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Investigation of Synergy Between Electrochemical Capacitors, Flywheels, and Batteries in Hybrid Energy Storage for PV Systems

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Abstract

This report describes the results of a study that investigated the synergy between electrochemical capacitors (ECs) and flywheels, in combination with each other and with batteries, as energy storage subsystems in photovoltaic (PV) systems. EC and flywheel technologies are described and the potential advantages and disadvantages of each in PV energy storage subsystems are discussed. Seven applications for PV energy storage subsystems are described along with the potential market for each of these applications. A spreadsheet model, which used the net present value method, was used to analyze and compare the costs over time of various system configurations based on flywheel models. It appears that a synergistic relationship exists between ECs and flywheels. Further investigation is recommended to quantify the performance and economic tradeoffs of this synergy and its effect on overall system costs.

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Acronyms and Abbreviations

ATTB	Advanced Technology Transit Bus
CMOS	complementary metal-oxide semiconductor
DARPA	Defense Advanced Research Projects Agency
DOE	U.S. Department of Energy
EC	electrochemical capacitor
EPRI	Electric Power Research Institute
EV	electric vehicle
HEB	hybrid electric buses
HEV	hybrid electric vehicle
NASA	National Aeronautics and Space Administration
NPV	net present value
NREL	National Renewable Energy Laboratory
PNGV	Partnership for a New Generation of Electric Vehicles
PV	photovoltaics
RFQ	request for quote
T&D	transmission and distribution
TSI	Tribology Systems, Inc.
UPS	uninterruptible power supply
VRLA	valve-regulated lead-acid

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1. Preface

The focus of this study was an investigation of the synergy between electrochemical capacitors (ECs) and flywheels in combination with each other and with batteries as energy storage subsystems in photovoltaic (PV) systems. The focus was driven partly by economics; the high cost of available ECs precluded their use as direct replacements for lead-acid batteries in virtually all applications that require moderate to high energy densities. Thus, this study focused on how the unique capabilities of ECs (fast response, longevity, tolerance of temperature extremes, etc.) could justify their use in combination with other storage media. During the course of the study an emerging EC technology was identified that may be available at a cost low enough to challenge the initial high cost assumptions for ECs. If the new technology delivers on its potential, both for energy storage and cost, ECs could become a viable replacement for lead-acid batteries in certain applications.

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2. Introduction

Sandia request for quote (RFQ) BD-0005 was directed at the first phase of a possible multiphase research project to identify user needs and application requirements for improved integration of renewable energy generation technologies with energy storage systems. In response to this RFQ, a team headed by Solarex proposed to investigate the feasibility and potential of using ECs and flywheels, either singly or in combination, as energy storage media in PV power systems.

Three-quarters of the PV systems deployed today use batteries as storage, despite the fact that in many of these systems batteries have known drawbacks, most notably:

- The poor life span match between batteries and PV. In a typical system, the battery bank is replaced three or four times in the first 20 years of the PV array's life. Replacement is expensive, not just in purchase price, but in transportation and installation.
- The incompatibility of remote sites (common for PV systems) and batteries' maintenance requirements and weight.
- Their comparatively poor (approximately 50%-70%) energy efficiency in a PV system.
- The safety and environmental considerations, detailed later in this report.

These drawbacks illustrate the technology "gap" (in terms of the RFQ), where battery systems do not truly meet the needs of existing applications and, additionally, have not been broadly adopted by emerging applications such as standby power and transmission and distribution (T&D) support stations. This study looks at those systems as potential applications for new storage systems, and investigates the possibility of these new media broadening the applicability of PV power to applications not presently served.

Team member JME provided information on ECs and identified ESMA (a Russian company) as a possible source of low-cost "traction" capacitors. Team member Tribology Systems, Inc. (TSI) provided information on flywheels and TSI flywheels were used as representative models in this study. Preliminary analysis suggests a synergy between ECs and flywheels. ECs respond very quickly to changes in input and load, which complements the low-loss storage capability of the flywheel. Both are virtually maintenance free, potentially expanding PV's already significant penetration of the remote power market. Further, both are environmentally benign.

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3. Storage Technologies

This section describes the energy storage technologies investigated with respect to their general characteristics as storage media in PV systems.

3.1. Flywheels

Flywheel development has been directed primarily at two areas: vehicular propulsion and storage as part of an electrical system. Flywheels are particularly compatible with electric and hybrid electric vehicles (EVs and HEVs), where they can serve as a primary storage medium or as a surge power source enabling enhanced vehicle acceleration and battery life. They are also compatible with the regenerative braking systems common to these vehicles. They have been investigated for vehicular purposes since the late 1960s, when Oerlikon operated several buses in South Africa utilizing flywheels as primary propulsion.

The technology advanced significantly with the development of carbon composite materials for the rotor. Replacing steel, these materials provide more strength with less weight, and greatly reduce the risks previously associated with rotor disintegration. Various prototypes that employ composite rotors are presently in use, including one in a BMW demonstration vehicle. Another prototype is to be installed in an EV presently being tested at Hanscom Air Force Base in Massachusetts.

Flywheels are also being developed or are in prototype demonstration for several modes of use in electric systems.

- A flywheel manufactured by Trinity Flywheel of San Francisco is intended to provide power smoothing, covering the variations in grid power that can disrupt sensitive equipment, and to provide short-term backup power in an outage.
- Team member TSI provided a prototype, production-size flywheel (see Figure 1) for telecommunications backup power to Bellcore. TSI participated with the regional Bell Telephone Operating Companies developing the generic requirements for back-up telecommunications power units to be purchased for beta sites in the next few months and for widespread deployment next year. Prices for production quantities up to one million annually have been quoted.

Figure 1. TSI Bellcore flywheel.

- TSI's recent application to flywheels of solid-lubricated, hybrid-ceramic bearings and sliding surfaces greatly reduced flywheel cost in comparison to designs that use magnetic bearings. This breakthrough evolved from TSI technology and products developed over three decades.^{1,2,3} These bearings are used not only in TSI's own flywheels, but as primary or backup bearings in wheels made by United Technologies Corporation, including the units in the BMW and Air Force vehicles described above.
- Fifteen hybrid diesel-electric buses with flywheel storage and regenerative braking have been in use in Europe since 1988.⁴ These magnet motor units store 2 kWh with 150 kW peak output. The oldest of these buses has traveled 180,000 km and its flywheel has achieved 250,000 cycles.

As these and other projects demonstrate, flywheels are much further along the development curve than ECs, particularly those ECs used in a slow-discharge energy storage mode. With one exception (Russian "traction" capacitors), large capacitors developed to date have focused primarily on fast power response, not on energy storage. The performance parameters and economics of ECs with the characteristics needed for energy storage in PV systems are basically unproven.

¹ Sibley, L.B., and Allen, C.M. "Friction and Wear Behavior of Refractory Materials at High Sliding Velocities and Temperatures," *Wear* 5, 312-320 (1962).

² Taylor, K.M., Sibley, L.B., and Lawrence, J.C. "Development of a Ceramic Rolling-Contact Bearing for High-Temperature Use," *Wear* 6 (3) 226-240 (1963).

³ Sibley, L.B. "Silicon Nitride Bearing Elements for High-Speed High-Temperature Applications," Paper No. 5, NATO/AGARD Conference Proceedings No. 323 on Problems in Bearings and Lubrication (1982).

⁴ Belanger, M. "Flywheels for Energy Storage Applications," 6th International Seminar on Double Layer Capacitors and Similar Energy Storage Devices (1996).

3.1.1. Advantages in PV Systems

Advantages and disadvantages of both flywheels and electrochemical capacitors in PV systems are defined primarily by comparing them to the present storage standard, the lead-acid battery. Although other batteries and other energy storage systems, such as hydraulic storage, compressed air, and hydrogen generation are used in PV systems, the storage workhorse of PV systems is the lead-acid battery.

Much flywheel research has focused on use in vehicles and spacecraft, leading to an emphasis on minimizing the size and weight of the unit. Thus, much work has been directed at high-speed (up to 90,000 rpm) units, which theoretically require magnetic bearings for longevity. This work has not been fully successful to date.

The size and weight constraints of the typical PV system are far less severe. While transportation is certainly a consideration for many sites, present components (e.g., batteries) are heavy and fairly large. Because the flywheel rotor may be heavier for such systems, rotational speed may be less, and such units are farther along the development curve than high-speed wheels. The TSI wheel turns at 30,000 rpm, and has demonstrated longevity and reliability using ceramic bearings. This wheel represents the state of the art for this technology and is used as a representative flywheel in this report.

3.1.1.1. Compatibility with Remote Sites

The present, and to a greater extent, the projected characteristics of flywheels make them exceptionally well-suited to the remote locations that are typical of PV power systems. In part, this is because they share many of the characteristics of the PV module. These characteristics are discussed below. Flywheels are just beginning the prototype deployment stage in remote sites. Assuming the experience is favorable, it is probable that they will assume a major energy storage role in remote power.

Lead-acid batteries are widely used but, because of their maintenance needs and replacement frequencies (every 2 to 7 years depending on various factors), are a poor fit to many remote power systems, especially when compared to the PV component. Additionally, lead-acid batteries are expensive to transport and install, use hazardous materials, can be damaged by misuse or poor maintenance, and may generate hydrogen gas.

3.1.1.2. Longevity

Performance of prototype flywheels at TSI facilities and computer modeling suggest a life expectancy for TSI flywheels longer than 20 years for most applications. One TSI unit has been in operation since the 1950s without relubrication.⁵ Present fatigue design criteria are for 100,000 charge-discharge cycles per year⁶, which, at one cycle per day, equates to a 274-year life span. The calculated L10 life (the period over which 10% of units would be expected to fail) is 90 years.

⁵ Letters from Lewis B. Sibley of TSI to Bill Rever of Solarex. July 28, 1998 and May 5, 1999.

⁶ Sibley, Lewis B. "Advanced Technology Ceramic Bearings in the Flywheel Systems at World Flywheel Consortium." Presented at the Flywheel Energy Storage Workshop, Oak Ridge, TN. 1995.

The L10 life is calculated using the equation:

$$L = a_1 \times a_{SKF} (C/P)^3$$

Where a_1 is 1 (indicates “very clean” operating conditions) for 90% reliability, C is the basic dynamic load rating for each bearing size (based on the manufacturer’s specifications), P is the equivalent load on the bearing in service, a_{SKF} is 37 (calculated from manufacturer’s specifications). Therefore,

$$L = 37 \times 40^3$$

or 2,368 billion revolutions. At a typical 50,000-rpm continuous mean rotor speed,

$$L = 2368 \times 10^9 / (50000 \times 60 \times 8760)$$

or 90.1 years. In comparison, the batteries of a PV system require replacement at least three times, and as frequently as six times (depending on severity of cycling and thermal stresses) over what PV designers have considered the nominal lifespan of a PV system—20 years.

As experience with deployed PV systems has accumulated, major module manufacturers have gained confidence in the ability of their products to exceed this lifespan. Siemens recently extended the warranty period on their large modules to 25 years. Solarex has introduced a new series of large modules, the GSX series, with a 30-year warranty.

Furthermore, the failure mechanisms of deployed PV modules are, in general, either “infancy” failures or long-term gradual output degradation, which is not a true “failure,” although it may eventually cause inability to support the load. After infancy, modules are likely to function effectively for at least 30 years. As the PV industry has matured, the causes of infancy failures (thermal cycling of interconnects, material incompatibility, water migration, etc.) have been identified and corrected, and the failure rate has been dramatically reduced.

It is appropriate, therefore, to consider a lifespan longer than 20 years for PV systems and their components. Most of the comparisons in this report are based on a 30-year system life.

3.1.1.3. Lack of Maintenance

For all intents and purposes, the TSI flywheel is maintenance free as a result of its hybrid ceramic bearings and solid lubrication system. Alternative bearing systems are either very expensive (magnetic bearings) or incompatible with operation in a vacuum. Conventional bearings require periodic lubrication, typically with volatile petroleum-based lubricants that contaminate the vacuum.

In contrast, lead-acid batteries require inspection and terminal cleaning and some require watering between two and twelve times a year, depending on cycling and thermal climate.

3.1.1.4. Insensitivity to Deep Cycling

Even the best deep-cycle batteries suffer from shortened lifetimes if they are cycled beyond their specified depth-of-discharge limit, or are cycled frequently. These limitations force system owners and designers to trade off reliability against cost, either by using an oversized battery to ensure continuous power to the load or by including a low-voltage disconnect circuit that protects the battery but sacrifices the load.

Repeated overdischarge is catastrophic to a lead-acid battery, but flywheels are unaffected by it, both structurally and in terms of longevity and regardless of discharge frequency. This characteristic frees the system designer from the costly sizing/disconnect consideration above.

3.1.1.5. Surge Capability

The ability to respond to demand surges can be both a positive and a negative characteristic of a flywheel, depending on the design of the flywheel, the duration of the surge, and the criticality of the load's power requirement.

Figure 2 illustrates the specific power vs. specific energy (P/E ratio) of a number of current flywheel designs, and the characteristic durations associated with the P/E ratios.

Figure 2. Ragone plot for P/E ratios of current flywheels.

The flywheel's characteristic duration—the minimum period in which a device can deliver approximately 63% (the $1-1/e$ value) of its capacity to a

load⁷—varies from approximately 18 seconds for a wheel with a P/E ratio of 200 to approximately 360 seconds for a wheel with a P/E ratio of 10. Some storage media are less efficient for surge (high power) requirements shorter than approximately 5 times their characteristic duration.

As Figure 2 shows, most development work has concentrated on flywheels capable of fast response, a characteristic necessary for vehicular applications and any other application where the wheel must cope with a load that may vary rapidly. It does not illustrate the characteristics of wheels that could be designed specifically for PV systems, which could have durations on the order of an hour and P/E ratios well below 10. Such wheels, and the lower P/E wheels, illustrated, could not respond well to short-term demand peaks, particularly if the peaks required good power regulation.

Although PV battery banks generally have the ability to meet demand surges, if the surge is sufficiently large and repeated it will shorten the life of the battery bank. In systems that anticipate such surges, adding a fast-response flywheel or a capacitor to the power system may improve overall power quality and extend battery life.

3.1.1.6. Tolerance of Ambient Temperature Extremes

With solid lubricant, TSI flywheels are unaffected by any terrestrial ambient temperature, in terms of efficiency, longevity, and storage capacity.⁸

Battery capacity and life is typically optimized for, and rated at an operating temperature of 25°C, and a significant variation from that temperature compromises operating life or storage capacity. Manufacturers' literature indicates that a battery's rated life is reduced by half if it is operated continuously at 35°C, and that batteries fail very quickly if operated above 50°C. Battery capacity is reduced by approximately half (from rating) at 0°C.

A discharged battery may be destroyed by subfreezing temperatures. At 80% depth of discharge battery electrolyte freezes at -10°C, resulting in permanent damage to the plates and case. A fully discharged battery freezes at only slightly below 0°C.

3.1.1.7. Lack of Environmental Impact

Batteries use hazardous materials—among them lead, sulfuric acid, and cadmium—and thus present environmental concerns that must be addressed during their manufacture, use, and disposal. The materials used in flywheels have less environmental impact.

Safety concerns about containment of flywheel components in case of catastrophic failure have been addressed by several projects and studies, the most recent being a Defense Advanced Research Projects Agency (DARPA)

⁷ **Note:** Not all flywheel developers use 63% as the cutoff level for energy extraction. Varying this percentage will affect the flywheel's spin down time.

⁸ Sibley, L.B. "Silicon Nitride Bearing Elements for High-Speed High-Temperature Applications," Paper No. 5, NATO/AGARD Conference Proceedings No. 323 on Problems in Bearings and Lubrication (1982).

project that included extensive analysis in conjunction with the National Renewable Energy Laboratory (NREL).⁹

The high kinetic energy of a bursting flywheel is expressed almost entirely as high circumferential rubbing speeds when fragments centrifugally impact the containment housing. The containment system of the TSI flywheel used in this study is based on multiple burst tests (in all of which the rotor was completely contained) and advanced computerized testing.¹⁰ Additionally, in many PV applications the flywheel can be buried, which provides redundant protection in case of flywheel failure.

3.1.2. Disadvantages in PV Systems

A flywheel's disadvantages in a PV system are few but significant: cost and the development status of the technology. Substantial progress has been made since the 1960s, but current designs have yet to undergo the ultimate test of long-term deployment. Experience with PV systems indicates the potential for presently unidentified remote-site problems with the flywheel itself and the electronics that control power input and output.

3.1.2.1. Cost

Team member TSI configured four representative flywheel models in various sizes to meet the requirements of the specified systems. As with batteries, these units would be used in multiples to provide the exact amount of energy storage required for a specific system.

Table 1 shows the development costs and several production volume and timing assumptions for each of the representative models. These costs are based on TSI's knowledge of the economics of flywheel development and volume production costs associated with TSI's own flywheel technology. The comparisons between storage technologies are not adjusted for inflation or other time effects. The production volume figures are fairly aggressive estimates of total annual volume for all markets, not just those associated with PV. This report addresses life-cycle issues, inflation, and other time effects using the net present value (NPV) method described in Section 5.1.

⁹ Sibley, L.B. "Design Optimization and Proof Testing of Safety Containment Systems for Flywheel Energy Storage Systems," Final Report on Subrecipient Agreement No. MARCAV 9602-12 of DARPA Contract MDA 972-95-3-0019 (1998).

¹⁰ Sibley, L.B. "Design Optimization and Proof Testing of Safety Containment Systems for Flywheel Energy Storage Systems," Final Report on Subrecipient Agreement No. MARCAV 9602-12 of DARPA Contract MDA 972-95-3-0019 (1998).

Table 1. TSI Flywheel Production and Development Cost Estimates

	Flywheel Model & Usable Capacity			
	0.5 kWh	2.5 kWh	25 kWh	200 kWh
Development Cost	Negligible	\$150,000	\$350,000	\$500,000
First Unit Cost	\$35,000	\$65,000	\$275,000	\$450,000
Production Start in:	Cost			
	Annual Production Quantity			
1 year	\$2200 50-80K	\$9800 30-50K	(1)	(1)
3 years²	\$1000 300-500K	\$6800 200-300K	\$50,000 40-60K	\$210,000 3-4K
5 years²	\$750 600K-1M	\$3200 400-600K	\$21,000 80-100K	\$90,000 8-10K
10 years²	\$500 3-5M	\$1000 2M-3M	\$8700 400-600K	\$55,000 40-60K
Lowest \$/kWh	\$1000	\$400	\$348	\$275

1. Development time precludes production start in 1 year.

2. Estimates for 3 years and longer are conservative; cost could be less if volume levels are met.

The smallest unit (0.5 kWh) requires little development and could be ready for production in less than 1 year, with an initial cost, assuming production of 50,000-80,000 units per year, of \$2200. Under the 10-year, high-volume (3 to 5 million annually) assumption, these units are projected to cost \$500 or less each, equating to \$1000 per kWh.

The largest models (25 and 200 kWh) require substantial development work, estimated at 12 to 18 months; thus, no 1-year production figures are given for them. As would be expected, the largest unit, the 200-kWh model, is projected to provide the least expensive storage—\$275 per kWh under the 10-year, high-volume assumption. Under the 1-year production case, the smallest unit (0.5 kWh) provides the most expensive storage at \$4400 per kWh.

In comparison, high-quality lead-acid batteries cost approximately \$100 to \$120 per kWh. They may not, however, be fully discharged without shortening their usable life. Assuming 50% of their nominal capacity is used, their effective cost increases to \$200 to \$240 per kWh. Thus, using the 10-year production models, the projected cost of flywheel storage ranges from a high of five times as much as batteries to almost equal to that of batteries. In the short term (1 year), flywheel storage is much more expensive, up to 20 times more expensive for the smallest units.

These storage costs are based on TSI's estimates for *production* units, not prototypes. The pilot production units will be substantially more expensive than production units due to material volume considerations and the cost of custom machining and other labor-intensive production steps. These costs are reflected in the *First Unit Cost* entries in Table 1.

3.1.2.2. Reliability

Although, as described above, calculations of predicted flywheel lifetimes are impressive and supplement laboratory and prototype experience, long-term remote deployment is the ultimate test. The PV industry knows from experience that deployment tests the system as a system, in situations where failure of one component means total system failure.

In particular, the flywheel's control electronics require field testing. The rigors of remote-site systems—lightning, animal damage, substandard transportation, marginal installation, etc.—can wreak havoc on PV control systems that appear bulletproof on the design board.

3.1.2.3. Surge Capability

As previously mentioned, wheels designed specifically for PV systems (and any wheel with slow characteristic response time) cannot respond well to short-term demand peaks if the peaks require good power regulation. Although the flywheel has sufficient energy to meet the peak, its control electronics must respond almost instantaneously to some loads (e.g., computers) to maintain nominal operation.

In addition to response time and power quality considerations, a flywheel's electrical response is limited by the size of its power-handling conductors. Motor-generator windings must be sized to handle surge requirements, which could be impractical for some loads. Additionally, the heat generated by any component inside the containment vessel presents a dissipation requirement. For these reasons, an EC may be a worthwhile addition to many remote power storage systems, particularly those which could have substantial surge requirements.

3.2. Electrochemical Capacitors

ECs have achieved substantial acceptance in the electronics industry, replacing backup batteries in many complementary metal-oxide semiconductor (CMOS) memory applications. Many commercially available ECs are directed at this market, and, consequently, are of limited size and power performance. These limitations are not inherent in the technology but rather due to the market forces that have driven the design. Much larger, higher-voltage capacitors with greatly enhanced power performance have been available for several years from some suppliers and currently are being developed by others. These ECs are directed at new markets, among them automotive starting, lighting, and ignition circuits and, in Russia, vehicle motive power.

One early Russian application of ECs was for starting vehicles in cold climates. In Siberia, the cold-weather advantages of ECs over chemical batteries were quickly apparent. In addition, the Russian firm ESMA now has over two years' experience using ECs as the sole energy source for forklifts, electric trucks, and buses. The Russians are presently operating six 1.5-ton trucks, three buses, two street-sweepers, and twenty forklifts with ECs serving as the motive batteries. Additional details of

their experience are described in "New Ultracapacitors Developed by JSC ESMA for Various Applications."¹¹

Major automotive manufacturers have been developing EVs to meet zero emission vehicle requirements. Domestic manufacturers have also been developing HEVs through sponsorship by the federal government under the "Partnership for a New Generation of Vehicles" (PNGV). In addition, transit bus manufacturers have programs to develop hybrid-electric buses (HEBs). One such program is the Advanced Technology Transit Bus or ATTB being developed by Northrup Grumman Corporation.

High-energy-density capacitors have been identified as an enabling technology for many of these low-pollution applications, and recent development efforts have focused primarily on EC technology. ECs appear well suited for such applications because they offer high volumetric capacitance density. This advantage is derived from the use of high-surface-area electrodes to create a large "plate area" and from storing energy in the so-called diffuse double layer. This double layer, created naturally at a solid/electrolyte interface when voltage is imposed, has a thickness of only approximately 1 nm, forming an extremely thin "plate separation." Consequently, ECs with very high capacitance density can be made using high-surface-area electrodes. Some ECs show enhanced capacitance derived from pseudocapacitance charge storage in addition to double layer charging. One Russian company manufactures an asymmetric EC having energy density greater than 10 Wh/kg.

Compared to batteries, ECs have longer cycle life and higher rate capability, but lower energy density. They require a much simpler charging circuit than a battery, and display no "memory effect." Physical, rather than chemical, energy storage is the key reason for the EC's cycle life and its high power density compared to other capacitors. Furthermore, ECs have the potential to meet important cost targets because their electrodes typically consist of relatively low-cost material, for example, activated carbon derived from wood or coal.

Significant advances have been made in the development of large capacitors during the past decade, stimulated by Isuzu's 1990 development of a "revolutionary new battery." Some investigations have focused on using ECs to level the load on energy storage systems in electric and gas-electric hybrid vehicles, reducing stress on the chemical batteries and extending their life. Other development activities, funded primarily by the U.S. Department of Energy (DOE), have been directed at starting internal combustion engines, electrically preheating exhaust catalytic converters, powering uninterruptible power supplies (UPSs), and other automotive applications.

Most of these applications require large capacitors capable of delivering a substantial fraction of their stored energy in a few seconds. This power performance requirement is a major departure from the established computer memory backup applications, where discharge times are typically hours or days. These design drivers are similar to

¹¹ Varakin, I.N., Klementov, A.D., Litvinenko, S.V., Staroduvtsev, N.F., Stepanov, A.B. "New Ultracapacitors Developed by JSC ESMA for Various Applications," 8th International Seminar on Double Layer Capacitors and Similar Energy Storage Devices (1998).

energy system drivers where an EC would meet power surges, but very different from system drivers where an EC would be the primary energy storage medium.

Team member JME used published data, correspondence, and discussions with developers and manufacturers to compile a summary of products and technologies of various vendors (see Appendix A). Manufacturers' addresses are included as Appendix B.

3.2.1. Advantages in PV Systems

Electrochemical capacitors have significant advantages for deployment in PV systems, particularly in remote settings.

3.2.1.1. Lack of Maintenance

In contrast to the battery maintenance requirements described previously, capacitors require no maintenance. The financial and systemic ramifications of this are enormous, greatly reducing system cost over time and allowing the storage system to be located in places impractical for chemical battery systems (e.g., buried).

3.2.1.2. Longevity

Because capacitors store charge physically rather than chemically, cycling has virtually no effect on their capacity or longevity. The lifetime of most capacitors is limited by electrolyte loss. Twenty-year life is easily achieved by proper selection of materials and control of operating parameters. It is anticipated that thirty-year life is also achievable, although this will require development and may increase product cost.

3.2.1.3. Environmentally Benign

Capacitors do not employ toxic materials, and thus present no environmental threat in manufacture, transport, or disposal. They do not outgas in use and present no threat of explosion.

3.2.1.4. High Discharge Rate Capability

Capacitors can be discharged at very high rates without damage. High rates, however, reduce the delivered energy of the unit.

3.2.2. Disadvantages in PV Systems

3.2.2.1. Self-discharge Rate

The self-discharge rate of most capacitors is substantially higher than that of batteries or flywheels. This limits their application in grid-independent settings to systems with multiple storage media capable of offsetting this self-discharge. In grid-connected systems, where they could serve to attenuate drastic demand swings, self-discharge is not a major consideration.

Team member JME indicates that the self-discharge of the ESMA EC is lower than that of any other capacitor type. It is expected to take 8 months to discharge to 50% of capacity. This is very similar to the rate for some shallow-cycle batteries, which can lose up to 6% per month to self-discharge. (Good deep-cycle batteries are substantially better.)

Battery self-discharge is usually of little consequence in PV system sizing because its magnitude is small enough to be hidden in procedures necessary to account for solar variation. If self-discharge in ECs proves to be high, however, it would have to be compensated for in system sizing procedures, and should be quantified in any further investigations.

3.2.2.2. Cost

JME's original estimates of the cost of appropriate EC storage for PV applications were in the range of \$10 to \$20 per kJ, or \$10,000 to \$20,000 per MJ, based on extrapolating current EC costs to higher production levels with modest technological advances. At this price, between 12 and 30 times that of batteries, capacitors appeared unattractive in economic terms, particularly as straight replacements for batteries, despite the favorable characteristics discussed above.

However, during the course of this study, major Russian firms that specialize in manufacturing large ECs were asked to provide price estimates based on modifying typical EC design drivers (power delivery and response time) to drivers compatible with stand-alone PV systems, greatly reducing the need for volume power and eliminating the requirement of fast response.

ESMA's response, quoted below, cut projected purchase cost to 50 cents per kJ. The NPV analysis (discussed in Section 5.1), which includes such factors as the cost of periodic battery servicing and replacement, indicates that a capacitor selling at this price would provide storage at about three times the cost of batteries.

ESMA states:

Given certain relaxed constraints as per your information, we may concentrate on "traction" capacitor technologies. These technologies allow [us] to ensure lower prices per 1 kJ of energy. If compared to prices for batteries (per your information – U.S. \$120 per 1 kWh), the pinnacle of our desires today with respect to "traction" capacitors is about U.S. \$1700-1800 per 1 kWh (which corresponds to U.S. cents 47-50 per 1 kJ). Again, the foregoing levels may be reached only in case of large-scale batch production and under cheaper electrode production technologies. These prices are currently several times higher.

This projection is preliminary, and is subject to all the technical and economic uncertainties that affect a technology as new as ESMA's. While the Russian experience is promising, there are many steps between ESMA's current product status and the deployment of ECs as a component in a cost-effective, reliable PV power system. These steps include developing a less costly electrode production method, scaling up production significantly, prototyping, and field testing.

Additionally, the volatility of the present Russian economy and currency make this cost projection less certain than if it had been offered by a firm located elsewhere. However, regardless of the country of origin, the offer represents the state of the art in large traction ECs today. If ESMA does not

apply its knowledge to producing PV-compatible ECs in Russia, firms in other countries probably will.

3.2.2.3. Output Voltage Control

Although the output of a PV device is well-suited to charging a capacitor, capacitor discharge characteristics are significantly different than lead-acid battery discharge characteristics. Battery voltage drops slowly under load until a substantial portion of the battery's usable energy has been extracted. In a typical PV application, battery voltage drops about 11% as 90% of its energy is extracted.

Extracting 75% of a battery's energy produces a voltage drop of 7 to 8%. In contrast, extracting 75% of an EC's energy produces an approximately 50% voltage drop. The consequence is a broad voltage swing, which severely limits the applications to which ECs may be applied without power conditioning.

Many present PV applications require no power conditioning or voltage limiting. These loads tolerate the voltage swings of the battery as it charges and discharges. A virtue of such systems is their simplicity—with no circuitry between the battery and the load other than a high-reliability switch (used primarily to protect the battery from deep discharge) their failure modes are limited. In fact, some critical systems have no active element between the battery and the load, valuing load support above battery longevity.

Virtually all traditional PV applications would require power conditioning between the output of an EC and the load, either a DC/DC converter for DC loads or an inverter for AC loads. This requirement adds to system cost and reduces system efficiency and reliability.

The corollary to the voltage range of a discharging capacitor is its available energy. Although discharging an EC below 50% of its rated voltage does not harm its structure, for most applications additional discharge is impractical. Thus a capacitor's available energy is typically only 75% of its rating.

3.3. Capacitor/Flywheel/Battery Combinations

Quantifying the efficacy of flywheels and ECs as storage media in PV systems is difficult. Although the EC's energy storage capability has been known for a century, no real market existed until the development of low-current-draw volatile computer memory circuits. Most development and commercialization effort has focused on this market and on improving the device's response speed and short- and mid-term energy storage characteristics. With the exception of recent Russian efforts, little has been directed at optimizing ECs for the characteristics important to PV systems, particularly efficient long-term energy storage.

The little development that has been done in this area indicates that ECs not only can be substantially improved for this purpose, but that their cost per joule can be reduced substantially in the process. Cost reductions can be effected because of reduced labor and inherent efficiencies of scale. Further, per joule, long-term storage requires more of the EC's active elements (primarily carbon) and less of the inactive elements (i.e., packaging, separators, current collectors, interconnect bus sizes, etc.), which are generally more expensive than the active elements.

Flywheels have progressed much further towards integration into PV power systems, but their recent development has been so rapid that in-system performance projections are difficult. The following are among the most important developments:

- Development of graphite fiber rotor materials with dramatically improved strength and energy storage capability (see Table 2).
- Demonstration of product safety, with rotor fragments fully contained in DARPA burst testing.
- Demonstration of low-friction, solid-lubricated, non-magnetic bearings.

Table 2. Characteristics of Flywheel Rotor Materials

	Composite Strength* (Gpa)	Composite Density (kg/m³)	Theoretical Max Specific Energy (Wh/kg)	Relative Max Specific Energy (Steel=1.0)
Graphite fiber (1995)	4.8	1609	414	11.2
Graphite fiber (1989)	3.4	1609	293	7.9
S-glass (fiber)	2.1	2190	133	3.6
E-glass (fiber)	1.8	2205	113	3.1
Maraging steel	2.1	7860	37	1.0

* Ultimate strength for fibers, yield strength for steel

Although flywheels have been used in demonstration projects (primarily in transportation applications) since the 1960s, the wheels have used a great variety of materials and components and the experience gained is only partially applicable to state-of-the-art units. Such units (for example, the TSI unit presently being tested by Bellcore) have not yet established a field operating record, and their characteristics in PV systems cannot be projected precisely. The important parameters yet to be established include the following:

- The ability of the control electronics to cope with varying loads, particularly surges;
- The ability of the control electronics and other subsystems to cope with the environmental extremes (e.g., lightning) of remote sites; and
- The ability of the bearings and other subsystems to make the transition from the laboratory environment to the range of transportation and installation conditions faced by PV systems (e.g., multi-G shock loads imposed by 4-wheel vehicle transport on poor roads, deployment in developing countries).

Despite our present inability to quantify these performance and cost factors accurately, we feel that the synergies below are promising and bear additional investigation.

3.3.1. Flywheel/EC Systems

Although flywheels respond quickly to demand, their characteristic response time is longer than an EC's, which can cope with the millisecond-level response required by such applications as UPSs. The motor-generators of many existing flywheel systems, including those manufactured by TSI, use an electrolytic capacitor for starting and to smooth transients. Replacing this capacitor with a high-capacity electrochemical unit could, in addition to the electrolytic's function,

- greatly improve the system's ability to respond to demand surges and simultaneously relax the design requirements for the mechanical components of the flywheel system; and
- extend the unit's life substantially. Present electrolytic capacitors last, at best, 10 years. ECs can be made for 20- or 30-year lifetimes, a span compatible with the demonstrated life of PV arrays and the expected life of flywheels.

3.3.2. Battery/EC Systems

Batteries have the ability to provide extremely high power levels on demand. Although most PV applications make no use of this characteristic, other battery applications do. One such application is telephone substations, which use large batteries to maintain service during utility power outages. These batteries are cycled infrequently, but heavily, and must cope with large surge requirements. They display short lifetimes, sometimes as short as one year.

These substations are one example of grid-supplemental systems, which includes the category of UPS systems. UPSs vary tremendously in size, from units serving individual computers to systems supporting vital circuits in large buildings or building complexes. By definition, these systems must respond instantly to power outages, and often rely on battery banks to bridge the period between loss of grid power and delivery of backup power from their fuel-powered generators. These "bridge" batteries are severely cycled, subjected to heavy surge demands, and are short-lived.

Electrochemical capacitors paralleled with these battery banks could respond quickly to bridge power needs, cope with the transients generated during source changeover, absorb demand surges that would otherwise stress the batteries, and greatly extend battery life.

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4. Applications

The analysis of applications began with the identification of seven application categories that are either established or emerging markets for PV systems with conventional energy storage. The examples range tremendously in scale, from systems with 5-W arrays to systems with 1-MW arrays.

These applications are summarized in Table 3. The first four applications are small- to mid-size systems with well-established markets. The last three applications are larger and address markets that can be characterized as rapidly developing. Although numerous examples of grid-connected commercial and transmission and distribution (T&D) support systems exist, most are prototypes or are supported by corporate or government development programs.

This section discusses the application categories and the system sizes necessary to meet their requirements. Example system configurations, based on the representative flywheel sizes discussed in Section 3.1.2.1, and consisting of a PV array, a flywheel or multiple flywheels, and an electrochemical capacitor attached to each flywheel are provided for reference. The ECs in these example systems would provide limited energy storage to cope with transients, provide fast response to demand surges, and maintain power quality. These ECs are sized to provide up to half of the load's peak demand for three seconds. This capacity is sufficient to support a significant surge in a stand-alone PV system. As a point of reference, the Electric Power Research Institute (EPRI) reports that approximately 92% of line "voltage sag" events last three seconds or less.¹²

While we highly recommend further investigation into the role of ECs as a primary energy storage medium, we do not have sufficient data at present to configure them, even conceptually, as a system's sole energy storage device.

Table 3. Application Categories for PV Systems

Application	Input to Storage	Output from Storage	Nominal Capacity	Temperature Range	Potential Market
<i>Instrumentation/ Highway Call Box</i>	5-30 W @ 12 V	Continuous 1-5 W @ 12 V; Max 100 W	50-600 Wh	-40°C-60°C	50K/yr
<i>Grid-independent Residential</i>	30-120 W @ 12 V	Max 200 W	500-2500 Wh	-10°C-40°C	100K/yr
<i>Telecommunications</i>	500 W-5 kW 80% @ 48 V 20% @ 24 V	Continuous 25- 500 W; Max: 1 kW	5-100 kWh	-25°C-40°C	1000/yr
<i>Grid-connected Residential</i>	1-5 kW @ 48 V, 120 V, 240 V	5 kW	5-30 kWh	10°-30°C	10K/yr
<i>EV Charging Station</i>	25 kW-50 kW	50 kW-100 kW	1-2 MWh	Ambient	100/yr
<i>Grid-connected Commercial</i>	25 kW- 500 kW	Continuous same as PV array; Max: 300 kW-1 MW	0.2-2 MWh	Conditioned	50/yr
<i>T&D Support</i>	200 kW-1 MW	Continuous same as PV array; Max: 500 kW-2 MW	2 MWh	Ambient	10/yr

¹² EPRI Distribution Power Quality Report #RP3098-01.

4.1. Instrumentation/Highway Call Box

This group represents a number of small PV applications. These are applications where a small amount of power is needed for small electronic devices such as instruments, sensors, data loggers, radio telemetry transceivers, or cellular phones. These applications typically require from 5 to 50 Wh per day, which can be generated by 5 to 30 Wp of PV.

System configuration example: One 0.5-kWh flywheel and a 2.4-kJ EC.

4.2. Grid-independent Residential

Systems of this scale can be remote vacation-type cabins or homes in developing countries and developing sections of the U.S. and other industrial countries. Such systems have been deployed in Africa, Asia, U.S. Indian reservations, and other low-energy homestead locations.

A persistent problem in these applications—particularly in those areas where residents are not personally involved in selecting and financing the systems, and where residents do not understand the system's characteristics—is battery abuse. The services provided by the system (lighting, television, refrigeration) are valued and are heavily used—so heavily that it is common for batteries to be deep-discharged with such frequency that their life is very short. Agencies involved in providing these power systems specify low-voltage disconnect circuits intended to prevent deep discharge, but residents commonly wire jumpers around the disconnect switch, defeating its intended purpose. Consequently, this application needs storage that will not be harmed by deep discharge, which makes it a promising application for flywheel-based storage.

This application was specified as including PV arrays with outputs ranging from 30 W to 120 W and battery storage between 500 Wh and 2500 Wh. It is important to note that this storage is expressed traditionally as nominal battery capacity. Given the realities of battery characteristics and use, actual usable capacity is about half these figures.

System configuration example: One to three 0.5-kWh flywheels each with a 2.4-kJ EC.

4.3. Telecommunications

The range of applications in this category would use PV arrays with peak outputs between 500 W and 5 kW.

System configuration examples: 5-kWh system—two 2.5-kWh flywheels each with a 6-kJ EC, *or*, 100-kWh system—four 25-kWh flywheels each with a 20-kJ EC.

4.4. Grid-connected Residential

The range of applications in this category would use PV arrays with peak outputs between 1 kW and 5 kW. Mid-sized flywheels (2.5 kWh to 25 kWh) with appropriately sized ECs (6 kJ to 20 kJ) could be configured to meet the requirements of this application.

4.5. Electric Vehicle Charging Station

This application would use PV arrays with peak outputs between 25 kW and 50 kW.

System configuration example: Five to ten 200-kWh flywheels each with a 160-kJ EC.

4.6. Grid-connected Commercial

This range of applications would use PV arrays with peak outputs between 25 kW and 500 kW.

System configuration example: One to ten 200-kWh flywheels each with a 160-kJ EC.

4.7. T&D Support

One example of this application is a community located at the end of a single transmission line whose capacity, adequate at most times, is strained by peak loads. Such situations are not uncommon; a good example is an island community with growing population.

The power systems specified in Table 3 include flywheel storage of 2 MWh with PV arrays providing between 200 kW and 1 MW. Even without the PV array, this system could provide substantial peaking capability. The flywheels (or flywheel) could be fully charged during off-peak hours with grid power available, because of timing, at the lowest possible rate. The flywheels would then make this power, generated by efficient plants during low-cost periods, available in an energy-strapped community during peak hours.

The PV array would extend the capability of the system, using similar principles. With peak output at solar noon, the array would assist in fully charging the flywheels. The array would typically provide significant (though not peak) output throughout the afternoon, contributing to community's energy needs and conserving the flywheel's capacity for the late afternoon peak.

System configuration example: Ten 200-kWh flywheels each with a 160-kJ EC.

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5. Market Analysis

5.1. Net Present Value Analysis

A spreadsheet was used to analyze the costs over time of various system configurations. This analysis provided the cost comparisons that are referenced in other sections of this report.

We analyzed three comparable systems using the lowest projected costs for a nominal 1-kW PV system. The primary differences are in the first costs of the storage systems and in their placement and maintenance. It was assumed that the power electronics for all of the systems would need replacement every 10 years, the chemical batteries would need to be replaced every 7 years, and the flywheel systems would be maintained at 5-year intervals with an annual inspection. Chemical batteries were also assumed to be maintained once per year. A 30-year system life was assumed, corresponding with the nominal design life of the PV modules.

The NPV method was used to compute the life-cycle costs of the three systems. In this method, the time value of money is accounted for by discounting future cash flows at a fixed discount rate. This rate is the owner's after-tax cost of capital, and will vary with the type of entity owning the equipment; the owner's tax status, credit worthiness, and risk preferences; and the capital market situation in the country where the system is installed. A typical rate at the present time for U.S. corporations is 10%, so this rate was used in the analysis. Higher rates reduce the value of future costs and therefore make systems with lower initial costs but higher operating costs more favorable. Lower rates have the opposite effect – making future costs relatively more significant.

The NPVs of the flywheel/EC system and the lead-acid battery system with a 10% discount rate are close enough to be comparable, given the uncertainty over the future costs of the systems. The analysis clearly shows that the new systems have the potential to compete effectively with chemical storage in PV applications and, as discussed below, to extend the range of PV applications.

Given these assumptions, a system with a 1-kW array and nominal chemical battery storage of 25 kWh (approximately 8 days) results in NPVs of \$18,200 for the lead-acid system, \$16,600 for the flywheel system, and \$52,700 for the system with EC storage only. A printout of this example is included as Appendix C.

5.2. Potential Markets

The potential applications for the advanced storage technologies can be divided into three broad categories:

- Current PV applications that would be compatible with or enhanced by the new type of energy storage.
- Emerging PV applications that would also be compatible with or enhanced by an advanced energy storage technology.
- Applications that primarily require energy storage but might be complemented by PV.

Some overlap could exist between the second and third categories, as a number of the emerging PV applications derive value from reducing the effects of peak loading on the generation, transmission, or distribution of electricity. The applications identified here generally fall into the first and second category, as these markets are the best understood.

The potential markets that were shown in Table 3 are an estimate of what could reasonably be achieved within 5 years assuming that reliability, performance, and cost goals are achieved. The following sections discuss each of these potential markets in detail.

5.2.1. Instrumentation/Highway Call Box

This group represents a number of small PV applications that require a small amount of power for small electronic devices such as instruments, sensors, data loggers, radio telemetry transceivers, or cellular phones. In most cases the equipment is in a remote area or the power requirement is so small that it is less expensive to install a small PV system than to make a connection to the utility grid. These applications typically require from 5 to 50 Wh per day, which can be generated by 5 to 30 Wp of PV. Today, these applications are served by chemical storage batteries, most of which are the valve-regulated lead-acid (VRLA) type. Depending on the type of battery, the installation of the equipment, and the climate, these batteries will typically have a 2- to 5-year service life, although a service life as short as 1 year can occur in hot climates where the batteries are in enclosures exposed to the sun. In these situations, the life-cycle cost of the system is driven by the battery replacement cost, and energy storage systems with substantially higher first costs could be tolerated if they possessed longer lifespans. This characteristic is expected for both the ECs and the flywheels.

An estimate of market potential was developed by looking at today's market for this type of PV system and assuming a certain penetration could be achieved over time. The market for this type of system today is approximately 3 MW of PV per year with an average system size of about 15 W, or roughly 200,000 systems per year. A growth rate of about 15% means that the market will double in 5 years to 400,000 systems. Nevertheless, this may be a conservative estimate, both in terms of the underlying PV market and also because further market expansion may occur if better storage systems become available. Clearly some applications of this type have not used PV because of the weaknesses of conventional battery systems.

The principal advantages of the EC and flywheel in this application are their extended cycle life and performance over a wider range of operating temperatures. These features could extend the use of PV in this application. The disadvantages could be higher weight and/or bulk, especially when the containment for the flywheel systems are considered. This added size could be turned into an advantage in some situations, where the larger units might present a barrier to theft.

5.2.2. Grid-independent Residential

Systems in this category account for about one third of today's PV market, or (according to industry reports) roughly 40 MW of PV in 1998. The average system size is about 80 W, which translates to sales of about 500,000 systems in 1998. Annual growth rates in this segment have averaged 15 to 20%, at which rate the market will at least double in the next 5 years.

This market has two distinct segments: systems on remote homes in industrialized countries and systems for basic household needs in developing countries. While the basic characteristics of these systems are similar, there are substantial differences in the system components and the approach to the market.

If the advanced storage systems achieve a life-cycle cost comparable to chemical batteries, systems with advanced storage will certainly be able to penetrate both segments of the market, especially in the industrial countries where long-term financing is available and the labor costs of replacing conventional batteries are high. It seems reasonable to expect a 10% share of this market if the objectives are met, giving a potential of 100,000 units per year.

In this category of applications, the principal advantages would be the greatly reduced maintenance and the long life of the EC and flywheel systems. The principal disadvantage would be the higher first costs, especially in developing countries where interest rates are high and financing is hard to obtain.

5.2.3. Telecommunications

Telecommunications is the largest single market for PV, accounting for roughly 20 MW in 1998 based on industry reports. Applications range widely, from small rural subscriber telephone systems to microwave repeaters, cellular sites, and satellite earth stations. Roughly half of this market falls into the range of 500 to 5,000 W of PV with the average size of these systems around 2 kW; meaning that 5,000 systems will be sold in 1998. (Smaller telecommunications systems were discussed in Section 5.2.1).

This market is also growing at about 15% per year, thus doubling over the next 5 years to 10,000 systems. It seems reasonable that a 10% penetration could be achieved if advanced storage systems reach parity with chemical storage batteries on a life-cycle cost basis, which gives a potential market of 1,000 systems per year.

The advantage of wider operating temperature range and longer maintenance intervals over chemical storage batteries could extend the range of potential PV use in this application. The cost of replacing batteries in this segment could also be very high, giving an edge to the longer-lived storage technologies. The disadvantages would be potentially higher weight and bulk, and also higher first costs. Because many telecommunications systems only have 10- to 20-year life cycles due to technological obsolescence, it could be hard to justify substantially higher first costs.

5.2.4. Grid-connected Residential

Grid-connected systems are the fastest growing segment of the PV market and now represent over 30% of the world PV market, or about 40 MW in 1998. Over 80% of these systems are on homes. The average size is about 3 kW, giving a market of about 10,000 residential systems in 1998. This segment is growing at over 30% per year and in 5 years is estimated to be approximately 50,000 systems per year. Currently, most of these systems do not incorporate storage, but over half of the users surveyed have expressed an interest in storage. Present battery technology has not been attractive primarily because of the hazardous nature of chemical batteries and the need for multiple replacements over the life of the system.

Incorporating storage into these systems is desired by many homeowners to provide backup power in the event of an outage and could become a key selling feature of the systems. In fact, the backup system could be popular without the PV. Using systems such as the EC and flywheel that can tolerate extensive cycling would also enable true peak shaving, by shifting the power from midday to later in the afternoon. This could encourage the acceptance or even purchase of PV systems by utilities. Another segment that could be accelerated by adding this kind of storage is grid-connected systems for homes in developing countries. Many upper- and middle-class homeowners in these countries have access to the grid, but power is very unreliable, in some cases operating only a few hours per day or a few days per week. These homeowners have expressed substantial interest in PV systems with storage that would eliminate the reliability problems of the grid.

The advantages of the new storage systems over conventional batteries are much longer life, better cycling ability, and elimination of hazardous materials from the home. The disadvantages would be the higher first cost, and the containment required for the flywheel systems.

5.2.5. EV Charging Stations

There are about a dozen PV-powered EV charging stations operating in the world today, but it would be difficult to call this small number a true market. These systems have generally been installed on parking garages or other facilities owned by electric utilities as demonstrations. Electric utilities are promoting the use of electric vehicles as the normal operating cycle of the vehicles (used during the day, charged at night) will add to kWh sales while taking advantage of generally underutilized nighttime capacity. Electric vehicles are being promoted and even mandated in some areas to lessen air pollution; however, some environmentalists are skeptical, claiming that charging the EVs from fossil-generated electricity is simply moving the pollution from one place to another. Solar charging stations overcome this objection and demonstrate that EVs can truly represent a sustainable alternative to the internal combustion engine. Although EV mandates have recently been pushed back in some states, it is likely that tens of thousands of EVs will be in use by the middle of the next decade. As these vehicles begin to populate the highways, there will also be a need for roadside charging stations to assist vehicles running low on power. Taking all of these variables together we

believe there could be a market for 10 systems per year by the middle of the next decade.

The flywheel and EC storage systems present a major advantage in this application because of their extensive cycling capability and the ability to discharge rapidly without damage. This application would be substantially limited if only chemical storage batteries are available. There are really no disadvantages to the advanced storage systems in this application.

5.2.6. Grid-connected Commercial

The grid-connected market for PV, as previously discussed, is approximately 40 MW per year and is growing at over 30% per year. While the majority of the market is for residential systems, the balance is mainly on commercial buildings, a market of 6 to 8 MW per year.

This segment is also growing rapidly and will probably reach 25 MW in 5 years. The average system size is about 50 kW, which translates to sales of 500 systems per year in 5 years. Few of these systems are using energy storage today. As in the residential segment, there is considerable interest in systems that can provide back-up power during an outage, and in systems that can be used to shave peaks. Both of these capabilities have measurable economic value in commercial buildings. Given these considerations it seems reasonable to project that if cost and performance targets are met, the advanced storage systems could achieve a 10% penetration of this market, or 50 systems per year in a 5-year period. As with residential systems, the ability to supply backup power will probably extend the range of application of these types of systems, especially in developing countries.

The advantages of long life and extreme cycling capability will allow storage to be used in these systems where it has typically not been used before. There are no substantial disadvantages in this application (assuming cost effectiveness is achieved).

5.2.7. T&D Support

In the last ten years, half a dozen PV systems have been installed to provide T&D support. Essentially these systems are arrays placed at substations to provide additional power and voltage support where existing transformers and possibly T&D wiring are taxed during peak load periods. This application is a vast potential market for PV. At a PV price of \$3 per Wp AC, it has been estimated at over 4 GW. PV prices are currently about double that, so today's applications have largely been demonstrations.

This market segment will also see considerable competition from other technologies (e.g., microturbines and other energy storage systems). This market segment is real, but it is hard to differentiate between PV generation and energy storage systems. Energy storage systems, including banks of flywheels or ECs, could store grid energy during off-peak hours and discharge it to meet peaks. PV could enhance this function by providing more energy or, to the extent PV output and peak demands overlap, by reducing the amount of storage capacity needed. Given the limitations on this market we have estimated a potential market of ten systems per year. There could actually be more market for the storage systems, but it largely depends on the available alternatives.

5.3. Market Scale

Table 4 shows the projected 5-year flywheel market totals for the applications described, and the assumptions underlying the projections. For those applications served by a range of system sizes (e.g., telecommunications, with systems ranging from 5 kWh to 100 kWh), an estimate representing an average was used. Summing the last column of Table 4 by unit size gives the market projections shown in Table 5.

Table 4. Flywheel Market Projections Based on TSI Flywheels

Application	Flywheel Units per System	5-yr Flywheel Cost Projection	Potential Market	Flywheel Volume	Potential Market (\$)
<i>Instrumentation/ Highway Call Box</i>	1 @ 0.5 kWh	\$750	50K/yr	50K	\$37.5M
<i>Grid-independent Residential</i>	1-3 @ 0.5 kWh	\$750	100K/yr	200K	\$150M
<i>Telecommunications</i>	2 @ 2.5 kWh	\$3200	1K/yr	1K	\$3.2M
	4 @ 25 kWh	\$21,000		2.5K	\$52.5M
<i>Grid-connected Residential</i>	4 @ 2.5 kWh	\$3200	10K/yr	30K	\$96M
	4 @ 2.5 kWh + 1 @ 25 kWh	\$21,000		5K	\$105M
<i>EV Charging Station</i>	5-10 @ 200 kWh	\$90,000	100/yr	750	\$67.5M
<i>Grid-connected Commercial</i>	1-10 @ 200 kWh	\$90,000	50/yr	250	\$22.5M
<i>T&D support</i>	10 @ 200 kWh	\$90,000	10/yr	100	\$9M

Table 5. Projected 5-year Annual Flywheel Market Size Based on TSI Flywheels

Example Flywheel Size	5-year Annual Flywheel Market
0.5 kWh	\$187.5M
2.5 kWh	\$99.2M
25 kWh	\$157.5M
200 kWh	\$109M

Projections of the market size for capacitors are substantially less certain due to the infancy of the EC technology for these applications. The financial ramifications are illustrated in Table 6, which shows the contrast in near-term (1-year) and projected 5-year costs for the ECs to be included in the four systems. JME, the capacitor consultant for the Solarex team, believes that the 1-year EC costs are best estimated at between \$30 and \$70 per kJ, with the cost increasing as the capacitor size drops. However, applying the updated ESMA cost projections to these capacitors ("5-year cost") produces far lower costs, by factors of up to 60.

The capacitor volumes generated by our projected PV-related production (the total of all applications shown in Tables 4 and 5) would not be sufficient to drive EC costs down to the 5-year cost levels shown in Table 6. These costs will be achieved only if ECs prove to be worthwhile replacements for chemical batteries in applications such

as those now demonstrated in Russia. If that occurs, EC production volume will skyrocket and costs may fall to the projected level.

In this case, adding EC capability to the example energy storage systems described in this report will be a very small segment of their impact on the whole field of energy storage technology; just how small is indicated by our projected EC market total. If all applications in Tables 4 and 5 were realized, the annual flywheel market would total \$553 million. However, the cost of the associated ECs, using 5-year costs, would be only \$1.3 million.

Table 6. Comparison of Near-term and 5-year EC Costs Based on TSI Flywheels

Example Flywheel Size	Capacitor Size	1-year Cost	5-year Cost ¹
0.5 kWh	2.4 kJ	\$168	\$4
2.5 kWh	6 kJ	\$300	\$5
25 kWh	20 kJ	\$600	\$10
200 kWh	160 kJ	\$4800	\$80

1. Assumes implementation of ESMA technology resulting in costs 50¢-\$1.50/kJ.

Figure 3 shows the scale of the overall market that these systems target. As shown, the total value of the U.S. market for power quality equipment in 1992 was \$1977 million. This market is projected to grow to \$5 to \$6 billion in 2002.

Figure 3. U.S. power quality equipment market segments.*

*Source: EPRI Distribution Power Quality Report (#RP3098-01)

Consequently, the flywheel/EC systems described constitute 10-15% of the power quality equipment market as it exists today. The true market would be substantially larger, as it includes remote power (approximately \$1 billion in the PV market alone) and other segments not considered in the data represented by Figure 3.

6. Conclusions

6.1. Flywheel Status

The representative TSI flywheel used in this study is presently in the prototype test stage as a direct replacement for a storage battery in a communications application, and should also be tested as the primary storage medium in a demonstration PV system. TSI and Solarex are proceeding independently with a preliminary investigation of the interaction of PV modules and the TSI flywheel.

6.2. Development of Low-cost ECs

The Russian firm ESMA has substantial experience in designing and operating ECs in a number of applications, including demonstration projects with the U.S. Army, the National Aeronautics and Space Administration (NASA), and EPRI. Of particular interest is the use of ECs as the sole energy storage medium for various vehicles, which required the development of ECs with characteristics very different from traditional capacitor applications, but very close to those which could replace lead-acid batteries in PV applications and other applications. ESMA's projected prices are drastically lower than current capacitor prices. This issue should be addressed with respect to broad use in energy systems, including PV systems.

6.3. Flywheel/Capacitor Synergy

The primary hypothesis this study—that a synergistic relationship exists between flywheels and ECs in energy storage/delivery systems—has been confirmed conceptually. Further investigation is needed to quantify the performance and economic tradeoffs of this synergy and its effect on overall system costs.

Specifically, effort should be directed at determining whether adding a large EC to a flywheel would, by insulating the flywheel from demand surges:

- enable major changes in flywheel design (lighter shaft, smaller conductor, etc.);
- enable reduction in nominal flywheel capacity for a given application;
- lengthen system life; and/or
- significantly decrease the overall storage system's cost.

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7. Appendix A: Capacitor Manufacturers and Technologies

Alupower

The technology is a double-layer capacitor based on carbon electrodes with an organic electrolyte. Their capacitor has an RC time constant of 2.5 s. The form factor is prismatic. Operating voltage is set at 3.0 V maximum. Alupower has pilot line equipment in place.

Asahi

The technology is a double-layer capacitor based on carbon electrodes with an organic electrolyte. The form factor is a cylinder. They have product lines of low-voltage ECs in sizes up to 50 F, sold mainly for memory backup and related applications. Asahi Glass has presented several papers describing development activities of large, high-power capacitors.

Cap-XX

The technology is a double-layer capacitor based on carbon electrodes with an organic electrolyte. Cap-XX has an operating pilot production line and anticipates that costs will decrease as production volume increases.

ECOND International, Inc.

The technology is a double-layer capacitor based on carbon electrodes and an aqueous electrolyte. Their form factor is a right cylinder. ECOND has been manufacturing large, high-voltage capacitors for more than 10 years, and has many thousands of units in use in various military and automotive applications in Russia, and more recently in the U.S. They recently supplied 1.6 MJ of 200-V capacitors to NASA for a hybrid bus project. These units were rated at 50 kJ each. ECOND presently manufactures their product in Moscow.

ELIT Stock Co.

ELIT has two technologies: a symmetric carbon system and a carbon/metal-oxide pseudocapacitor with an aqueous electrolyte. Their system has an RC time constant of 0.25 s, and a prismatic form factor. They have been manufacturing large, high-voltage capacitors for more than 7 years, and have many thousands of units in the field in various Russian military and automotive applications. ELIT presently manufactures their product in Kursk, Russia.

ESMA Joint Stock Co.

The technology is a combination of double-layer capacitors based on carbon electrodes with an aqueous electrolyte, and metal-oxide pseudocapacitors using an aqueous electrolyte. Starting capacitors have an RC time constant of approximately 1.0 s and a prismatic form factor. Their traction capacitors have an RC time constant of approximately 12 minutes. They have been manufacturing large, high-voltage capacitors for more than 5 years, and have many units in the field, including several vehicles powered by their traction capacitors.

Evans Capacitor Co.

The technology uses an electrolytic capacitor anode (aluminum oxide on aluminum) combined with an electrochemical cathode. This approach circumvents potential voltage imbalance problems associated with multicell components. The component has an RC-time constant of less than 0.5 s, and a right cylinder form factor. Evans is presently fabricating laboratory prototypes.

Federal Fabrics

The technology is a double-layer capacitor based on carbon electrodes with an organic electrolyte. They have presented papers describing the performance of their small devices.

GE

The technology is a double-layer capacitor based on carbon electrodes with a non-aqueous electrolyte. The form factor is unspecified. Operating voltage is set at 2.5 V maximum. GE has been under contract to Ford Motor Co.

Maxwell Technologies

The technology is a double-layer capacitor based on carbon electrodes with an organic electrolyte. The capacitor has an RC time constant of 1.4 s, and the form factor is nearly prismatic. Maxwell has a pilot production line in place. They have assembled large banks of capacitors for UPS applications, and understand how to maintain voltage balance in high-voltage systems.

NEC Corporation

The technology is a double-layer capacitor based on carbon electrodes and an aqueous electrolyte. Their main product lines are low-voltage (5.5 V) ECs for memory backup and related applications. NEC has presented papers on development of large capacitors over the past 5 years.

Panasonic Industrial Co.

The technology is a double-layer capacitor based on carbon electrodes with an organic electrolyte. The capacitor has an RC time constant of 1.5 s, and a right-cylinder form factor. Panasonic has a pilot production line in place and has been sampling this product (470-F to 1500-F capacitor rated at 2.3 V) for more than 3 years.

Polystor Corp.

The technology is a double-layer capacitor based on carbon electrodes with an organic electrolyte. Papers have been presented on small (AA-size) single-cell devices.

REDOX, Inc.

The technology is a double-layer capacitor based on carbon electrodes with an organic electrolyte. The capacitor has an RC time constant of 7.0 s. The form factor is prismatic. Redox presently assembles laboratory prototypes, and has constructed several 45-cell modules.

SAFT

The technology is a double-layer capacitor based on carbon electrodes with an organic electrolyte. They have reported on cylindrical devices for use in applications ranging from wireless communication to UPS systems.

SRI

The energy storage component is based on lithium-ion battery technology. It has been described as a very-high-rate battery having a sloping discharge, like a capacitor. The electrolyte was said to be nonflammable. The RC time constant and the form factor of the technology was not provided. Cycle efficiency is unknown, as is state-of-charge power performance behavior. SRI is developing a pilot line for their product. It is not clear that they have investigated voltage balance in the high-voltage configuration.

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8. Appendix B: Vendor Information

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9. Appendix C: Net Present Value Analysis (Example)

Conventional Batteries					Flywheel				Electrochemical Capacitor			
Year	PV Array	Storage	Other BOS	Total	PV Array	Storage	Other BOS	Total	PV Array	Storage	Other BOS	Total
1	6	3	1	10	6	9	0	15	6	45	1	52
2			0.5	0.5			0.1	0.1			0	0
3			0.5	0.5			0.1	0.1			0	0
4			0.5	0.5			0.1	0.1			0	0
5			0.5	0.5			0.5	0.5			0	0
6			0.5	0.5			0.1	0.1			0	0
7		3	0.5	3.5			0.1	0.1			0	0
8			0.5	0.5			0.1	0.1			0	0
9			0.5	0.5			0.1	0.1			0	0
10			1	1			0.5	0.5			1	1
11			0.5	0.5			0.1	0.1			0	0
12			0.5	0.5			0.1	0.1			0	0
13			0.5	0.5			0.1	0.1			0	0
14		3	0.5	3.5			0.1	0.1			0	0
15			0.5	0.5			0.5	0.5			0	0
16			0.5	0.5			0.1	0.1			0	0
17			0.5	0.5			0.1	0.1			0	0
18			0.5	0.5			0.1	0.1			0	0
19			0.5	0.5			0.1	0.1			0	0
20			1	1			0.5	0.5			1	1
21		3	0.5	3.5			0.1	0.1			0	0
22			0.5	0.5			0.1	0.1			0	0
23			0.5	0.5			0.1	0.1			0	0
24			0.5	0.5			0.1	0.1			0	0
25			0.5	0.5			0.5	0.5			0	0
26			0.5	0.5			0.1	0.1			0	0
27			0.5	0.5			0.1	0.1			0	0
28		3	0.5	3.5			0.1	0.1			0	0
29			0.5	0.5			0.1	0.1			0	0
30			1	1			0.5	0.5			1	1
Total				38				20.3				55
Discount Rate	10%											
NPV				18.2				16.6				52.7

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