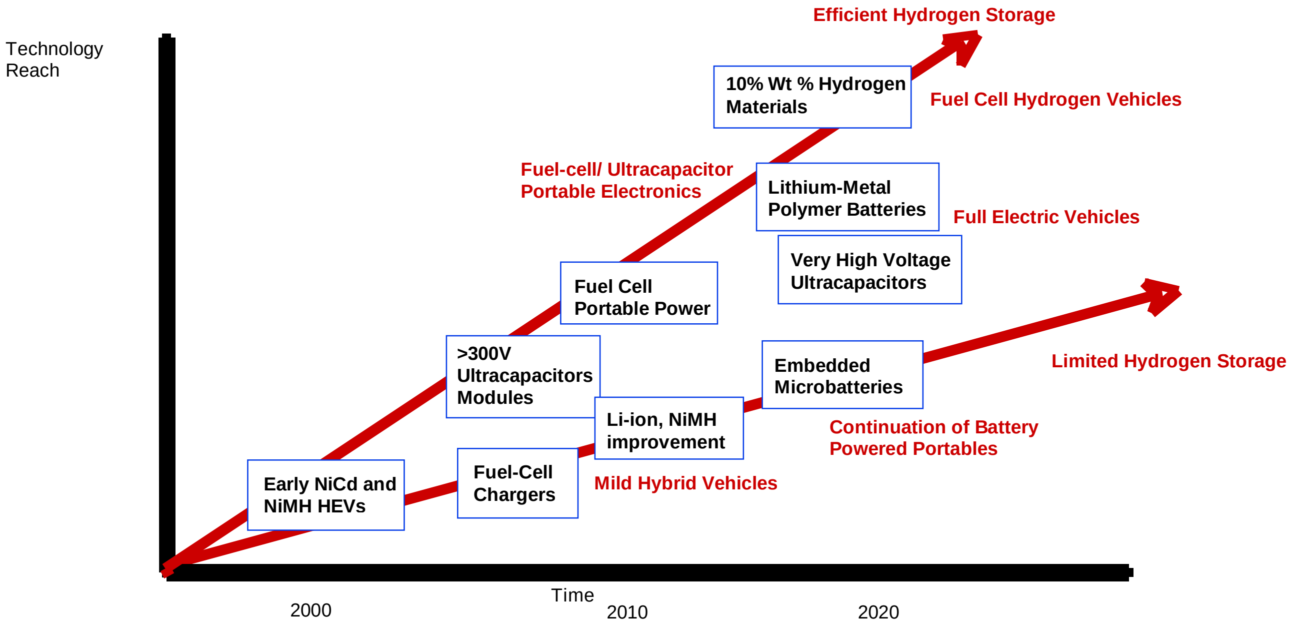
APPENDIX B: ENERGY STORAGE MATERIALS (BACKGROUND)

The Technology

Figure 3[1]
TECHNOLOGY ROADMAP: SELECTED ENERGY STORAGE MATERIALS



Source: SRI Consulting Business Intelligence

Energy Storage Material Technologies

By definition, energy storage materials comprise those materials that can provide or store energy in a useful form—oil, coal and uranium are perhaps the ultimate energy storage materials. This profile concentrates on hydrogen storage (particularly for use in a fuel cell), ultracapacitors (that store electrical energy in the form of charge), and batteries (that store energy electrochemically).

- *Hydrogen Storage*. On a weight-for-weight basis, hydrogen has the highest energy content of any element and it is the most abundant element in the universe, which makes it attractive as an energy source. Unfortunately, it is also the lightest element and, therefore, the least densely concentrated element in the universe, so it is difficult to concentrate sufficient hydrogen in one place to make it economically efficient to use as an energy source for most human activities. Existing technologies to generate hydrogen are economically and environmentally expensive, devices to concentrate and

[1] The Technology Roadmap highlights the timing, features, and applications of significant technology milestones that would be necessary for developers of this technology to achieve if successful (equivalent to commercial) application—and possible disruption—is to occur by 2025.

store it are typically too big, too heavy, inefficient or otherwise economically unacceptable, and the infrastructure to transport it and to dispense it are typically inefficient and unfriendly to end consumers. Many metals, with their relatively larger molecular voids, and many chemicals, have an affinity to absorb hydrogen into, or onto, themselves (to “take up” hydrogen). Therefore, metal hydride and chemical hydride materials are the focus of much of the attention in hydrogen storage materials. None of these materials have reached the density of storage that is necessary to enable commercial acceptance. Therefore, early portable power and transportation power fuel cell designers are using liquid fuel alternatives, such as direct methanol fuel cells, where the hydrogen is “stored” in a fuel like methanol and taken directly into the fuel cell. Other fuel cell systems use a liquid or gaseous hydrocarbon fuel and “reform” it into hydrogen, which can then be taken up by the fuel cell. Liquid fuel hydrogen storage leaves a waste product that must be disposed or a spent fuel that must be “regenerated” or recycled to refill it with hydrogen. In a couple of cases, liquid hydrogen is stored cryogenically on vehicles for direct combustion, rather than in a fuel cell. Liquid fuels, cryogenic storage, and reforming of fuels add complexity to the overall fuel cell system.

- *Ultracapacitors*. Ultracapacitors are a specific type of capacitor—an electrochemical double-layer capacitor (EDLC)—that can store a large amount of electric charge and then discharge that charge to give a significant amount of power (often over 10 kW) over a time frame of over a few seconds. They typically comprise high surface-area carbon electrodes, with a molecule-thin ionically conducting electrolyte—such as a salt or organic electrolyte in liquid form—and with a dielectric separator electrically isolating the two electrodes. Ultracapacitors have much higher capacitance than normal capacitors (typically 1000 Farads), but this charge is stored at a low potential, such as 2-3 volts. Though the low voltage of ultracapacitors does not matter for portable battery applications, where their high capacitance is useful, it does for higher power applications. Ultimately, the degree of disruption of ultracapacitors (particularly in vehicle applications) is the extent to which ultracapacitors could be developed that would store more energy, with both a high capacitance and, in particular, an increased operating voltage. Ultracapacitors have an opposite set of characteristics to batteries in that although they typically have lower energy density (Wh/kg) they can dissipate much higher levels of power (charge), measured in W/kg or W per unit volume—typical energy densities are 5-10 Wh/kg and power densities of 5-10 kW/kg. This attribute makes them ideal in applications that require high start up powers, such as in various types of motors (including electric motors for cars), in backup battery applications, and for smoothing out the power from some renewable energy sources. Ultracapacitors often work in parallel with batteries to provide advantages of high peak power and high energy.

- *Batteries*. A battery is a device that converts the chemical energy contained in its active materials directly into electric energy by means of an electrochemical oxidation-reduction reaction. The reaction involves the transfer of electrons from one material to another through an electric circuit. Though the term battery is most common, the basic electrochemical unit is actually the cell. A battery consists of one or more of these cells, connected in series or parallel or both, depending on the desired output voltage and capacity. A cell has three major components: the anode—or negative electrode—that releases electrons to the external circuit and undergoes oxidation during the electrochemical reaction; the cathode—or positive electrode—that accepts electrons from the external circuit and undergoes reduction during the chemical reaction; and the electrolyte—ionic conductor—that provides the medium for transferring ions inside the cell between the anode and cathode. The electrolyte is typically a liquid—such as water or other solvents, with dissolved salts, acids, or alkalis—to impart ionic conductivity, although solid and semisolid electrolytes are finding increasing use in advanced battery systems. The names of the majority of batteries reflect the materials that make up their electrode combinations, with the most advantageous anode and cathode materials combining light weight with high cell voltage and capacity.

The Enabling Building Blocks

Each energy storage material has its own enabling technologies:

- Hydrogen Storage
  - *Materials*. The U.S. Department of Energy has determined that in order for hydrogen to replace gasoline as a fuel for automobiles, the onboard hydrogen storage system must contain 6.5% hydrogen by weight (wt %) by 2010 (when early fuel cell vehicles might be expected to appear for sale) and 9.0 wt % by 2015 (when fuel cell vehicles might be sold in large volumes). These levels of storage imply dramatic improvements in materials technology. Recent research includes versions of complex or light-metal hydrides such as the relatively inexpensive magnesium hydride (MgH2), which can theoretically absorb up to 7.6 wt % hydrogen. “Complex” metal hydrides include alanates (aluminum-containing compounds), such as sodium alanate (NsAlH4) and lithium alanate (LiAlH4), which can theoretically reversibly produce up to 7.4% and 10.5 wt % hydrogen, respectively, but they require the addition of a catalyst, such as titanium or zirconium, to work. Metal-organic frameworks (MOFs or “moffs”) have gained attention for their ability to adsorb relatively large amounts of hydrogen, but more work is needed to increase the amount of hydrogen able to be stored to the DOE requirement levels. Aminoboranes (H_3BNH_3) are liquids that are also of high interest, because they can store and release up to 19.6 wt % hydrogen and can be carried as a liquid fuel, similar to gasoline, but also release a by product, boron nitride, which must be recovered and recycled.
  - *Carbon nanotubes*. A specific enabling materials technology could be carbon nanotubes (CNTs). CNTs were once reported as having great potential in hydrogen adsorption, but early experiments were found to be faulty, not controlling properly for temperature and pressure, and many if not most researchers gave up on CNTs, perhaps too soon. Some scientists are taking new approaches to see if the potential is still there. As researchers at Stanford University point out, every carbon atom in a single-walled CNT (SWNT) should be able to chemically absorb one hydrogen atom, which gives SWNTs a theoretical ability to store 7.7-wt % hydrogen. One problem has been that (like MOFs) the interaction energy between the hydrogen and the CNT is highly sensitive to the size of the nanotube.

- *Hydrogen production*. A hydrogen economy will require fast and cheap production of hydrogen, ideally using a non-petroleum, non fossil fuel source. Producing hydrogen from water would be the ideal option. “Solar hydrogen,” “wind hydrogen,” and “nuclear hydrogen” are terms that refer to the source of electricity for splitting water into hydrogen, which can then be stored at a fuel cell fueling station, and oxygen. In this way, fueling stations could exist remotely, free of disruptions of a petroleum-based infrastructure, as long as a source of water is present.
- *Clean, safe, and convenient dispensing of hydrogen*. Completing the overall hydrogen infrastructure is the distribution and dispensing of hydrogen to and by consumers. Fueling stations, whether public or at the home, could be linked by pipelines, but hydrogen gas tends to be absorbed by metals and other materials, which leads to embrittlement and ruptures. More likely the hydrogen will be distributed in another form, compressed in canisters or as natural gas at first, and hydrogen will be generated as near as possible to the point of use or refueling of a hydrogen storage device. Engineering solutions will be necessary to prevent excessive emission losses and accidents while the fuel is being dispensed, and yet is convenient to be dispensed by the average consumer.

- Ultracapacitors
  - *Electrode materials*. Electrodes need to have a high surface area to store charge and typical approaches are some form of nanostructuring. Typical surface areas of commonly used activated carbon or aerogels are 700 to 2000 m2/g, but transition metal nanooxides (such as ruthenium oxide and nickel oxide) are challenging carbon aerogels and offer charge-storage advantages. A number of organizations are looking at other more exotic materials such as tailored nanoporous carbon, and carbon nanotubes. Researchers at the University of California (Davis, California) have used a highly concentrated colloidal suspension of carbon nanotubes to create thin-film electrodes, and the resulting ultracapacitors exhibit power densities up to 30 kW/kg. Researchers at the Massachusetts Institute of Technology are also investigating nanotube-enhanced ultracapacitors. Their research has shown that using a matrix of vertically aligned carbon nanotubes to form electrodes can achieve ultracapacitors with an energy density of some 60 Wh/kg and a power density of 100 kW/kg—about three orders of magnitude better than those of lithium-ion chemistries.
  - *Dielectric materials*. Another area of performance improvement is to increase the operating voltage of ultracapacitors, since the energy stored by a capacitor increases with the square of the operating voltage. This means developments in dielectric materials that must be able to withstand high electric fields since the role of thin dielectrics is also to increase the capacitance levels. The typical voltages of ultracapacitors are 2-3 V, but start-up company EEStor claims to have developed new barium titanate powders as a high-k dielectric that would allow substantial increases in operating voltage (up to 3000 volts), thereby allowing an enormous increase in stored energy, about 10 000 times greater than currently available ultracapacitors. There is little independent evidence at present

to confirm the validity of the company's claims, including whether such high dielectric constant can be maintained as the voltage or temperature rises.

- Batteries
  - *Electrode materials*. A solution to extended run times and improved battery performance lies in the development of electrode materials with greater energy-storage capacities than the capacities of conventional electrode materials. Among the carbon-based nanomaterials that have attracted attention in recent years are fullerenes and carbon nanotubes. Although much research has focused on the application of these materials in fuel-cell electrodes, interest in using them in batteries is also growing. An alternative approach that some battery makers and developers are exploring is the use of nanoparticulate-processing technology, both to reengineer conventional carbon-based electrode materials to improve battery performance levels and to develop new types of electrodes materials. The small size of the particles that form these nanomaterials provides an increased electrode surface area for a given weight of material. Increasing the electrode surface area not only provides much faster charge/discharge rates, but also leads to improvements in energy density. However, the cost of nanoparticle-electrode materials—currently some 50 to 100 times more than the cost of electrodes from conventional bulk materials—has so far constrained their widespread application in battery production. Several organizations are focusing on the development of novel nanomaterials that will enable this performance improvement. For example, lithium-ion battery technology for HEVs from A123 Systems features proprietary nanoscale electrode technology built on research at the Massachusetts Institute of Technology.
  - *Electrolyte materials*. Commercially available Li-ion cells use either liquid or semisolid gel-polymer electrolytes. However, in spite of the commercial success of gel-polymer technology, semisolid gel electrolytes will not provide the parameters necessary to enable lithium-ion batteries to reach their full energy potential. Only fully solid—or dry—polymer electrolytes that manufacturers can combine with lithium-metal electrodes will enable the production of high-energy-density, high-power, lithium-metal polymer (LMP) batteries. batScap—a subsidiary of French company Bollore Group—is putting its faith in the technology for the development of the company's BlueCar EV. However, the development of rechargeable LMP batteries has been fraught with problems—rival Avestor (Boucherville, Canada) was developing the technology for both EV and standby power applications but went into liquidation in 2006—largely due to the difficulty of overcoming the poor ionic conductivity of the polymer electrolyte.

Implications of Advancement in Various Technological Capabilities

All of the energy storage material technologies discussed here require improvements in cost and energy density, the amount of energy stored per kilogram or unit volume. The higher these figures become, the greater the number of applications that could be impacted. From an ultracapacitor and fuel cell perspective, initial advances would see greater penetration into portable battery markets, in which the energy requirements are relatively low. Here, an ultracapacitor might replace a portable battery altogether, as opposed to working in parallel with it.

Hybrid-electric vehicles are already in development, but the disruptions that would emerge with improvements in cost and energy density would come about because of dramatic changes to fuel consumption, emissions and gasoline usage. An initial improvement in ultracapacitors (used with another electric energy source such as a battery or fuel cell) is for the ultracapacitor to play a greater role in idle-stop applications, regenerative breaking and acceleration. If the energy and power density of ultracapacitors was sufficiently high (and at low enough cost), they could take over more of the powering applications. In an extreme case, if the ultracapacitor could operate at high enough voltage, the energy might be enough to power an entire vehicle using an ultracapacitor.

If hydrogen storage became possible at a sufficiently high energy density it would have a major implication for the future of fuel cells. In certain scenarios, including the synergistic need for clean energy for the hydrogen conversion process, the resulting boost for fuel cells usage would lead to a step change in the demand for oil from transportation applications in particular, and in the requirements for fueling and hydrogen conversion infrastructure.

Synergistic Technologies

Energy storage materials will most likely not develop independently of one another, nor, most certainly, without development of a myriad of enabling and synergistic technologies.

- *Parallel development*. The most likely technological synergy that is occurring (and will continue to occur) in the areas of ultracapacitors, battery technology and fuel cells is their operation in parallel, particularly ultracapacitors in conjunction with either batteries or fuel cells, but also fuel-cell—battery hybrids. The implication is that for the largest disruptive impact, improvements are needed in all areas in terms of improved performance and lower cost.
- *Nanomaterials*. One underlying synergy is that all three areas rely on improvements in nanomaterials. Indeed many companies that are developing new nanomaterials for energy storage are able to leverage their developments from one application to another—some companies developing materials for ultracapacitors or fuel cells also sell materials for battery applications. Given the high cost contribution from raw materials in all energy storage applications, nanomaterials development and cost reduction is important. The need to lower the cost of carbon nanotube costs is likely to benefit from its synergistic development across a wide range of nanomaterial and nanoelectronic applications.
- *Hydrogen infrastructure and energy supplies*. A hydrogen economy requires not just the storage materials but ways to efficiently generate and distribute hydrogen, including new materials for piping—hydrogen tends to permeate through most materials.

Applications

Key Uses and Instantiations of Energy Storage Materials

The key use of an energy storage material is to store energy in a form for later use (storing cheap energy at one time of the day to be released at a later time), even though energy storage materials can be used for grid applications. Energy storage materials are particularly linked to portable and autonomous applications. These materials store energy in a portable device or autonomous vehicle, and release that energy on demand to provide power for motion, communication, and other functionality.

Current Affected Products or Services

Table 7 indicates a number of specific applications that these energy storage materials play a role in. The table highlights a strong overlap in the types of applications that the three technologies can play a role indicting the potential for both synergy and competition. Some of the industrial applications are currently more mature and represent some of the early-adopter applications for ultracapacitors and fuel cells, though the future potential disruption may be lower than in transportation and portable power.

Table 7

APPLICATIONS OF ENERGY STORAGE MATERIALS

Application	Potential Level of Disruption	Disruptive Energy Storage Technology		
		Batteries	Ultracapacitors	Fuel Cells/Hydrogen Storage
Automotive	High	Limited current hybrid electric vehicles	In combination with batteries/fuel cells or standalone powering	Future full and hybrid vehicles
Trains, Trams, Buses	High	Limited full or hybrid electric vehicles	Idle-stop and regenerative braking; future potential standalone powering	Limited zero-emission prototypes; Future full and hybrid vehicles
Consumer Electronics	Medium-High	Current de facto technology of choice	Backup and peak power in combination with batteries; potential battery replacement	Potential battery replacement
Renewable Energy	Low-Medium	Backup energy storage	Backup and emergency power storage; wind-turbine pitch systems	Energy storage and backup power
Industrial	Low-Medium	Uninterruptible power supplies	Wide variety of uses in interruptible power supplies and peak power to motors and actuators	Interruptible power supplies and backup power

Source: SRI Consulting Business Intelligence

- *Batteries*. Batteries are currently the power source of choice for portable electronic devices and as the secondary power supply in automotive vehicles. Zinc-carbon and zinc-alkaline manganese are the most popular primary batteries, with secondary (rechargeable) NiMH and Li-ion dominating in high-value applications such as digital cameras, mobile phones, laptop computers and handheld devices. In the automotive sector, lead-acid technology is the most widely use electrochemical system in starting, lighting, and ignition applications, with NiMH technology currently dominating in hybrid-electric and electric vehicles. However, expectations are that the advent of higher capacity Li-ion batteries will lead to the technology's dominating in HEV and EV applications with a few years. The development of a safe and reliable lithium-metal polymer battery would also ensure that batteries remain the technology of choice for portable devices for some considerable time. LMP technology would enable the production of high-energy-density rechargeable flexible batteries that could be made as simply and in as many forms as paper is made—in any size, at low cost, and using mass-production techniques.

- *Ultracapacitors*. The characteristics of ultracapacitors make them suited to providing short bursts of power for applications requiring a high peak power, or to act as a backup power source. In consumer electronics, the advent of new devices or features that require high instantaneous or peak power (such as battery lens actuators, camera flash and burst communications) makes the use of capacitors well suited. Though batteries could in principal provide the same functionality, the result would be a need for much larger batteries. Combining a battery with an ultracapacitor gives high power when it is needed while retaining small battery sizes; one roll of the battery then becomes to charge the ultracapacitor in idle mode. Ultracapacitors are also used in some motors to provide peak power, such as in some elevators, forklift trucks and robotic arms. Ultracapacitors are also used in a wide variety of backup power applications, particularly uninterruptible power supplies for telecom and industrial applications, where their near instantaneous power dissipation makes them valuable. They can also provide backup power capability in applications where the failure of the main power source would be crucial.
- *Fuel Cells*. Fuel cells of various types and sizes are being sold into specialty military and industrial applications and are nearing commercialization in some consumer applications. Forklift trucks powered by fuel cells have been sold for demonstration projects in warehouses, where zero emissions and quiet operations are desired and the lift trucks can be refueled at central stations. Other zero-emission, quiet operation applications are being tested, from seaport materials handling trains and cranes to airplanes. Sales of fuel cells as backup power for cell phone towers, communications centers, and computer centers have increased recently, particularly after hurricanes in Florida, where many battery-based backup power systems failed. Automobile and bus companies are testing fuel cell-powered vehicles worldwide, in anticipation of potential early sales to consumers in 2010 to 2012. Current test systems use compressed hydrogen gas as the fuel, but a more convenient hydrogen storage system will be necessary for high-volume sales for personal transportation. Fuel cells for portable electronic devices are in use for military applications and are near commercialization for consumer applications, in order to increase the amount of time and the ability to anticipate the time needed between charges/refueling. Most current portable fuel cells use methanol cartridges as the hydrogen source. The methanol cartridges have been approved for carrying onto airlines, in anticipation of consumer use, although some companies are developing hydride materials for portable applications, in order to reduce the size and convenience of hydrogen storage components.

New Capabilities Created by Energy Storage Materials

Energy storage materials offer several advantages over traditional sources. Most often cited are potential energy efficiency and lower carbon emissions compared to traditional fossil fuel energy sources, particularly in the transportation sector. Also notable are zero emissions and quiet operation in close-quarter, contained, or indoor work environments as well as in residential and night time operations for industrial and government service operations. Fast, reliable response in remote and backup power applications is another advantage of batteries, ultracapacitors, and hydrogen-powered fuel cells over combustion engines and generators, which sometimes fail just as they are needed in remote, unmanned stations.

Timeline

The following events are likely to occur in the suggested timeframes if developments in energy storage materials continue at today's rate

2007-2010

- Hybrid electric vehicle sales grow, with Toyota and Honda dominating the market.
- Ultracapacitors appear alongside lithium-ion batteries for idle stop applications

2010-2015

- Hybrid electric vehicles reach the low millions of units of production. The plug-in electric vehicle market begins to grow.
- Ultracapacitors appear alongside lithium batteries for regenerative braking and acceleration in automobiles
- Ultracapacitors replace batteries in some portable applications, and micro-fuel cells begin to make some inroads into the portable device market.
- The first hydrogen fuel-cell vehicles emerge

2015-2020

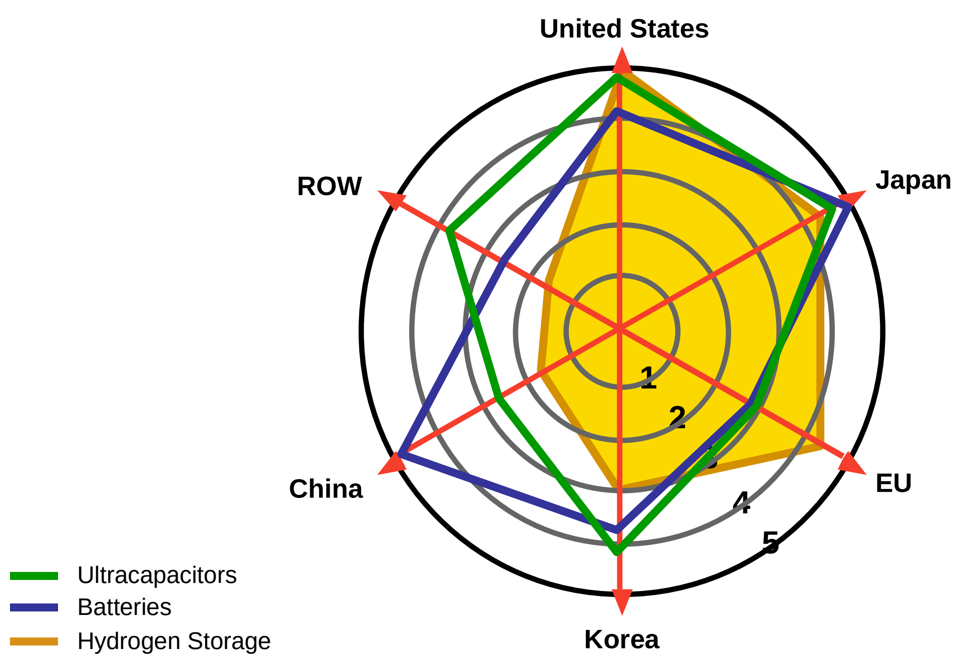
- Production of hybrid electric vehicles ranges between 5 and 10 million units.
- Lithium metal polymer batteries are developed and all-electric battery vehicles begin to compete with HEVs
- Hydrogen storage reaches around 9-wt % driving the market for hydrogen fuel-cell vehicles.
- Commercial ultracapacitor-powered vehicles emerge (wildcard).

Issues Determining the Development of Energy Storage Materials

Governments around the world are increasingly concerned that petroleum is no longer a reliable or sustainable source of energy for economic growth and social well being into the future. Some forecasters predict that oil has already or soon will reach its production peak, just as many countries, such as China and India, are beginning to expand their economies and place more demand for oil. Therefore, an alternative energy source is being sought. However, the difficult policy balance for any new energy technology is how to privilege development, and provide economic incentives in the early stages of development, while not placing an entire economy at risk. The answer in most regions has been targets for solutions such as renewable energy developments, policies for reduced emissions, and targets for more energy-efficient vehicles.

In the areas of battery development, the boom in portable devices, particularly mobile phones, laptops and so forth, has been the primary driver of new battery chemistries, and this is reflected by the strong positions in battery technology (particularly lithium-ion technology) in Korea, China and Japan. A strong position in battery technology, combined with an advanced automotive sector, has enabled Japan, in particular, to be at the forefront of electric vehicles. Many industry observers and manufacturers—including battery maker Sanyo and leading hybrid electric vehicle developer Toyota—believe that lithium-ion batteries will become the battery of choice for hybrid electric vehicles by 2010. Toyota is already looking to adopt lithium-ion technology in the redesigned Prius due to be launched in the second half of 2008.

Figure 4
INTERNATIONAL STATUS OF RESEARCH AND MANUFACTURING OF ENERGY STORAGE MATERIALS



Note: 1 = Niche player: Limited level of research and/or manufacturing
3 = Medium player: Reasonable level of research and/or manufacturing
5 = Global leader: Leadership in research and/or manufacturing

Considered under ROW were specifically Russia, India and Australia

Source: SRIC-BI

Although lacking the same manufacturing based for lithium-ion batteries, the United States retains considerable battery expertise, including primary battery manufacture and development, and an advanced position in nanomaterials for new battery chemistries. The United States is a leading developer of ultracapacitors and the leader in materials for hydrogen storage. Arguably it is the strength of U.S. innovation among its institutes and start-up companies, and the role that defense funding can play (portable power including pulse power is important for defense applications) that has led to this situation.

Another advantage in some regions (notably the United States, Europe and Japan) is the breadth of commercial interests that exist along the entire value chain in areas like hybrid electric vehicles, fuel cells and future hydrogen storage. As one example, BASF in Germany occupies many positions in the value chain for necessary fuel cell components. This breadth of expertise puts smaller countries like South Korea and developing countries like China at some disadvantage, at least for the time being.

Items to Watch

The barriers to a move to these three new energy storage technologies particularly relate to the development of cost-effective materials. Substantial opportunities exist in the development of new materials as higher-voltage ultracapacitors, for high energy-density batteries and for hydrogen storage. For hydrogen storage, a further barrier is the need for efficient hydrogen production from a non-petroleum, ideally non-fossil fuel source. Synergistic developments in renewable energy, nuclear power or other clean energy sources would be beneficial.

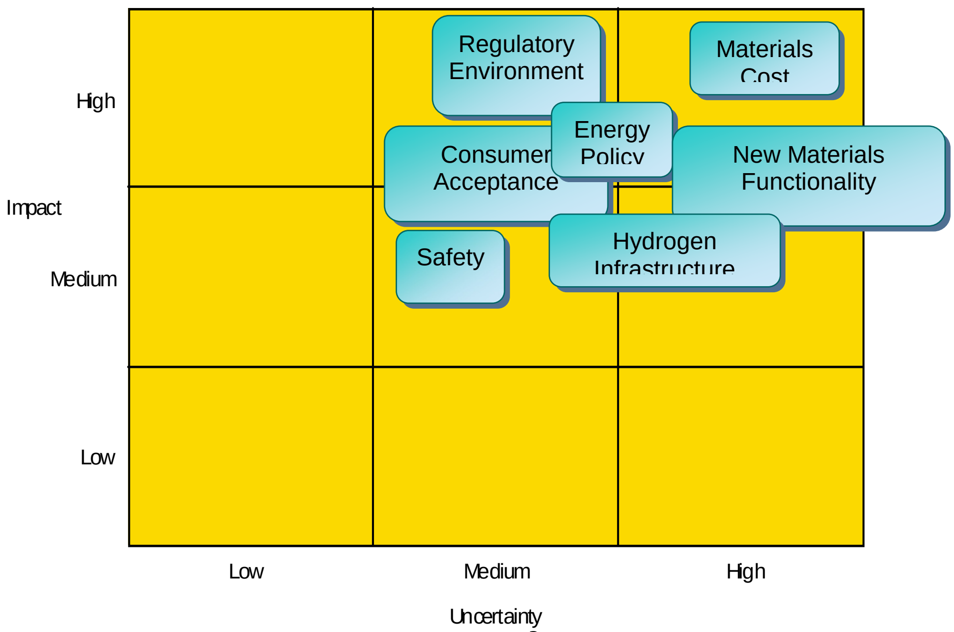


Figure 5[2]

ENERGY STORAGE MATERIALS: ISSUES AND UNCERTAINTIES

Source: SRI Consulting Business Intelligence

[2] Figure 5 illustrates major issues and events that will have an impact on the rate or direction of a technology's development and thereby application. The impact of these issues and events is plotted against a measure of uncertainty, where uncertainty implies insufficient knowledge of how (and usually just when) the issue or event will be resolved or be sufficient to drive or hold back development of the technologies. An organization that is able to accurately predict or (better) influence or dictate the outcome (thereby moving the issue/event to the left of the figure), will have a distinct advantage over organizations that are still in the dark or just passively following developments.

From Figure 5, the key areas of uncertainty to monitor and better understand are:

- *New materials functionality*. A key to all energy storage material technologies will be the availability of new materials to provide enhanced functionality. For hydrogen storage, this means materials that can store a large fraction of their weight in the form of hydrogen; for ultracapacitors, the need is for both improved electrodes and new dielectrics that enable ultracapacitors to operate at greater voltages. Typical ultracapacitors store charge at low voltage, but high-power applications, ideally require a higher operating voltage is needed. New battery chemistries such as lithium metal polymer are also required to match the demand for portable power, but all developments are open to uncertainty in terms of timing and economics.
- *Safety*. An uncertainty is how safe high-power ultracapacitors would be, since an electrical short could mean an enormous instantaneous dissipation of energy.
- *Materials cost*. Developing materials at low cost will be key to success for all energy storage materials. For example, ultracapacitors are currently very expensive on an energy-stored basis. Many of the energy storage techniques rely on exotic new nanostructured materials, including carbon nanotubes, whose cost needs to come down substantially for them to see use in anything other than the current high value niche applications.
- *Regulatory environment*. The regulatory environment, in particular control of emissions and oil consumption, may play a large role in determining the direction of electric vehicles, idle-stop functionality, regenerative braking, and so forth that could drive the role of ultracapacitors. The list of standards to be met is a long one, but the basic ones include that the energy produced by the hydrogen must be able to power the fuel cell vehicle to travel the same distance under the same conditions as a normal, gasoline-powered consumer vehicle would. The hydrogen storage tank must fit in the same volume of space as the gasoline tank does. The hydrogen must be stored and released at approximately the same, ambient temperatures under which gasoline is in use. The hydrogen must be dispensed from a fueling station (or at home, in some scenarios) as easily and as safely as gasoline is today.
- *Consumer demand*. Consumers will often say one thing on a survey and do another thing when they purchase a product. Although some “green” consumers might be willing to pay a little more for a green product, they still expect it to perform as well as the alternative (the basic “if I build it, will they buy it” problem). In the case of hydrogen-powered, fuel cell vehicles, consumers will expect the same speed, range, acceleration, hot and cold weather operation, startup time, and so forth. Consumer responses to climate change could prove to be a substantial driver for electric vehicles.
- *Hydrogen infrastructure*. The hydrogen infrastructure needed to sustain a consumer fuel cell vehicle fleet does not exist today, which concerns some vehicle developers, but has caught the attention of many government agencies. Some of the uncertainty exists over whether the fuel cell vehicles will succeed, necessitating the building of a new infrastructure, which would prove a costly mistake if fuel cells flop (the basic “which comes first” and “who pays for it” problems). In addition, uncertainty exists over which form of hydrogen production fits best with the infrastructure. Solar, wind,

and nuclear have been mentioned as “clean” (low emissions) and “sustainable” sources, but natural gas and clean coal (where carbon is captured and sequestered in the ground or in some industrial process) are also being considered and most of these alternatives are actually in experimental use. The future reality will likely be a mix, depending on local economies and availabilities.

- *Energy policy*. As national energy policies in the renewable energy sector (particularly solar) have shown, energy policy can have a substantial impact on technology development and the rate of penetration of new energy technologies. National policy responses to future potential oil price rises are crucial areas to monitor.

Directional Signposts

Identifying the major issues that will determine how energy storage materials technologies will develop and understanding the uncertainty of items important to watch help us to understand better the potential dynamics of development and application that we might see in the future. That heightened sense of awareness is necessary because the United States will want to formulate a policy and act before unambiguous evidence on the drivers and barriers to, and direction of advancement of energy storage materials technology is available. Preparation for a watch-and-respond system is essential to identify correctly the signposts that would indicate whether the advancement of the technologies is proceeding rapidly or not. The following developments are likely to occur near the suggested years, and their would indicate that the above issues and uncertainties were being resolved in the direction of positive development and application of energy storage material technologies.

- 2007—Hybrid gasoline-electric vehicles have made some inroads into the car market.
- 2009—Ultracapacitors in high-voltage modules appear alongside batteries to supplement power in HEVs.
- 2010—Lithium-ion technology is the technology of choice for HEVs, but is beginning to come under increasing pressure from microfuel cells and ultracapacitors in some portable applications.
- 2012—Improvements in ultracapacitor costs and higher voltage leads to their use in regenerative braking applications.
- 2015—Hydrogen storage capacity reaches 9 wt %
- 2015—Lithium metal polymer batteries finally reach production at a cost that enables electric vehicles to compete with HEVs
- 2020—High-voltage dielectrics for high voltage/energy ultracapacitors become viable.
- 2020–25—Even most pessimists expect that some large percentage of new automobile production will use some non-fossil fuel source.

Within the timeline that these developments are likely to occur, it will be important to watch for and monitor various signposts that will indicate the direction and pace with which the field is advancing and so assess any resultant potential threats to and opportunities for U.S. interests. Key signposts, which, if positive, would enhance the progress in energy storage materials, include:

- The natural availability and the price of oil. Gradual declines in availability and increases in prices would increase the decisions to support alternatives; new giant field discoveries might delay policy decisions to support alternatives
- Improvements in performance and cost of materials relevant to ultracapacitors, batteries and hydrogen storage
- Energy technology choices in BRIC and the European Union. Look for competition for petroleum, reliance on coal, decision to go nuclear, successful investments to compete in alternatives, especially solar, wind, and biofuels
- Global sales volumes of portable electronic devices, including cell phones, PDAs, music players, and wearable medical devices
- Trials, production, and sales volumes of hybrids, fuel cell vehicles and ultracapacitor-powered vehicles
- Investment and development of nuclear energy and alternative energy technologies, particularly solar, wind, and biofuels
- Investment in energy storage materials and commercial successes by type of material

Abbreviations

The following abbreviations are used in this Energy Storage Materials disruptive technology profile:

BRIC	Brazil, Russia, India, and China
CNT	carbon nanotube
DOE	Department of Energy (United States)
EDLC	electrochemical double layer capacitor
EU	European Union
EV	electric vehicle
g	gram
GDP	gross domestic product
HEV	hybrid electric vehicle
IT	information technology
kg	kilogram
kW	kilowatt
kWh	kilowatt hour
LMP	lithium-metal polymer
m	meter
MOF	metal-organic framework
PDA	portable digital assistant
SWNT	single-walled CNT
V	volt
Wh	Watt hour
wt	weight