Energy Storage for Sustainable Systems

A White Paper on the Benefits and Challenges of Kinetic Energy Storage

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Opportunity

The search for sustainable energy systems is an effort toward the optimal use of renewable sources. The attributes of those sources and natures of the loads they must serve, however, require that all systems must operate with some way to mitigate the effects of uncorrelated variations in the sources and loads. Several effective solutions have been developed to store the energy produced. Nuclear, hydroelectric, and geothermal plants are generally large and operate with nearly constant output for long periods. Since these plants do not have good capability to react to varying loads, they usually serve to provide power to the base load in a network. In the discussion of this situation, it is useful to establish a basic, consistent vocabulary. The electrical network, or grid, accumulates, i.e. connects together a very large number of individual loads, each of which can be highly variable. This can be expressed:

$$L(T) = \sum l_i(t), \qquad (1)$$

where the summation is over all of the loads on the network. The lower case t is used to denote instantaneous time; while the upper case T is typically measured on a coarser scale of minutes to hours. Traditionally, each $l_i(t)$ can be represented as

$$l_i(t) = l_{iu}(t) + l_{ic}(t), \qquad (2)$$

where $l_{iu}(t)$ is the uncorrelated portion of an individual load and $l_{ic}(t)$ is that part of the load that is correlated with other loads. Correlation occurs because a large number of loads will add lighting when it gets dark or heating when it gets cold, as examples. The implication of this type of load averaging is that:

$$L(T) = \sum (l_{iu}(t) + l_{ic}(t)) = C + F(T), \qquad (3)$$

where C is a constant, representing the base load on the grid, and F(T) is a slowly varying function of time that has obvious daily and annual periodicity. Because electricity has no shelf life, unless actively stored, two strategies have been adopted to cope with load variations. On the short term, variations in individual load $l_i(t)$ are compensated by small changes in system frequency. These variations may also manifest themselves as voltage variations in the vicinity of the varying load. Longer term changes, those represented by F(T), are handled by changes in the number or power level of sources connected to the grid. So, in a stable system:

$$S(T) = L(T), \qquad (4)$$

where $S(T) = \sum s_i$ and s_i is an individual, nearly constant source. Grid operators have also found it cost effective to provide consumers with a financial incentive to give the grid operator the authority and access to disconnect preselected loads to prevent

$$S(T) < L(T). \tag{5}$$

If all else fails, the grid operator imposes rolling blackouts to keep

$$S(T) \approx L(T). \tag{6}$$

Wind-driven or solar power sources introduce a different type of complexity into this mix. These sources are not approximately constant, i.e. $s_i = s_i(t)$. Moreover, variations in the load are generally not well correlated with the source variations. Two approaches have been developed to compensate for this feature. One is to use the grid as a buffer and the other is to use local storage. Small grid-connected wind or solar systems generally take advantage of the fact that they are a very small contributor to either the sources or loads on the grid. Conceptually, being small means that they can be handled as negative loads rather than sources. If an individual unit is as large as 0.5 to 1 MW, the grid operator generally needs to take special cognizance of the installation to address grid protection issues.

As the number of units increases, however, the system behavior becomes volatile. Using the notation of Equation 3, the properties of wind or solar systems are such that, when they are managed as a load, their uncorrelated portion increases $F(T)$ and their correlated portion decreases C, thus increasing volatility. The need to manage this volatility may stimulate the spread of distributed storage and power exchange protocols.

For small isolated grids or stand-alone installations, additional local storage is necessary. These are the cases in which there is little smoothing due to accumulation of loads and, in general,

$$l(t) \neq s(t). \tag{7}$$

The only solution for reliable operation is to have some technique to either store or provide energy to temporally match the load and the source. Assuming that the amount of energy buffered is $\Delta(t)$,

$$l(t) = s(t) \pm \Delta(t). \tag{8}$$

This combination is also useful in a grid application if excess power is provided to the grid or needed from the grid. In this case,

$$s_i = s(t) \pm \Delta(t) \pm l(t). \tag{9}$$

In this case, the storage is selected so that the combination of it, the variable source, and the variable load is a constant.

Microturbines and fuel cells are technologies that show promise of providing additional time to develop truly sustainable sources of power by using existing fuels more efficiently and producing less net pollution. Although some work has been done to develop fuel cells that can react to variable loads, both of these sources work best into a constant load. Today, they tend to power relative small loads and use either batteries or the grid to compensate for load variations.

So it is clear that, today, sustainable sources of energy rely on the fact that the electric grid exists and that it is sustained by fossil fuel plants. This situation is fairly stable when most of the power is provided by a regulated monopoly that is required to accept, and pay for, small amounts of power from other sources as was the situation established by cogeneration regulations. Deregulation, however, changes the whole picture. Initially, in a deregulated power system, some entity attempts to accumulate load connected to the grid, power providers sell power into the grid at negotiated prices, and the grid operator charges for use of the grid.

A basic premise for this approach is equations 3 and 4, which is simply the assumption of a predictably varying load and adequate generation to supply the load. One consequence of this approach is the recognition that it is most profitable to sell power to the grid only when the demand is high. In that way, suppliers can maximize their profit margin. This situation is raising the possibility of further regulation, regulation that could conceivably disadvantage sustainable systems. In this environment, sustainable systems have a better opportunity to contribute if they are temporally reliable and predictable. As indicated by equation 9, to be constant and predictable requires some type of storage. So storage may be important for sustainable systems to be dispatched in the existing grid structure.

With modern communications and metering a different deregulation approach is also possible. It is technically feasible to provide instantaneous trading in electricity with the price depending on the imbalance between supply and demand. This free market approach is being advocated and would provide a significant demand for storage. With appropriate storage, small load centers such as houses or small establishments could provide power to the grid when prices are high while running off of their local storage system. They could then economically extract power from the grid during periods of low cost when supply exceeds demand. As consumers begin to shop for their electricity, the markets will likely open for reliable solar, wind, microturbine, or fuel cell systems, particularly among larger consumers or cooperatives. This will have two effects:

1. It will drive down the cost of sustainable technologies.

2. It will raise the cost of electricity from the grid by removing the larger consumers.

In the absence of government intervention, the market consequence is that more consumers invest in some generation capability until market equilibrium is reached. Early indications are that equilibrium will be one in which there is relatively high volatility to the price of power provided to the grid while the volatility is averaged somewhat for the consumer. This is a situation in which there is both an economic and a technical motivation for energy storage at the source.

Energy Storage Systems

There are three generic ways to store excess energy for later use:

1. Chemical
   The most popular form of rechargeable energy storage today is probably the battery.

2. Mechanical
   Mechanical approaches include pumped storage, in which water is pumped uphill or gas is compressed, and kinetic energy storage in which a rotating mass stores the energy.

3. Electrical
   Both capacitors and inductors are useful for short-term storage, e.g. storage times less than a few seconds. For longer-term storage, inductive storage using a superconducting coil appears to be the most feasible.

While all of these are finding application in the power system today, potential advances in materials, power electronics, and controls show promise for much wider application of mechanical storage using flywheel technology. Similarly, with increasing volume applications, it is likely that electric storage will become more competitive. While improvement will continue to be made in chemical storage, the wide use and long development of this technology makes it less likely, but certainly not impossible, that additional significant advances will occur.

Specific Sample Applications

One application for which storage is important is on the International Space Station. The primary power source is solar power, but the station must continue to operate while in eclipse. The initial design uses battery storage, but an interesting alternative system is under development by NASA. This system uses an integrated flywheel, motor, and generator as a “flywheel battery”. A conceptual drawing is shown in Figure 1.

The flywheel battery has some interesting attributes that make it attractive on the space station and elsewhere. It fits in the same space as the chemical batteries that is replaces. It is lighter than the chemical batteries. The rated life of the flywheel batteries appears to be at least three times longer than the chemical batteries that it is to replace. It can power the load for twice the time as a chemical battery without recharging. Finally, the state-of-charge of the flywheel battery is always known; it is merely the rotational velocity.

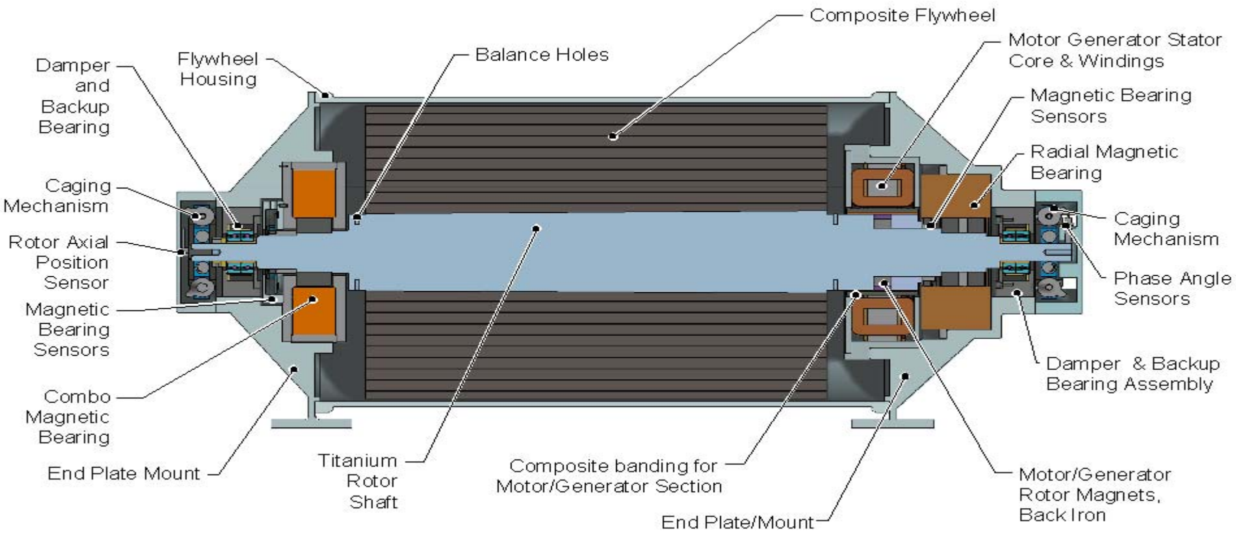

Figure 1: Design drawing of a flywheel battery.

Each of the flywheel units will store in excess of 3.5 kWhr and can deliver a deliver peak power of more than 3.5 kW. Each unit is designed to fit within an existing battery box. The weight of a motor, generator, and flywheel assembly is less than 275 lbs. If all of the battery boxes are replaced, 48 flywheels will be used and they will be capable of producing more than 150 kW. NASA estimates that more than $200 million will be saved if flywheels replace the first generation of space station batteries. The system is also reasonably efficient, as shown in Figure 2. The losses in cycling through a charge and discharge cycle are largely due to residual eddy current and hysteresis losses in the magnetic bearings and the motor-generator.

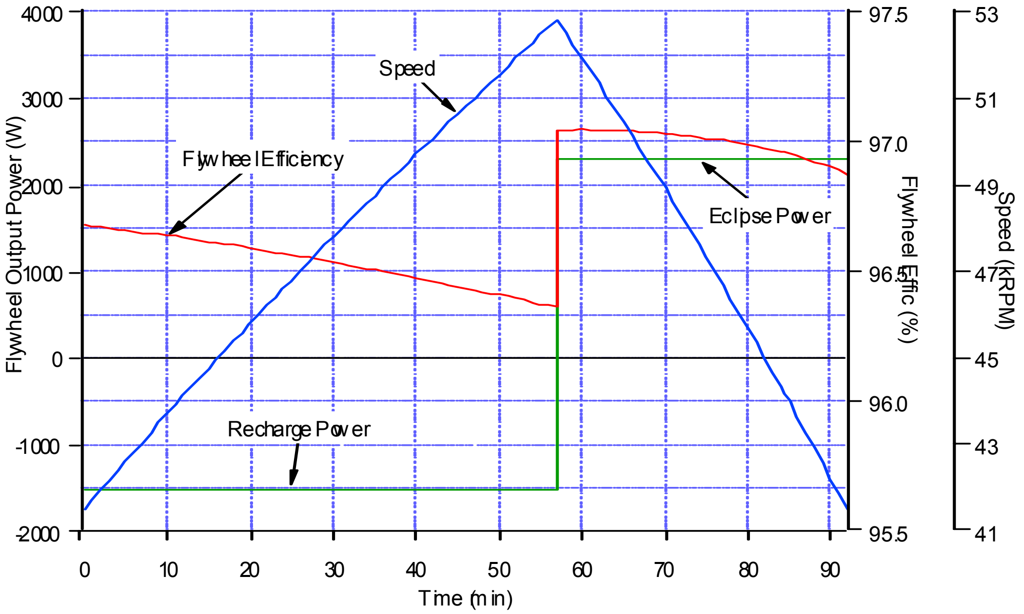

Figure 2: The calculated speed and efficiency of a flywheel battery during one earth orbit. The net efficiency of the charge-discharge cycle is 93.7%.

Flywheel batteries are currently also being adopted for terrestrial utility applications. The initial commercial application is as part of an uninterruptible power supply. The role of the flywheel battery is, in the event of a power failure, to provide sufficient power to give time for a diesel generator to come up to operating speed. These are important outages, but long outages are relatively infrequent.

Data provided by the Electric Power Research Institute suggests that about 88% of the interruptions are less than one second long. This duration, coupled with the power needs of most critical loads, provides an excellent match with the properties of flywheel batteries alone.

Superconducting magnetic energy storage systems (SMES) are being marketed to grid operators to improve system reliability and to protect against the low voltage conditions that result when the load exceeds the system supply. Typical commercial units store about 1 kWhr and deliver about 3 MW. While they do not typically have the energy or power density capacity of flywheel batteries they have found good use in utility applications where physical space is not at a premium.

These applications are interesting in their own right as adjuncts to renewable sources. The state of development of both flywheel batteries and SMES suggests that cost savings are possible with additional technical development. Today, chemical batteries have a tremendous economy of scale that has driven down cost. The other two technologies may still benefit from such growth. The following table summarizes some attributes of lead acid batteries, flywheel batteries, and SMES.

Table 1. Comparison of Lead-Acid Batteries, Flywheel Batteries, and SMES

	Lead-Acid Battery	Flywheel Battery	SMES
Storage mechanism	Chemical	Mechanical	Electrical
Life (years in service)	3 – 5	>20	~20
Technology	Proven	Promising	Promising
Number of Manufacturers	~ 700	~ 5	~1
Annual Sales ($ in millions)	~ 7000	~ 2	A few
Temperature Range	Limited	Broader, but still limited	Controlled
Environmental concerns	Disposal issues	Small	Small
Relative size (equivalent power/energy)	Larger	Smallest	Smaller
Maximum time to hold a charge	Years	Hours	Days
Price ($/kW)	50 – 100	300 – 400	>300

As the table suggests, today lead-acid batteries have about one fourth the cost and one fourth of the service life of flywheel batteries. So, on a life cycle cost basis, the two approaches are approximately competitive. If the power quality applications spur significant growth, there are likely to be economy of scale benefits yet to be realized by flywheel batteries. This could make the technology more affordable for sustainable applications.

Research Needs for Flywheel Batteries

The research required to exploit mechanical storage falls into three categories.

- Flywheel Materials

  Flywheels are typically made of nested composite rings because of the high strength that can be achieved in composite materials. Materials research is needed to reduce manufacturing cost for these composite rings while assuring a quality product, to increase strength, and to predict a safe life. In particular, *in situ* cure monitoring could increase the reliability of manufacturing rings as would appropriate nondestructive evaluation techniques keyed to the particular failure mechanisms of rotating devices. The discovery of higher strength composite materials could provide higher safety margins, allowing greater manufacturing latitude. Alternatively, the additional strength could be used to make smaller lighter machines. Finally, these materials are subjected to thermal and mechanical cycling for years. Safe life testing approaches, models, and design criteria need to be developed.

- Magnetic bearings

  The need for higher power and energy density is pushing flywheel batteries to higher rotational velocities. Magnetic bearings have very low losses and can operate at the required speed. A key impediment to wider use of magnetic bearings is the lack of data on the magnetic and fatigue properties of the laminates at the frequencies of interest. A fundamental challenge is that the magnetic and mechanical properties of an alloy likely optimize with different grain structures.

- Power conditioning

  Power conditioning today is driven primarily by what power semiconductors are available. Work needs to be done at the system level to optimize the voltage and current waveforms produced by the primary source, required by the load, required by the magnetic bearings, required by the motor, and produced by the generator. Then power semiconductors and packaging schemes need to be developed to produce, and convert power among, these optimized waveforms for the various sources and loads.