

Energy Research and Development Division
FINAL PROJECT REPORT

**LOW-COST FLYWHEEL ENERGY
STORAGE DEMONSTRATION**

Prepared for: California Energy Commission
Prepared by: Amber Kinetics, Inc.



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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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Low-Cost Flywheel Energy Storage Demonstration is the final report for the Low-Cost Flywheel Energy Storage Demonstration project (grant number PIR-11-010) conducted by Amber Kinetics, Inc. The information from this project contributes to Energy Research and Development Division's Energy Technology Systems Integration program area.

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ABSTRACT

Energy storage for stationary, grid-scale applications is a large and rapidly growing market opportunity. Energy storage technologies can support durations that range from several seconds to several days. Energy storage systems with multi-hour durations have the potential to replace a significant percentage of peaking power plants, and to enable California to meet its Renewable Portfolio Standards (RPS), that mandate severe penetration of non-dispatchable renewable generation onto the California grid. The objectives and implications for California's electrical grid are mirrored across the United States, and worldwide.

A flywheel energy storage system is essentially a mechanical battery that stores kinetic energy in a large rotating mass—the flywheel. Flywheel energy storage technology has traditionally focused on storage durations ranging from seconds to minutes, mainly due to the high cost of rotor designs used in preceding flywheel technologies, and due to relatively high self-discharge rates of preceding technologies. Amber Kinetics saw a path for developing a multi-hour duration flywheel capable of meeting the two important criteria noted here. The core of this technical solution relies on the use of a low-cost, high-strength steel rotor design. In executing on the project, the Amber team developed and demonstrated a series of prototype steel rotor flywheel energy storage systems. The demonstration confirmed that the system ultimately developed has an energy discharge capacity of 25 kWh, with energy available over a four-hour duration. Average self-discharge losses were measured to be 200 W. This observed technical performance, in conjunction with the capability of tens of thousands of full discharge cycles, without loss of energy or power capacity, makes the developed flywheel technology a prime candidate for participation in the emerging California utility system energy storage rollout. The results are for a forthcoming commercialization effort, responsive to the opportunity in California.

Keywords: Energy storage; flywheel; steel rotor; capacity; frequency regulation; ancillary services

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EXECUTIVE SUMMARY

Energy Storage Background and Overview

Energy storage for stationary, grid-scale applications is a large and rapidly growing market opportunity. Energy storage durations can range from several seconds (ultra-capacitors) to several days (pumped hydro). This report will focus on multi-hour applications for energy storage.

Energy storage systems with four-hour durations have the potential to replace a significant percentage of peaking power plants; typically, power plants run only when there is a high demand for electricity. Many technologies are being developed and tested for this purpose. Example technologies include, but are not limited to lithium batteries, flow batteries, sodium batteries, advanced lead batteries, flywheels, and compressed air. To date, the challenge has primarily been one of safety, cost, round-trip efficiency, and to a lesser extent, siting restrictions.

Flywheel Energy Storage Background and Overview

A flywheel energy storage system is essentially a mechanical battery that stores kinetic energy in a large rotating mass—the flywheel. Flywheel energy storage technology has traditionally focused on storage durations ranging from seconds to minutes. This has primarily been due to two long-standing technical challenges:

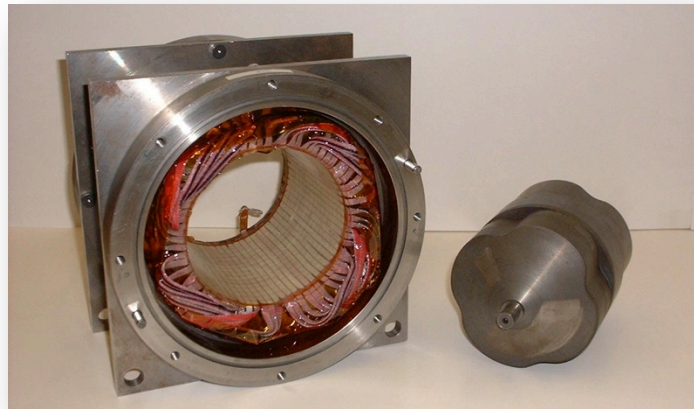
1. The traditionally high dollar per kilowatt-hour rotor cost
2. The potentially high self-discharge rate of flywheel systems due to multiple sources of electrical and mechanical loss while operating

In the late 1990s and early 2000s, several well-funded and competent flywheel start-ups worked on commercializing carbon fiber-based rotor designs; however, the projected cost reduction of carbon-fiber material did not materialize in a manner that made carbon fiber-based flywheels a cost-effective solution for storage durations above a few minutes. Flywheels subsequently found a comfortable niche in backup uninterruptible power supply applications where the dominant requirement was high power and low energy.

Several years later, Beacon Power advanced flywheel technology forward by commercializing a flywheel with 15-minute energy storage duration. However, Beacon Power's target application, frequency regulation, was focused on "power" and not intended for four-hour "energy" durations; thus, design decisions involving flywheel architecture and material selection were perhaps not focused primarily on the lowest possible dollar per kilowatt-hour cost and lowest possible self-discharge rate. Frequency regulation is the common term for provision of an ancillary service, which addresses bridging the instantaneous gap between electrical power supply and demand on a section of the grid. The consequence of such an instantaneous mismatch of supplied and demanded power, is a drift in system frequency. Thus, a system with capability of accurately and responsively injecting or removing power from the grid is needed and used for effecting frequency regulation.

Amber Kinetics saw a path for developing a four-hour duration steel flywheel capable of meeting the two important criteria set forth: low dollar per kilowatt-hour cost and low self-discharge rate. Researchers performed early technology and prototype development work at the University of California, Berkeley Power Electronics Laboratory. This work required a monolithic high-strength steel rotor as both an energy accumulator and as the rotor of the integrated electric machine. The UC Berkeley system was designed, dimensioned, and specified for application in a passenger hybrid electric vehicle.^{1,2} The UC Berkeley system mechanical hardware is depicted in Figure 1.

Figure 1: Prototype Hybrid Electric Vehicle Flywheel



Guided by this early work, Amber Kinetics has pursued a flywheel development path to demonstrate flywheels with four-hour durations at both low cost and low discharge rates.

Project Goals and Objectives

The goal of this project was to demonstrate the performance, safety, reliability, and low cost path for Amber Kinetics' modular, four-hour duration flywheel system.

The objectives for meeting the above goal were to:

- Design, develop, install, and test a commercial-scale, 25 kilowatt-hour Amber Kinetics flywheel energy storage system.
- Measure and confirm target performance specifications.

¹ P. Tsao, "An Integrated Flywheel Energy Storage System with a Homopolar Inductor Motor/Generator and High-Frequency Drive", PhD Dissertation, U.C. Berkeley, September, 2003

² Perry Tsao, M. Senesky, S.R. Sanders, "An Integrated Flywheel Energy Storage System with Homopolar Inductor Motor/Generator and High-Frequency Drive", IEEE Transactions on Industry Applications, vol. 39, no. 6, pp. 1710-1725, Nov-Dec, 2003

- Highlight a commercialization plan for achieving low production costs, as measured on a dollar per kilowatt-hour basis.

Conclusion

Amber Kinetics successfully tested and demonstrated the company's 6.25 kW, 25 kWh flywheel system. This system meets utility customer requirements and is both practical and feasible for cost-effective manufacturing. The product is now at the final development and testing stage.

CHAPTER 1: Project Approach

1.1 PIER Project Background

The purpose of the project was to demonstrate the functionality of Amber's 6.25 kilowatt (kW), 25 kilowatt-hour (kWh) flywheel system. The project proceeded in three major increments: system design, manufacture, and testing/demonstration.

1.2 Flywheel System Description

A flywheel energy storage system stores kinetic energy in the flywheel, which is a large rotating mass. A motor/generator coupled to the flywheel rotor shaft converts electrical energy to kinetic energy; the motor/generator accelerates the flywheel rotor when charging the system and decelerates the flywheel when discharging. Other key components include a bearing system to support the rotating mass, a vacuum system to minimize windage losses inside the enclosure, a compliant suspension to manage the vibrational modes of the structure, and power electronics to connect the motor/generator to the grid. Figure 2 is a photograph of the vacuum enclosure.

1.3 Major Flywheel Subsystems

Figure 2: Amber Kinetics 25 kWh Flywheel System



1.3.1 Rotor

Kinetic energy stored in a flywheel is proportional to the stress swing, shape factor, and volume of the rotor. Effective rotor designs optimize rotor shape and achieve the highest working strength to cost ratio. It is significant that solid rotors built from isotropic materials are able to support bi-axial stresses, enabling an effectively high shape factor. For comparative purposes, Table 1 illustrates the cost considerations that motivate use of a high-strength steel rotor.

Table 1: Rotor Material Comparison

Material	Strength	Density	Strength/ Density	Cost	Strength/ Cost	Comments
	MPa	kg/m ³	MPa/(kg/m ³)	\$/kg	Mpa/\$	
Steel	1400	7780	0.2	1	1400	Conventional metal working
Carbon fiber composite	4000	1750	2.3	20	200	Costlier process, separate curing steps
Glass fiber	1200	2100	0.6	3	400	As above
Kevlar fiber	3500	1200	2.9	12	292	As above

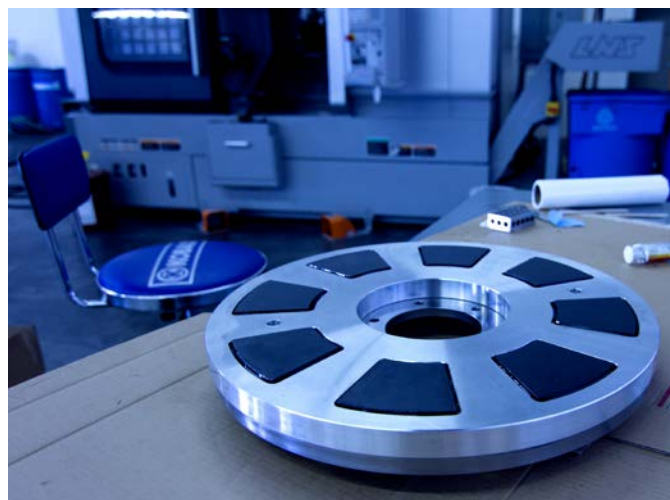
Table 1 shows that, when measured on a strength per unit cost ratio (MPa/\$), traditional steel offers a significant and practical cost advantage compared to composite materials.

The flywheel described in this report is made from approximately 5,000 lbs. of solid steel. At its top speed, it stores nearly 29 kWh of kinetic energy. However, because the minimum operating speed is limited by system resonances, the available energy in the rotor is just above 25 kWh. Mechanical-to-electrical conversion losses further reduce the extractable energy.

1.3.2 Motor/Generator

This demonstration project employed a permanent magnet motor/generator design. It is an axial flux, 8-pole, 3-phase machine, with rotor as shown in Figure 3. The motor/generator was designed and built by Amber Kinetics.

Figure 3: Motor/Generator Permanent Magnet Rotor



1.3.3 Bearings

The bearing system uses a hybrid mechanical and magnetic bearing arrangement, that results in long life, low drag, and fail-safe functionality. The researchers designed the bearing system to safely sustain operation in the face of seismic disturbances up to 1G, well in excess of the class IV-rated ground accelerations for the seismically active California region.

1.3.4 Vacuum System

The housing of the flywheel unit serves as both mechanical support for the bearing system and vacuum vessel. The researchers typically ran a $\frac{3}{4}$ horsepower (hp) vacuum pump continuously to achieve a vacuum between 10 and 50 milliTorrs (mTorr). However, leakage tests indicate that this pump can be operated intermittently at a low-duty cycle without significant penalty in pressure. Alternatively, this pump could serve multiple flywheel units.

1.3.5 Suspension System

A key consideration for high-speed machinery is the resonant modes of the structure, at which large vibrational displacements can occur. The researchers carefully tuned the masses of the primary system components and the stiffness of their couplings to ensure that no resonant modes occur at frequencies within the normal operating range.

1.3.6 Power Electronics

Although power electronics were not a focus of this report, a simple system to couple the variable speed alternating current (AC) motor/generator with the 60-hertz (Hz) line could be constructed from a pair of AC-DC inverters coupled at the direct current (DC) side. A typical utility scale installation would aggregate the output of multiple motor/generator inverters at the DC bus for connection with a single large central inverter. As discussed in Section 2.1.4, the research team considered round-trip efficiency at this DC bus to be a key metric, as the upstream equipment (central inverter, transformer) is common to many storage technologies.

1.4 System Testing

Amber Kinetics built two prototype flywheel systems, designated “alpha”, and “beta,” for this program. The research team fabricated and assembled virtually all of the components for the two systems at Amber Kinetics’ Union City facility, with some ancillary equipment being purchased off the shelf. The systems underwent basic functional qualification testing before being installed, sequentially, at the company’s outdoor test site in Alameda, California for full-speed field-testing.

Because line power was not available at the test site, power for experiments was provided by a 208-volt (V), 3-phase gasoline generator. Discharging power was dissipated in a bank of load resistors.

The researchers’ primary considerations when testing the prototype units were to: (1) demonstrate the functionality of the system, (2) verify the frequencies of resonant modes, and (3) quantify spinning losses and motor/generator efficiency.

CHAPTER 2: Project Outcomes

2.1 Test Results

This section discusses key test results from the Amber Kinetics flywheel program conducted under contract with the Energy Commission. The data given below are from the beta unit, which was tested through the speed range to 8500 revolutions per minute (rpm).

2.1.1 Resonant Modes

The flywheel housing was instrumented with a dual-axis accelerometer. The axes were aligned to capture lateral accelerations (which are normal to the rotor axis) and “rocking” accelerations (which appear in the axial direction when measured at a radial distance from the axis).

Resonances matched the design values, within tolerance margins, with the main resonance occurring at approximately 2500 rpm—substantially below the active speed range. Resonances were also well damped, showing peak values less than 0.2 G for both axes.

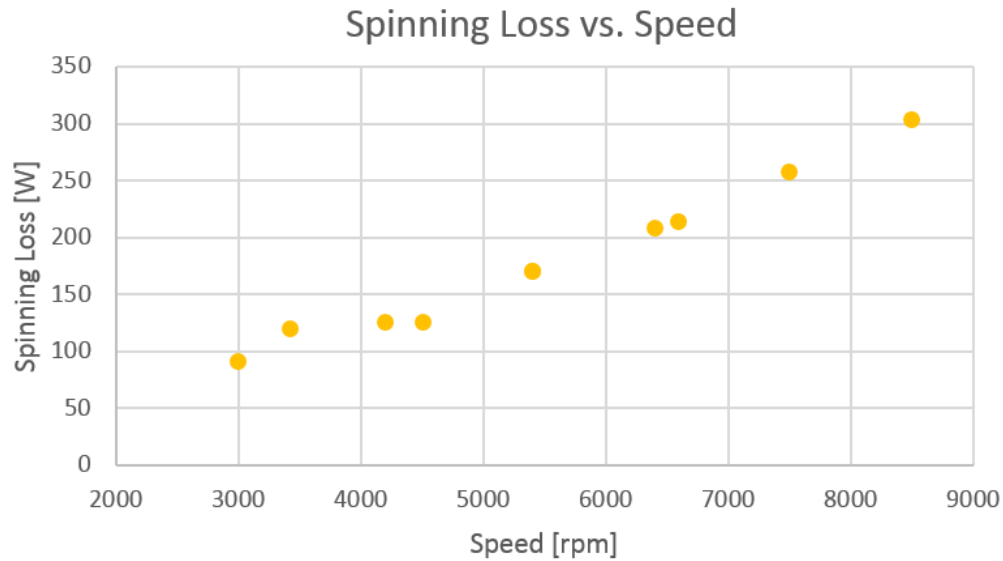
The balance of the rotor can also be inferred from the acceleration data. Both alpha and beta rotors exhibited excellent balance. Residual unbalance resulted in housing vibration amplitude of 0.01 G, or 0.1 m/s², across the active speed range. As such, acoustic emission and vibration were not perceptible to the human ear.

2.1.2 Self-Discharge

Self-discharge (spinning loss) results from a combination of mechanical ball bearing drag, windage, and electromagnetic drag torques. It is very challenging to disaggregate these losses from each other, as they occur simultaneously. However, the researchers calculated that the electromagnetic drag torque in their design is essentially negligible. Windage and bearing losses are thus assumed to constitute the main components of spinning loss.

Spinning loss can be accurately measured by simply recording the rate of deceleration of the flywheel in an idle state and then calculating the corresponding power loss. Such measurements are shown for the beta prototype in Figure 4.

Figure 4: Measured Flywheel Spinning Loss in Beta Prototype



When averaged over the full state of charge range, the measured spinning loss is approximately 200 W. There is a strong speed dependence, suggesting that operational profiles should be weighted toward low-speed rather than high-speed idle states. Further reduction in self-discharge is expected with improvements in vacuum system and bearing adjustments.

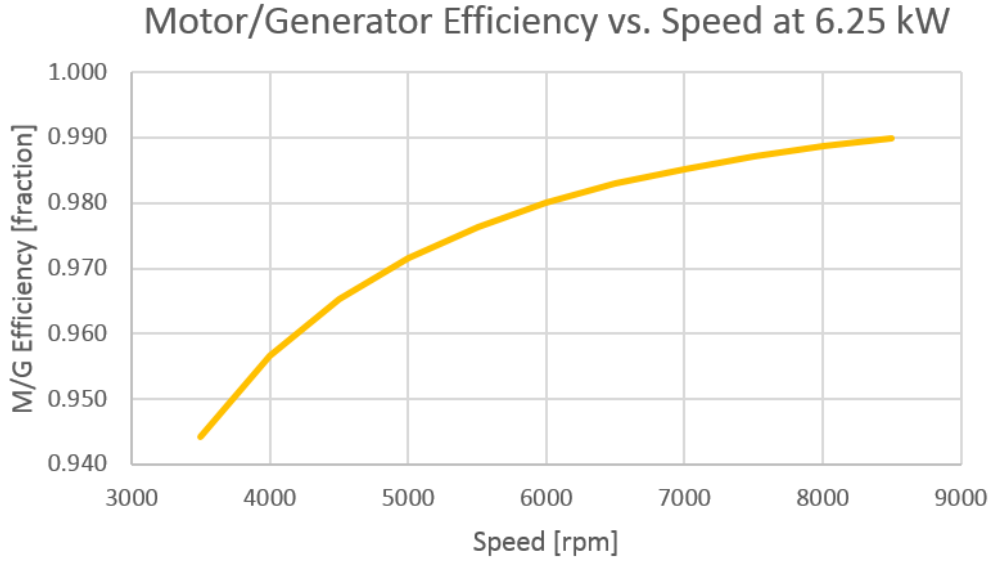
2.1.3 Motor/Generator Efficiency

Motor/generator losses can be divided into conduction loss and core loss. As noted above, the stator core material used in the prototypes should have negligible losses at the operating flux and frequency levels. Thus, motor/generator efficiency is well characterized by the stator winding impedance and back-emf, as given by the measured values in Table 2. An efficiency curve based on these parameters is also plotted in Figure 5 for maximum power of 6.25 kW over the operating speed range. Average motor/generator efficiency over the full state of charge range is 97.9 percent.

Table 2: Measured Motor/Generator Electrical Parameters

Parameter	DC Resistance, L-N	Self-Inductance, L-N	Back-EMF, L-N
Value	58 mΩ	133 uH	192 mVrms/Hz

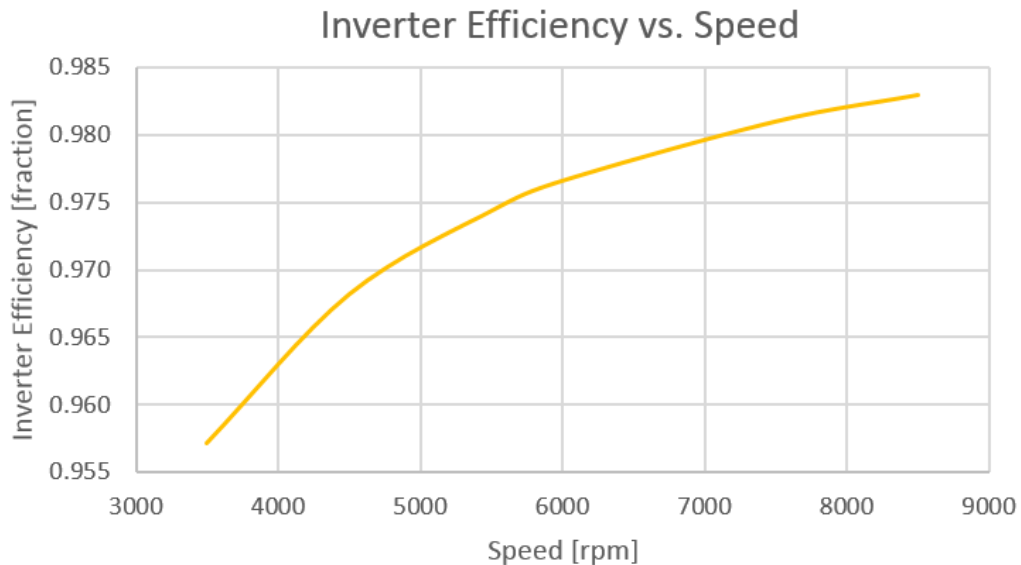
Figure 5: Motor/Generator Efficiency Curve at 6.25 kW



2.1.4 System Efficiency

In order to estimate system efficiency, the researchers considered the contribution of a representative AC-DC inverter. The modeled topology is a standard 6-switch IGBT inverter with reactive filter elements, operated in voltage-source PWM mode. Figure 6 shows calculated losses for this model. Average inverter efficiency over the state of charge range is 97.6 percent.

Figure 6: Inverter Efficiency Curve at 6.25 kW



Taking the motor/generator losses and inverter losses described above, the researchers estimated the average round trip efficiency at the DC bus to be 91.3 percent.

2.1.5 Ancillary Power Consumption

Ancillary power loads are comprised of the control electronics and the vacuum pump. These values are given in the table below. The power consumption of the vacuum pump represents a measured value of 240 watts (W) scaled by a duty factor of 10 percent. The total aggregate ancillary power consumption is thus approximately 65 W. The research team expects ancillary power consumption to be reduced further as they proceed toward commercialization.

CHAPTER 3:

Conclusions and Recommendations

3.1 Conclusions

Amber Kinetics successfully tested and demonstrated the company's 6.25 kW, 25 kWh flywheel system. Field demonstrations confirmed that the flywheel system met major design specifications, and the researchers have agreed on an effective set of operational and cost targets for a four-hour flywheel system. This system meets utility customer requirements and is both practical and feasible for cost-effective manufacturing. The researchers have also developed a commercialization plan to bring to market a commercially viable four-hour flywheel energy storage system. The product is now at the final development and testing stage.

3.2 Commercialization Potential

Flywheels have a unique set of technical features that are attractive for grid-scale storage applications:

- The potential for very low system costs (measured on a \$/kWh basis)
- High round-trip efficiency
- 30-year calendar life
- 30,000 full depth of discharge cycles
- Minimal self-discharge losses
- No capacity degradation
- No water or active cooling required

Based on the technology demonstrated in this PIER program, the research team believes that flywheels will be an important energy storage technology for several grid-scale storage applications. Having completed the project, Amber will now be able to leverage lessons learned to expand flywheel energy storage into appropriate markets and applications.

3.3 Recommendations

The research team recommends further collaboration between public and private entities to support and fund flywheel energy storage research, development, and demonstration programs. Future programs designed to demonstrate utility-grade; multi-hour flywheel systems at MW-scale would be beneficial in highlighting the potential for flywheels to emerge as a viable alternative to chemical batteries for multi-hour storage applications.

3.4 Benefits to California

The primary benefit of this project lies in the potential of the lower-cost energy storage technology demonstrated by the research team to benefit both the environment and California

ratepayers. When this technology is commercialized, it will support greater penetration of clean solar and wind energy, resulting in lower electricity costs and reduced greenhouse gas emissions. These benefits are in line with California objectives as quantified in the state's renewable portfolio standards (RPS) and in the state's energy storage law AB2514.

The flywheel energy storage technology demonstrated in this PIER-supported project exhibits capability of multi-hour discharge at full power, high roundtrip efficiency, low self-discharge losses, no power or energy capacity fade over life nor over state of charge, capability of 30,000 full deep discharge cycles, capability of calendar life of 30 years, and simple material recycling at end of life. In contrast, none of the existing commercial flywheel technologies support more than 15 minutes of full power discharge.

The most visibly prevalent electrochemical energy storage technology at present is represented by the family of Li-ion batteries. Although Li-ion batteries show promise of an aggressive cost down path, partly enabled by the scaling of electric and hybrid electric vehicle manufacturing, the Li-ion technologies suffer from capacity fade with accumulated cycles, modest life cycles, and poor end-of-life recycling characteristics. As such, this demonstration project has opened the door to an enabling technical solution to the state's most demanding electrical energy challenge.

GLOSSARY

Term	Definiton
AC	Alternating Current
CAISO	California Independent System Operator
DC	Direct Current
G	Gravity
HP	Horsepower
IGBT	Insulated-Gate Bipolar Transistor
kW	Kilowatt
kg	Kilogram
kWh	Kilowatt-Hour
lb	Pound
m	Meter
ms	Millisecond
MPa	Megapascal
mTorr	Millitorr
MW	Megawatt
PIER	Public Interest Energy Research
rpm	Revolutions Per Minute
UC	University of California