solar generation to better match peak requirements
- UPS systems that address electricity reliability for customers, and therefore may want 3 to 4 days of storage

In the solar PV market today, storage is a non-issue. Installers and customers don't worry about storage and let the grid handle backup when solar PV power is unavailable. There is very little outage or disturbance protection being sold with solar PV.

A lot of the worry for consumers and utilities involves the little transients, which only need a little bit of storage to cover demand for a quarter hour or less. A significant problem is the lack of inverters and control systems that are really capable of taking advantage of peak pricing.

**Zero Energy Buildings and Market Applications**

Many of these issues are coming up with zero energy buildings (ZEB) in the residential sector. ZEBs that combine very energy efficient homes with solar energy do exist. Current ZEB systems can cut homeowner's utility bills in half and reduce summer peak load to almost zero. In some states, time-of-use rates and the combination of efficiency measures and solar can save homeowners 85% of their gas and electric bill. As ZEB expands, if there are 1000 homes that save 2 to 3 kW through time of use rates and ZEB technology, then 2 to 3 MW of electricity capacity can be offset. Another advantage is that ZEBs can relieve local distribution systems stress – if the utility generates the peak power it still has to move through transmission lines and the distribution system to the customers, adding stress to those systems. ZEB puts the generation at the customer site, avoiding stress that is greatest during peak demand periods on the grid. The objective is to eventually reduce peak demand from ZEBs by 100%.

There are major hurdles in terms of how ZEBs are viewed by utilities. In the case of Centex they were threatened with exit fees for taking part of their customer loads out of utility service. Net metering is important to provide a cash flow for excess generation from solar systems, but it is not available in all states, and how it is implemented varies widely from state to state. Storage could take care of some of the net metering issues by keeping more of the generation within the customer's control, but is it really optimal to design storage to avoid exporting excess generation to the grid? Eventually as more ZEBs are built it could allow the creation of "virtual utilities" made up of distributed generation and storage where communication and coordination between dispersed generating and storage sources could provide reliable, predictable generation on a statistical basis. Basically the variations in one dispersed generator that might be caused by passing clouds or other transient issues would be reduced to insignificance by the predictable generation profile of a group of distributed generation and storage technologies deployed over a wide area. Theoretically the aggregation of multiple ZEB homes over multiple subdivisions over a wide geographical area could appear to a utility operator as a reliable, predictable source of power and demand reduction that could be contracted and delivered as a unit.

**Research on Applications and Markets**

In summary there is a market here and now for residential, commercial and utility applications of solar PV, and it is helping with peak loading on distribution lines and providing on peak generation. In the next 5 to 10 years storage and solar on customer sites has the possibility of expanding into the role of reducing distribution system stress as part of utility distribution system investments. What is needed is a utility benefits study that clearly defines where solar and storage fit into the system, and what value they deliver. Comparisons need to include both the wholesale and retail value of the generation, and the impact of reduced utility capital investment by getting customers to buy what is essentially a part of the utility distribution system. A study should also investigate the incentives utilities are offered by regulation, which increases their focus on central station solutions.

Another area of study should be contracting mechanisms that can more effectively define and capture all of the benefits of a distributed solar/storage installation and make them part of the transaction. Theoretically a ZEB installation could be delivering value to the utility by reducing demand on an overstrained area of the grid, delivering peak demand reductions and conservation savings to the homeowner, and helping the utility avoid peak demand. But there are little or no contract mechanisms for involving all of the beneficiaries in paying for the installation.

**Regulatory and Incentive Issues**

One of the criticisms of current incentives is that non-participants pay them. They redistribute funds from all ratepayers regardless of their income to people who install solar PV systems, who generally have high incomes. Better targeting and documentation of system-wide benefits would help justify some of the incentives. It might also target more installations to locations with the greatest system-wide benefits. A careful study would also have to include a better understanding of rates and rate structures for different utilities and customer classes. There are big differences between residential consumers paying 8 to 10 cents/kWh versus industrial and commercial customers operating in the 4-cents/kWh range. A better quantification of energy independence, energy security, energy reliability and environmental benefits should also be a part of the analysis.

<u>Utility Restructuring and Regulation</u>

A major concern is where is utility regulation headed? And where are rate structures going in the future? The future of utility restructuring in general is difficult to predict, and so are directions in rate structures. In fact it would be dangerous to assume that distributed generation, if it starts to take off, won't impact rate structures. If solar, storage and/or ZEB do have a significant impact in shaving peak demand, utilities are bound to adjust their incentives for customers in response to the change. The utility sector will be dynamic over time as power needs change, and it is important to put some thought into what those changes may be, or should be.

Many utility bills are moving toward flat fee structures that charge a low rate but have high fixed charges, particularly for customers that exceed a set demand level. Even one short excursion above a demand charge level can move a customer to a higher tariff level until the next billing period. This puts a high premium on absolutely reliable, predictable demand reduction from solar, storage, and energy efficiency measures. Because of these subtleties in utility tariffs it is very important to accurately define peak savings and what the implications are for the customer and the utility of natural variations in output or equipment failure.

The true value and capability of solar PV and storage to deliver peak shaving from a utility point of view also deserves further attention. Participants familiar with utility planning emphasized that unless a utility can dispatch a resource they do not recognize it as peaking capacity. Even if solar PV statistically generates when summer peaks occur, the inability to dispatch reduces its value to utilities because, for reliability, they will still want to maintain enough truly dispatchable capacity to meet demand, as if the solar will not be available.

There have been some interesting developments in other areas of distributed generation that illustrate the issues involved if solar PV on its own becomes a significant source of generation. For example, in Hawaii the utilities do not buy wind energy outside of their peak demand periods because accommodating the intermittent resource on the grid results in other grid stability and reliability problems. In Denmark wind power is a significant resource, but to accommodate it the utilities have incorporated significant storage and reserve generation to deal with the intermittent variations in wind power input. It is not clear that solar electricity would create similar problems, but stability impacts should be considered, and may be an area where solar electricity and storage are complementary. In general there needs to be a better understanding of how solar would fit into competitive dispatch, integrated with storage, load management measures, and other firming strategies.

Other Market Drivers

Outside of dispatch, other potential market drivers for solar and storage technologies are only weakly reflected in markets – fragile grids, energy security and environmental benefits.

**International Market Comparisons**

Looking at the most successful solar PV markets in the world, Germany and Japan, shows that their approaches have not encouraged storage. Almost none of the European or Japanese solar PV systems involve storage. The case for combining the two and under what conditions it is beneficial still has to be made. The fact is that the grid in developed countries is quite reliable. Developing countries do have problems with their grids that might make the combination more attractive, with solar and storage acting as an extended UPS. Trace DR went to the Dominican Republic and basically sold inverter systems to recharge batteries when the grid was on, so that customers could switch to batteries during frequent outages.

**Why do people buy solar and/or storage products?**

People buy because of the “green” environmental appeal of solar. Some are interested in energy security. Aesthetics can be a negative factor if the solar systems look out of place, but in a growing number of cases people are showing off their solar systems – they are becoming status symbols.

In addition to these more general characteristics, people want low maintenance, low costs, reliability, and safety. If a system can’t satisfy these requirements it does not have a good outlook.  In this regard flooded batteries and battery maintenance in general is a considerable concern for residential systems.  Beyond these requirements, what people want is still being defined.  People don't know what they want in terms of long-term power storage versus short-term storage.  How much power is needed and for how long, and how much are people willing to pay for it?  Is having power for the TV essential?  At what cost of storage and solar do conveniences that people would give up today become affordable?  At least part of the appeal for solar – whether it is realistic or not – has been freedom.  People perceive it as giving them freedom from their utility.  In fact, without storage they are not free from their utility, but if that aspect of solar and storage can be developed effectively, it may be an effective marketing strategy.

Why Consumers Would Combine Solar and Storage

The group discussed three areas for storage that are related to why people might combine solar and storage technologies.  The first is non-electrical storage in the form of thermal energy and/or hydrogen in the future, which complement solar electricity by reducing loads and in the case of hydrogen shifting energy generation.  The second area was grid-interactive systems, in which the storage would be relatively small scale and perhaps cover only a few minutes of generation to shelter a user from the most typical, transient outages.  So far in Europe and Japan there has been almost no storage integrated with solar PV.  The developing countries are a stark contrast, with a need for hours of storage in India and China where the grid is very unreliable.  Finally, utility-scale storage systems can increase grid stability and the ability to accommodate distributed generation in general, including solar energy.

Looking just two years into the future, development needs to consider how much power needs to be delivered in a small amount of time to provide protection from transient outages.

To be utility friendly the combination of storage and solar energy should ideally reduce a home's demand during peak periods by 90% to 100%.  To make it work, homes will need controls that are able to combine the results of energy efficiency measures, generation, storage and utility needs.

**Storage Technology Characteristics and Issues**

This brought the conversation back to what technologies are available, and reference to Figure 1 (which was presented by John Boyes) as a good illustration of how storage capacity and discharge time influence applications.  The list of technologies to consider includes:

- Storage that answers utility needs
    - Compressed Air Energy Storage (CAES, approximately 200 MW currently deployed in Iowa and Texas)
    - Superconducting Magnetic Energy Storage (SMES is more appropriate for grid stability problems, providing very short-term but high energy grid inputs)

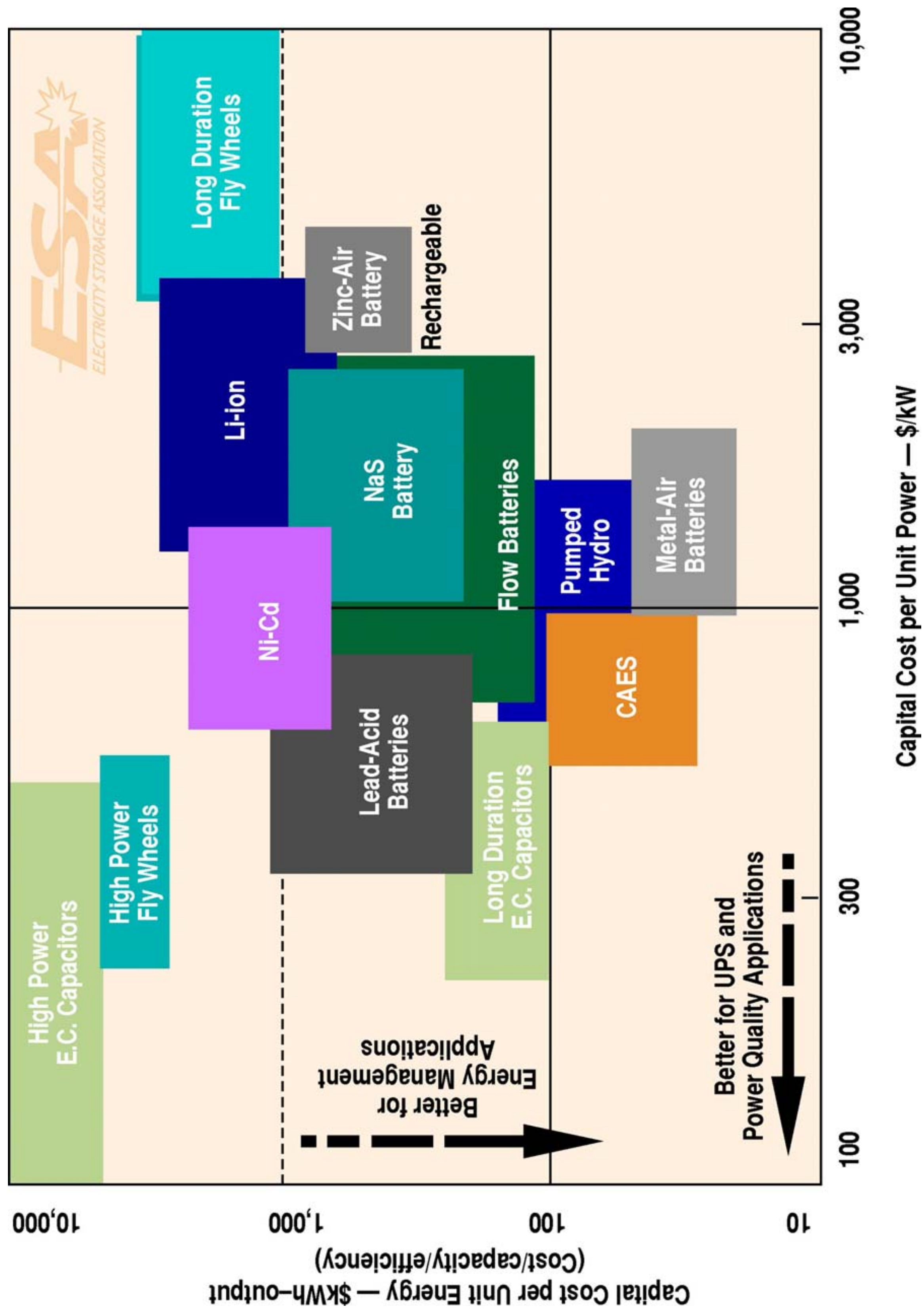


**Figure 15: Storage Technologies and Applications**

    - Pumped hydro (very dispatchable, but with limited expansion potential because of siting constraints)
    - Flow batteries
    - Conventional batteries

- Low-Level Storage Options
    - Batteries
    - Flywheels
    - Supercapacitors

<u>Role of Inverter Technology</u>
Inverters are a critical supporting technology, and in this area there are important issues. First, inverters are needed that can handle battery, solar, and grid back up. There are no inverters that are currently available in large grid operations with battery back up. Power quality is an issue. Currently the drivers for storage development are outside solar, so these problems are not the first priority. An inverter that can combine solar/grid/storage is the technology needed to bring the pieces together. When consumer applications are involved, storage needs to make advances in safety and reliability, low maintenance and low costs.

Clearly, there are issues with inverters. Inverter development should be structured to look at low cost, high performance and low maintenance. The solar program does have three contracts for high performance inverter development, with GE, Xantrex, and Satcon. There will also be a workshop in October 2004 to develop a roadmap for inverters. Inverters should be thought of as an integral part of the system and the controls, responding as needed to changing conditions. There is also a need for large-scale utility/storage inverters. DOE should consider funding research at Universities for their high efficiency inverter initiatives.

<u>Charge Controllers</u>
There is also a lack of charge controllers to recharge batteries reliably, particularly for new battery types. Work is needed on diagnostics and on-off equalization. There are always trade-offs between simplicity and increased sophistication, which may improve performance, but will also cost more. Charge controllers have to deal with more and more variables as different battery technologies – with different characteristics – emerge into the market. Adding to the complexity are variations in sizing and storage needs. When there is quality in the battery system, quality is necessary in the charge control system – an exceptional battery can be killed by a faulty charge controller. The quality of the components has to match each other. At the same time, long life may not be ideal. The PV module may last 20 years, the battery 15 to 20 years, but the charge controller itself only 5 years because the technology/software elements of the controller will continue to advance, and may need to be replaceable.

Communication Interfaces

In addition to controlling charging, systems may need intelligence to interact with the building, the utility and with the manufacturer. Ideally a system would be able to communicate with the utilities and/or other distributed generation systems to dispatch power when it is most valuable. Maintenance would also be easier if affordable remote monitoring and feedback systems existed. There are tradeoffs in making the equipment more complicated versus the value of knowing that it works, but they need to be examined. Feedback systems for customers should also be revisited – some of the ZEB developers have found that providing customers with a meter that shows what they are consuming/generating in real time leads to greater awareness and responsiveness to maintenance issues and managing their energy use. Feedback systems for diagnostics and maintenance also need to consider consumers – how much information do they need (or can they handle) about the performance of their solar/storage systems?

Codes and Practices

Contracts, codes, installation and safety are some of the issues between customers and utilities that are still being resolved. Issues completely beyond customers' control include utility restructuring, tariffs, and national policy that impact their choices. Consumers are only vaguely aware of many of the issues, and even the people selling and installing (and at the utility and local government offices, reviewing) need more education about how to deal with solar and storage.

Batteries

The first important indicator to be tracked in batteries is the time between failures. How a storage technology becomes part of a system and is converted to electricity has to be taken into consideration in battery design because it affects lifetime – how fast and how deep will the discharges be, what will be the duration of discharge and charging cycles? When chemical storage as hydrogen comes in there is a very different situation from batteries, plus there are opportunities for combining heating, cooling and power with different system configurations. There needs to be some thought about where the boundaries of systems will be as technology progresses, particularly between utilities and consumers. Most of today's research is focused on individual components, much less on how they fit into a system. A systems approach would emphasize that the energy converter is an integral part of the whole.

Leveraging Research into EV/HEV Technology

Leveraging current EV/HEV battery strategies is important because they are driving battery development, but there are important differences in requirements. The power/energy ratio is a key factor in battery design for vehicle applications, but is far less demanding for solar PV because it's a stationary application in a building. The same reasoning applies to weight. Finally, flooded batteries are a problem when homeowners are the source of maintenance – the hazards inside a home are different from the hazards inside a vehicle. Cycling characteristics for vehicle batteries will also be very different in terms of frequency, and the depth of the cycling. Thermal management and resistance appropriate to a vehicle should be compared to conditions in a household installation.

Life Cycle Cost issues:

Generally the lower the initial cost of a storage system and the lower the replacement cost is likely to be as technology improves, the lower the acceptable life. Cost makes the difference between a strategy based on durability versus a strategy based on easy replacement. Customers are heavily influenced by the first cost, especially in the residential sector where people move from house to house over a shorter period, compared to turnover in commercial building ownership. Commercial building owners are also much more likely to base their purchasing decisions on careful lifecycle cost analysis than a homeowner. Generally the life of the system should be comparable to the module life of a solar system, but it has to be limited by the first cost of the complete system. The response to cost also depends greatly on what value people think they are receiving – what they are willing to pay if they believe they need essential power services will probably be different from what they are willing to pay to offset some of their peak demand. If there are high costs associated with an outage or interruption, a consumer will accept higher costs for a system that will help avoid outages.

Value of Essential Power

The value of essential power, and what people consider essential, is still being defined. Perhaps 20% of building loads are essential, but it depends heavily on what services are being provided. Home medical equipment that depends on electricity is a classic example (with growing potential as the population ages), but essential power can also include emergency lights, water, furnace ignition and fans in cold regions or some cooling in areas with extreme temperature/humidity, communication… the definition depends largely on the consumer's perception and specific conditions. The definition is also different for residential, commercial and medical needs. A home refrigerator is not impacted by a 15-minute outage. Refrigeration for medical or research purposes may be more sensitive. The impact on household electronics may be no more serious than blinking clocks, but for a business loss of power to electronics and communications can mean lost data and dropped financial transactions that have serious monetary impacts.

Hazards and Risks

Many of these needs have been met simply by deploying storage, but solar adds an interesting aspect in being able to generate power to shave or shift peaks and reduce electricity consumption during non-emergency periods – because the fuel is free there is no incentive to disconnect solar power generation. Experience with essential power and solar is limited today. When it begins to expand, attention to avoiding mishaps that have been documented in commercial and residential storage systems will be important. There should be standards in installation, battery hookup and maintenance before disasters that cause bad publicity can happen. Part of optimizing current batteries for solar PV applications is recognizing that they become a part of people's homes – an accident at home puts people's lives at risk, where an accident in a commercial building is more likely to be limited to property damage.

In situations where utilities have offered battery storage, they have often insisted on a leasing arrangement where the utility retains ownership and responsibility for maintenance, simply because they are unwilling to accept the liability if the batteries are improperly maintained. Improved sensors and tools for detecting and managing problems would be useful. Items to consider should include the potential for telemetry for remote monitoring and diagnostics, cheap hydrogen sensors, measures to reduce shorts on exposed terminals, temperature sensors and temperature algorithms to help predict the end of life of batteries, temperature sensors and controls to help detect and control thermal runaway, measures to maintain structural integrity during events like earthquakes, and ways to identify loss of capacity so that customers can be assured that systems will actually perform when essential power is needed. There is no benign, non-toxic chemical storage medium for batteries, so safety measures will always be needed, along with recycling for lead, cadmium, antimony and other elements in the battery.

Flywheels

Flywheels can work in distributed generation, but raise different issues. How long can they provide power? What are the safety implications of a high-density fly wheel revolving at high RPMs? Discharge times for flywheels need to be matched against user requirements – 1000 W for 3- 4 hours would mean a 4-kWh system.

Microgrids

Microgrids have potential for serving industrial parks, business and academic campuses, and even large residential developments. To operate successfully, the grid users/operators need to be technologically aware of the power quality and reliability issues involved, and the cost of having to fall back on external grid power. In a microgrid, solar may just be an added generation source to supplement other technologies. In that case it will simply be taking advantage of the storage capability of the microgrid. Equipment and controls should be capable of quickly responding to demand on the microgrid, and careful control to avoid demand charges and utility purchases when they are most costly. Remote dispatching would help, so that a local microgrid can respond to conditions throughout the grid in order to maximize its value. An institutional/community framework for operating microgrids is as important as the equipment – how much authority for controlling a system will be delegated to the local utility, how much will be in the hands of private operators, and how much responsibility will fall on the occupants served by the microgrid? Substation service agreements that are used to serve hospitals with their own generation from medical waste incineration and backup generators are a starting point for working out some of the issues. But there is still work to be done in developing business models for distributed generation at substations, how regulators will treat distribution system investment that could be displaced by distributed generation, and how to coordinate distributed generation and storage at multiple sites to create an effective virtual utility dispatch. There are also technology opportunities in microgrids – they offer a situation where flow batteries could be used effectively for larger applications.

## Discussion of Overlaps with Other Market Sectors / Common Research Issues

The main question posed to the group was: How do the technologies relate to storage, the grid, inverters, and controls, to make the system work?

**The System of Components**
Not as much money is spent on researching systems as a whole. Connectivity is needed between the components from a technical and educational aspect – customers and installers both need to know more about the how and why of solar energy and storage. While there are interested customers, the technology/systems are not ready. There is no industry (they are separate industries), and really no market. This is analogous to the chicken and egg scenario, where we are struggling with whether the product or demand for the product needs to happen first. Morning Star, Xantrex, etc., are examples of the players who are not getting necessary feedback about their equipment and what is needed to work in these applications.

**Problems of Charging**
In charging scenarios there are too many variables involved, and not all of the complexity is necessary. Utility applications could be much more standard. But to accomplish that there needs to be better characterization of different situations, a manageable number of situations. A significant problem is understanding the variations in utility power. How standard is it? There are quality variations, voltage drops and reactions to the grid that further complicate system design.

**Peak Shaving**
From a peak shaving perspective, storage can be justified on its own but we need a better understanding of how it combines with solar. Can we get capacity storage with solar PV? The perspective on peak shaving also varies from the utility to the customers – utilities are reluctant to recognize solar as peak load capacity because they can't dispatch it and it only addresses a portion of the peak demand. But from the customer perspective, if they are paying time of use rates, it definitely shaves what they have to pay the utility for peak service. We also need to recognize that tariffs will adjust to revenue requirements, and if demand changes then tariffs will change – the peak charges we are relying on for our economics are not static. Generally we are looking at solar PV and storage, not storage and solar PV. Storage is something that can enhance the value of a solar PV system, but it will come first in the purchase decision. Customers who buy storage alone are not as likely to then go ahead and buy solar to add to their systems.

**Reaching Customers, New Adopters:**
For a price/metering strategy people need simple tools, like an Excel spreadsheet, to look at rates and at their system's performance to give them the information they need to make decisions. Ultimately tools will have to deal with both solar and energy storage. There has been some DOE funding in this area. For the early adopter it would show the value-added from storage options -- something to add value to the green image that is driving purchases now. It could show what they might gain from adding a UPS backup system

or choosing other add-ins. Right now grid-connected systems with storage are not UL listed, and the storage component is a pain in the neck because of the inverter issues – problems that are invisible to most consumers.

New adopters constitute about 3% of the population. Based on raw polling, out of that group about 11% of this group purchased solar PV because they wanted back-up capabilities, because they experienced power quality or safety issues with their normal utility service. That implies that the other 89% are not driven by financial loss, discomfort, safety and risk issues. So why are they buying? We need consumer research to set targets instead of using life cycle analysis. Lifecycle analysis is only one element of the purchase equation. Different attributes that make up the system have to be defined and the features that are liked have to be discovered. How important to customers are: cost, back-up, capabilities, emissions, maintenance, noise, and a standard warranty term? Research will help identify the points where solar and storage takes off in different applications, and what values people place on different solar/storage attributes.

**Experience with Wind Energy**
From the utility perspective, we should look at wind and how it is treated for insights into solar PV and storage that are not fielded as distributed generation. In the case of wind the application of storage is very location dependent, and exists on the utility level. The value of storage is in its ability to firm the wind energy. There might be some deferral of transmission and distribution system investments. In Hawaii there is a significant wind energy/grid stability issue because of their small grid and the location of wind energy sources on it. Denmark is encountering similar issues, and using storage to address it.

**Solar PV in Urban Center**
There is very little information about solar PV potential in downtown areas, where solar/storage would be competing against diesel backups. The only research has been some work by Southern California Edison for their PV Friendly Neighborhoods effort.

## Group Report Summary
To summarize, charts were suggested that would address issues of the on-grid solar storage. The following variables were applied at the utility, commercial and residential level.

1. Markets (PV only, PV w/h, 1 hr, 3 to 5 hrs, Essential Energy, UPS)
2. Dispatching (Simple Timing, Communication with Utility, Time of Day, Pricing, Grid Stability)
3. Storage Technology (Lead-acid, Lithium-ion, etc.)
   (Also $/kW vs. Time of Storage chart suggested.)
4. Interface (Remote Communication, Peak Shaving, Price Response)
5. Storage (Safety, Corrosion, Maintenance, Contracts, etc.)

**Summary of Issues:**
- There is a hard match between solar and storage.
- There is a need to understand cost and variances in these applications.
- Inverters are not really plentiful at this time. Systems are customized.

- A strong enough interest is needed to market the storage technology.
- The interest now lies in off-grid markets.
- There is not a lot known about distribution systems concerning storage and solar.
- There is a consumer versus utility market viewpoint on peak shaving.
- There is an issue of how to interest utilities in solar.
- Storage is good for wind applications but not for solar.
- There needs to be a decrease in prices.  The prices for solar PV are too high and the prices for storage are too high.

**Workshop on Systems Driven Approach for Solar Applications of Energy Storage**
**Breakout Group 3: Transportation Applications for Solar Storage**

## Participants:

Moderator: Dennis Fargo (McNeil Technologies)
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Vince Battaglia (Argonne National Laboratories)
Jack Brown (ElectroEnergy Inc.)
Paul Gifford (Texaco Ovonic Battery Company)
Jerry Ginn (Sandia National Laboratories)
Tom Hund (Sandia National Laboratories)
Shlomo Kass (Advanced Technologies Upgrading Ltd.)
Albert Landgrebe (International Electrochemical Systems and Technologies)
Mike Nispel (C&D Technologies, Inc.)
Michael Ropp (SD State University)
Tien Duong (U.S. Department of Energy)
Russ Owens (Antares Group, Inc.)
Ray Sutula (U.S. Department of Energy)

## Relevant Storage Technologies for Transportation Applications—Background

The intent of this session was to explore transportation energy storage systems and their market potential for solar applications. The discussion focused on market penetration for relevant technologies that are available today, and what we can expect to see up to five and ten years out.

The group agreed that the predicted time frames for when these technologies will hit the marketplace should pertain to the commercialization of a technology rather than the development of a technology. The group also agreed that the discussion should remain within a ten-year time frame since beyond ten years, it is difficult to try to make any quality predictions.

Due to the workshop constraint of discussing technologies connected to/compatible with the grid, the group tried to determine what markets to address in their discussion. With regard to storage systems for transportation applications, the grid comes into play if you are charging the batteries for pure electric vehicles (EVs) or plug-in hybrids. Because neither of these applications is largely relevant for the commercial consumer transportation market over the next ten years, the group chose to include off-grid storage applications, which are currently playing a larger role in the transportation sector, as a part of their discussion.

The group also attempted to clarify the relationship between storage technologies relevant for transportation and solar applications. It was decided that in order to drive advanced energy storage technology for transportation applications, overlapping markets are needed. Broadening the market for such technologies to include solar applications will help increase funding toward research, which will help speed development and drive down costs. The different sectors can work together to leverage resources, providing more funding for both transportation and solar research.

The group chose to begin their discussion by listing all of the possible transportation applications for energy storage technologies:

- Automobiles (Pure battery electric vehicles (EVs) and plug-in hybrids)
- Power-assisted hybrids
- Heavy duty, full-size trucks (EVs and plug-in hybrids)
- Hybrid electric locomotives
- Military vehicles (such as general fleet, ships, etc.)
- Vans
- Buses (EVs and hybrids)

The group noted that there are also transportation-related non-mobile technologies that are independent of the grid, such as signage. However, the group agreed that the discussion should focus primarily on mobile applications.

The group then addressed the vehicle categories above to determine time frames for when we will see various storage technologies hitting the commercial marketplace. The discussions focused mainly on consumer automobile and military markets.

## Automobiles

For automobiles, the group agreed that grid-connected options such as EVs and plug-in hybrids are not feasible within a 10-year time frame. The smaller hybrid systems are presently too small to be connected to the grid. A significant-sized battery is required to plug in, so battery costs must decrease considerably before this is possible. Such bigger, better systems may be as much as 20 years out. It was also suggested that, since the whole point of a hybrid is to have a small battery, why plug in at all?

Many participants agreed that while commercialization of plug-in technology is possible, this would not happen unless development is regulation-driven. Without the regulations, there is little advantage to consumers of plug-in hybrids as opposed to non-plug in options. Based on the current marketplace, fuel-efficiency is clearly not a big driver for consumers. Less pollution is an incentive for society, but perhaps less of one for individuals.

There was some disagreement as to whether or not mandates are necessary to drive development of plug-ins, as it was suggested that there were no mandates to develop power-assisted hybrids, and that technology is here. Manufacturers simply realized that a power-assisted hybrid battery would be smaller, easier to develop, and more affordable.

Others believe that CAFE (Corporate Average Fuel Economy) standards *are* driving hybrid development and commercialization. However, although regulations and mandates may be somewhat difficult to predict, it was suggested that we must assume the mandates will exist and that the development of these types of technologies will continue.

One participant suggested that, since the grid is heavily stressed and new generation capacity is not being developed, plug-in hybrid vehicles could be used for grid support. In other words, individuals could use their automobiles as back-up generators in their homes. Since portable generators are expensive, it was suggested that individuals might choose to use cars that they already own. However, the majority of the group felt that plug-in hybrids would take energy off the grid—not put it back— because:

1. Society primarily needs back-up power during the day, and this is a time when people are using their cars for transportation away from home; and
2. Individuals may not wish to use their $20,000 vehicle in the same way as a $200 generator.

Moving the discussion off the grid, the group turned to standard power-assisted hybrids, which are currently part of the commercial market. Participants agree that this market will grow over the next 10 years. Again, however, although society values efficient, environment-friendly vehicles, individuals do not seem to place as high a value on them. For example, a common consumer attitude is that power-assisted hybrids are energy-efficient, but not "fun" to drive. Such attitudes regarding power/performance are changing the manufacturing strategy, compelling auto manufacturers to create higher performance hybrid vehicles. However, there will be continued hesitation on the part of the consumer to accept these vehicles because there simply isn't enough data with regard to their reliability.

With manufacturers continuing work on these issues, consumer purchase of hybrids will expand, and some EVs may eventually penetrate the market as well. However, the group agreed that it still could be difficult to justify the development of these technologies for this market.

## Military Vehicles

There is much higher potential for commercialization of EVs to be driven by the military market. Increased fuel-economy is a much bigger driver for the military than for other consumers, especially considering the high cost of getting diesel fuel to the battlefield. Military vehicles also require a fair mount of stored energy for their electrical systems, as well as for propulsion power. In addition, there is an incentive to use all-electric vehicles since they stay off of the thermal radar.

Some all-electric military vehicles, such as tanks, hummers, and unmanned undersea vehicles (UUV), currently exist. All-electric ships are imminent, and will probably be available in a five-year time frame. All-electric unmanned aerial vehicles (UAV) are also imminent if they don't already exist.

There is an even stronger driving force to hybridize 20% of military vehicles used for general troop transport, such as trucks and jeeps, in order to increase their fuel-efficiency. The military also has a strong need for advanced storage technologies that perform under wider temperature range conditions, such as Nickel Metal Hydride (NiMH) and Lithium-ion (Li-ion) batteries. NiMH technology is already in use in the military, although performance improvements are still needed for use of Li-ion technology. Unlike other market sectors, the military is willing to spend the money to speed these developments. We are likely to see wide commercialization of these technologies for military applications over the next five years.

## Other Market Applications

There is a reasonable market today for pure battery electric vans and neighborhood vehicles, and this market will increase over the next five to ten years. These vehicles include shuttle buses, small delivery vans, postal fleets, and off-road vehicles such as forklifts and golf carts.

Pure electric and hybrid electric buses also exist today, and these markets will increase over the next five to ten years. Buses in the U.S. are using lead-acid technology, and some smaller buses in Europe are now using NiMH technology. NiMH and Li-ion batteries have market potential for buses in the U.S., but costs must come down within a 10-year time frame to have an impact.

For heavy duty, full size Class 3 trucks (18-wheelers), large-scale commercialization of power-assisted hybrid technologies are about ten years away with decreases in cost. Some programs also exist to develop hybrid electric locomotives, but commercialization of these is probably beyond the scope of this discussion.

## Storage Technology Characteristics

The group then discussed the characteristics on which it is important to focus in order to develop successful markets/commercialization for storage technologies. They came up with the following list:

- Duty cycle
- Operating voltage (application-dependent, but higher voltage)
- Capacity (or energy density)
- Faster charging
- Increased efficiency
- Improved shelf life
- Increased cycle life
- Higher power output
- Smaller size/lighter weight
- Improved safety
- Operating characteristics (wider operating temperature range, shock mitigation, internal losses, etc.)
- Auxiliary systems (fewer, cheaper, less complex)

- Lower maintenance
- Lower life-cycle cost
- Better low-temperature performance

The group then prioritized the list, choosing the three most important characteristics to focus on in order to make the greatest strides in expanding the market for advanced storage technologies. While priorities are really application-driven, as every system has different requirements, the group agreed that the following priorities would have the largest commercial impact:

3. Lower life-cycle cost
4. Greater energy density
5. Reduced safety requirements

It also was noted that power output is an important characteristic for power-assisted applications, and less so for grid-connected applications. However, it was agreed that power is directly related to and covered by the energy density characteristic.

The group then discussed the external events that will drive the development of life-cycle cost, capacity, and safety improvements. Regulations and crises (power outages, hurricanes, etc.) were determined to be the major drivers. Advances are also dependent on materials, cathode, and electrolyte research.

## Technologies Under Development and Key Indicators of Success

Although several storage technologies were touched upon as part of the earlier discussions, the group then outlined more specifically the types of batteries that exist and/or are being developed for the transportation sector. The group also discussed the factors that will drive success in further developing and commercializing these technologies over predicted time frames.

- Lead-acid – Technology exists now, but weighs and costs too much to succeed on a mass scale. However, due to good low-temperature performance qualities, there is a continued role for lead-acid batteries in hybrids over the next 5-10 years in small niche markets.

- Nickel Metal Hydride (NiMH) – Has improved capacity, life, and safety over lead-acid, but are still quite expensive to produce. The main driver for further commercialization is cost

- Lithium-ion (Li-ion) – Has theoretically higher capacity than NiMH with similar cost issues, but currently not as safe. There are also thermal mass/size issues, but the main driver for further commercialization is safety. This means the battery must become more robust and resistant to abuse, overcharge, discharge, accidents (crush), and short-circuiting.

- Magnesium (Mg) – has the potential to offer low cost and long life. However, this technology requires additional research and scale-up before any predictions can be made with regard to commercialization.

The group agreed that for the consumer automobile market, the three most important storage technology characteristics discussed above (life-cycle cost, capacity, and safety) require significant advancement before we will see major commercial expansion of any of the advanced storage technologies. Research targets should therefore focus on relieving these three barriers. The group also agreed that it is very difficult to displace a technology in the marketplace, so a technology must demonstrate significant improvements in each of these characteristics, as well as in usability and performance, in order to displace any other.

For example, NiMH performs quite well over lead-acid, but the cost is still too high for widespread commercial use. But with improved life, capacity, and safety qualities, it is predicted that commercialization of NiMH will continue to expand over the next ten years as costs decrease.

Significant improvements in Li-ion safety are likely about seven to eight years away. However, it is believed that even with these improvements, this technology will not immediately overtake NiMH. Users of Li-ion technology will initially be those willing to pay higher prices, such as the military. However, similar to NiMH, once safety is improved and costs go down, commercialization in the auto market will also expand.

It was also noted that technologies such as NiMH and Li-ion can be de-rated so the performance is lower than capacity. This would make the systems safer, but still would not affect the cost.

Generally, for military applications, because improved performance is a key driver, cost and safety improvements may be much less important to large-scale commercialization of these technologies for the military than other markets. It was suggested that commercialization would follow next in government community fleets, and lastly in consumer markets.

The following table summarizes the discussions on energy storage systems for transportation applications, and presents a predicted timeline for the commercialization of technologies in these markets:

| Table 1: Timeline for Commercialization of Storage Applications for Transportation | | | | |
|---|---|---|---|---|
| | **Now** | **5 yrs** | **10 yrs** | **15 yrs or More** |
| Automobiles | Standard Hybrids<br>Lead-acid | NiMH | Li-ion, Mg | EVs<br>Plug-In Hybrids |
| Military Vehicles | EVs *(UUVs)*<br>Plug-In Hybrids<br>Lead-acid<br>NiMH | EVs (*Ships, UAVs)*<br>Plug-In Hybrids<br>*(Tanks, Hum-Vs, Fleet)*<br>Li-ion | | |
| Class 3 Trucks | | | Standard Hybrids<br>NiMH | |
| Trains | | | | Standard Hybrids |
| Buses | EVs<br>Plug-In Hybrids<br>Lead-acid<br>NiMH *(Euro)* | | NiMH *(U.S.)* | Li-ion |
| Vans | EVs<br>Standard Hybrids<br>Lead-acid | | NiMH | Li-ion |

## Technology Pathways

The group then discussed strengths and weaknesses of each technology in order to pin-point research targets to achieve marketing breakthroughs.

Mg batteries are still in the early development stage. There is not enough information available to state what the barriers are. A scale-up of the technology and high-capacity cathode work is needed.

Li-ion batteries have a theoretically high capacity. However, large amounts are not tolerant to abuse, such as overcharging. There is a limitation on resource availability, materials cost is high, and improvements in low-temperature performance is needed. Safety improvements are being addressed, including non-flammable electrolytes, shut-down separators, and a recombination mechanism (shuttle).

NiMH batteries have a high processing and materials cost and also don’t perform as well in low-temperature conditions. However, its strengths are a very robust chemistry and a well-established manufacturing base. To overcome the low-temperature power issue, new alloy compositions are needed.

Lead-acid batteries will continue to lose market share; there is no reasonable development for the transportation sector. Separators will allow the batteries to work at higher temperatures to produce more power. However, their theoretical capacity is very low, so while progress can be made to decrease maintenance and increase reliability, lead-acid will never be competitive with other technologies.

## Overlap with Other Market Sectors

The group explored ideas/issues regarding overlap of transportation energy storage technologies with market applications for solar storage.

It was determined by the group that for grid-connected solar PV applications, lead-acid batteries are currently and over the next several years the best technology on a cost basis. Outside of lead-acid, any grid-connected battery for solar PV would have to be either NiMH or Li-ion. However, presently these are much too expensive to be realistic in a shorter time frame.

For transportation applications, currently and over the next 10 years, NiMH and Li-ion are the most promising technologies. Therefore, the group explored all sub-optimal characteristics of lead-acid batteries that would drive potential research and breakthroughs for NiMH and Li-ion. Any breakthroughs that would make the use of advanced storage batteries compelling in the transportation sector and also more attractive for solar would lead to overlap between transportation and solar applications.

It was suggested that solar PV applications need batteries that produce energy for $0.15 a kilowatt-hour or less. The group asserted that NiMH and Li-ion are currently significantly more expensive than lead-acid, so we need to determine the cost/performance tradeoff.

For example, as Li-ion technology matures over the next five to ten years, Li-ion cells may have a 20-year life. It was suggested that some consumers, such as the U.S. Coast Guard, would be willing to pay five to ten times the cost of lead-acid for a high-power quality advanced battery with a 20-year life and reduced maintenance requirements. However, it was also suggested that while a 20-year life cycle may be desired, it might not be a necessary feature. For NiMH, it was also stated that if we were able to reduce the manufacture cost, its higher performance qualities would make it desirable as a replacement for lead-acid in solar PV applications.

In summary, significant breakthroughs in characteristics such as an increase in cycle life and decrease in cost are the type of developments that will drive overlap between the transportation and solar PV markets for these technologies. A number of sub-optimal characteristics of lead-acid batteries as compared to NiMH and Li-ion may create further incentive to pursue their use for solar PV applications:

- Lower cycle life (which is directly tied to cost);
- Lower battery life if used in harsh outdoor environments, particularly in extreme higher temperature applications;
- Lower power density/power quality, which may be problematic when there are short power bursts, surges, or interruptions, such as in storm/lightning conditions;
- Larger size and weight, with the assertion that floor-loading/space constraints are problems for most sites (with the exception of utility substations);
- Higher maintenance requirements; and

- Environmental issues such as battery disposal and release of toxins into the environment.

With regard to battery life, the wider operating temperature ranges of advanced batteries make them more desirable than lead-acid.

With regard to safety, it was noted that for larger solar PV systems, it would take a lot of work to prove the safety of Li-ion batteries, but that this is necessary to drive overlap for Li-ion. Right now, even if the cost came down for Li-ion, it is unlikely that a safe system would be replaced with an unsafe one.

The issue of maintenance was highlighted as a very important driver toward overlap and use of the more advanced batteries for solar PV. There was some discussion that Li-ion and NiMH batteries can be maintenance-free for up to 15 years, but not quite 20 years. Presently, there are processes and plants in place to recycle both NiMH and Li-ion batteries.

With regard to environmental issues, there was some disagreement among the group whether or not disposal issues are important to the average consumer. However, ultimately the cost of disposal will be borne by the consumer.

In another more general comment with regard to overlap, the group suggested that the same manufacturing facility could be used to manufacture different batteries for different applications.

Also, it was suggested that we attempt to seek second uses for depleted batteries. For example, at the end of vehicle battery life, a battery may still be operational at 80% capacity. While this is unsuitable for transportation purposes, the batteries may be sold to secondary use markets, such as for stadium lighting.

## Next Steps to Implement a Systems Driven Approach

The group suggested that a next step would be to conduct sessions to define specific performance targets for several solar PV applications. The industry would then overlay these targets with their own specifications to see where there are overlaps with transportation storage requirements. These results would lead to coordinated research efforts, exchanging hardware for testing, etc.

The remainder of the discussion revolved around the market for rechargeable batteries. While the U.S. invented Li-ion technology, for example, there is no manufacture of Li-ion batteries in the U.S. This is because overseas they are able to manufacture these products at a much lower cost.

Participants agreed that there is a need to explore ways to indirectly leverage the resources of overseas competition. It was suggested that a seminar to discuss these ideas would be an important, well-attended event.

**Workshop on Systems Driven Approach for**
**Solar Applications of Energy Storage**
**Breakout Group 2: Off-Grid Applications for Solar Storage**

## Participants:

Moderator: Anna Seiss Cooper (McNeil Technologies)
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Jiang Fan (Gold Peak Industries)
Dr. Imre Gyuk (US Department of Energy)
Charles Hanley (Sandia National Laboratories)
Jim Hoelscher (Antares Group Inc.)
Ed Mahoney (Concorde Battery Corporation)
Lumas Kendrick (Sentech Inc.)
Andy Rosenthal (New Mexico State University)
Alex Schechter (IdeaOne)
Pali Singh (Villanova University)
Dr. Philip Symons (Electrical Engineering Consultants, Inc)
Dan Ton (U.S. Department of Energy)
Dr. Ed Witt (National Renewable Energy Laboratory)

## Relevant Storage Technologies for Off-Grid Solar Applications—Background

The purpose of this session was to identify relevant storage technologies for solar applications that are off-grid– today, 5 years from now, 10 years from now. This group was supposed to identify and assess:

1. Relevant off-grid storage technologies;
2. The characteristics of these technologies;
3. How these technologies will change over time to open up new applications
4. How certain are these advances; and
5. What are the advances dependent upon, i.e., DOE funding, industry research etc?

## Relevant Off-Grid Storage Technologies

The group was asked to brainstorm and list the relevant battery technologies for off-grid solar applications. Traditional battery technologies were identified as:

- Lead-acid,
- VRLA,
- Flooded gel,
- NiCd (Nickel Cadmium)

Next the group listed the Metal Ion systems as:

- Ni-MH (Nickel Metal Hydride),
- Li-Ion (Lithium-ion)

Battery storage technologies for larger systems were identified as:

- Flow batteries - Regenesys

The group identified a vast number of off-grid applications and finally decided that because there are so many applications it was best to find a way to group or categorize the applications by either size, range of sizes, size of the battery or storage required etc. It was agreed that the off-grid applications would be for off-grid stationary applications. Ultimately it was agreed to group the off-grid applications by the following sizes.

| Table 2: Off-Grid Storage Application Size Categories | | |
|---|---|---|
| **XS** | Extra Small | < 100 Watts |
| **S** | Small | < 10 Kilowatts |
| **M** | Medium | 10 to < or = 100 Kilowatts |
| **L** | Large | > 100 Kilowatts |

The following current and potential storage applications were identified and grouped by size:

| Table 3: Current and Potential Off-Grid Storage Applications by Size | | | | |
|---|---|---|---|---|
| **XS < 100 Watts** | **S < 10 Kilowatts** | **S/M** | **M/L** | **L > 100 Kilowatts** |
| Electric Fencing | Lighting/Signage/Navigational Aids & Beacons | Telecommunications | Facilities-Power | Moving Water |
| Gate Opening | Telephones | PV Vehicle Battery Charging | Storage (turbine) | Mini Grid |
| Consumer Electronics | Work Area Protection | Village Power | | |
| | Residential | Community Battery Charging Stations | | |
| | Transportation Safety Devices | Light Commercial | | |
| | Lawn & Garden Equipment | Space | | |
| | Cathodic Protection | Water Purification | | |
| | Charging Stations | | | |
| | Weather Stations | | | |
| | Remote Monitoring/ Security | | | |
| | Mobile Boats/Recreational Vehicles | | | |
| | Water Pumping & Livestock Irrigation | | | |
| | Refrigeration | | | |
| | Emergency Preparedness | | | |
| | Rural Health Clinics | | | |

There was agreement that some of the storage applications listed will become more prevalent in the near future, e.g., mini-grids, remote sensing, and other applications.

A participant noted the potential usefulness of making several plots for each application with power on the x-axis and energy on the y-axis such as we had seen in the previous day's presentations. It was thought that this would eventually become more important as each type of storage has different fluctuations in insolation and different storage requirements, some hours and some days.

The group was then asked to identify the key PV storage markets for the next five years. The following key markets for off-grid applications were identified and ranked according to an ABC type scoring in terms of growth potential. The A markets will be the fastest growing markets followed by the B and C markets. The group then identified the storage technologies that were expected to meet the needs of these market technologies.

| Table 4: Off-Grid Storage Applications and Growth Potential | | |
|---|---|---|
| **A** | **B** | **C** |
| **Mini-grids/Village Power** (Li-Ion, Lead Acid & Magnesium) | **Remote Sensing/ Security** (Lead Acid, Magnesium & Li-Ion) | **Consumer Electronics** (Li-Ion) |
| **Telecommunications** (Lead Acid, Magnesium & Li-Ion) | **Mobile Applications** (Li-Ion,? Lead Acid & Magnesium) | **Moving Water** (Lead Acid & Magnesium) |
| **Residential** (Lead Acid & Magnesium) | **Lighting** (Lead Acid& Magnesium) | |

In the near-term, (the next five-years) the following PV storage technologies were identified as having the most growth potential.

| Table 5: Off-Grid Growth Potential by Battery Type | |
|---|---|
| Battery Storage Technologies | Market Change |
| Lead Acid | = |
| Magnesium Batteries (Mg) | + |
| Nichol-Metal Hydride (Ni-MH) | - |
| Lithium-Ion (Li-Ion) | + |
| Flow Batteries | + |

With regard to the future of these technologies, the group noted that NiCd is hazardous to dispose of and for a variety of reasons will likely be replaced by magnesium battery technology. Lithium-Ion battery technology may become more prevalent and the price of carbon is relatively inexpensive. The research and development costs of Lithium-Ion technology should also become less expensive in the future. There was agreement that lead-acid battery technology was established and the lead-acid model should be applied to other battery technologies. Participants recognized the importance of universal parameters and targets for battery technologies. There was also discussion regarding reliability issues and concerns about how reliability needs should be factored in.

The group moved on to classify battery technology available to match the current and projected markets as:

- Electrochemicals
  - Lead-acid (VRLA, Flooded)
  - Alkaline (NiCd, NiZinc, NiMH, NiFe)
  - Metal Air (Zinc Air, Aluminum Air);
  - Lithium-ion/Lithium-Polymer/Lithium-Metal
  - NaS (Sodium Sulphur)
  - Flow Batteries (Regenesys, Vanadium-Redox, Zinc-Bromides, Plastics)
  - Others to be determined/Speculative or unknown developments

- Biochemical

- Flywheels

- Thermal
  - Sensible (Water and Thermal Mass) and Latent Phase Changes, Tanks (Ice and Salts) Wall Panel

- Hydrogen
  - Hydrides
  - Gases
  - Liquids

- Ultra Capacitors
  - Symmetric
  - Asymmetric

- Potential Energy Storage
  - Pumped hydro
  - Springs
  - Gravity

## Research Requirements

The following storage research requirements were identified:

- Cycle-life/Lifetime,
- Intelligent/Monitoring and Control Systems (lead-acid batteries),
- System Design/Installation/Reliability,
- Modeling Battery Characterization under solar PV Applications/Battery & Size Array,
- Economic Modeling,
- Specific Energy Increase,
- Price Targets, and
- Battery Design.

A fuzzy-logic approach and smart battery concepts were also mentioned in the above discussion regarding research requirements.

The intent of this group was to also identify the key indicators of storage technology success in these markets and to identify what we should be modeling and focusing our attention upon in the Systems Driven Approach such as:

- System Lifetime/ MTBF/ MTFF
- Costs
- Efficiency
- Other?

The group was asked to brainstorm about potential markets and technologies for storage applications for 10 years from now. The consensus of the group was that the brainstorming about the five-year time frame would be sufficient and they did not have that much more insight into a 10-year period.

In the afternoon session, the off-grid group was asked to brainstorm about the overlap with other market sectors. Issues related to power quality and reliability were noted in this discussion. The following specific points were discussed:

- Overlap with Other Markets:

    - Residential (cost issues, cycling differences),
    - Load shedding by utility,
    - Rural Cooperatives (no line upgrading),
    - Customers with critical loads (Health essential), and
    - Fleet application.

- On-Grid:

    - Home and business – going off-grid and
    - Utilities offering batteries as grid alternatives.

- Transportation:
    - Vehicles connected to grid (recharge and backup).

A participant commented that off-grid storage requirements could be more forgiving than on-grid storage requirements. This participant also noted that plug-in hybrids are not likely to be available during a 10-year horizon. DOE representatives said that DOE would be looking at the results of this workshop, in particular the commonality among the market sectors, for areas to fund.

The group discussed the kind of modeling that would be of the most value to on-grid PV storage technologies. It was noted that the Systems-Driven Approach is of particular interest to DOE and that a general working model would be highly useful and allow plugging in data for specific applications.

In modeling storage in a system's driven approach it was determined that storage would be a function of the following critical variables:

- Load assessment
- End peak power requirement.
  - Average daily depth of discharge
  - Autonomy i.e., hours per days of storage required
  - Energy/Efficiency of Storage
- Operating Temperature
- Operating – Voltage/Variation
- Temperature Range
- Test Protocol
- Maintenance Available
- Life-Cycle Costs
- Charge/Discharge Rates
- Weight
- Characteristics
- Critical Load Requirements, and
- Alternatives.

The group noted the importance of having a better definition of all the inputs to model the parameters. There was agreement that the above list of variables could serve as the input parameters for individual applications. Life-cycle costing would require the selection of a product. The group discussed the need to optimize the variables and determine which variables would have the greatest impact, as each one is not weighted equally. It was agreed that sensitivity analysis would help identify critical variables. It was noted that some of these relationships are only vaguely known, such as the depth of discharge.

The following next steps were outlined:

- Benchmarking - Status of technology,
- Define range of input variables,
- Optimize critical variables,
- Sensitivity analysis,
- Coordination with storage, and
- Exogenous/Endogenous Variables.

Participants commented that to validate the model, it is helpful to bring as much data as possible to the table. Other participants noted that often the detailed information required exceeds current knowledge. There was agreement on the need for the right level of specificity for the modeling.

The off-grid breakout group adjourned and joined the main session for final discussion and wrap up.

# Conclusions

The twelve baseline presentations provided key insights into the present status of energy storage technologies with respect to utility grid-connected, transportation, and solar applications. It was clear from these presentations that there are many issues in common and issues only associated with the specific applications. Some applications require high power for a few seconds or less, some require large amounts of energy to be used over a period of hours or days, and some applications require both power and energy in small lightweight packages. Of particular interest in this report are the common issues. Energy storage needs to be reliable, safe, and at a relatively low cost in all energy storage applications. As to be expected, the established mature energy storage technologies, such as lead-acid and nickel-cadmium batteries, have the most accurate cost information, are the most reliable and can be operated safely. The lead-acid and nickel-cadmium battery technologies do have their limitations including high maintenance for lead-acid and high cost for nickel-cadmium batteries.

Any emerging energy storage technology such as Li-ion, NiMH, flow batteries, ultracapacitors, or flywheels will need to provide reliable, safe, energy storage at a competitive cost with respect to established technologies. To be cost competitive in solar (PV) applications requires that the emerging energy storage technology outperform the established technologies in one or more of the following areas:

6. Manufacturing costs, and/or
7. Life-cycle costs, and/or
8. Maintenance, and/or
9. Performance, and/or
10. Reliability.

There are also a number of special needs for emerging energy storage technologies. One is enhancing performance of advanced energy storage systems at intermediate states of charge. In this mode of operation system efficiency can be very high because of improved energy storage efficiency and there is the ability to effectively store additional energy during periods of high solar resource. The lead-acid and nickel-cadmium batteries require a full charge on a regular basis and thus have limited use at intermediate states of charge and low efficiency during the finish or full charge. The intermediate state of charge operation could significantly improve solar PV system performance by more effectively storing energy in high solar resource periods.

The worldwide solar (PV) on-grid markets have seen rapid growth approaching 30%/yr over the past few years with 2003 yearly sales approaching 575 MW. Seventy percent of the 2003 sales have been to on-grid markets. Most of solar PV growth has been in Japan and Germany with grid-connected residential systems without energy storage. Energy storage for these grid-connected systems is seen as an excessive added cost and reliability risk. If the life-cycle cost of energy storage could be reduced and the reliability and lifetime improved, then there would be a potential new market for energy storage associated with about 400 MW of PV. This market could provide improved power quality, peak shaving, load leveling, and emergency backup power for the residential systems. To make this energy storage market grow would require additional inverter electronics and controls in association with economical, maintenance free, and reliable energy storage.

The world wide solar PV off-grid markets at about 170 MW PV have not seen rapid growth, but are growing at modest rates using mostly lead-acid batteries for energy storage. The older lead-acid technology is available everywhere in the world and at an economical price. Lead-acid batteries do require regular maintenance and suffer from lower than expected performance as a result of the unpredictable nature of off-grid solar PV systems, and the lack of training for people responsible for their maintenance. Significant improvements in off-grid system performance could be achieved by using an energy storage system that does not require maintenance and does not require a full charge at regular intervals.

If emerging energy storage technologies are to penetrate the solar markets, work must begin to address the cost issues limiting their use. Below is a table showing the projected costs compared to lead-acid energy storage. In all cases the emerging energy storage technologies are considerably more expensive than lead-acid batteries. The goal for any advanced energy storage system is to be more economical and reliable than the lead-acid battery. The other mitigating factors, not included in the table below, are maintenance, performance, cycle-life, and reliability. Elimination of maintenance and a high cycle-life could justify considerably higher capital costs while providing lower life-cycle costs for energy storage in solar PV systems. Therefore, cost reduction strategies need to look at both capital and life-cycle costs to achieve a competitive position with the lead-acid batteries.

**Table 6: Emerging Energy Storage Technologies Life-Cycle Cost Study**

| Technology | Capacity | Capital Cost ($/kWh) | Replacement (years) |
|---|---|---|---|
| Lead-Acid | small to large | 150 | 6 |
| NiCd | small to large | 900 | 10 |
| Li-Ion | small | 500 | 5.5 |
| NiMH | small to medium | -- | -- |
| Flywheel | small to medium | 1000 | 20 |
| NaS | medium to large | 600 | 10 |
| Flow Batteries | large | 400 to 600 | 10 |
| Ultracapacitors | small | 45,000 | 20 |

Costs and cycle-life are based on a DOE energy storage systems program study by S.M. Shoenung and W.V. Hassenzahl, “Long- vs. Short-Term Energy Storage Technologies Analysis, A Life-Cycle Cost Study”, SAND2003-2783

Another conclusion that can be drawn from the workshop is that as solar and storage technologies develop, they may have an important influence on each other even as they pursue separate paths. Particularly in situations that impact the electric grid, the role of energy storage in grid stabilization, UPS and backup power will influence the role solar

PV will be able to play as a distributed energy technology. Similarly, advances in communications and controls will influence both storage and solar, making both easier to integrate into the grid and more effective at responding to grid problems. This is true even if solar PV and storage are completely separate.

Flow batteries and SMES are already being used for grid stabilization, in some cases on grids with intermittent generating sources. As solar PV and other intermittent generators increase on the grid, there could be increased demand for large-scale energy storage to address some of the problems intermittent generators introduce. Modeling a grid with more extensive energy storage and more sophisticated controls and information is an issue for Systems-Driven Approach analysis.

EPRI and others envision new batteries developed for transportation as potential sources of energy storage for distributed generation. Utilities could tap into this stored energy during times of peak demand or to address line stability or power quality problems. Both solar and storage technologies have the potential as distributed generation owned by consumers or by utilities. One of the challenges for the Systems-Driven Approach is the need to design models and analysis tools that are able to adopt the perspectives of utilities and end-users. An understanding of reactions to the new technologies, cost and market will be needed.

Recommended next steps would be to coordinate the development of the Systems-Driven Approach with both the Energy Storage and FreedomCAR programs, especially in modeling markets, applications and technology advances. The Solar Energy Technologies program should be looking at the impacts of advances in storage on future applications. When it does it should be using the same assumptions that bound the analysis conducted by Energy Storage and FreedomCAR Programs.

In the case of the FreedomCAR program, the Solar Energy Technologies program should also look at using, as much as possible, the battery/storage information embedded in its ADVISOR model, and adapting it to the needs of solar energy. In turn, solar can share its developments with the other programs to leverage research and management funds and gain universal support.

Finally, the programs should consider regular meetings to share technical information and get industry input for all three programs on storage technology issues and advances so that modeling and analysis are kept up to date.

## Other Reference Resources

**U.S. DOE**

***Office of Electricity Transmission and Distribution, Energy Storage Program***
http://www.electricity.doe.gov/program/electric_rd_estorage.cfm?section=program&level2=estorage

***Office of Energy Efficiency and Renewable Energy***
FreedomCAR and Vehicle Technologies Program,
http://www.eere.energy.gov/vehiclesandfuels/technologies/systems/energy_storage.shtml
Solar Energy Technologies Program, http://www.eere.energy.gov/RE/solar.html

**NREL**
Battery and Thermal Management Laboratory, http://www.ctts.nrel.gov/BTM/
National Center for Photovoltaics, http://www.nrel.gov/ncpv/

**Sandia**
Power Sources Technology Group, http://www.sandia.gov/pstg/battery.html
Photovoltaic Systems Research and Development, http://www.sandia.gov/pv/
Energy Storage Systems, http://www.sandia.gov/ess/

**Argonne National Laboratory**
Electrochemical Analysis and Diagnostics Laboratory,
http://www.cmt.anl.gov/facilities/eadl.shtml

**Electricity Storage Association,**
http://www.electricitystorage.org/

**US Advanced Battery Consortium (USABC),**
http://www.uscar.org/consortia&teams/consortiahomepages/con-usabc.htm

**EPRI**
Energy Storage for Transmission or Distribution Applications,
http://www.epri.com/target.asp?program=267782&value=04T094.0