Critical National Need: Advanced Composites for Flywheels

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Executive Summary

Better energy storage technology is an urgent national need, given the nations commitment to reducing greenhouse gas emissions and to maintain global competitiveness. Renewable generating technology such as wind and solar are highly intermittent and require energy storage on both a short and long term basis if they are going to make up a larger share of power generation. Current business models used in the utility industry do not adequately reward energy storage versus power generation, thus there has been little development in this area. An economical, large composite flywheel energy storage system would dramatically change the existing energy generation/storage landscape. Although flywheel energy storage has been developed for short term frequency regulation, longer term energy storage applications will require larger composite flywheels. Flywheel structures require light weight overall to reduce bearing loads, but very high tensile strength in the rim. Current state of the art composite manufacturing technologies are inadequate to address the complexities of such a flywheel which may require the integration of several types of composites. These composites may also benefit from nanoengineered materials such as carbon nanotubes for fiber and matrix reinforcement, to more ductile ceramics using nanoparticle precursors to increase the performance of the flywheel.

Introduction: The Need for Improved Energy Storage Technologies

Our nation's commitment to reducing global greenhouse gases[1] and supplying sufficient energy for our economy cannot be met using existing technology. The clarion calls sounded by the IPCC reports[2] have lead to public awareness of the threat posed by increasing volumes of global greenhouse gases including carbon dioxide (CO_2). Unfortunately, while coal power plants supply roughly half of the nations' electricity, these same plants also produce some 40% of the energy related carbon dioxide emitted in the U.S.[3] Thus, plans to reduce the nations emissions of carbon dioxide must take into account coal fired generating plants. Either some long term solution to reduce (by increasing efficiency) and store the carbon dioxide from these plants must be found, or alternative power generating technologies must be employed.

The US does possess abundant renewable resources in the form of wind, hydro, geothermal, and solar energy inputs. Hydro and geothermal sources have some advantages in power generation due to their more highly predictable availability compared to wind and solar, but there are some serious drawbacks to both of these energy sources. Most large hydroelectric sites have already been developed, often with high environmental costs. A major hydroelectric supplier in Quebec reports that peak power demand occurs during the winter months[4], but peak power production comes in the spring with rising water levels. Thus, the peak power outputs from hydroelectric sources do not correlate well with peak demands. Increasing utilization of geothermal resources may also prove problematic. Recent efforts to produce new geothermal sources by drilling may have lead to earthquakes, causing deep consternation in a community[5].

There are sufficient wind[6] and solar[7] energy inputs within the US's borders that would satisfy our energy needs for the foreseeable future. However, the intermittent nature of wind and solar

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[1] http://www.eia.doe.gov/oiaf/aeo/execsummary.html
[2] http://www.ipcc.ch/ipccreports/ar4-syr.htm
[3] http://www.scientificamerican.com/article.cfm?id=combating-climate-change-energy-supply
[4] http://www.cleanairalliance.org/files/active/0/powerofmutualbenefit.pdf
[5] http://www.nytimes.com/2009/06/24/business/energy-environment/24geotherm.html?scp=1&sq=deep%20in%20bedrock&st=cse
[6] http://www1.eere.energy.gov/windandhydro/pdfs/41869.pdf
[7] A Navigant Consulting Study in 2005 concluded that rooftop solar PV installations alone could provide over 700 GW of electricity or nearly 3/4ths of total current production. http://www.businesswire.com/portal/site/google/?ndmViewId=news_view&newsId=20050301005530&newsLang=en

energy on both a short term (minutes) and long term basis (hours/days), along with limited transmission lines and lack of energy storage has restricted their deployment to date[8]. The current inability to store the power generated by new wind turbine systems on either a short or long term basis has decreased efficiency and increased operating expense of these installations, leading to proposals to couple wind turbine installations with desalination plants[9]. While solar PV power production often matches peak demand (residential air conditioning is a major factor in peak demand), wind generated power does not. It is unlikely that even a smart grid will be able to cope with peak demands using solar and wind power generation without improvements in storing energy on a larger scale. Furthermore, as electricity usage has shifted from industrial customers to residential customers, there has been increased volatility in peak demand[10].

On April 16, 2009, Vice President Biden, accompanied by Commerce Secretary Gary Locke, gave a speech in Jefferson City, Missouri, where they announced plans for Smart Grid Investment Projects as well as Smart Grid Demonstration Projects funded by the Department of Energy (DOE)[11]. In his speech, Vice President Biden called for funding demonstration projects in three areas;

- **Smart Grid Regional Demonstrations** will quantify smart grid costs and benefits, verify technology viability, and examine new business models.
- **Utility-Scale Energy Storage Demonstrations** can include technologies such as advanced battery systems, ultra-capacitors, *flywheels* (italics added) and compressed air energy systems, and applications such as wind and photovoltaic integration and grid congestion relief.
- **Grid Monitoring Demonstrations** will support the installation and networking of multiple high-resolution, time-synchronized grid monitoring devices, called phasor measurement units, that allow transmission system operators to see, and therefore influence, electric flows in real-time. "

While Vice President Biden has called for the development of flywheel energy storage to help enable the smart grid, unfortunately the current state of the art systems (proposed) are limited to supplying power to the grid for 15 minutes at a 20 MW level[12]. Larger scale energy storage may require hydro installations, which suffer from relatively slow response times and have significant geographical constraints[13]. Thus, practical energy storage for solar and wind installations could potentially utilize a combination plant involving both flywheels and hydro as proposed in this paper on control algorithms for a Wide Area Energy Storage and Management System[14]. Development of larger scale flywheel systems would reduce the need for hydro energy storage, obviating some of the geographical constraints in energy storage systems.

The economic structure of the utilities which supply electricity to the nation has been focused on power generation and consumption. Utilities operate or lease power from centralized power generating facilities, largely using fossil fuels such as coal, uranium, or natural gas, as

[8] http://www.pewclimate.org/docUploads/wind-solar-electricity-report.pdf
[9] http://cat.inist.fr/?aModele=afficheN&cpsidt=21182214
[10] http://www.eia.doe.gov/neic/brochure/electricity/electricity.html
[11] http://www.energy.gov/news2009/7282.htm
[12] http://www.cleanedge.com/news/story.php?nID=6183
[13] There are currently some 22 GW of hydro storage available. EIA, Annual Energy Review, June 2008, p. 260. Available at www.eia.doe.gov.
[14] http://www.beaconpower.com/files/Regulating_Resources_with_Large_Scale_Wind_Power.pdf

well as some renewable hydro installations. Even renewable energy sources such as solar[15] and wind are often used in centralized power installations, rather than in distributed networks. Consequently, there has been little economic drive to develop more affordable and practical energy storage technologies. Without better energy storage technologies, utilities will be reluctant to ramp up purchases of power produced by solar and wind. Prices for these renewable technologies will remain higher than conventional fossil fuel technologies, putting the US in an unenviable position with regards to global competition in this upcoming industry. More affordable energy storage technologies will make both wind and solar power more attractive on a far larger scale when coupled with better transmission technology.

Comparison of Energy Storage Technology

One energy storage technology that has shown promise is flywheel energy storage. Although originally proposed during the 1970s as potentially replacing the internal combustion engine for personal transportation, the combination of gyroscopic precession and the challenges of containing the flywheel during a collision led to a lack of success in this implementation. Flywheels have been adapted to provide an uninterruptible power supply (UPS) for data server farms, where they successfully replaced the incumbent technology of lead acid batteries and garnered significant market share. Recently, Beacon Power was awarded a $2 million contract to develop 1 MW of flywheel energy storage for frequency regulation in Stephentown, NY, as a pilot for a 20 MW plant[16]. Frequency regulation requires power to be transferred to the grid on a very short time scale (<15 min) to damp out large swings in demand. However, longer term energy storage (hours/days) will require larger composite flywheels than are currently under development for frequency regulation. Larger flywheels have been dismissed as being uneconomical and challenging to manufacture due to the large composite structures required.

Flywheel energy storage[17] has some significant advantages when compared with other energy storage technologies as shown in the table below.

[15] Planned operation of concentrated solar power (CSP) plants in the near term could be far larger than the contribution of solar photovoltaics (PV) to the energy infrastructure as detailed here: http://www.scribd.com/doc/13578809/Solar-Program-Mypp-20082012
[16] http://www.cleanenergycouncil.org/node/4760
[17] This paper covers the theory and provides a diagram for a flywheel used for energy storage: http://infoserve.sandia.gov/cgi-bin/techlib/access-control.pl/1997/970443.pdf

Comparison of Energy Storage Technologies

Technology	Efficiency (losses)	Loss Rate	Cycle Life	Response Time	Technological Maturity	Footprint	Storage Capacity	Environmental Impact	Costs[18] per kW/hr over 10 yrs.
Flywheel	>90%	Very low	Very high	Seconds	Low to medium	Very Compact	100 kW+	Very low	$300 (steel)-800 (composite flywheel)
Compressed Air	Variable	Probably low	Moderate	Minutes	Low to medium	Moderate Volume	100 MW	Probably low	$400-600
Capacitor	Excellent	Moderate	Very high	Seconds	low	Moderately Volume	< battery	Very Low	$250
Battery	Variable	Moderate to high.	Low	Seconds	Moderate to high	Compact	kW	Variable	$150-800 depending on chemistry
Hydro	70-85%	Low (evaporation)	Moderate	Minutes	High	Large, with geographical restrictions	100 MW +	Moderate	~$45-90[19]

As shown in the table above, all energy storage technologies have some flaws. Current flywheel energy storage is limited in size to kilowatts. Larger flywheel installations of 100 mW or larger[20] are needed to make wind and solar more attractive with capacity for longer term energy storage (hours/days.) It is possible that larger units will drive the cost per watt of storage down, but the know how to build larger flywheels does not exist. Aside from the issue of size (and therefore cost), flywheels are quite an attractive solution. Flywheels supported on magnetic bearings have very low frictional losses and can maintain their rpm for energy storage for long periods of time (years). Flywheels can respond quickly to energy demands, and are highly efficient at storing energy- it is unlikely that there will be a more efficient technology since there are so few losses (bearings and air friction primarily). In practice, flywheel installations (using relatively small flywheels) used in data storage farms have been highly reliable and have very low maintenance requirements. When compared to lead acid batteries, these installations have a much smaller footprint, and far less environmental impact. Thus, if a larger flywheel could be developed, it would offer excellent performance for energy storage. Alternatively, if higher strength composites could be developed that would increase the operating range of existing flywheel installations, then the current technology for frequency regulation would receive a performance boost as well, reducing the overall cost of the installation and allowing renewables such as wind and solar to play a greater part in providing power to the grid.

Compressed air for energy storage has been demonstrated at a large enough size (110 mW) to also be considered for energy storage technology. A demonstration plant in Alabama has been in operation since 1991[21]. However, compressing air and releasing it rapidly wastes energy. The overall efficiency of a compressed air plant is dependent on a number of factors,

[18] All costs are taken from this report http://www.sandia.gov/ess/Publications/SEGIS-ES_SAND2008-4247.pdf with the exception of the cost structure of compressed air, reported here http://www.espcinc.com/

[19] From this reference http://www.bizjournals.com/sanfrancisco/stories/2009/02/23/story15.html, the Tennessee Valley Authority estimated that the 21.8 GW of pumped hydro storage cost between $1-2B in 2000..

[20] Current 20 mW proposed flywheel facilities use an array of flywheels. It is probable that to be economical, a flywheel of 1-10 mW capacity would be needed.

[21] http://www.espcinc.com/

often closely tied to an existing coal plant, but it cannot approach the overall efficiency of some other energy storage technologies. Furthermore, the pumps used to compress the air will require maintenance and periodic replacement.

Capacitors or ultracapacitors are currently more expensive than some batteries, have lower energy density and thus larger footprints, and leak charge rapidly. Although capacitors have demonstrated over a billion cycles, it is unlikely without some dramatic breakthrough in fundamental design that capacitors will play a role in energy storage applications.

Battery technology has been under development for over a century, yet new battery chemistries such as lithium iron oxide or lithium magnesium oxide are still technologically immature but already offer excellent charge/discharge efficiencies (~ 90%) and reasonable charge retention. In contrast, lead acid battery technology is technologically mature and is not suitable to play a role in large energy storage technology due to several reasons including cost, limited cycle life, limited recharging efficiency, charge loss over time and posing an environmental hazard. No battery chemistry has demonstrated the cycle life needed for this application at high charge/discharge rates and consequently, without significant breakthroughs, are unlikely to be used.

Hydro power is technologically mature and new pump designs have efficiencies of ~ 95%, and thus offer potential improvements in efficiency over legacy technology. However, there are additional losses in hydro power storage due to evaporation that are a function of local climate which can reduce efficiency to 70-85%. As noted above, the country already possesses some 22 GW of hydro energy storage, but unfortunately, permitting processes for new hydro systems are highly involved due to the large physical size of these installations and their potential impact to the environment[22]. Hydro power siting is quite challenging due to the need for two large volumes of water to be stored at different heights, yet in close proximity. Furthermore, the nature of establishing high mass water flow through a turbine means that rapid response times measured in seconds are not possible using current technology. The large installations and technological maturity of this technology establish something of a benchmark for costs, but costs are highly variable depending on the installation.

If larger composite flywheels could be developed which would reduce the cost of these energy storage installations, this development would alter the current constraints on energy storage (and production) dramatically, and help reduce the nations dependence on coal and imported oil[23].

Current Advanced Composite Technology

For decades, the advanced composites industry primary market has been in aerospace[24]. Most advanced composite development has been driven by either the military market or the commercial aviation market. Research in these composites has been carried out by either defense primes or their suppliers, along with government labs. Thus, composite performance and manufacture has been tailored to meet a relatively narrow set of requirements. The cost structure in this industry has inhibited more widespread use of advanced composites in other industries, and advanced composites remain dominated by the aerospace market. There

[22] http://earth2tech.com/2009/05/18/pumped-hydro-energy-storage-it-takes-a-heck-of-a-long-time/

[23] Much of the debate about the environmental impact of battery powered vehicles is based on coal plants power generation. Replacing coal plants with wind or solar makes the reduced environmental impact of a battery powered vehicle readily observable, thus reducing the demand for foreign oil for current internal combustion powered vehicles. Improvements in battery technology will speed this transition.

[24] Advanced Polymer Composites, BCC Research, P-023U, Samuel Brauer, 2000.

are still alarming gaps in our knowledge base about how to manufacture, repair, and maintain advanced composites. Composites today still fail well before the ultimate tensile strength of the fiber used due to flaws in the manufacturing process.

Most aerospace composites are based on carbon fiber with an epoxy matrix. While this composite is now considered to be reliable enough to be incorporated into a commercial aircraft's primary flight components, it may not be the ideal composite for a flywheel. A variety of other composite materials such as ceramic matrix composites or metal matrix composites may have performance advantages. Given the complexity of the loads on a flywheel, it will likely incorporate several different types of composites. Unfortunately, much of the research on some structurally promising composites such as ceramic matrix composites was halted when it was discovered that these materials possessed a large radar cross section and would thus be unsuitable for aircraft with stealth requirements.

Composites for Flywheels

There have been a variety of flywheel designs and demonstrations over the past few decades. However, most of these academic designs[25],[26],[27],[28] are generally too small for energy storage applications measured in MW, being suitable instead for short term grid load leveling or transportation applications. Although there has been some preliminary work done, knowledge of how to produce a larger composite flywheel in the MW range is still largely unknown.

It is also important to realize that much of the theoretical work done on larger flywheels for energy storage was done before new nanomaterials were developed in the past decade. Nanoengineered ceramic precursors have greatly increased the ductility of ceramics used in composites[29]. Carbon nanotubes offer potentially dramatic increases in tensile strength when coupled with carbon fibers[30] and have been used to reinforce epoxy glass composites commercially[31]. While larger scale flywheels may have been considered impractical several decades ago due to materials limitations, advances in nanoengineered materials may have rendered those assumptions incorrect.

Impact of the Research

Developing composite flywheels for energy storage applications is a daunting task with major challenges in both theory and manufacturing. While it may be possible to develop a successful computer model of a composite flywheel in the MW range, actually producing this flywheel will require the development of new manufacturing technology. Existing composite manufacture has not been required to produce such complex parts with a multitude of different materials in various sections. These parts will also have to be produced on a more cost effective basis than traditional aerospace composites, but have possible economies of scale not found in aerospace with potential part counts in the thousands.

[25] http://garage.cse.msu.edu/demos/index.html
[26] http://www.esm.psu.edu/labs/cmtc/flywheel.html
[27] http://www.utexas.edu/research/cem/Energy%20Storage%20Composite%20Rotor.html
[28] http://www.grc.nasa.gov/WWW/RT/RT1999/5000/5920abdul-aziz.html
[29] http://www3.interscience.wiley.com/journal/114292423/abstract?CRETRY=1&SRETRY=0
[30] http://pubs.acs.org/doi/abs/10.1021/la062743p
[31] http://www.eastonbike.com/TECHNICAL/technical_FAQ-zyvex.html

Industry sectors potentially affected by this research include:

1) Power generation[32] including renewables.
2) Transmission cable manufacturers.
3) Power distribution manufacturers.
4) Composite fabricators.
5) Existing flywheel producers.
6) Fiber manufacturers.
7) Carbon nanotube and other nanoengineered ceramic producers.
8) Computer modelers.
9) Advanced manufacturing developers.

While research in advanced composites for flywheels could potentially impact a number of existing industries, the lack of a defined market has limited corporate research in this area. Prototypes of larger composite flywheels are likely to cost in the millions of dollars, and smaller firms do not have the resources to develop this technology. While the defense primes and sub contractors do have the resources and some of the know how to build large composite parts, energy storage is not part of their core business. Thus, without government funding, research in this area will probably continue to languish.

[32] Although flywheel energy storage makes intermittent power sources such as wind and solar more economical, it also offers a mechanism to allow baseload technologies such as nuclear to operate at constant high levels of power generation which are more economical.