

Energy Research and Development Division

FINAL PROJECT REPORT

Flywheel Systems for Utility Scale Energy Storage

A Transformative Flywheel Project for Commercial
Readiness

California Energy Commission

Gavin Newsom, Governor

January 2019 | CEC-500-2019-012



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PREFACE

The California Energy Commission's Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The California Energy Commission and the state's three largest investor-owned utilities - Pacific Gas and Electric Company, San Diego Gas and Electric Company and Southern California Edison Company - were selected to administer the EPIC funds and advance novel technologies, tools and strategies that provide benefits to their electric ratepayers.

The Energy Commission is committed to ensuring public participation in its research and development programs which promote greater reliability, lower costs and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Flywheel Systems for Utility Scale Energy Storage is the final report for the Flywheel Energy Storage System project (contract number EPC-15-016) conducted by Amber Kinetics, Inc. The information from this project contributes to Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

The rapid growth of renewable energy sources like photovoltaic solar and wind generation is driving the need for cost-effective energy storage to capture energy during peak generation periods so it can be used during peak demand periods. The available solutions today have many drawbacks including environmental impacts, safety hazards, declining capacity, high maintenance requirements, limited operating conditions, and grid management constraints. The kinetic energy storage system based on advanced flywheel technology from Amber Kinetics maintains full storage capacity throughout the product lifecycle, has no emissions, operates in a wide range of environmental conditions, and is fully recyclable at the end of life.

This project has advanced the commercial readiness of flywheel technology by enhancing the product design, confirming performance and reliability, advancing manufacturing processes, validating the safety criteria, and demonstrating the management of a multi-unit array. More than 15 flywheel units have been tested with the fleet accumulating more than 38,000 hours of operating history. Numerous design and manufacturing enhancements emerged from this process. Multiple failure modes were intentionally induced to experimentally confirm the safety of the system design. And operations of paralleled flywheel arrays capable of achieving utility-scale deployment have been demonstrated.

Keywords: Flywheel, Reliable, Safety, Energy Storage, Multi-unit array,

Please use the following citation for this report:

Sutherland, Will, Matthew Senesky, Ph.D, Wei-Tai Kwok, Mark Stout, Seth Sanders, PhD., Ed Chiao and Ramnath Bhat. 2019. *Flywheel Systems for Utility Scale Energy Storage*. California Energy Commission. Publication Number: CEC-500-2019-012.

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EXECUTIVE SUMMARY

Introduction

Utility-scale power generation has moved beyond conventional coal-fired, natural gas, nuclear, and hydroelectric sources. Increasingly, significant amounts of electric power are generated by renewable sources such as wind, solar, and geothermal. California is at the forefront of this push to adopt renewable energy resources. On September 10, 2018, California passed Senate Bill 100, (De León, Chapter 312, 2018), requiring a mix of renewable portfolio standard-eligible and zero-carbon resources by December 31, 2045, for a total of 100 percent clean energy. However, generation from these renewable sources does not always align with the demand of power users. For example, the sun shines brightest in the middle of the day, and the wind blows when atmospheric conditions align, but not necessarily when there is peak energy demand. Therefore, energy storage is critical to help align the supply of renewable energy with demand by storing the energy when it's cheaper and abundant and using it when it's in high demand.

California recognizes this need and is driving the investor-owned utilities (IOUs) to invest in energy storage. Assembly Bill 2514 (Skinner, Chapter 469, 2010) has mandated procuring 1.325 gigawatts (GW) of energy storage by IOUs and publicly-owned utilities by 2020. However, there is a notable lack of commercially viable energy storage solutions to fulfill the emerging market for utility scale use. The traditional solution of pumped hydro faces growth challenges from limited geographic options, environmental impacts, and local resistance. Lithium ion batteries are an early winner to address growing demand, but this technology faces environmental, safety, capacity degradation, and operational restrictions that limit its viability as a solution. Additionally, as electric vehicle use increases, there will be greater competition for Lithium ion manufacturing capacity. There are other chemical-based solutions under development that have potential yet are far from perfect. A diversity of technology solutions is necessary to create a competitive marketplace and address all demands for the utility-scale energy storage challenge, including the flywheel.

A flywheel is a “mechanical battery” that stores kinetic or moving energy. The basic concept of a spinning mass is well-established and is found in many mechanical systems such as automotive engines. High-performance flywheels have been used for uninterruptible power supply and frequency-regulation applications, which require high power for a short duration. The flywheel offers long operating life with no capacity degradation. Additionally, flywheels are capable of many charge/discharge cycles per day (compared to many other energy storage technologies) without any degradation of performance over time, and they can provide ancillary services like frequency regulation, offering grid operators more value from an energy storage device. The technology can be used in a wide range of environmental conditions without using cooling loads, and there is no risk of fire or chemical discharge from this all-steel, recyclable product. A long duration flywheel is worthy of consideration for many emerging utility applications.

End users, such as utilities tend to be conservative with new technologies and require proof of operation and competitive costs. To make flywheels an option in the market, operational run time and lower costs are required. Bringing a commercially viable flywheel technology to market will provide IOUs with an additional energy storage option to choose from; furthermore, the technology will help to drive down pricing for IOU electricity ratepayers due to its advantages in optimizing grid management.

Project Purpose

Amber Kinetics, Inc. is the first company to design a long-discharge duration kinetic energy storage system based on advanced flywheel technology ideal for use in energy storage applications required by California investor-owned utilities (IOUs). The Amber Kinetics M32 flywheel is a 32 kilowatt-hour (kWh) kinetic energy storage device designed with a power rating of 8kW and a 4-hour discharge duration (Figure ES-1).

Figure ES-1: Amber Kinetics M32 Flywheel



Source Amber Kinetics

This project advanced the technology toward a commercial release of the product with three areas of focus:

- **Commercial readiness.** Establishing credibility in the utility scale energy storage market requires demonstration of reliability and performance over multiple units. The ability to consistently build a high-quality product is an important benchmark to commercialization. Under this grant Amber Kinetics set out to accumulate significant operating data under real-world conditions.
- **Safety validation.** Safety is a fundamental requirement of any technology, and the storage of energy in kinetic form presents a number of risks. The ability to demonstrate safe operation under multiple failure modes will address customer concerns and foster the adoption of the technology.
- **Array operation.** Flywheels are only viable for utility-scale energy storage when multiple units can be integrated into an array to achieve the necessary storage capacity. Developing hardware, software and a test platform is necessary to successfully demonstrate multi-unit array operation with balanced power and state of charge (SoC). The state of charge is an expression of the present energy storage capacity as percentages of its maximum energy storage capacity.

Successfully completing these efforts moved the Amber Kinetics flywheels toward commercial viability.

Project Process

The project activities were structured into three different groups: commercial readiness, safety validation, and multi-unit array operation. The three activities were independent but equally important in demonstrating a commercially viable technology for utility-scale energy storage.

Commercial Readiness

This effort demonstrated that Amber Kinetics flywheel units are capable of repeatedly and reliably delivering energy storage services. This was accomplished by building, instrumenting and operating multiple flywheel units. Accumulating operating hours was a key metric for the project as was the number of discharge cycles at full power. The performance of individual units was evaluated over time compared to design specifications and fleet averages.

Operating experience led to design and manufacturing changes on the rotor geometry to improve robustness and reliability on a continuous basis; units were often upgraded and compared to earlier versions of the product. Continually improving the units resulted in a more robust and higher performing energy storage system. The cycle time for building, installing, and commissioning new units improved throughout the project. Also, unit-to-unit consistency has improved.

Safety Validation

Any energy storage system has the potential to release its energy in an unplanned manner – flywheels are no exception. Amber Kinetics has taken this concern very seriously in the design and manufacturing of its products, using the resources provided by this grant to experimentally validate design assumptions and manufacturing quality and to characterize the system response to rare, unplanned events. The Amber Kinetics team identified a number of failure modes and structured a series of experiments to obtain feedback for the final product design.

Safety validation testing was performed at a remote site to allow flywheels to be stressed to failure in a safe manner. The failure modes tested included: loss of vacuum, overspeed, top and bottom bearing failure, and rotor burst. Temperatures, accelerations, electrical parameters, video footage and photographs were collected as appropriate.

Multi-Unit Array Operation

Sizing flywheel energy storage capacity to meet a utility scale requires integrating many units into an array. Before this project, Amber Kinetics only operated flywheels in an individual, stand-alone configuration. A hybrid approach using hardware and software was developed to simultaneously control multiple flywheel units in parallel, while maintaining balance of power and state of charge throughout the array.

Project Results

Design and manufacturing changes were made to improve the performance, lifetime, reliability, safety, and cost effectiveness of flywheel systems. Thousands of operating hours on more than a dozen units enhanced the credibility of flywheels as a viable solution for the IOUs. Extreme testing conditions were used to validate the design criteria and safety assumptions.

Additionally, operating multi-unit arrays connected to the grid has advanced the flywheel scalability for utility-sized energy storage.

Commercial Readiness

More than 38,000 operating hours have been accumulated on more than dozen flywheel units, completing more than 880 full charge/discharge cycles with zero degradation of capacity. Marathon runs of more than 1,000 continuous hours were completed on multiple occasions, with the lead flywheel unit accumulating more than 6,500 operating hours.

The design and manufacturing process for Amber Kinetics flywheels has stabilized during this project. The knowledge gained from the accumulated operating experience has led to design changes improving the reliability, performance, and unit-to-unit consistency while enhancing the credibility of these flywheels. One noteworthy advancement was upgrading the product energy storage capacity from the model M25 (25kWh) to the model M32 (32kWh), improving performance while reducing cost.

Amber Kinetics installed a M32 flywheel demonstration unit at Hawaiian Electric Company in January 2018, and has contracted with West Boylston Municipal Lighting Plant in Massachusetts for 16 M32 units to be installed in fall 2018.

Safety Validation

The safety design criteria have been validated through a series of induced failures and overstress events. Flywheels are a heavy rotating mass contained in a vacuum environment to minimize air friction. They are supported by an upper and lower bearing to axially constrain the rotation. Amber Kinetics has determined through multiple safety validation tests that flywheels can tolerate the loss of vacuum without damage. During the safety validation, no unusual behavior was noted in over speed tests, indicating a good performance margin. The units responded to bearing failures in a benign and safe manner. A catastrophic rotor burst is a very unlikely but potentially hazardous event; the installation concept endorsed by Amber Kinetics showed no release of fragments above-grade.

Multi-Unit Array

The capability to manage units has grown from single unit operation to arrays of up to four units. Features have been created to share power and maintain the charge balance among the units within the array. Bench testing simulations validated the processing and communications capability to handle 32 units, which is an important step toward utility scale use. The demonstration of multiple operating scenarios including frequency regulation, multi-cycle -per-day operation, and spinning reserves may improve grid management strategies for IOU's.

Outreach

Amber Kinetics engaged in different technology transfer activities by commercializing its flywheel technology in the U.S. and abroad. For example, Amber kinetics presented its technology pilot project in a press conference and ribbon cutting with Hawaiian Electric at the Campbell Industrial Park Generating Facility on Oahu to demonstrate the flywheel's real-world capabilities on the distribution system. The Amber Kinetics team also participated as presenters in different conferences such as the Maui Energy Conference and the Hawaiian Electric Flywheel Pilot Project. They also presented at the Energy Storage Association's Annual Conference and at the Roosevelt Strategic Council Microgrid & DERS Summit in Alexandria, VA.

Moreover, the Amber kinetics team is contributing to shaping the UL 9540 standard for "Energy Storage Systems and Equipment" to apply updated and improved public safety standards regarding flywheels.

Benefits to California

This project contributes multiple benefits to California's electricity ratepayers. Any form of energy storage allows the IOU's to add additional solar and wind capacity without risking the need for curtailment. The strategic locating of storage capacity and multi-cycle capability of flywheels can save millions of dollars in transmission congestion costs. There are even larger savings to ratepayers due to the deferral of transmission and distribution system upgrades. Industrial customers can effectively reduce the demand charge element of their electrical bills through a peak shaving strategy. Storing energy to use during peak demand periods reduces the need to add new generating capacity.

The Amber Kinetics flywheels offer many added benefits. The fast system response can provide many benefits to IOU's by stabilizing the local grid and offering ancillary services like frequency regulation. The flywheels are a long-duration, high use, cost-effective solution that does not degrade over time and can operate in a wide range of environmental conditions without heating or cooling which reduces system operating losses and improves reliability. Service reliability to electrical ratepayers can be improved through strategic location of storage facilities. Flywheels have no emissions, consume no water, emit no noise, and have no risk of fire or hazardous material spills making them a good neighbor solution to California's energy challenge.

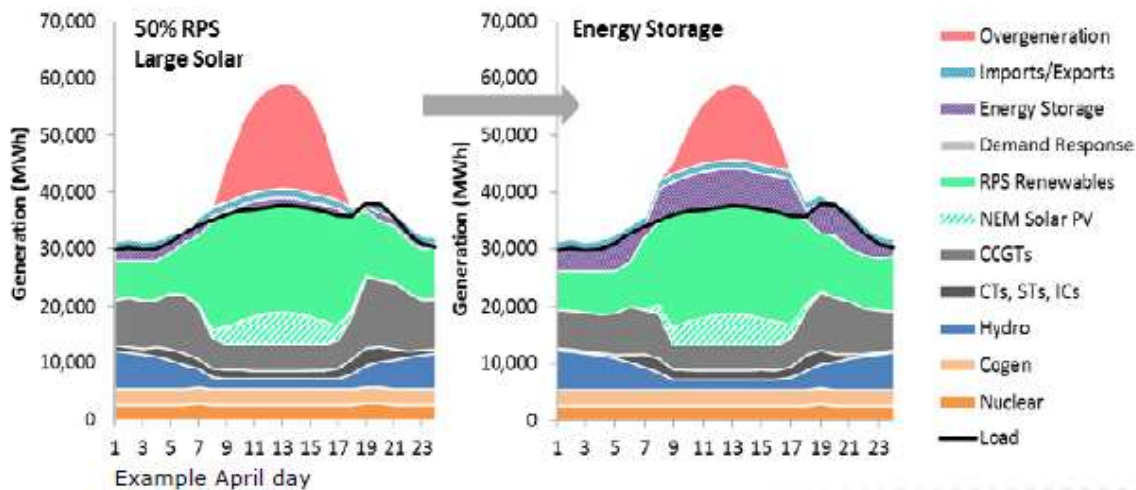
CHAPTER 1: The Need for Flywheel Energy Storage

California’s Ambitious Energy Storage Goals

Utility-scale power generation has moved beyond the tried and true coal-fired, oil-burning, natural gas, nuclear, and hydroelectric stages. Increasingly, significant amounts of electric power are generated using generally smaller, “alternative” sources such as wind, solar, tidal, and geothermal. On September 10, 2018, California passed Senate Bill 100, (De León, Chapter 312, 2018) this bill requires that it is the policy of the state that eligible renewable energy resources and zero-carbon resources supply 100% of retail sales of electricity to California end-use customers and 100% of electricity procured to serve all state agencies by December 31, 2045. Renewables, however, are not always reliable, which makes it challenging for utilities. Energy storage is a critical element of any plan to increase reliance on small generation sources; the only alternative is curtailment where generators are required to reduce output from what could otherwise be produced. Storage is able to absorb excess PV solar generation during the day to be used later in the day when the demand for electricity increases (Figure 1).

Figure 1: Solar Curtailment Opportunity With Storage

+ Storage charges during daylight hours and generates at night to displace fossil generation and meet evening ramps



California recognizes this and is driving the investor-owned utilities (IOU) to invest in energy storage. Assembly Bill 2514 (Skinner, Chapter 469, 2010), approved in 2010, mandated the procurement of 1.325 gigawatts (GW) of energy storage by IOUs and publicly-owned utilities (POUs) by 2020. Assembly Bill 2868 (Gatto, Chapter 681, 2016), approved in 2016, mandated procuring an additional 500 megawatts (MW) of distribution-interconnected energy storage, evenly distributed between the three major electric IOUs. However, there are not a lot of commercially viable energy storage solutions to fulfill the merging market for utility scale deployment. The traditional solution of pumped hydro faces growth challenges from limited geographic options, environmental impacts, and local resistance. Lithium ion batteries are an early winner to address growing demand, but this technology faces environmental, safety, capacity degradation, and operational restrictions that limit its viability as a solution. There are other chemical-based solutions being developed with potential but are far from perfect. More solutions are necessary to create a competitive marketplace and address all the utility scale energy storage challenges.

Flywheels Add Value

Flywheels are a well understood, mechanical battery that stores energy as kinetic or moving energy and releases it back to the grid when there is demand. The origins of flywheels go back hundreds of years to the potter’s wheel. Many mechanical systems, like automotive engines, incorporate flywheel concepts into their design, but most flywheel systems today target applications that demand short burst of high power. In the power industry, flywheels can be found commonly in uninterrupted power supply (UPS) and frequency regulation applications.

This project is to demonstrate that this technology can address the requirements of energy storage at a utility-scale. Long duration discharge, low cost, high reliability, high efficiency, and long life are some of the requirements for utility scale storage that demand new innovations in flywheel design.

Flywheel Energy Storage Can Provide Versatility

Unlike previous flywheels designs, Amber Kinetics flywheel energy storage system, (FESS) can potentially deliver the full range of energy capacity, ancillary services products relevant to utilities, Independent Power Producers (IPPs), and commercial & industrial (C&I) customers. The system’s all-steel design provides superior operating performance and capabilities relative to batteries without the risks of complicated, volatile or toxic chemistries. Applying widely-available, low-carbon steel to proven flywheel technology results in a product with the structural integrity to outperform and outlast battery alternatives, making it highly desirable to customers who demand reliability and durability. Some of the potential capabilities of Amber Kinetic’s flywheel are listed in (Table 1).

Table 1: Amber Flywheel Capabilities

Operating Flexibility	<ul style="list-style-type: none"> ▪ No dispatch restrictions and unlimited daily cycling ▪ Ability to instantaneously switch between energy, capacity and all ancillary services products to obtain the highest hourly and sub-hourly intervals and capture the real-time market's price volatility
No Degradation	<ul style="list-style-type: none"> ▪ No degradation and 30-year design life - eliminates the costs of oversizing systems to meet contracted

	<p>capacity and replacing depleted battery stacks every 7-10 years</p> <ul style="list-style-type: none"> ▪ No variable Operations & Maintenance (O&M) costs means the FESS will be dispatched more in wholesale markets and will capture more energy arbitrages spread
Extreme Temperature Operation	<ul style="list-style-type: none"> ▪ Requires no HVAC and can operate in extreme temperatures (-40 to 50 C) and humidity ▪ Minimal fixed O&M (one maintenance outage every 10 years) make the FESS well-suited for remote environments and renewables + storage under long-term contracts
Safe and Sustainable	<ul style="list-style-type: none"> ▪ No chemicals or hazardous materials, posing far less risk of fire or of environmental liability upon disposal ▪ 98% steel product can be recycled

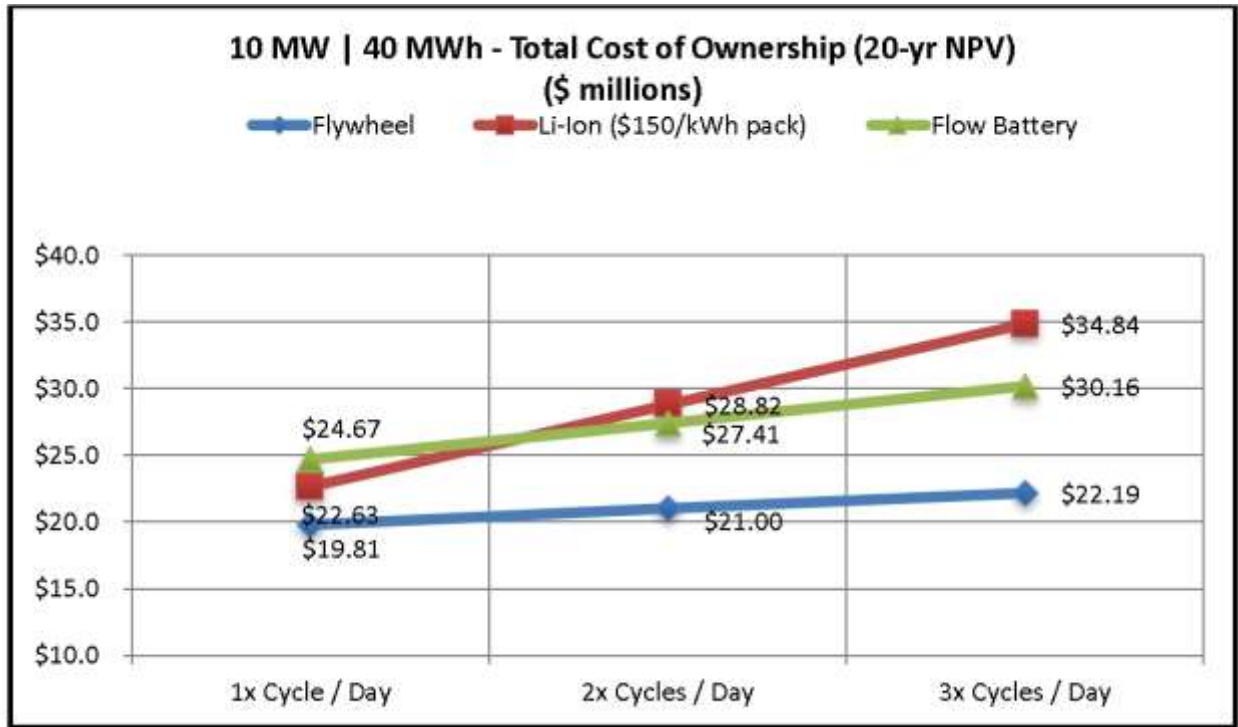
Source: Amber Kinetics

Flywheel Energy Storage Delivers Greater Value

Priced competitively with Li-ion and flow batteries, the company's FESS offers greater short- and long-term value. The FESS has a **lower total installed cost**, and with a 30-year design life, low fixed O&M and \$0/kWh variable O&M, the FESS also has a **lower total cost of ownership** – a gap that grows with each cycle. Figure 2 compares the potential Total Cost of Ownership of the Amber Kinetics flywheel with Li-ion and flow batteries. Taking into account the flywheel's minimal O&M cost and the need to replace batteries over time, the life-cycle cost of the FESS is lower than the battery technologies at one cycle per day – and the difference grows for multiple cycles per day because the FESS does not degrade.

Amber kinetics has estimated that the economics of the FESS is the opposite of batteries: the higher the use, the better the economics. As the company plans to shift from low volume production at the California research and development facility to high volume production, the researchers have identified a cost reduction roadmap that allows continued cost-competitiveness with Li-ion now and in the future. Greater durability at a lower cost presents clear value to the growing energy storage market, which is aware of Li-ion's limitations and is seeking cost-effective energy storage alternatives.

Figure 2: Energy Storage Total Cost of Ownership Comparison



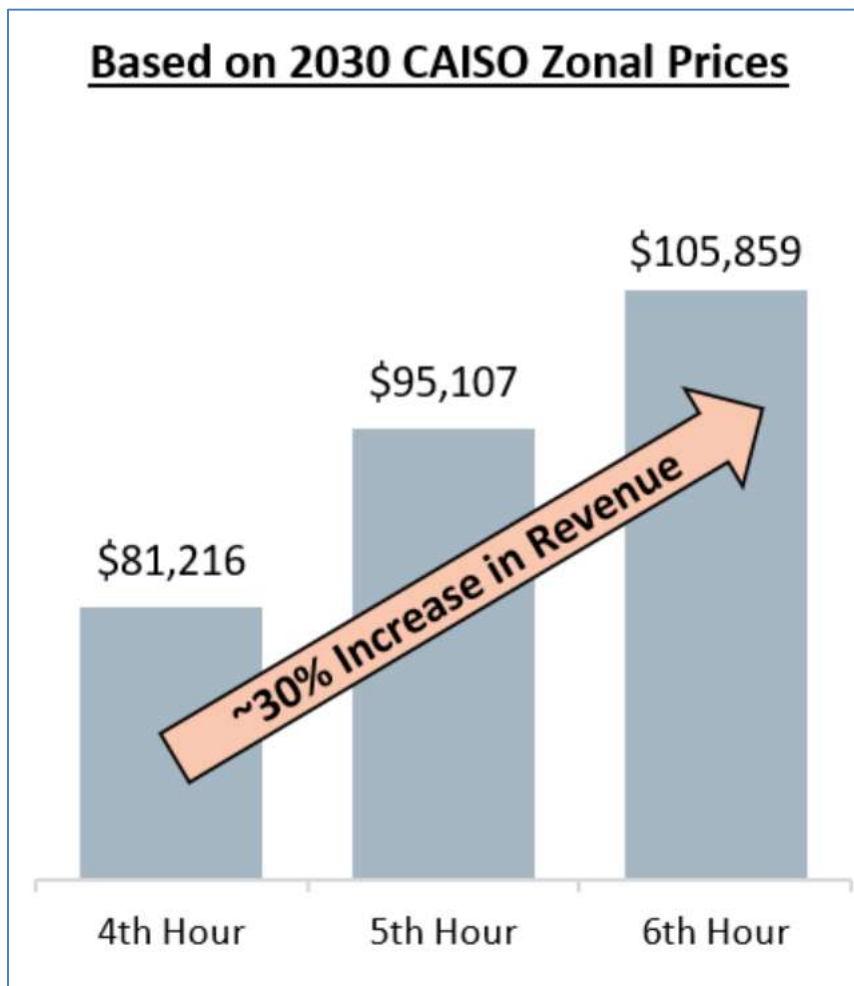
Source: Amber Kinetics

Flywheel Energy Storage Unlocks Operation Flexibility

Unlike Li-ion and flow batteries, the company’s FESS has no dispatch restrictions and can operate multiple cycles, 24 hours per day to provide capacity, energy, and ancillary services. The system can switch between services almost instantaneously to capture the highest price at hourly and sub-hourly intervals and can generate longer than four hours for utilities and industrials with broad peaks. This optionality can add 15-30% more in revenue than one cycle per day of Li-ion batteries, as renewables increase peak/off-peak spreads and volatility.

- Multiple Cycles Per Day:** Amber Kinetics marginal cost of a cycle (defined as 0% to 100% state of charge (SOC) and back) is \$0. The FESS can operate multiple cycles per day at no additional cost. Revenues are projected to increase as energy price spreads widen due to increased renewables penetration.
- 24 Hour/Day Operation:** The FESS \$0 marginal operating cost means that the system can be dispatched 24/7, earning revenue 24 hours per day, switching between energy and ancillary services to maximize revenue.
- Capturing Intra-Day Price Volatility:** The FESS can cycle between 0% to 100% output multiple times per hour to take advantage of the real-time market’s price volatility. Figure 3 shows a simulation comparing a 1 MW/4MWh storage system’s performance operating in the day-ahead and real-time California ISO markets in 2015. While capturing the full revenue potential represented in Table 2 would require perfect knowledge, there is clearly potential to earn more than being limited to operating in the day-ahead market.

Figure 3: California ISO Revenue Potential



Source: Helman Analytics and Amber Kinetics, Feb 2017

CHAPTER 2:

Commercial Readiness

Assessing the commercial readiness of any product is subjective especially with the stringent, expectations of the utility industry. Utility assets commonly operate for decades in harsh environments with high availability and reliability. Typically, investor-owned utilities are reluctant to use new products and technologies without an extensive operation track record. Operating data are important for supporting the commercial use of a product, particularly a utility-scale energy storage product.

This project was to advance Amber Kinetics' flywheel as a viable energy storage technology for California's investor owned utilities. Several different criteria were addressed including design stability to manufacturing capability to system performance to reliability of operation. The team's approach was to build and operate multiple units since the operating experience provides real world feedback to support design enhancements and the cumulative history builds a foundation of credibility to support market adoption.

The Starting Point

Amber Kinetics had built a small number of engineering prototype flywheels which had been operated for short durations totaling about a 100 operating hours. FW4 had been built and tested prior to the project and demonstrated good energy storage capabilities and roundtrip efficiencies, however there were limitations that had to be addressed before it could be considered a commercially viable product. The unit was a proof-of-concept system lacking manufacturability, serviceability, and reliability.

Based on the experience gained from FW4, the company designed the M25 model flywheel for this project. Three units of this new improved design were being manufactured when the project was awarded in February 2016. Shortly after the project award the first unit for the project, FW5, was installed at company's Alameda Test Site (ATS).

The team spent time debugging the M25 during initial use and limited the operating hours during the first few weeks. The units were returned to the factory for analysis, rework, and adjustments. The units started accumulating meaningful numbers of hours beginning in April when FW5 operated continuously for three weeks and completed the first full power cycle.

Method

This effort was to accumulate operating hours and full power cycles on multiple flywheel units; however, the benefits and measures of success were to go well beyond the accumulation of metrics. Amber Kinetics wanted to study flywheel behavior to characterize performance over a wide range of operating scenarios.

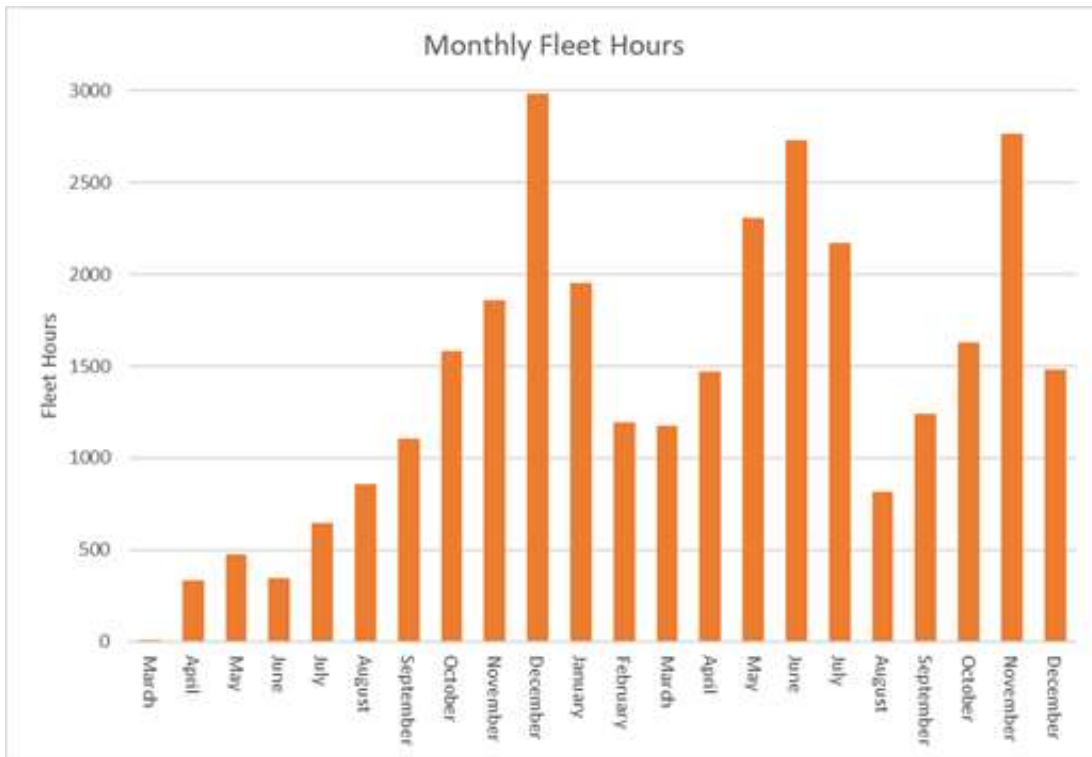
System faults, component issues, performance anomalies, and other observations were not considered as failures but opportunities to enhance and improve the design. A closed loop feedback loop was used throughout the project to identify issues to drive corrective actions. The specific issues encountered, and solutions adopted were beyond the scope of this report; however, the process used and progress towards commercial readiness resulting from this project will be discussed.

Results

Fleet Operating Data

Accumulating operating hours was an important success metric for this project. Utilities require reliable systems with asset lifetimes typically exceeding 30 years. Potential customers must see a track record of improvement for any new technology. It is important to characterize performance of energy storage devices over numerous charge and discharge cycles to determine whether there is any degradation of capacity over the lifetime of the product. And it is always valuable to measure the results over as many units as feasible (Figure 4).

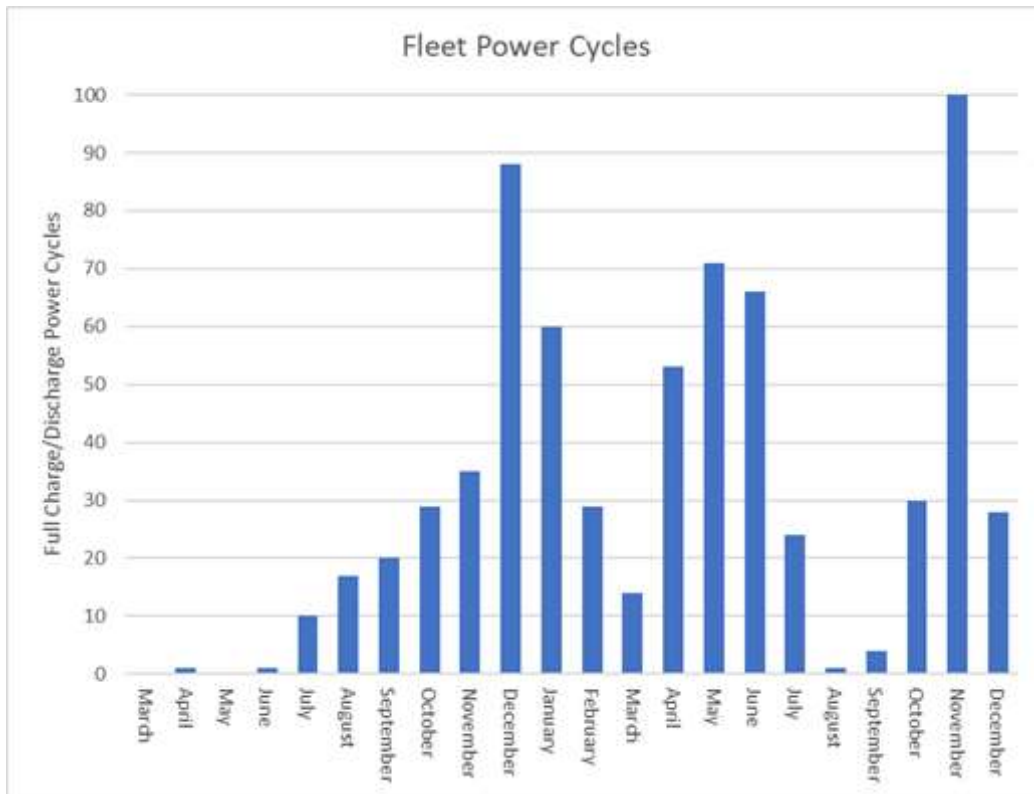
Figure 4: Fleet Operating Hours



Source: Amber Kinetics

The project team operated the flywheel units for more than 38,000 hours accumulating more than 35MWh of stored energy, a remarkable feat during the timeline of the project. The first unit (FW5) was operated for about a month with the first few weeks focused on infrastructure improvements and system debugging. By the second month, however, FW5 had spun continuously for more than three weeks. The on-line of the units continued to improve and by September, the flywheel achieved a 1,000-hour continuous marathon run. By then, the fleet of seven units had accumulated more than 4,000 hours of service and completed 56 full charge/discharge cycles (Figure 5).

Figure 5: Full Charge/Discharge Cycles

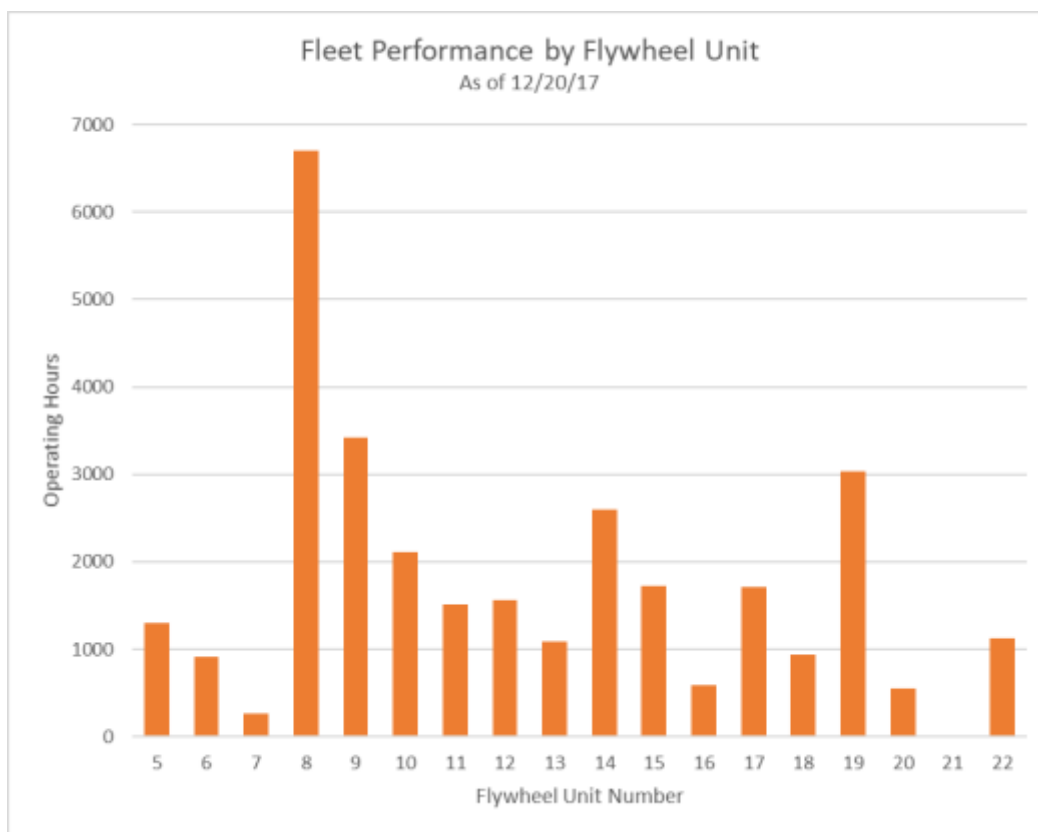


Source: Amber Kinetics

The rate at which Amber Kinetics was able to accumulate hours was initially restricted by the availability of only two test pits at ATS. Also, there were other test priorities competing for time in the pits. The company collaborated with two customers to install demo units on their sites to accelerate collecting operating data. As a further advancement, the company added a second test site, the Central California Test Site (CCTS) primarily for validation testing.

A high-water mark for service hours was achieved in December 2016. The two test cells at ATS recorded 1,401 hours of service, a remarkable 94% uptime in spite of ongoing engineering tests. The customer demonstration sites and CCTS contributed more than 1,500 more hours for a total of almost 3,000 operating hours in one month. There were 89 full charge/discharge power cycles completed during that productive month; that was the record until November 2017 when an intense test period racked up 100 full cycles (Figure 6).

Figure 6: Operating Hours by Unit Number



Source: Amber Kinetics

The focus on operating hours by the project team transitioned to other project and company priorities, but operating hours have continued to accumulate over the duration of the project. The most recent data shows that 38,649 hours of operation and 35.6 megawatt-hours (MWh) of cumulative energy storage on the fleet since the start of the project. During that time, more than a dozen units within the fleet have completed more than 880 full charge/discharge power cycles. This data is a solid foundation for establishing the reliability of flywheels to meet the demands of utility scale energy storage.

Energy Storage Capacity

The rated energy storage capacity for the M25 at the beginning of the project was 25 kilowatt hours (kWh) with a 4-hour discharge duration (6.2kW power rating). The safety validation overspeed testing was an important input to uprating of the M25 unit to 32kWh of energy storage capacity (8kw power rating). Other performance parameters like roundtrip efficiency and accumulating operating hours were also key.

Design Stability and Manufacturability

There are a numerous encouraging signs towards the commercial readiness of the M32 flywheel during the design validation testing. The M25 design has eliminated the weaknesses identified in the first units and the manufacturing processes have been standardized and quality control points more clearly defined resulting in more consistency unit-to-unit. The time required to build and test a flywheel unit has significantly decreased as the work cells have become

formalized, parts stocked, designs and processed documented, and performance expectations more predictable.

A case study demonstrating the progress toward commercial readiness during this project was to compare the record of the first flywheel (FW5) to one of the recent units (FW21). The first unit took a team of engineers more than four weeks to build and document the unit and more than six weeks were required before operation was stable. The design of the current unit can be manufactured in about a week; installing in the test vault takes less than a day and full speed is achieved by the next day (Figure 7).

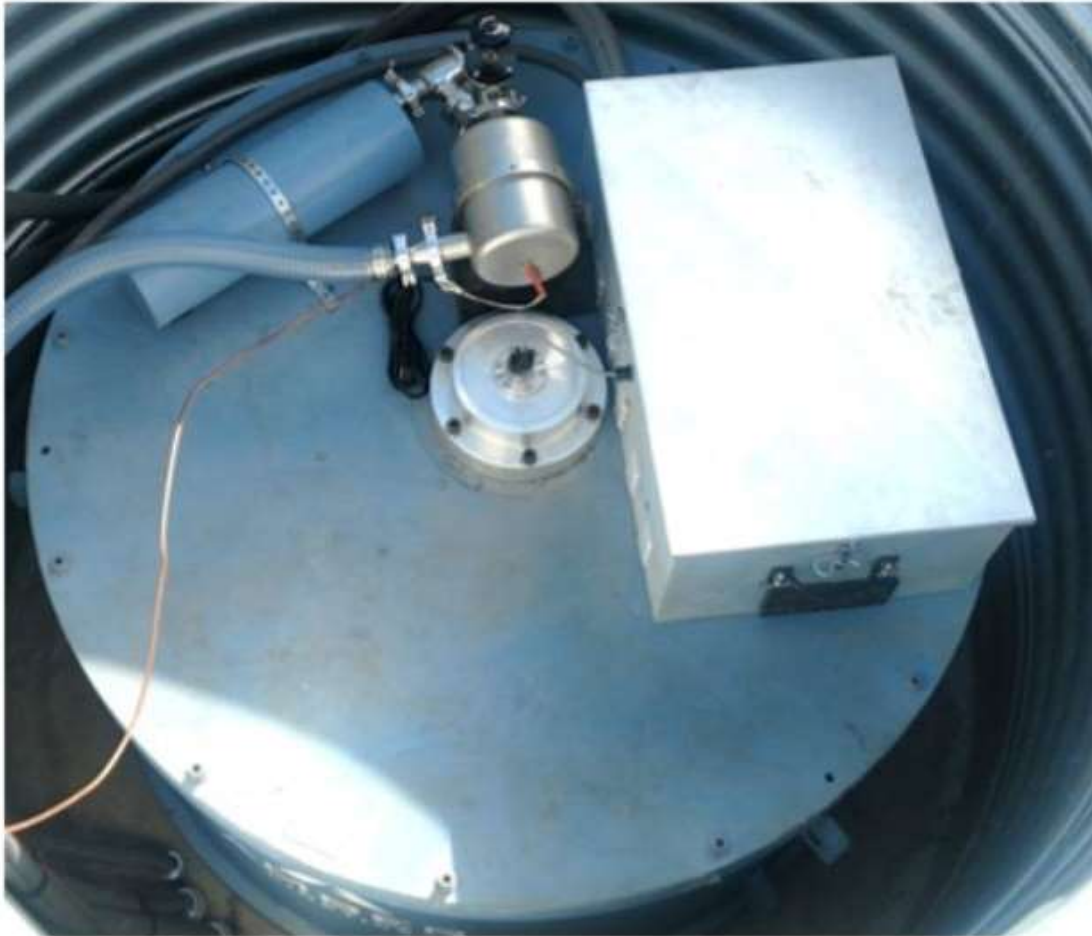
The next step in the process is to scale the production capability of Amber Kinetics and the company is working with a contract manufacturing partner to begin commercial producing in 2018 the latest flywheel system -the M32 (Figure 8).

Figure 7: M25 Unit Installed in Original Containment Design



Source: Amber Kinetics

Figure 8: M32 Unit Installed in New Containment Design



Source: Amber Kinetics

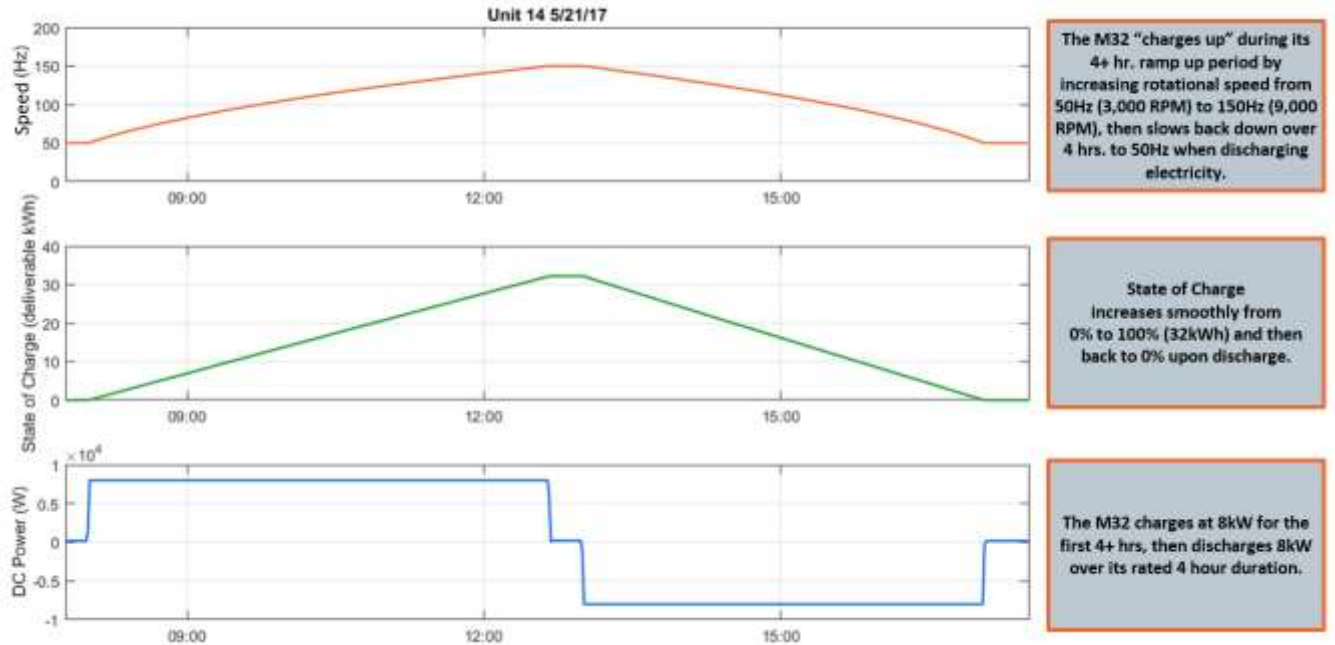
Design Validation

Any new product goes through a period of debugging, refinement, and optimization before it is ready for release. A system failure during this early stage is not a setback as much as an opportunity for improvement, a chance to make a more reliable product. The circular engineering process of design, build, test, evaluate, and repeat was used throughout the project; continuous improvement is only possible when care is taken to identify and eliminate the root cause of problems.

Testing must be conducted on multiple units to flush out whether the observed results are random behavior of a single unit or systematic to the design. This project advanced the commercial readiness of the Amber Kinetics' flywheels by supporting the time consuming, deliberate, and necessary process of preparing the product for release. There is no single test that certifies the product is ready; it is the cumulative results and the effectiveness of corrective actions that builds confidence in the product.

Figure 9 shows test data from May 21, 2017 on a single M32 flywheel. The unit was fully charged then discharged during a business day. This charging sequence demonstrated the ability of the M32 to store 32kWh of mechanical kinetic energy consistent with design expectations, and to discharge 8kW over the specified 4-hour period.

Figure 9: Example of M32 Power and Energy Validation

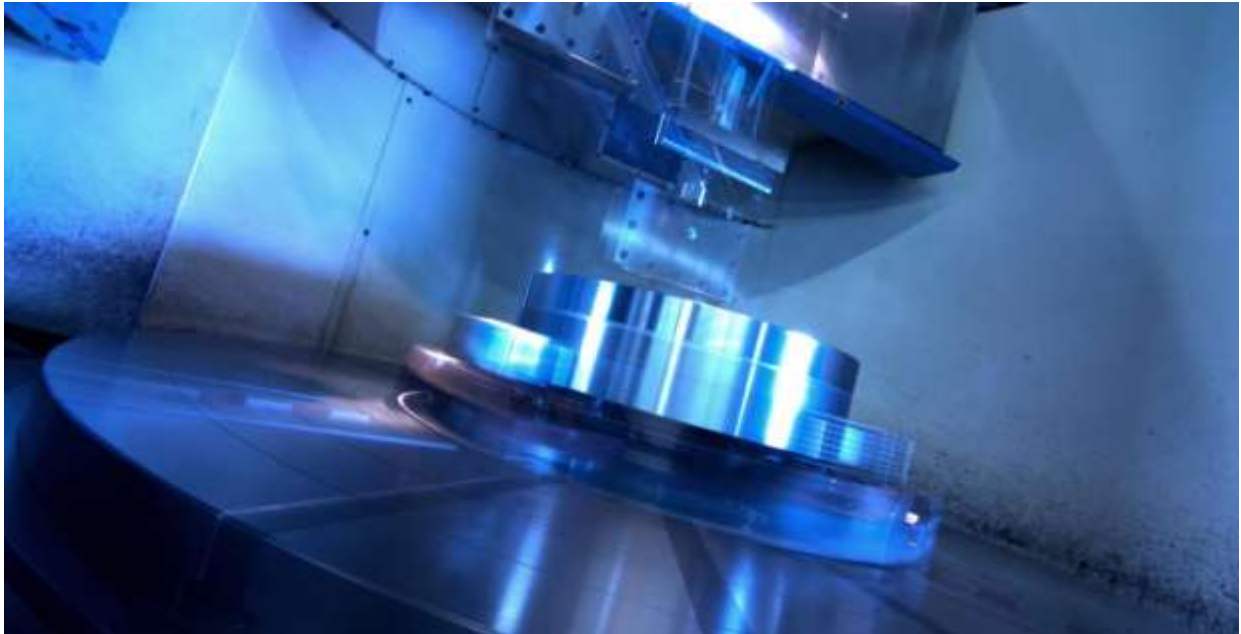


Source: Amber Kinetics 2017

The continuous improvement cycle was used during the efforts to improve the dynamic performance of the magnetic actuator that reduces load on the bearings. Several iterations of the control printed circuit board (PCB) were tested, with improved performance each time as well as resolving several bugs. The end result of this iterative effort was a reduction of the bearing load by almost 70%, enabling roughly a 10-year service life for the bearings.

The testing of multiple units during the project has refined the specifications of the product. The company is able to confidently promote the product capabilities because there is statistically relevant data from more than 20 units to back up the claims. Basic performance metrics such as energy storage capacity and roundtrip efficiency are consistent unit-to-unit and in-line with the demands of the energy storage market. The design and advanced manufacturing process are producing consistent, repeatable, and predictable results (Figure 10).

Figure 10: Advanced CNC Machining of High Precision Parts



Source Amber Kinetics

Amber Kinetics has pushed beyond the original plans of the project to validate the readiness of the M32 flywheel design for utility scale energy storage. One of the advantages of flywheel technology is the environmental tolerance; chemical batteries perform poorly outside of a limited temperature range which often necessitates auxiliary heating and cooling systems that reduce system power conversion efficiency.

Demonstrating environmental compatibility of complete flywheel systems over a wide range of conditions from -20-40° Centigrade (C°) has been challenging, however notable progress has been made in the field and the lab. Components have been subjected to repeated cycles of hot and cold in an environmental chamber. Entire flywheels were placed in a chiller where operating conditions were simulated (Figure 11). And two units were used as customer demonstrations in a hot, humid climate. The results to date support the expectation that flywheels can operate reliably in a wide range of environments without the need for ancillary heating or cooling.

Figure 11: Environmental Test Chamber to Validate Temperature Requirements



Source Amber Kinetics

Third Party Validation

Internal testing of products is central to validating commercial readiness, but direct feedback and operational experience from customers is equally important. During the project, Amber Kinetics collaborated with multiple customers on demonstration projects and while these efforts were not part of this project, the experiences add to the narrative.

San Diego Gas and Electric

In October 2016, ASWB Engineering, an engineering, training, and energy management consulting firm, was directed by San Diego Gas & Electric (SDG&E) Emerging Technologies Program to conduct a measurement and verification analysis of the Amber Kinetics FESS. The analysis determined the applicability of this emerging technology to various sectors of the energy distribution grid. The testing for the SDG&E analysis was performed at ATS where two identical flywheels were located in separate underground concrete bunkers, with an on-site monitoring and control room inside of a separate structure.

This study :

- Used Amber Kinetics data monitoring systems, monitor various system metrics throughout the testing procedures, including rotational speed and energy usage.
- Confirmed maximum energy capacity.
- Confirmed maximum charge/discharge rates.
- Confirmed manufacturer efficiency claims.

- Calculated cost savings associated with load shifting based on SDG&E's AL-TOU Secondary rate.
- Determined flywheel ancillary services potential.
- Conducted a life cycle cost analysis.

To monetize the load shift associated with the FESS, a Time of Use (TOU) utility rate is necessary. At the request of the SDG&E project manager, this report used the AL-TOU-Secondary rate from SDG&E.

Because the AL-TOU-Secondary rate has a seven-hour summer On-Peak period, and the FESS can only discharge at max power for four hours, two scenarios were considered for evaluation. Scenario A assumes that the discharge rate was lowered so the discharge period spans the full seven-hour summer On-Peak period. Scenario B uses the maximum discharge rate for four of the seven On-Peak hours. Scenario B produced better results than Scenario A, but at a greater risk of setting higher peak demand levels in the remaining three On-Peak hours where the FESS is no longer discharging.

Scenario A and Scenario B were evaluated with 1) no incentive, 2) a hypothetical Permanent Load Shifting (PLS) incentive, and 3) a hypothetical SGIP incentive. Table 2 demonstrates the simple payback financial analysis of the study.

Table 2: Financial Payback Analysis

SCENARIO	IMPLEMENTATION COST	ANNUAL ENERGY COST SAVINGS	ANNUAL DEMAND COST SAVINGS	TOTAL ANNUAL COST SAVINGS	SIMPLE PAYBACK (YEARS)
A - Without Incentive	\$900,000	(\$7,998)	\$52,503	\$44,506	20.22
A - With PLS Incentive	\$658,672	(\$7,998)	\$52,503	\$44,506	14.80
A - With SGIP Incentive	\$141,264	(\$7,998)	\$52,503	\$44,506	3.17
B - Without Incentive	\$900,000	(\$9,199)	\$76,655	\$67,456	13.34
B - With PLS Incentive	\$477,676	(\$9,199)	\$76,655	\$67,456	7.08
B - With SGIP Incentive	\$141,264	(\$9,199)	\$76,655	\$67,456	2.09

Source ASWB Engineering

Conclusions were documented in ASWB Engineering report, “The technology was able to perform as the manufacturer claimed. Based on the results of this study, the FESS is able to effectively convert between electric energy and kinetic energy while minimizing losses. This capability can be used for permanent load shifting, as well as potentially providing supplemental load during scheduled Demand Response (DR) events (assuming a Permanent Load Shifting strategy is not already in effect, which would eliminate the DR baseline). Based on the results of this study, it is recommended that the FESS be adopted into the SGIP program. The assessment provides sufficient information to demonstrate the flexibility and capabilities of this technology.”

This third party independent analysis of Amber Kinetics' FESS is publicly available and downloadable on the internet.¹

Emerging Power Inc., Subic Bay, Philippines

An early unit from the project, an M25 with a power capacity of 6.25kW and 25kWh energy storage capacity flywheel, was temporarily sent to a site in Subic Bay Philippines by Emerging Power, Inc. to demonstrate integrating energy storage into their 150MW solar-wind facility (Figure 12). Additionally, there was an opportunity to test the M25 early design flywheel capabilities in real world operational scenarios by providing load shifting and fast ramping response services. This demonstration spanned more than 1.5 years with valuable information gained including project siting, remote deployment challenges, infrastructure requirement, and general system operation. The lessons learned included flywheel reliability improvements, civil design considerations, user interface feedback, and operation challenges in harsh environments which will facilitate improved future uses, however, at this time, the specific test results are confidential to Emerging Power.

Figure 12: Demo Installation at Subic Bay, Philippines



Source Amber Kinetics

Hawaiian Electric Company (HECO), Campbell Industrial Park, Hawaii

On March 12, 2018, Hawaiian Electric, in partnership with Amber Kinetics and Elemental Excelerator launched operations of a four-hour kinetic energy storage system (KESS) powered

¹ Flywheel Energy Storage Study, Prepared for Emerging Technologies Program, San Diego Gas & Electric by John Baffa, PE, and Mark Hinrichs of ASWB Engineering, March 22, 2017. <https://www.etcc-ca.com/reports/flywheel-energy-storage-study>

by the latest M32 flywheel technology (Figure 13). The pilot project is the first commercial use of Amber Kinetics' advanced technology in the U.S.

The M32 has a power capacity of 8kW and 32kWh energy storage capacity for local grid reliability and can support and aid in integrating renewable energy. Technical field data is being collected and is expected to guide planning for future utility-owned energy storage projects in Hawaii. Communications and controls Amber Kinetics is developing in collaboration with Hawaiian Electric will be tested in a real-world setting and scaled to other jurisdictions.

Figure 13: Demo for HECO at Campbell Industrial Park, Hawaii



Source Amber Kinetics

Summary

This project demonstrated that Amber Kinetics flywheel units are capable of consistently and reliably delivering the energy storage services required by utilities. The project team built and operated multiple flywheel units, accumulating numerous operating hours full power cycles.

Operating experience led to design and manufacturing changes in a closed loop feedback loop; units were often upgraded and compared to earlier versions of the product. This continuous improvement process resulted in a more robust and higher performing energy storage system. The cycle time for building, installing, and commissioning new units improved throughout the project. The unit-to-unit consistency also improved.

There are other metrics of commercial readiness that go beyond the scope of the effort for this project. A commercially viable product must be cost effective and the supply chain should be stable to support the business plan. There must be manufacturing capacity in place to produce the required numbers of units. The project helped to significantly advance these efforts, but considerable work remains on these fronts.

CHAPTER 3:

Safety Validation

All products have risks, however the chances of an event occurring and the impact if that event occurs are important considerations when evaluating if a product or technology is to be commercialized..

Stored energy in any form can be unintentionally released which inherently creates risk. All energy storage technologies must assess their inherent risks and design appropriately. Lithium ion batteries, for example, are at risk of fire if exposed to air; an uncontrolled chemical reaction can aggressively spread. Flywheels, on the other hand, store energy kinetically; the spontaneous release of that energy could be dramatic.

Amber Kinetics used two strategies to mitigate the inherent safety risks of kinetic energy storage. The first was designing the flywheel unit to minimize the chances of an uncontrolled release. The second recommended an installation design to customers that offer the best chance to contain the energy release in the unlikely event that it does occur. Validations of the safety design criteria for the flywheel and containment design are critical to demonstrating the viability of flywheels for utility scale energy storage.

A test site in Central California (CCTS) was prepared to conduct a series of experiments. Multiple different failure modes were simulated, and the results analyzed to better understand flywheel performance (Figure 14).

Figure 14: Amber Kinetics Central California Test Site



Source: Amber Kinetics (2018)

Test Plan

The test site was chosen to minimize any potential risk to the Amber Kinetics team and neighbors to the test site. Units were to be subjected to extreme operating conditions, and the potential results were uncertain. Safety was a primary consideration.

Units that had completed service in the reliability test program were designated to the safety validation tests. One of these five M32 test units was installed in a vault at the CCTS. Five different failure modes were considered for this safety validation testing.

- Overspeed
- Loss of vacuum
- Lower bearing failure
- Upper bearing failure
- Stub shaft failure
- Catastrophic rotor failure

Test Results

Overspeed Test

Amber Kinetics has done extensive modeling of the stresses in a rotor under operating conditions, so it was important to validate the assumptions of basic rotor strength in field use.

The flywheel was brought to full speed (9,000 rotations per minute [rpm]) which is equivalent to the maximum energy storage capacity of 32kWh for the M32 flywheel. Using custom controls software, the speed was increased to 9,653 rpm which is a 15% overstress condition to the flywheel rotor. This overstress condition is consistent with industry norms for stress testing.

Two M25 units were tested using this procedure. The speed, acceleration, and internal pressure were monitored throughout the test. No unusual behavior was noted on either unit during the test program. There was no damage or degradation to either unit. At the conclusion of the tests, the units were functioning normally and were advanced to the next round of testing.

A third unit was tested in a more extreme overspeed condition during another phase of the safety validation testing. For this unit, a series of tests were conducted where the unit speed was progressively increased. The rotor achieved a top speed of 11,800 rpm, a 95% overstress condition, before the unit suffered a failure unrelated to rotor stress. The team concluded the M25 design has a large rotor stress safety margin .

The results of the overspeed testing were the final confirmation of the safety margin of the rotor design and the company to increase the rated energy storage capacity for the FESS from 25MWh to 32MWh. The project played a role in boosting the energy storage capacity by more than 28%, a dramatic impact on the cost effectiveness of the technology.

Loss of Vacuum

Amber Kinetics flywheels operate in a vacuum to minimize the friction loss from air. Rapidly introducing atmospheric pressure into the rotor chamber could have unforeseen impacts to the operating the flywheel. At a minimum, the air will act to slow the flywheel and for composite rotors, the sudden air friction can cause a destructive failure to occur.

The test unit was brought to full speed. After operating normally for a period of at least 2 hours, a solenoid valve released the vacuum almost instantaneously. The speed, accelerations,

internal pressure, and shell temperature were logged. The rotor spun down within 10 minutes. Accelerations were modest during the event and the unit remained fully intact. The shell temperature rose 110°C from the friction of the air.

The test unit was allowed to cool down. All systems were inspected and found to be in working order. The team concluded that this failure mode is very benign and the unit was restarted.

The original test for the project planned on this test for one flywheel. Amber Kinetics has repeated the loss of vacuum test while doing other development activities. The subsequent tests have confirmed the initial findings.

Lower Bearing Failure

The design of the M32 flywheel includes an electromagnet to lift the load of the rotor from the bearings. This reduces friction losses and extends the life of the bearings. There is a reasonable concern about what might happen if the magnet fails and the full load of the rotor were placed on the lower bearing. It is expected the bearing to eventually fail because it is stressed beyond the design limits in this test however, it is not clear what happens next.

The test unit was brought to full speed. The speed, acceleration, and internal pressure were monitored throughout the test. After operating normally for a period of at least 2 hours the electromagnet was deactivated, and the full weight of the rotor fell on the lower bearing. The system was driven in charge mode to maintain the rotor at full speed until the failure. The bearing survived almost 30 minutes before failure. During this time, the flywheel behaved normally, and accelerations were low. The unit began to shake when the bearing was failing, lasting just seconds.

The flywheel remained fixed to the mounts in the vault. The rotor remained inside of the shell. There were no overt signs from the outside that the unit had failed. The unit was removed from the vault and directed to failure analysis. When opened, it was obvious the unit was destroyed. The rotor had made contact with the motor generator assembly. Salvage operations were limited to recycling. But the failure mode was very benign from a safety perspective.

Upper Bearing Failure

This test is similar to the lower bearing failure test. It is possible that the upper bearing could fail prematurely through normal wear and tear or from a control system failure that overloads the upper bearing. Regardless of the cause, it is valuable to characterize how the flywheel will respond to this potential failure mode.

The test unit was brought to full speed. The speed, acceleration, and internal pressure were monitored throughout the test. In this case, the electromagnet was driven to high power to overload the upper bearing. The system was driven in charge mode to maintain the rotor at full speed until the failure. This bearing also survived about 30 minutes before failure. During this 30 minutes, the flywheel behaved normally, and accelerations were low. The unit began to shake when the bearing was failing; lasting a few seconds.

The flywheel remained fixed to the mounts in the vault. The rotor remained inside of the shell. There were no overt signs from the outside that the unit had failed. The unit was removed from the vault and directed to failure analysis. When opened, it was obvious the unit was destroyed. The rotor had made contact with electromagnet before dropping onto the motor generator assembly. Salvage operations were limited to recycling. The failure mode was benign from a safety perspective.

Stub Shaft Failure

The M32 flywheel design has a stub shaft mounted to the rotor with the bearings attached to the stub shafts. There is a good safety margin in the stub shaft mounts which makes such an event unlikely. The project plan did not even intend to test this failure mode, however circumstances in other tests lead to a unit failing in a manner consistent with a stub shaft failure.

One of the units used in the safety validation testing is believed to have experienced a stub shaft failure. During the failure analysis it was observed that the stub shaft had become disengaged from the rotor. In spite of this extreme overstress condition, the flywheel behaved normally for several hours until almost the instant of failure; at that moment, the unit began to shake. The event lasted seconds before the unit came to rest.

The flywheel remained fixed to the mounts in the vault. The rotor remained inside of the shell. There were no overt signs from the outside that the unit had failed. The unit was removed from the vault and opened; it was obvious the unit was destroyed. The rotor had made contact with electromagnet before dropping onto the motor generator assembly. Salvage operations were limited to recycling however, the failure mode was benign from a safety perspective.

Catastrophic Rotor Failure

The worst possible failure of a flywheel system is a catastrophic rotor failure. This failure mode is similar to a jet engine suffering a rotor failure. Great efforts have been taken to minimize the chance of such an event occurring with the M32 flywheel, however the company recommends installing the flywheels in some type of containment vessel should this failure happen.

The first challenge of this test turned out to be finding an effective method to induce a failure. It took multiple attempts to get a rotor to fail. Initial engineering analysis suggested that a series of grooves or notches on the surface of the rotor would be adequate to induce a crack and lead to failure. After a period of normal operation, the unit was brought to a 15% overstress condition at 9,563rpm. The unit did not fail. The rotor was removed, the notches enlarged and the test repeated; the results were the same. The unit was cycled repeatedly in an unsuccessful attempt to grow the cracks to failure. The stress level (speed) was increased incrementally until the unit finally reached 11,800 rpm which is an overstress level of 71%. At that point another failure mode destroyed the unit in a benign manner.

The next attempt deployed 10 inch slots cut into the rotor. There were some difficulties achieving balance of the rotor with the notches and high accelerations caused failures to other systems on two attempts. Finally, the team was successful in inducing a failure on the third try with the slot design. The same approach was tried on a second system using 4 inch slots instead to increase the energy level of the burst event. The fragments of both rotors were logged for size and location (Figure 15). This data was analyzed to support modeling of different flywheel models, operating scenarios, containment designs, and spacing requirements.

Figure 15: Rotor Burst Forensics



Source: Amber Kinetics (2017)

The most significant finding from this test was that all fragments were released in a radial direction. All fragments were contained in the soil or rocks surrounding the containment vessel. There was virtually no axial element to the trajectories. Items sitting above the flywheel such as the electronics and vacuum pump were barely impacted during the event. The shell and vault liner were destroyed (Figure 16).

The results of this testing suggest that a below grade installation with soil or rocks between units is an effective design to contain a catastrophic rotor failure. The vault liner should be designed adequately to hold back the soil, but no attempt should be made to have the vault liner contain the rotor fragments. A reinforced concrete vault should be avoided as it may cause fragments to ricochet uncontrollably.

Figure 16: Vault Liner after Burst Test



Source: Amber Kinetics

Seismic Event Tolerance

Testing the FESS tolerance to seismic event was not planned as a part of the project, however, a preliminary relevant data point was obtained during the project. A magnitude 4.4 earthquake occurred at 2:39 am on January 4, 2018 in Berkeley, California. The epicenter was 8.2 km from the Alameda Test Site.

The operating data from a flywheel discharging at the time showed higher than normal accelerations in the accelerometer data, and the electromagnet feedback loop detected higher than normal forces. This triggered a force fault of the unit which resulted in the flywheel being automatically placed in a coasting mode. Less than one second later the electromagnet force stabilized. The unit suffered no damage and was returned to active operation by an operator several hours later.

Summary

A wide range of safety validation tests were conducted on the Amber Kinetics M32 flywheel. The results of the testing exceeded expectations. The system is tolerant of several potential failure modes. The system behavior was more benign in several harsh failure modes than was predicted in advance. The difficulty bursting a rotor which led to unit operation in high overstress conditions demonstrates that the product design has more than an adequate safety margin. This project has advanced the safety validation of flywheels for utility scale energy storage.

CHAPTER 4:

Multi-Unit Arrays

Before this project, Amber Kinetics flywheels had only been operated in standalone, single-unit installations. While useful from a product development point of view, single-unit operation represents a subset of the technology required for multiple-unit arrays storing energy on a utility scale. The project's third goal was to advance the hardware and software required to operate multi-unit arrays. A multiple-unit array offers additional degrees of operational freedom, but requires careful attention to communications, system dynamics, and unit-to-unit power and state-of-charge balance.

During this project, a flywheel management system (FMS) was developed using utility-grade hardware. Communication protocols and control algorithms for coordinating multiple flywheels were developed. A multiple-unit test site was constructed, and operation of multiple flywheels on a common direct current (DC) bus was demonstrated. The project was successful in demonstrating multiple operating scenarios for charging and discharging multiple flywheels. Also, the performance of arrays as compared to single flywheels was evaluated.

System Development

Multi-Flywheel Array Controls

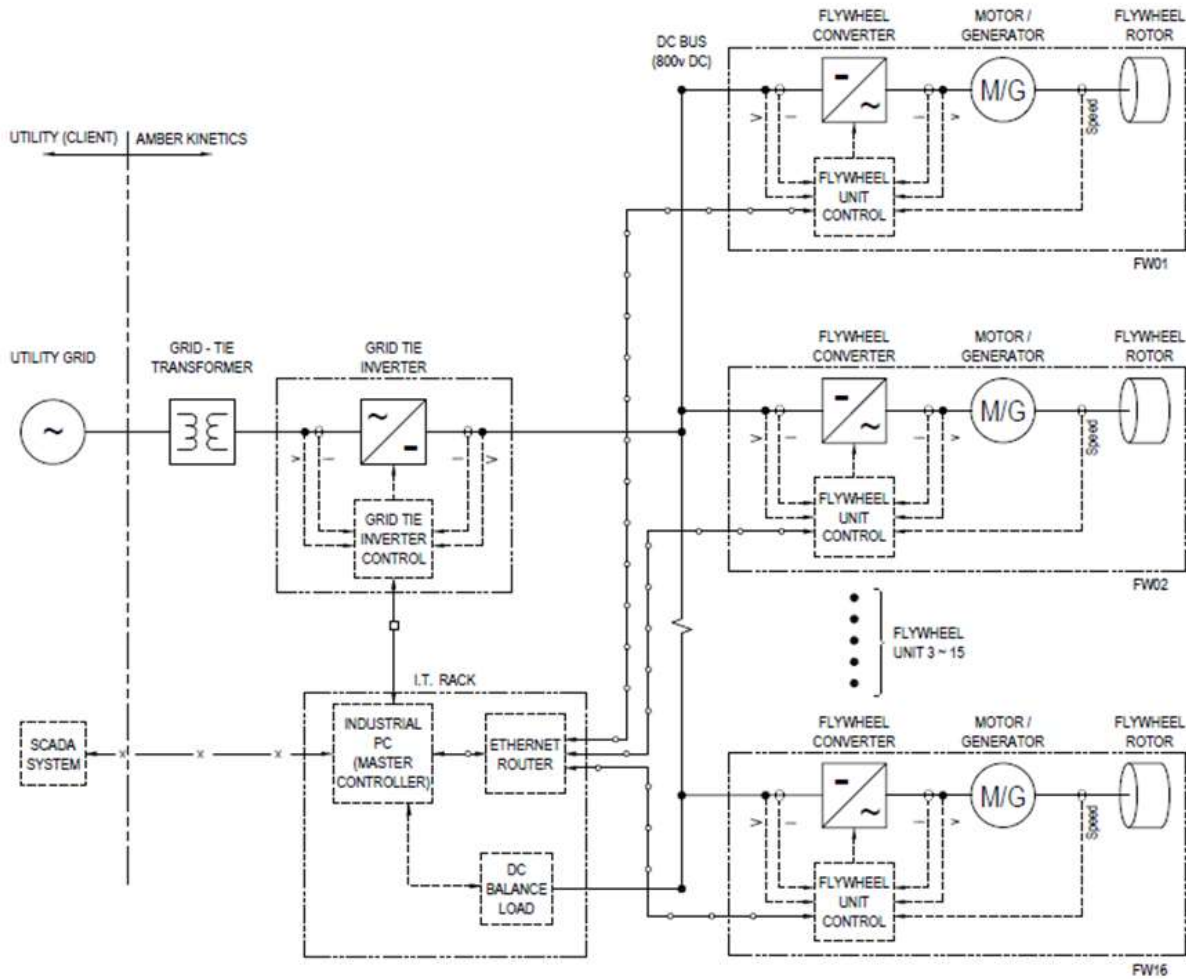
There are two objectives in implementing multi-unit array controls: maintaining a stable balance of power among units so that maximum site power can be achieved without violating individual flywheel power limits and maintaining balanced state-of-charge across the array so that maximum site power is always available over the full SOC range. The following implementation strategy was chosen:

- Multiple flywheels share a common DC bus with a grid inverter.
- High-bandwidth power balancing is implemented locally on each flywheel with a droop control scheme.
- Low-bandwidth state-of-charge balancing is implemented in the central FMS using an adaptive droop parameter update.

Hardware Development

A multi-unit flywheel array operates as a single, integrated system. The chosen architecture for this project was to connect all flywheels to a common DC bus feeding a grid inverter using the 30B3-4xF inverter from Ideal Power.. A central FMS was designed around an industrial computer from Advantech. Communications between the FMS and flywheels use transmission control protocol/ internet protocol (TCP/IP); the FMS accepts commands and returns data to a connected supervisory control and data acquisition (SCADA) system via distributed network protocol(DNP3) (Figure 17).

Figure 17: Multi-Unit Array System Architecture



Source: Amber Kinetics

Software Development

Several major software blocks were developed for array operation:

- A distributed balancing control algorithm for the individual flywheel microcontrollers.
- A state-of-charge balancing algorithm for the FMS.
- Algorithms for aggregate power dispatch.
- A user interface for array control.

Multi-Unit Array Testing

The multi-unit control system has been used at ATS and CCTS. Up to four units were simultaneously operated at CCTS while ATS was limited to the two vaults available there. Recent data shows more than 900 hours of operation and 1.9 MWh of cumulative energy storage at CCTS and an additional 400 hours of operation and 1.8MWh of cumulative energy storage at ATS. Additional benchtop testing has validated communications for up to 32 units simultaneously.

In June 2017, Amber Kinetics and Enel² signed a two-year agreement to cooperate on jointly assessing Amber Kinetics' technology and to explore the possible development of future projects. Enel pursues highly efficient, sustainable operations using the best available technologies based on a cost-benefit approach. Enel has been measuring the performance of Amber Kinetics' flywheel energy storage systems, beginning with two M32 units purchased by Enel, which are currently installed at CCTS (Figure 18).

Figure 18: Enel Multi-Unit Test Array



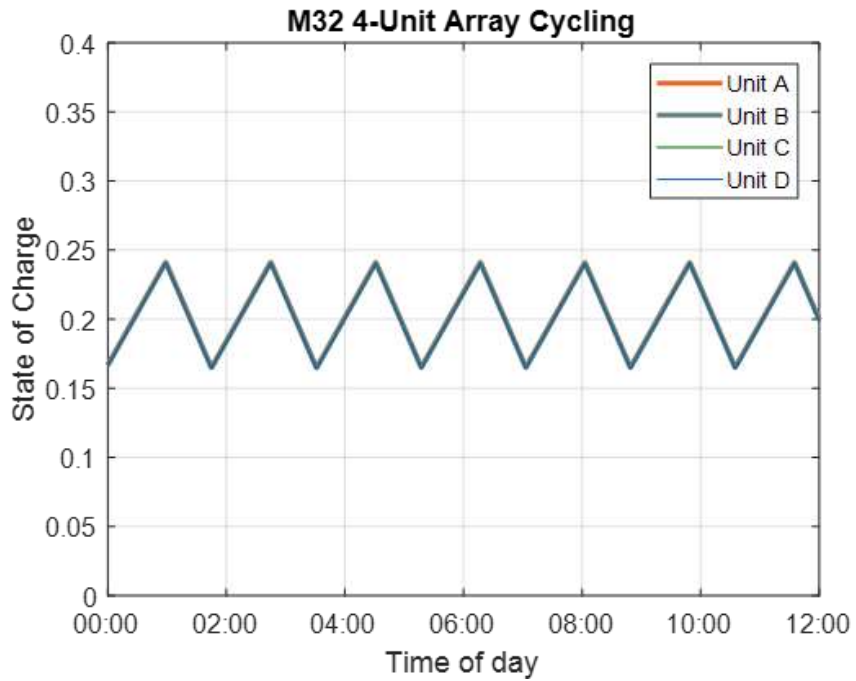
Source: Amber Kinetics (2017)

State of Charge Balance

One objective of the testing was to demonstrate how well units worked together when configured as an array. Figures 19 and 20 show test data for a four unit array at CCTS under a synchronized state of charge conditions. In the plots, the traces for the four units are indistinguishable from each other due to the excellent balance of power and SOC imposed by the controls. Full power operation at ATS with two units have shown similar results. The four flywheels continue to operate at CCTS as a four unit array supporting ongoing software development and data collection.

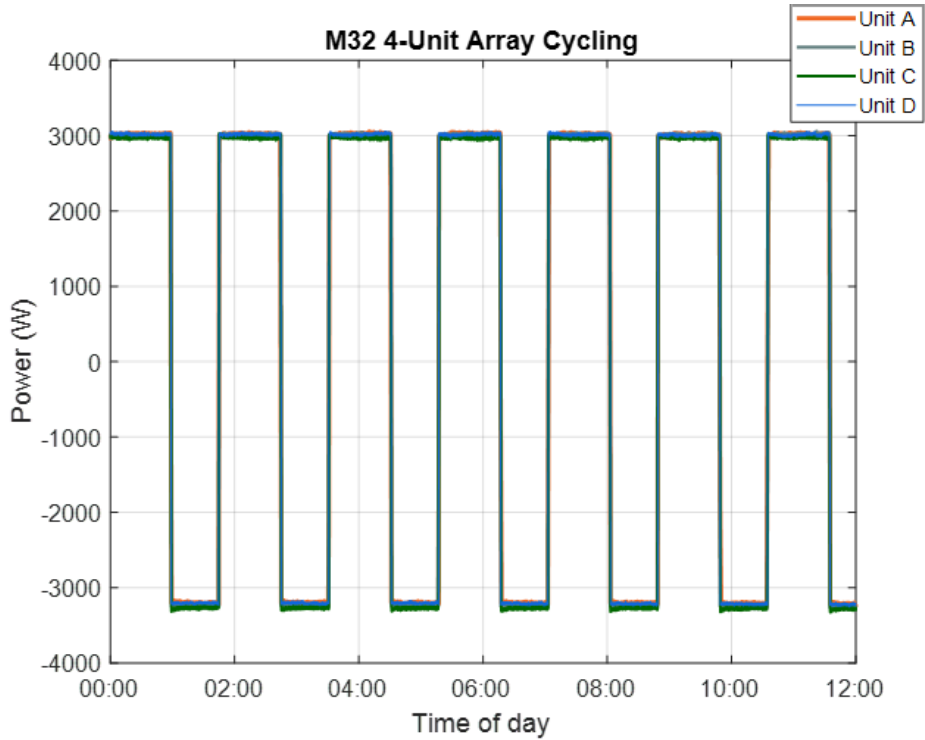
² Enel is Europe's largest utility and one of the world's leading integrated utilities with a presence in more than 30 countries across five continents.

Figure 19: Four Unit Array SOC Results



Source: Amber Kinetics

Figure 20: Four Unit Array Power Tracking

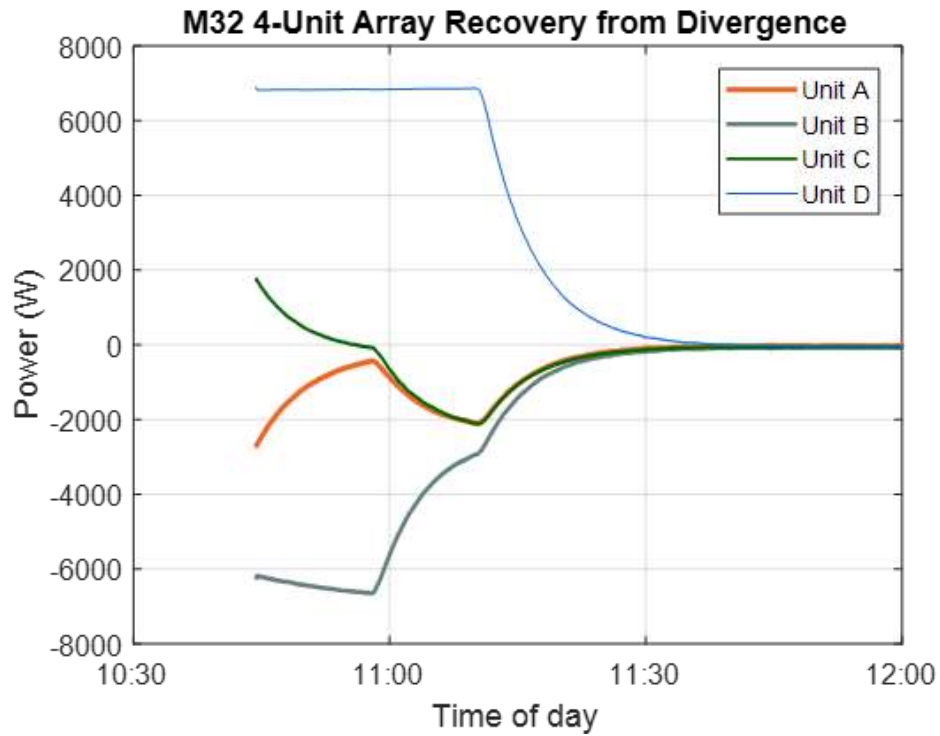


Source: Amber Kinetics

Recovery from Divergence

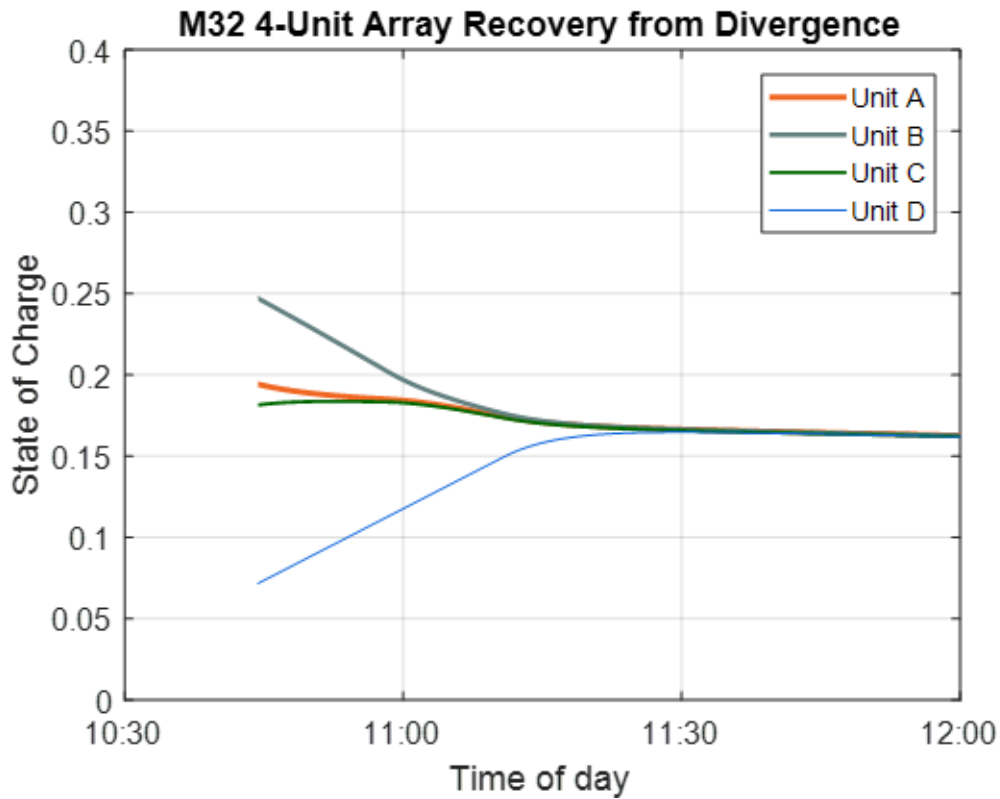
In another test, units were set to different states of charge and the SOC balancing algorithm was then made active (Figure 21). Each flywheel charges, or discharges for a time to bring to aligns its SOC with the rest of the array, and a rather large SOC imbalance converges quickly (Figure 22).

Figure 21: SOC Balance Test (Power)



Source: Amber Kinetics

Figure 22: SOC Balance Test (State of Charge)



Source: Amber Kinetics

Summary

Amber Kinetics was successful in developing hardware and software to support the operation of M32 flywheel arrays. The resulting system expands Amber Kinetics' capability from single-unit deployments to multiple-unit deployments. The system has been used to operate two and four unit flywheel arrays in the field. The available power and efficiency of the flywheel array showed no degradation compared to the aggregated single flywheel performance. The proprietary balancing algorithms successfully balanced power and SOC among the units.

CHAPTER 5:

Results of Project

Project Goals and Objectives

This project explored flywheel energy storage R&D to reach commercial viability for utility scale energy storage. This required advancing the design, manufacturing capability, system cost, storage capacity, efficiency, reliability, safety, and system level operation of flywheel energy storage technology. The team tested three specific areas to support this goal: commercial readiness, safety validation, and multi-unit array operation.

To test the commercial readiness of the flywheel the team built and operated multiple, discrete flywheel units. The flywheel units accumulated as many service hours as possible and were stressed in multiple ways to identify opportunities to improve the reliability and repeatability of the product design. Building multiple units presented the opportunity to define, document, and optimize the manufacturing process and quality controls necessary to consistently produce flywheel units.

Safety validation subjected the flywheels to predictable failure modes and assessed the system response. The team evaluated vacuum system failure, overspeed operation, bearing overload, and a rotor burst. Repeat tests were conducted whenever possible to increase confidence in the results.

The path to utility scale use of FESS was through multi-unit arrays; a single 1MW, 4-hour discharge duration flywheel was not feasible with current technology and utility scale requiring significantly more storage capacity. Amber Kinetics developed the system level hardware and software required to manage and control multi-unit arrays. Testing the capabilities and limits of array operation is an important validation step. Simulating various operating scenarios would help to define the advantages of kinetic energy storage to the IOUs.

Progress Assessment

As a result of this project in October 2018, Amber Kinetics had achieved the commercial release of the M32 flywheel product with the company first shipping production units from their first manufacturing facility.. This will give California IOU's new choices when addressing their energy storage needs. A robust and healthy marketplace for energy storage solutions is vital to supporting California's clean energy goals.

Commercial Readiness

This project team was successful in establishing a baseline record for the reliability of the FESS for utility scale energy storage. Although the duration of the project was limited, the company was able to accumulate more than 38,000 operating hours on a fleet of more than 15 flywheel units. The flywheels completed more than 880 full charge/discharge cycles with zero degradation of capacity. Marathon runs of more than 1,000 continuous hours were completed on multiple occasions. The fleet leader has accumulated more than 6,500 total operating hours. Although small to the lifetime expectations for utility storage, they are a foundation that demonstrates the viability of the Amber Kinetics FESS.

Several major utilities contracted Amber Kinetics to conduct technology trials of the FESS. For example, Emerging Power Inc of the Philippines (EPI) embedded a unit in its planned 150MW wind and solar farm in Subic Bay. *“Amber Kinetics’ technology will be very useful in smoothing out the energy generation of our solar and wind farm by taking out the variability. We are very excited to work with Amber and hopeful that this milestone deal will be replicated in future renewable energy projects in the country,”* said Alberto Guanzon, EPI Head of Marketing.

Europe’s largest utility, Enel, acquired two M32 units in late 2017. Enel’s Head of Global Thermal Generation, Enrico Viale, explained publicly at the time that *“due to the growing energy demand on grids, it is increasingly important to find grid balancing solutions to peaks in demand. Amber Kinetics’ flywheel addresses this issue with an interesting alternative to traditional batteries, providing Enel with a flexible solution to energy demand peaks that can be applied across the company’s diverse generation mix.”*

Hawaiian Electric is currently testing a unit in Oahu, Hawaii, and according to Colton Ching, Hawaiian Electric senior vice president for planning and technology, *“Hawaiian Electric is eager to test the grid stabilizing and renewable energy storing of the flywheel. Our evaluation of this very promising energy storage system will help us determine how we can use flywheels to help integrate renewables at a lower cost while improving reliability and resiliency of the grid.”*

The project was designed to do more than just accumulate operating hours. New products must to be validated, refined, and optimized. The product design and manufacturing process for the Amber Kinetics FESS have stabilized during the course of this project. Unit-to-unit performance variability is small, manufacturing cycle times have been dramatically reduced, and quality has improved. Operating units in a wide variety of environmental conditions demonstrates a robust product design. The progress made as a result of this project helped advance the commercial release of the Amber Kinetics FESS to the energy storage market. Plans to scale production in a new factory are becoming a reality, clearly achieved its goals.

Safety Validation

The project team conducted a comprehensive series of tests to characterize the safety of the Amber Kinetics FESS. Consideration was given to safety in the design of the product, however it is imperative to conduct field tests in predictable fault scenarios to observe the system response. The safety design criteria were validated through a series of induced failures and overstress events.

The flywheels were completely tolerant of a number of fault scenarios such as a loss of vacuum, loss of power, and overspeed; they survived these types of events without damage and were easily put back into service. The overspeed tests also validated that the rotor has a large safety margin above the design stress levels; furthermore, the lack of any unusual behavior by the units during the testing supports the case for product robustness. Other potential faults like bearing failures were induced and resulted in benign and safe outcomes for the unit.

A catastrophic rotor burst is a very unlikely but a potentially hazardous event; the testing conducted as a part of this project demonstrated that the energy released during such an event is entirely in the radial direction. The subterranean installation concept endorsed by Amber Kinetics was demonstrated to successfully contain this event. Any company adopting kinetic energy storage would benefit from considering this approach.

Multi-Unit Array

The path to utility scale energy storage requires scalability with multi-megawatt installations common. For flywheels, large arrays of units installed as an “energy storage farm” will be commonplace.

The hardware and software to manage and control multiple units was developed. During the project activities, arrays of up to four units were operated through multiple power cycles under a range of operating scenarios. In the lab, Amber Kinetics’ flywheel management system demonstrated the capability to simultaneously control 32 units. The concept of operating multiple units on a common DC bus to share power and maintain SOC balance was demonstrated.

The technology to provide flywheel energy storage at a utility scale has advanced considerably as a result of this project. Simulating multiple operating scenarios demonstrated some of the inherent advantages of the Amber Kinetics FESS compared to other energy storage technologies. The system response to command signals of less than one second combined with multi-cycle per day and partial cycle charge options offers the potential to improve grid management strategies compared to lithium ion batteries for IOU’s, micro-grid managers, and commercial and industrial users including uninterruptible power supply (UPS), frequency regulation, and spinning reserves.

Benefits to California Ratepayers

This project contributes multiple benefits to California’s electricity ratepayers. Any form of energy storage enables the IOU’s to add additional solar and wind capacity without the challenge of back feeding onto the transmission system. Furthermore, storing energy for use during peak demand periods reduces the need to add new generating capacity, and adding a new technology to the market for utility scale energy storage that broadens the served market and increases competition to help drive down the costs. This project has advanced the commercial viability of flywheels to compete in the energy storage marketplace.

Amber’s proposed flywheel energy storage project is the culmination of several years of flywheel R&D. Energy storage technology that does not show degradation can be applied to solve multiple problems the current aging electric grid faces. This project will contribute multiple benefits to California’s electricity ratepayers by providing following savings.

Reduce Transmission Congestion and Losses

California’s transmission systems are becoming congested because of more renewable energy generation. Storage systems used on either side of the transmission congestion can be dispatched during the hours of congestion to reduce system constraints and transmission congestion costs and losses. Flywheels have shown they have the capability to respond quickly to California ISO demand signals, charging and discharging electricity to help better manage the grid and reduce costs.

A 1 MW 4 MWH project that has ability to cycle up to three times a day can reduce 12 MWH hours of congestion. If the average cost of congestion is \$40 megawatt hour, then congestion savings per year would be \$175,000 per project for California rate payers. If a 100 MW (400 MWH) were installed by the IOU’s then California rate payers could save \$17.5 million per year in congestion savings. At this time other storage technologies, such as lithium ion batteries, can only do one cycle a day resulting in third of the savings.

Transmission and Distribution Upgrade Deferral

The FESS can significantly avoid transmission and distribution upgrades for the utility by reducing the peak load and avoid having to replace overloaded circuits. Upgrading transmission and distribution systems cause the most increases for ratepayers. .

A 100 MW (400 MWH) installation would avoid distribution upgrades of 100 MW which can save close to \$600 million over life time of the system.

Peak Shaving and Energy Arbitrage

Amber flywheel can be installed in customer specific locations significantly reducing demand charges and large portion of their electricity bills. Installing 100 MW's worth of flywheels used for distribution can reduce demand charges by \$36 million and provide \$8 million of energy savings a year since the FESS can eliminate mid-day peak and evening peaks of electricity use. Lithium battery technology can only do one peak reduction a day.

The Amber flywheel provides flexibility and unique operational characteristics and can be used to tackle multiple use cases for utility and behind the meter applications. The company is developing a product road map to provide all the use cases that can help California rate payers significantly reduce their costs while enhancing grid reliability. Installing 100 MW worth of flywheels can reduce \$37 million per year for utility deployments and \$42 million per year for customer sited deployment.

Production Readiness Plan

This project has significantly advanced the design stability and manufacturing processes for flywheels, helping Amber Kinetics move toward the mass production of the kinetic energy storage system. Fundamental product needs have been addressed including refinement of design documentation, definition of manufacturing procedures, establishment of test procedures and quality standards, and qualification of the supply chain. These results have allowed the company to start down the road to building the infrastructure to mass produce the flywheels.

The size and weight of flywheels present a unique challenge to the manufacturing strategy because logistics can add considerably to the product cost. Mitigating this challenge requires that system integration be located close to the fabrication centers for rotors and housings so that the system ships as a complete unit to project sites, or that facility should be located close to the project site to minimize post assembly transport costs. A large, central factory does not make much sense for this business case.

Amber Kinetics has built a pilot production facility at the Union City, California headquarters; all units used in this project were made in this facility. Production units are currently being shipped to customers from this factory. In addition to meeting customer demand, this facility is developing, documenting, and refining the manufacturing process and create a template for growth on a global scale. Amber Kinetics will use critical learnings from its California production facilities to prepare to expand production throughout markets in North America and worldwide.

The first units have been built, and the production capacity is being scaled to planned capacity of 1,000 flywheels per year to address customer demand. Additional factories in the United States and around the world are in the planning stage.

Customer demand for Amber Kinetics FESS is emerging on a global scale. Orders for production units have been received from four continents plus the island nation of the Philippines. West Boylston Municipal Lighting Plant in Massachusetts recently ordered 16 units scheduled for delivery fall 2018.

Technology and Knowledge Transfer

Amber Kinetics engaged in different technology transfer activities through commercialization of its flywheel technology in the U.S. and abroad. For example, Amber kinetics presented its technology pilot project in a press conference and ribbon cutting with Hawaiian Electric at the Campbell Industrial Park Generating Facility on Oahu to demonstrate the flywheel's real-world capabilities on the distribution system. The Amber Kinetics team also participated as presenters in different conferences such as the Maui Energy Conference and the Hawaiian Electric Flywheel Pilot Project. They also presented at the Energy Storage Association's Annual Conference and at the Roosevelt Strategic Council Microgrid & DERS Summit in Alexandria, Virginia.

Moreover, the Amber kinetics team is contributing to shaping the UL 9540 standard for "Energy Storage Systems and Equipment" to apply updated and improved public safety standards regarding flywheels. Amber kinetics firmly believes that supporting and adopting standards will help eliminate existing shortcomings on how flywheel safety is defined, leading to more transparency and ultimately safer outcomes.

GLOSSARY

Term	Definition
EPIC	Electric Program Investment Charge
Smart Grid	Smart Grid is the thoughtful integration of intelligent technologies and innovative services that produce a more efficient, sustainable, economic, and secure electrical supply for California communities.
CCTS	Central California test site
ATS	Alameda test site
SOC	State of charge
kW	Kilowatt
kWh	Kilowatt-hour
MW	Megawatt
MWh	Megawatt-hour
FESS	Flywheel Energy Storage System
IOU	investor owned utilities
FMS	Flywheel Management System
C&I	commercial and industrial
IPP	Independent Power Producers
UPS	Uninterruptible power supply
A/S	ancillary services
California ISO	California Independent System Operator
CPUC	California Public Utilities Commission
CEQA	California Environmental Quality Act
DOE	U.S. Department of Energy
O&M	operations and maintenances
QA/QC	quality assurance/quality control
SDG&E	San Diego Gas and Electric
UI	user interface
M25	Flywheel rated for 25kWh energy storage
M32	Flywheel rated for 32kWh energy storage
Rpm	Rotations per minute

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