APPLIED PHYSICS

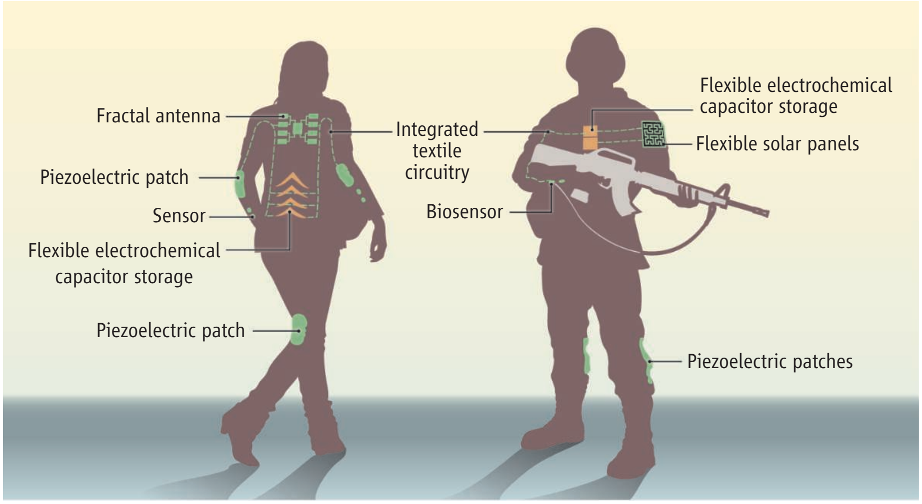
Valuing Reversible Energy Storage

A process based on laser-converted graphene is used to fabricate high-value energy storage material.

John R. Miller

The development of new materials that provide the capability of high-performance energy storage combined with flexibility of fabrication opens up the possibility of a wide range of technological applications. On page 1326 of this issue, El-Kady *et al*. (*1*) describe thin and highly flexible electrochemical capacitors (ECs) that were created by means of a very simple and innovative process. Unlike the usual approaches of making thin graphene electrodes that start with a particulate and use roll-coating, screen printing, or ink-jet printing (*2*), their process involves focusing a low-power laser onto a thin graphene oxide deposit to convert it into graphene. The incorporation of graphene in electrodes created with mechanical processes tends to be in agglomerates that provide little performance advantage over traditional particulate-activated carbon electrodes. El-Kady *et al*.'s approach also contrasts with plasma-assisted chemical vapor deposition processes that have been used to grow vertically oriented graphene nanosheet electrodes (*3*). Although graphene structures grown by such methods are well-formed and offer performance advantages over traditional activated carbon materials, they require complicated vacuum process equipment, plus the graphene growth rate is very slow (*4*). The somewhat simple EC electrode fabrication process reported by El-Kady *et al*. therefore appears to circumvent many of the difficulties encountered with traditional processes.

Whenever a new energy storage technology is reported, almost inevitably the first question asked and the first data cited focus on its "watt-hours per kilogram" (Wh/kg) value. This measure refers to specific energy, a metric that dates historically to the days when heavy batteries provided almost the only means available to store electrochemical energy. Despite, and almost in defiance of, the emergence of newer energy storage technologies, however, specific energy continues to be referenced without further consideration as the most important characteristic of any new energy storage technology, the gold standard of its worth or value (*5*). This is all wrong—specific energy is only one of many metrics by which the value of storage technology can be measured. Indeed, it may be one of the least important when it comes to assessing its value for use in today's newest and most innovative applications (*6*).



Power dressing. Design concept for self-powering "smart" garments, outfitted with piezoelectric patches to harvest energy from body movements and flexible electrochemical capacitors to store the energy. Power to camouflage uniforms is one possible use.

Usually the second question asked is the cost, the most popular metric being "cost per unit of energy" ($/kWh). The table lists the three types of capacitors and two different battery technologies, using dollars per kilowatt-hour as the cost metric (*7*). The value for electrostatic capacitors (metalized-film capacitors) is $2.5 million per kWh. Electrolytic capacitors cost $1 million per kWh. Curiously despite such extremely high costs, both technologies are found in almost every piece of electronics available today. Much lower in cost, at a mere $20,000 per kWh, are ECs (*8*). But the stark comparison to lithium-ion batteries at $1000 or lead acid batteries at $150 per kWh suggests that $/kWh is not actually a very important metric in some decision-making. Cost is but one of the many ways by which storage technology can be measured, and again it may be one of the least important when it comes to assessing the value of an energy storage technology for use in applications.

DEVICE PRICE LIST

Technology	Cost ($/kWh)
Electrostatic capacitor	2,500,000
Electrolytic capacitor	1,000,000
Electochemical capacitor ("super" or "ultracapacitor")	20,000
Li-ion battery	1000
Lead acid battery	150

Reversibility, essentially the efficiency of a round-trip cycle that first stores then later uses the stored energy, is also an important metric for energy storage technology in many present and emerging applications. Unlike money that may be deposited in an honest savings bank that later is totally returned and often with interest, energy deposited in any storage device has associated losses that prevents the full return. Then the question is what fraction of the deposited energy will eventually be returned. This strongly depends on the storage media as well as the rate at which energy is stored, the storage time, and the rate at which energy is extracted (*9*). Unlike batteries that typically have higher losses during charge than during discharge, ECs can be totally charged and discharged very quickly with high efficiency. Energy reversibility is often a most important factor in establishing the value of a storage technology for many of today's energy conservation applications.

Cycle life goes hand-in-hand in importance with energy reversibility. Some energy

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conservation applications, for example, regenerative energy capture during the stopping of a hybrid city transit bus, may require more than 1 million charge/discharge cycles during their operational life. A storage system can be replaced several times or "supersized" to reduce the depth of discharge in each cycle and increase cycle life, practices commonly used for battery technologies. However, both approaches mean that the storage system will have higher cost. ECs, by contrast, rely on physical rather than chemical storage and do not suffer from limitations of cycle life. They effectively can be "right-sized" at the start and last the entire life of a given application. In short, cycle life can impart great value to an energy storage technology.

Storage system shape is another factor that may have high value in some applications. Energy density advantages generally can be best achieved with shapes approaching a cube, whereas power density advantages can be best achieved with thin, large-area designs. A given energy storage technology may lend itself to either one of these extremes. Besides offering power advantages, very thin energy storage devices may enable a broad range of new applications. If these devices have mechanical flexibility, then there are even more potential applications. One example is a fabric EC that is charged by piezoelectric transducers that harvest and store body-movement energy. This would allow the creation of "smart" garments for making fashion statements or to power flexible electronics that may be embedded in a military uniform (see the figure). Other examples include energy storage for use in camouflage, for car interiors, and to make electronic wall paper.

An interesting feature of the conversion process reported by El-Kady *et al.* is that graphene patterns can be "laser scribed" directly onto very thin graphene oxide deposits (*10*). As one example, interdigitated planar structures of graphene can be created, which after receiving an electrolyte overcoat become planar ECs. This route for producing extremely thin and highly flexible energy storage structures is quite exciting and shows great promise.

References and Notes

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7. Capacitor costs were derived by using the largest commercial products available.
8. ECs are sometimes referred to by the product names supercapacitor or ultracapacitor.
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AIDS/HIV

HIV Interplay with SAMHD1

A protein that controls nucleic acid metabolism affects the balance between HIV infection and immune responses.

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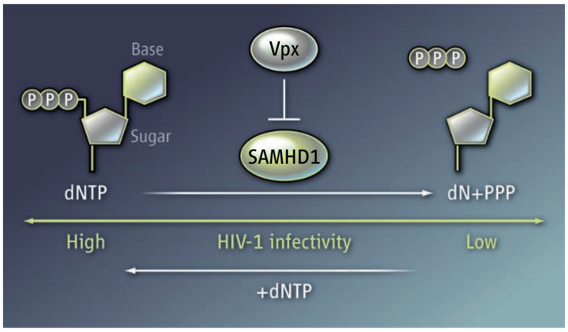
New insights into the complex interplay between human immunodeficiency virus (HIV) and simian immunodeficiency virus (SIV) and their primate hosts are being gleaned from studies of viral accessory proteins. It is now apparent that these proteins (which are often dispensable for replication in cell culture) frequently antagonize host innate and adaptive immune responses. In several cases, accessory proteins repress specific host cell inhibitors of infection known as restriction factors (*1*). That the genes encoding restriction factors have been subjected to Darwinian selection pressure suggests the evolutionary importance of their function (*2*, *3*). These general themes have recently been reprised through studies on the Vpx accessory protein of HIV-2/SIV_{smm} and the discovery of its host cell target called sterile alpha motif (SAM) and histidine/aspartic acid (HD) domain–containing protein 1 (SAMHD1).

Cells of myeloid origin (including dendritic cells and monocytes) are often poorly permissive for HIV-1 infection compared to activated CD4+ T cells. HIV-1 infectivity can be increased by introduction of the Vpx protein of HIV-2 and some SIV strains (*4*). Similarly, Vpx-deficient strains of HIV-2/SIV_{smm} are much less infectious in myeloid cells than wild-type viruses. The Vpx-mediated enhancement of infectivity correlates with the increased accumulation of viral cDNAs (*4*), key intermediates in the replication of retroviruses.

The *vpx* gene most likely originated by recombination or duplication of *vpr*, a related gene in primate lentiviruses whose contribution to HIV-1 replication and pathogenesis remains uncertain. Vpx and Vpr engage cellular ubiquitin ligase complexes (which modify proteins, among other activities, for destruction by proteasome), providing the rationale for seeking cellular Vpx/Vpr binding partners as candidate regulators of HIV and SIV replication. Last year, SAMHD1 was defined as a target for Vpx: As predicted, SAMHD1 is degraded by the proteasome in the presence of Vpx, and its depletion from myeloid cells promotes more efficient HIV-1 infection (*5*, *6*).

More recently, in vitro enzymatic assays demonstrated that the dimeric SAMHD1 core domain has 2′-deoxyguanosine 5′-triphosphate (dGTP)–stimulated deoxynucleoside triphosphate (dNTP) triphosphohydrolase activity and converts dNTPs to deoxynucleotides (dNs) and triphosphate (*7*, *8*). By showing that Vpx expression or SAMHD1 depletion each increases the amount of dNTPs in macrophages, and that the extracellular addition of dNs to macrophages enhances HIV-1 infection (*9*), a model has emerged in which SAMHD1 inhibits HIV and SIV infection of myeloid cells by elimi-



Restricting HIV infection. SAMHD1 regulates dNTP concentrations and HIV-1 infection in myeloid cells. The viral accessory protein Vpx blocks SAMHD1, targeting it for destruction by proteasomes. PPP, triphosphate

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