Flywheels for Rapid-Response Regulation of the Electricity Grid

Course No: R01-007

Credit: 1 PDH

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Benefits from Flywheel Energy Storage for Area Regulation in California—Demonstration Results

A Study for the DOE Energy Storage Systems Program

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Benefits from Flywheel Energy Storage for Area Regulation in California—Demonstration Results

A Study for the DOE Energy Storage Systems Program

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Abstract

This report documents a high-level analysis of the benefit and cost for flywheel energy storage used to provide area regulation for the electricity supply and transmission system in California. Area regulation is an 'ancillary service' needed for a reliable and stable regional electricity grid. The analysis was based on results from a demonstration, in California, of flywheel energy storage developed by Beacon Power Corporation (the system's manufacturer). Demonstrated was flywheel storage systems' ability to provide 'rapid-response' regulation. (Flywheel storage output can be varied much more rapidly than the output from conventional regulation sources, making flywheels more attractive than conventional regulation resources.)

The work was sponsored by the Department of Energy and Sandia National Laboratories Energy Storage Systems Program. The demonstration was supported by the California Energy Commission's Public Interest Energy Research program. It was located at the Distributed Utility Integration Testing facility managed by Distributed Utility Associates and located at the Pacific Gas and Electric Technological and Ecological Services research facility in San Ramon, California. The intended audience for this report includes electricity storage vendors, technology developers, system integrators and advocates, energy policymakers and researchers.

ACKNOWLEDGMENTS

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Acronyms and Abbreviations

ACE	area control error
AGC	automatic generation control
CAISO	California Independent System Operator
CEC	California Energy Commission
CO_2	carbon dioxide
CPS	control performance standards
DCS	disturbance control standard
DUA	Distributed Utility Associates
DUIT	Distributed Utility Integration Testing
EMS	Energy management system
ISO	independent system operator
kW	kilowatts
MW	megawatts
NERC	North American Electric Reliability Council
NO_x	nitrogen oxide
OASIS	Open Access Same-time Information System
PCS	power conversion/conditioning system
PG&E	Pacific Gas and Electric Company
PIER	California Energy Commission Public Interest Energy Research program
PW	present worth
T&D	transmission and distribution
WSCC	Western Systems Coordinating Council

Glossary

Ancillary Services* – Services other than scheduled energy which are required to maintain system reliability and meet Western Systems Coordinating Council (WSCC)/ North American Electric Reliability Council (NERC) operating criteria. Such services include spinning, non-spinning, and replacement reserves; regulation (automatic generation control or AGC); voltage control; and black-start capability.

Area Control Error (ACE)* – The sum of the instantaneous difference between the actual net Interchange and the scheduled net interchange between the California Independent System Operator (CAISO) control area and all adjacent areas, taking into account the effects of control areas and the CAISO control area's frequency bias, correction of feter error and time error correction obligations.

Automatic Generation Control (AGC)* – Generation equipment that automatically responds to signals from the CAISO's energy management system (EMS) in real time to control the power output of generating units within a prescribed area in response to a change in system frequency, tie-line loading, or the relation of these to each other, so as to maintain the target system frequency and/or the established interchange with other areas within the predetermined limits.

Area Regulation – See Regulation Service.

Carrying Cost – The cost to own capital equipment including return *on* principal (equity and/or interest), return *of* principal, depreciation, taxes, and insurance. Carrying cost does not include consumables or variable and fixed operations costs.

Demand – The rate of electric energy delivery, normally in kilowatts (kW) or megawatts (MW) for utilities (not adjusted for power factor).

Distribution – See Electricity Distribution

Down Regulation – Decreased use of generation equipped with governors and AGC to maintain minute-to-minute generation/load balance within the control area to meet NERC control-performance standards.

Electricity Distribution –Part of the electricity grid that delivers electricity to end users. It is connected to the transmission system which, in turn, is connected to the electric supply system (generators). Relative to electricity *transmission* the distribution system is used to send relatively small amounts of electricity over relatively short distances. In the U.S., distribution system operating voltages generally range from several hundred volts to 50 kV (50,000 V). Typical power transfer capacities range from a few tens of MW for substation transformers to tens of kW for small circuits.

Electricity Subtransmission – As the name implies, subtransmission transfers smaller amounts of electricity, at lower operating voltages than transmission. For the purposes of this study, transmission and distribution (T&D) is assumed to include subtransmission and not high-capacity/high-voltage transmission systems.

Electricity Transmission – Electricity transmission is the backbone of the electricity grid. Transmission wires, transformers, and control systems transfer electricity from supply sources (generation or electricity storage) to utility *distribution* systems. Relative to electricity *distribution* systems, the transmission system is used to send large amounts of electricity over relatively long distances. In the U.S., transmission system operating voltages generally range from 200 kV (200,000 V) to 500 kV. Transmission systems typically transfer the equivalent of 200 to 500 MW. Most transmission systems use alternating current, though some larger, longer transmission corridors employ high-voltage direct current.

Equipment Rating – The amount of power that can be delivered under specified conditions. The most basic rating is the 'nameplate' rating: nominal power delivery rate under 'design' conditions. Other ratings may be used as well. For example, T&D equipment often has an 'emergency' rating (*i.e.*, the sustainable power delivery rate under emergency conditions such as when load exceeds nameplate rating by several percentage points). Operation at emergency rating is assumed to occur infrequently, if ever.

Peak Demand – The maximum power draw on a power delivery system, usually year specific.

Regulation Service – Increased or decreased use of generation equipped with governors and AGC to maintain minute-to-minute generation/load balance within the control area to meet NERC control-performance standards. The CAISO defines regulation in terms of generation: the portion of a generating unit's unloaded capability that can be loaded, or loaded capability that can be unloaded, in response to AGC signals from the independent system operator's (ISO's) EMS control computer. Regulation is used to provide control-area balancing, frequency bias, and time-error correction.

Subtransmission – See Electricity Subtransmission.

Up Regulation – Increased use of generation equipped with governors and automatic generation control to maintain minute-to-minute generation/load balance within the control area to meet NERC control-performance standards.

Value Proposition – A value proposition comprises all benefits and all costs, including risk, that are associated with an investment or purchase.

* Definitions supplied by the CAISO.

Executive Summary

Purpose and Scope

This report describes a high-level evaluation of the financial viability of using flywheel electricity storage as a grid regulation resource. The evaluation was based on results from a flywheel storage system demonstration. That demonstration was undertaken to demonstrate 1) flywheel energy storage's overall performance as a regulation resource and 2) the presumed advantage that flywheels have over generation for regulation – the ability to vary power output very rapidly and reliably.

Key Results and Conclusions

The performance of the flywheel storage system demonstrated was generally consistent with requirements for a possible new class of regulation resources – 'rapid-response' energy-storage-based regulation – in California. In short, it was demonstrated that Beacon Power Corporation's flywheel system follows a rapidly changing control signal (the ACE, which changes every four seconds).

Based on the results and on expected plant cost and performance, the Beacon Power flywheel storage system has a good chance of being a financially viable regulation resource. Results indicate a benefit/cost ratio of 1.5 to 1.8 using what may be somewhat conservative assumptions. (A benefit/cost ratio of one indicates that, based on the financial assumptions used, the investment's financial returns just meet the investors' target.)

Introduction

This report documents results from a demonstration of flywheel electric energy storage (flywheels) for area regulation, an ancillary service required for electric grid operation. The work was sponsored by the California Energy Commission's (CEC's) Public Interest Energy Research (PIER) program and the U.S. Department of Energy's Energy Storage Systems Program. The flywheel is made by Beacon Power Corporation (Beacon Power).

In addition to demonstrating flywheels' overall performance as a regulation resource, one key objective of the project was to demonstrate the presumed advantage that flywheels have over generation for regulation – the ability to vary power output rapidly and reliably.

Flywheel Energy Storage

Flywheel systems include a cylinder with a shaft that can spin rapidly within a robust enclosure. A magnet levitates the cylinder so there are limited friction-related losses and wear. The shaft is connected to a motor/generator and stator. Kinetic energy is converted to electric power via an external power conditioning system (PCS).

The flywheel system demonstrated was a 100-kW pilot version of Beacon Power's 20-MW Smart Energy Matrix™. The pilot system comprises seven individual flywheels, a PCS, and communication and control subsystems. It can discharge at full output for 15 minutes. The response time is described by Beacon Power to be "less than 4 seconds (at full power)." The demonstration was located at Distributed Utility Associates' (DUA's) Distributed Utility Integration Test (DUIT) testbed, at Pacific Gas and Electric's (PG&E's) Technical and Ecological Services facility in San Ramon, California.

Project Background

The Beacon Power high-speed flywheel electricity storage system is nearing commercialization. One apparently superior application of the technology is for electric power system regulation (also known as area regulation, or simply regulation).

Regulation involves balancing the minute-to-minute fluctuations of *demand* for electricity and electricity *supply* capacity. Most regulation is provided by conventional thermal electric generation plants. Those plants provide 'up' regulation by increasing output when electricity demand exceeds supply and 'down' regulation by reducing output when electricity supply exceeds demand.

Storage provides up regulation by discharging energy into the grid, and storage provides down regulation by absorbing energy from the grid. Notably, the rate of power from (or into) flywheel storage can change quite rapidly whereas output from conventional regulation sources – primarily thermal generation plants – changes slowly. Generation plants' output (up or down) changes by percentage points per minute whereas flywheels' output can change from full *output* (discharge) to full *input* (charging) – and *vice versa* – within a few seconds.

Project Purpose

The demonstration had one overarching goal—demonstrate the flywheel's ability to follow a rapidly changing control signal such that the value of regulation from the flywheel is worth significantly more than regulation provided by generation plants. This report documents an evaluation of the demonstration plant's performance as a high-value regulation resource and the possible financial costs and benefits from a commercial flywheel storage plant used as a regulation resource. The evaluation was performed in parallel to a similar analysis undertaken by Beacon Power. Consequently, it provides the basis for a second opinion regarding the financial viability of flywheels for high-value regulation.

Flywheels for Area Regulation: The Value Proposition

A value proposition comprises all benefits and all costs that are associated with an investment or purchase. The value proposition evaluated for this report is use of flywheel energy storage to provide area regulation.

A key premise underlying the value proposition investigated for this research is that the rapid-response characteristic of electricity storage makes it especially valuable as a regulation resource. In fact, flywheel storage advocates and some experts contend that the benefit associated with regulation from flywheels is on the order of two times that of regulation provided by generation.

Additionally, if storage is a more effective regulation resource than generation, the amount of generation freed up to serve electric demand may exceed the amount of storage capacity (MW) deployed. Furthermore, though not the subject of this work, if electricity storage is used for regulation in lieu of generation, there may be less wear and tear on generation equipment; reduced fuel use per kWh generated; and reduced emissions due to reduced plant ramping and reduced part-load operation.

Regulation Service

Regulation is a type of ancillary service[1] involving management of "interchange flows with other control areas to match closely the scheduled interchange flows" and moment-to-moment variations in demand within the control area. The primary reasons for including regulation in the power system are to maintain the grid frequency and to comply with the NERC Control Performance Standards (CPS) 1 and 2 (NERC 1999a). Regulation also assists in recovery from disturbances, as measured by compliance with NERC's Disturbance Control Standard (DCS).[1]

Regulation is typically provided by "generating units that are online and producing energy, equipped with AGC equipment, and that can change output quickly (MW/minute) over an agreed upon range of power output (MW)." Generation facilities used for up regulation and those used for down regulation are operated at levels below maximum output and above minimum output, respectively.[2]

When there is a momentary *shortfall* of electric supply capacity, generation facilities' output to the grid is increased to provide up regulation. Conversely, plant output is reduced to provide down regulation when there is a momentary *excess* of electric supply. Typically, thermal power plants are most efficient when operated at a specific and constant (power) output level. Similarly, air emissions and plant wear and tear are usually lowest when thermal generation operates at constant output.

[1] Ancillary Services are electric resources – other than the conventional power generation – that are used to maintain reliable and effective operation of the electric supply and transmission systems. Most often ancillary services are provided by utilities, though an increasing portion are provided by third parties. Six key ancillary services are 1) scheduling, system control, and dispatch; 2) reactive supply and voltage control from generation sources; 3) regulation and frequency response; 4) energy imbalance; 5) spinning reserve; and 6) supplemental reserve.

Storage provides up regulation by discharging (injecting energy into the grid), and it provides down regulation by charging (energy is taken from the grid to be stored). Unlike thermal power plants, flywheels' performance is not affected much as output varies. And, while thermal power plants can require minutes or even hours to change power output significantly, flywheels can change power output level quite quickly – going from full output to no output in seconds. In fact, flywheels can transition from discharging at full (rated) power to charging in seconds.

Benefits

At minimum, regulation from flywheels is at least as valuable as regulation provided by slower generation capacity. Regulation from flywheels, however, may be even more valuable. First, flywheel storage can provide both up regulation and down regulation during the same time period (though not simultaneously). Second, because of the rapid-response feature – ability to change power input and output rapidly – flywheels may provide regulation that is more effective than regulation provided by slower, generation-based resources. Because of this advantage, regulation from flywheels is assumed to provide twice the benefit to the grid as regulation from generation.[3][4][5]

Revenue for providing up and down regulation services for an entire year (8,760 hours) is estimated based on CAISO published hourly prices for both services for the year 2006 (see details in the *Results and Conclusions* section). The hourly prices are multiplied by two, to reflect the higher benefit from flywheels relative to generation-based regulation, before annual revenues are estimated.

In addition to the price for regulation in specific hours of the year, another important criterion affecting the flywheel-for-regulation value proposition is flywheel plant availability. This is because the amount of time that the flywheel is available to provide regulation affects total profit that can be realized during the year. Notably, because of the modularity of flywheel storage (the Beacon Power design is quite modular) equipment diversity should result in high reliability. Specifically, a 20-MW, commercial-scale plant is expected to comprise a few hundred flywheel units.

Though not included in the financial analysis, additional benefits derived from the use of flywheels for regulation may include the following: reduced need for generation capacity, reduced fuel for generation, reduced air emissions from generation, and reduced generation equipment wear and tear. As an indication of the prospects for reducing air emissions, consider results from a study performed by KEMA, Inc (kema.com), shown in Table 1. Based on results from that study, flywheels used for regulation in California could reduce carbon dioxide (CO_2) emissions by 26% when compared to pumped hydroelectric storage used for regulation, 53% if the flywheels replace baseload gas-fired generation, and 59% if a natural-gas-fired peaking generator is displaced. Similarly nitrogen oxide (NO_x) emissions may also be reduced by 20% to nearly 50%.[6]

Table 1. Potential Air Emissions Reduction

Flywheel Emission Savings Over 20-year Life: CA-ISO					
	Coal		Natural Gas		Pumped Hydro
	Baseload	Peaker	Baseload	Peaker	
CO_2					
Flywheel	91,079	91,079	91,079	91,079	91,079
Alternate Gen.	322,009	608,354	194,534	223,997	123,577
Savings (Flywheel)	230,930	517,274	103,455	132,917	32,498
Percent Savings	72%	85%	53%	59%	26%
SO_2					
Flywheel	63	63	63	63	63
Alternate Gen.	1,103	2,803	0	0	85
Savings (Flywheel)	1,041	2,741	-63	-63	23
Percent Savings	94%	98%	n/a	n/a	27%
NO_x					
Flywheel	64	64	64	64	64
Alternate Gen.	499	1,269	80	118	87
Savings (Flywheel)	435	1,205	16	54	23
Percent Savings	87%	95%	20%	46%	26%

Cost

The primary cost element for flywheel storage is the cost to own the plant itself (carrying cost) including the cost for financing and taxes. Other important, though much less significant, elements of total cost are expenses, primarily repairs and equipment replacement required during the service life of the equipment and the cost for 'make-up' energy needed to offset losses associated with charging and discharging storage. Details about cost and performance for the Beacon Power flywheel are provided in the next section.

Evaluation Assumptions and Approach

Assumptions

This section describes the approach and assumptions used for financial analysis. Readers should note that two key assumptions – storage system service life and the discount rate used to calculate present worth over the service life – are intended to represent a *generic* circumstance. For any *specific* circumstance, situation-specific assumptions may be appropriate. (Figure 1 provides a general indication of the effect that service life and discount rate have on lifecycle financials.)

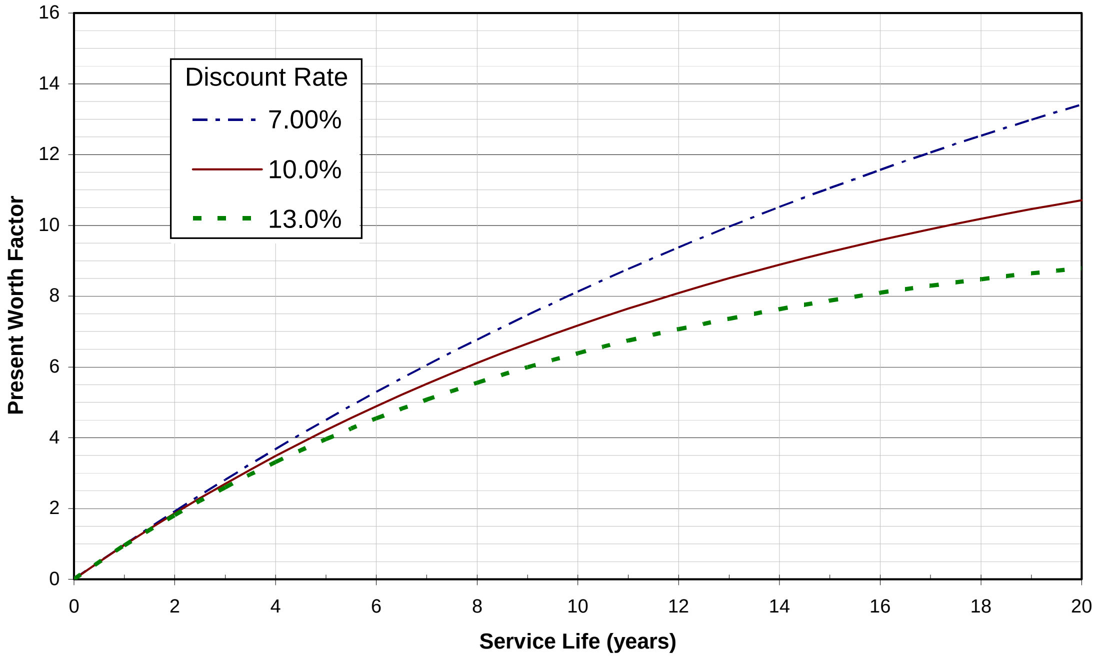
Benefits and costs associated with flywheel energy storage systems used for regulation are calculated using the financial bases shown in Table 2. Specifically, the present worth of expense and benefit streams are calculated using the following standard values: 1) 10- year storage system service life, 2) 10% discount rate, and 3) 2.5% annual price escalation (inflation) rate. The annual carrying cost for the (capital) plant and equipment is calculated using a fixed charge rate of 0.13 for utility-owned equipment and 0.20 for private/non-utility ownership. (Fixed charge rates are used to estimate 'levelized' or annuity-like payments that reflect the owner's cost of capital, taxes, and insurance associated with owning the capital plant and equipment.) Given that flywheels for the value proposition considered are assumed to be owned by a non-utility entity, the fixed charge rate used is 0.20.[7]

Table 2. Financial Assumptions for Lifecycle Benefit/Cost Analysis [8]

Parameter	Value
Service Life	10 years
Discount Rate	10.0%
General Inflation Rate	2.5%
Utility Fixed Charge Rate	0.13
Non-utility Fixed Charge Rate	0.20

Methodology

The first three criteria described above – service life, discount rate, and inflation – are used to calculate the present worth (PW) factor. As shown in Figure 1, PW factors provide a simplified way to represent a discounted present worth of a stream of regular revenues or payments, for a range of time periods (1 to 20 are plotted), for various discount rates (three are plotted).



Escalation Rate: 2.5%/yr. Mid Year Convention.

Figure 1. PW factors for three discount rates and various service lives.

Consider an example: It will cost $100,000 in the first year of operation for a storage plant. That annual cost is assumed to escalate at 2.5% per year over the 10-year service life. The owner uses a 10% discount rate. The present worth of all costs (before tax) is about $717,000 (7.17 PW factor × $100,000 in Year 1). For comparison, consider present worth values for the other discount rates shown in Figure 1. For a first year cost of $100,000, the present worth (over 10 years) is about $813,000 if the discount rate is 7% per year and the 10-year present worth is about $630,000 if the discount rate is 13% per year. The 7.17 PW factor is the one used for revenues and for expenses for this report.

For the capital plant, the installed cost for the capital equipment is multiplied by the fixed charge rate to calculate the levelized capital carrying cost for the plant in the first year. That same annual charge is assumed to apply for the life of the plant (10 years for this analysis). Finally, the 10 years of annual carrying cost values ($Current) are discounted using the 10% discount rate. Using the PW factor method described above and assuming no inflation[2], the PW factor used is 6.44.

Readers should note that the standard plant life used is 10 years. However, Beacon Power expects the flywheels to last 20 years. To compensate, the PW of revenues and expenses not related to carrying cost is increased by about 50%, to account for operation in the second 10 years of the plant's life. As shown in Figure 1, that increment is estimated based on a PW factor of 10.7 for 20 years, not the 7.17 PW factor for 10 years used throughout the rest of this report.

[2] By definition, levelized payments do not change throughout the life of the plant, like mortgage payments.

Flywheel Energy Storage Cost and Performance

The values shown in Table 3 are flywheel storage system cost and performance assumptions plus the price for make-up energy. The cost and performance values for flywheels reflect expected values for a 20-MW, commercial-scale plant. Installed cost reflects a 20% uncertainty adder. This value is used to account for the normal uncertainty associated with technology scale up and commercial project development (*e.g.*, siting, contracts, construction delays, *etc.*).

Table 3. Flywheel Storage Cost and Performance Assumptions

Criterion	Value
Commercial Plant Scale	20 MW
Plant Installed Cost	$1,566/kw
Plant Availability	95%
Round-trip Efficiency	81%
Variable Operation Cost	$3.14/MWh$_{out}$
Fixed Operation Cost (Year 1)	$11.60/kW
Make-up Energy Price	$40/MWh

Price for Conventional Regulation Service

The key data used for estimating the regulation benefit is the hourly price for up- and down-regulation services (each priced separately). That price is denominated in $/MW per hour of service. Hourly prices for up and down regulation in California in 2006 are shown in Figure 2 and Figure 3, respectively. Annual average prices used for the valuation are $21.48/MW (up) and $15.33/MW (down) per service hour, for a total of $36.70/MW per service hour.

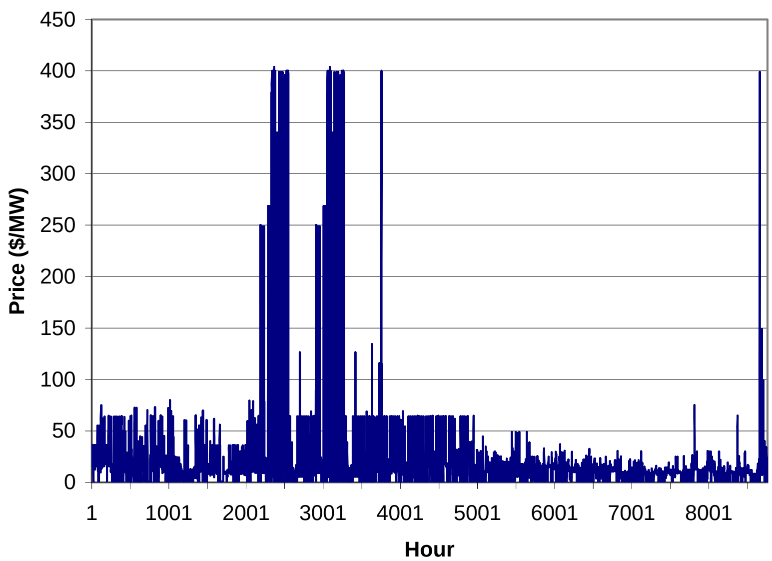


Figure 2. 2006 up-regulation prices in California.

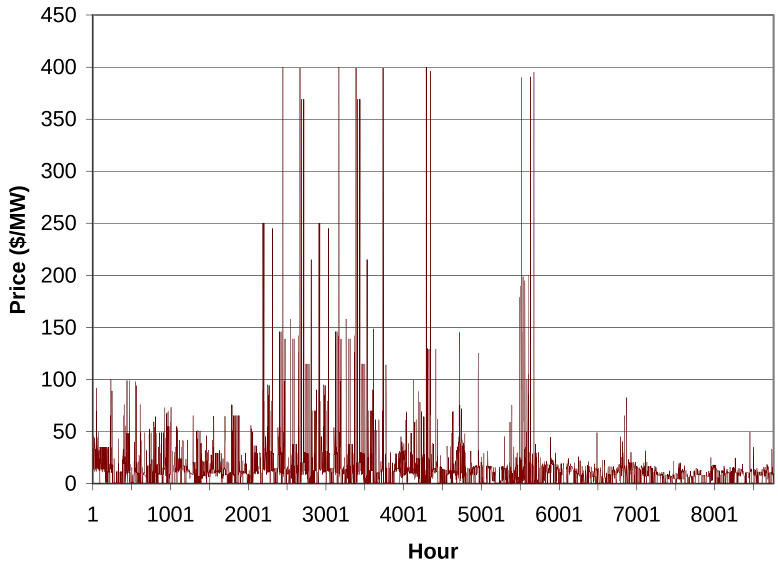


Figure 3. 2006 down-regulation prices in California.

Value of Regulation from Flywheels

As described elsewhere in this report, it is assumed that flywheels used for regulation provide twice as much benefit to the grid as generation-based regulation. Specifically, it is assumed that regulation resources are twice as valuable if they follow the ACE signal closely. That signal changes every several seconds to reflect the momentary difference between the amount of power that is online and the amount needed to keep supply and demand balanced and to maintain the electrical stability of the grid (especially the 60-Hz frequency). Based on this assumption, flywheel storage used as a regulation resource is treated as if it is eligible for payments that are twice as much as prices shown above for conventional generation-based regulation.

Market Potential

In addition to financials, the CEC/PIER is interested in the market potential (in MW) for the flywheels-for-regulation value proposition. Unfortunately, the authors of this report do not have the resources needed to establish that value rigorously or credibly. Nonetheless, the authors speculate that a conservative estimate of the market potential in California could be on the order of 50 to 60 MW of the total regulation market managed by the CAISO over the next ten years. (The CAISO does not manage all of the regulation resources within the state. Some of that capacity could be in play as well.) This speculation has two primary bases. The first is a cursory review of regulation capacity requirements available at the CAISO Open Access Same-Time Information System (OASIS) website (http://oasis.caiso.com/) under the ancillary (services) tab and on discussions with representatives from Beacon Power. The second is a discussion with representatives from Beacon Power.[9]

Methodology Observations and Caveats

- The make-up energy price assumed was not developed rigorously. Although this value is probably adequate for the purposes of this report, it should be developed more rigorously when evaluating the financials for an actual project.
- Based on results from the demonstration project, flywheel systems with 15 minutes of storage can store enough energy to provide regulation during 97.5% of the time that the storage is used. For the purposes of this evaluation, the financial implications of that criterion are assumed to be modest and are ignored.
- The project was a demonstration of the flywheel's ability to respond to rapidly changing control signals without regard to the magnitude of the response (in MW) that might be needed. Consequently, the results herein reflect the value for regulation capacity on the margin.
- The market potential estimate used for this evaluation (though adequate for a high-level estimate of the magnitude of the statewide economic impact) is imprecise. Unfortunately, little is known about the effect of significant penetration of rapid-response regulation capacity on the need for regulation or the price for regulation.
- The premise about how much more valuable flywheels are than generation-based regulation resources (as meritorious as it may be) may not be reflected in regulation pricing without a significant amount of confirmation, regulatory accommodation, and time.
- The 0.20 annualization factor used to estimate annual carrying cost for the plant, though perhaps imprecise, does provide a reasonable general indication of the cost to finance plant and equipment using non-utility equity.
- Another important assumption affecting results is the 20% uncertainly adder that increases the assumed installed cost for a commercial plant (provided by Beacon Power). That value is used to account for the myriad unforeseen challenges that are likely to beset *any* technology development enterprise and project development effort.
- Finally, the design service life for a commercial Beacon Power flywheel plant is 20 years. For at least two reasons, the assumed service life for the evaluation described in this report is 10 years. Perhaps most importantly, guidelines established by CEC/PIER for evaluating the merits of various storage demonstrations require using generic standard assumptions as bases for comparing financials for all demonstration projects sponsored. Those generic assumptions include 10-year life, 10% discount rate, and 2.5% price escalation rate. Second, though the authors do not mean to refute the 20-year expected life assumed by Beacon Power, a more conservative 10-year life expectancy was used for this report because both the technology and the value proposition are so new.

Results and Conclusions

Perhaps the most important result from the project is that the sponsors and vendors successfully demonstrated the ability of the Beacon flywheel to follow control signals that change very rapidly—much more rapidly than the signal used to control the output of generation-based regulation. Although they are not addressed in this report, readers should be aware of similar results from work in New York State involving Beacon's flywheel energy storage. [10] [11]

Results

Demonstration plant availability for three plant output levels (relative to full rating) is summarized in Table 4. Also shown is the availability assumed for a commercial plant. As shown, the demonstration unit operated 51.4% of the time at full capacity (full capacity means that all seven flywheels were operating). Similarly, the demonstration unit operated nearly 53% of the time at 85.7% of rated capacity (85.7% capacity represents six flywheels of seven). There were at least five of seven flywheels (71.4% of full rated capacity) operating almost 88% of the time. Note that the demonstration plant's availability would be somewhat higher when accounting for research-related outages which include downtime due to causes that would only affect operation of a research or pilot project (*e.g.,* no control signal was available, access to the demonstration facility was restricted, or the system could not be connected to the grid). Downtime to due equipment failure is *not* considered research-related.

Table 4. Demonstration Plant Actual Availability and Commercial Plant Expected Availability

Capacity (% of Full)	Availability (Actual)	Without 'Research-related' Outages	Commercial Plant (Expected)
100%	47.3%	51.4%	95.0%
85.7%	52.7%	56.9%	
71.4%	87.8%	92.0%	

The financial implications of the availability results are summarized in Figure 4. Calculation details are provided the Appendix. The left axis shows $/kW in Year 1. Those units reflect a single-year amount, in the first year, for each kW of plant rating. The right axis indicates the corresponding lifecycle value over the plant's (assumed) 10-year life. Results are shown for three levels of annual average power output: 71%, 86%, and 100% of plant rating. Note that 71% represents 5 of 7 flywheels in the demonstration system, 86% represents 6 of 7 flywheels, and 100% represents 7 of 7 flywheels. Results are presented, for those three plant output levels, for a range of plant annual availability levels. Also shown is the break-even amount, reflecting the carrying cost for a commercial plant. The uppermost plot indicates results for plants operating at full rating. The next two plots indicate financials for a plant operating at 86% and 71% of its rating, respectively. Thicker parts (to the lower left) of the three plots reflect results from the demonstration. Endpoints on all three plots indicate financials for a plant operating at the respective portion of rated output, if the plant operates as much as a commercial plant is expected to operate (95% of the year, full-load equivalent).

In the upper right portion of the figure, a box indicates financials that would be expected for a commercial plant, based on the assumptions discussed above. The benefit/cost ratio for such a plant ranges from $500/kW benefits ÷ $313/kW break-even = 1.6 to $554/kW benefits ÷ $313/kW break-even = 1.77. Note that plant designers expect a 20-year service life for a 20-MW, commercial-scale plant, though the assumed service life for this report is 10 years. To account for the difference, the present worth of additional benefits increases by about 50%.

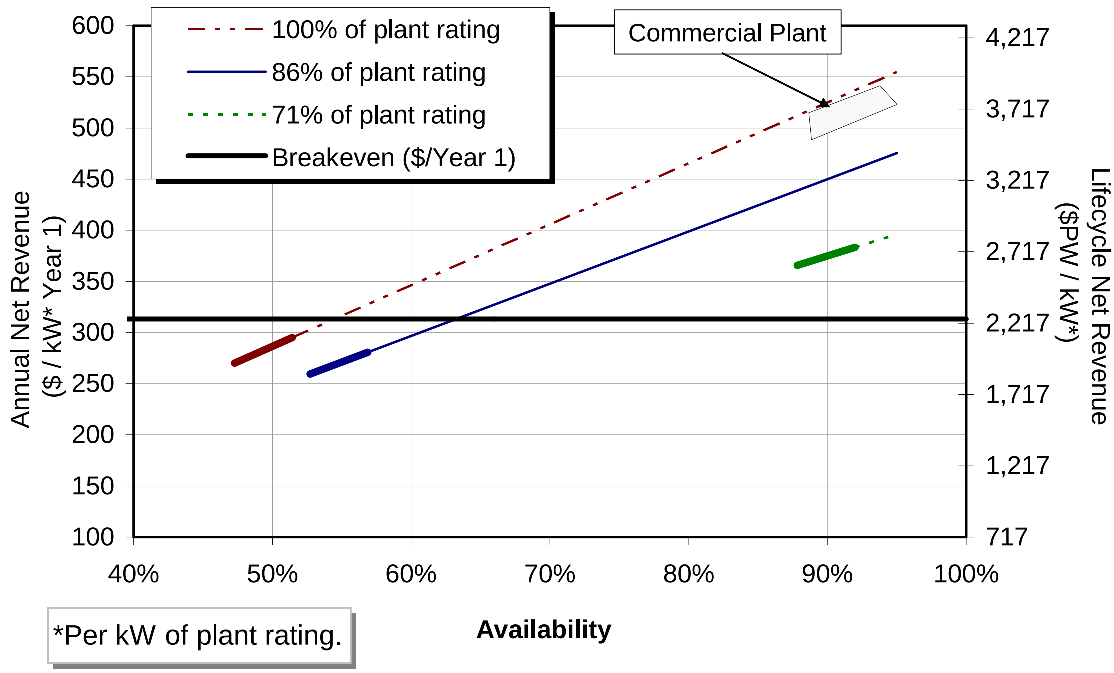


Figure 4. First year and lifecycle net revenue, with break-even indicator.

Conclusions

Based on the results and on expected plant cost and performance, the Beacon Power flywheel storage system has a good chance of being a financially viable regulation resource. Results indicate a benefit/cost ratio of 1.6 to 1.8 using somewhat conservative assumptions.

The market potential (in MW) is less certain. Uncertainty about technical market potential is driven in part by a lack of knowledge regarding how the use of rapid-response regulation resources on the margin will affect overall demand and the price for regulation. Regarding market share, there is always uncertainty regarding competing options, including other vendors/developers and other technologies or approaches.

Needs and Opportunities for Research and Development

One compelling question for this value proposition is *"How much of this resource could be used and how much will be used?"* Consistent with the hypothesis that rapid -esponse storage is twice as valuable as generation-based regulation capacity, another hypothesis to test is that only half as much regulation is needed if all regulation is rapid response. Additionally, if all regulation is rapid-response regulation, *generation* capacity is freed to provide power or other more valuable ancillary services and will probably produce less pollution and use less fuel per MWh delivered.

Another way to broach the question is *"What are key implications for the grid if all regulation is provided entirely by rapid-response regulation?"* More specifically, what are the implications for 1) the amount of regulation needed, 2) the total cost to ratepayers for regulation, and 3) fuel use and air emissions from generation?

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Appendix—Cost and Benefits Worksheets

Plant Target Cost ($/kW)	1,305
Plant Cost Uncertainty Adder	20.0%
Discount Rate	10.0%
Present Worth (Annualization) Factor	0.20
Plant PW Factor	6.44
Plant Availability	95.0%
Variable Operartion Cost ($/$MWh_{out}$)	3.14
Roundtrip Efficiency	81%
Makeup Energy Price ($/$MWh_{out}$)	40.00
Fixed Operation Cost ($/kW, Year 1)	11.60
Price Escalation	2.5%
Expenses & Revenue PW Factor	7.17

Plant Installed Cost ($/kW) with 20.0% uncertainty adder	1,566
Plant Annual Capital Cost ($/kW, Year 1)	313
Lifecycle Plant Capital Cost ($PW/kW, 10 Years)	2,017
Plant Annual Operation Hours* *50.0% for UP regulation	8,322
Plant VOC ($/kW, Year 1)** **For 4,161 "full load" hours of up regulation.	13.05
Makup Energy Charges ($/kW Year 1)** **For 4,161 "full load" hours of up regulation.	7.9
Fixed Operation Cost ($/kW, Year 1)	11.6

Cost Summary

	$/kW, Year 1	
Capital Plant Cost	**313.2**	=> Used as Breakeven
TOTAL Expenses	**32.6**	Fuel + VOC and FOC
Total Cost	**345.8**	

Case: Beacon Flywheel Energy Storage

Regulation Type	Up	Down	Total
Average Annual Price ($/MW per hour)	21.48	15.23	36.7
Annual Total Revenue ($/MW, Year 1)	188,140	133,426	321,567
($/kW, Year 1)	188	133	322

	$*	per kW
Capital Plant Installed Cost	156,600	1,566
Annual Carrying Cost	31,320	313
Lifecycle Carrying Cost**	201,701	2,017
**6.44 Present Worth Factor		
Annual Expenses Includes Fuel and Operations Costs	5,862	58.62

**For a 100 kW plant.

Benefit Scaler	2.00
Plant Nominal Rating (kW)	100
Roundtrip Efficiency	81.0%
Makup Energy Charges ($/kW, Year 1)**	33.29
Makeup Energy Price: $40.0 / MWh	
Variable Operating Cost ($/kW, Year 1)**	13.74
VOC Unit Cost: $3.14 / MWh out	
**For 4,380 "full load" hours of up regulation.	
Fixed Operating Cost ($/kW, Year 1)	11.60

	Availability				Annual Gross Revenue ($, Year 1)				Annual Operating Cost ($ Year 1)			
Plant Power (kW)	Demo., Actual Availability	Demo. w/o Commu-nication-related Outages	Demo. w/o Research-related Outages	Commercial Plant, Target Availability	Demo., Actual Availability	Demo. w/o Commu-nication-related Outages	Demo. w/o Research-related Outages	Commercial Plant, Target Availability	Demo., Actual Availability	Demo. w/o Commu-nication-related Outages	Demo. w/o Research-related Outages	Commercial Plant, Target Availability
100	47.3%	47.3%	51.4%	95.0%	30,407	30,407	33,087	61,098	3,383	3,383	3,579	5,627
85.7	52.7%	52.7%	56.9%	95.0%	29,062	29,062	31,359	52,369	3,119	3,119	3,287	4,823
71.4	87.8%	87.8%	92.0%	95.0%	40,342	40,342	42,256	43,641	3,778	3,778	3,918	4,020

	Annual Net* Revenue ($ Year 1)				Lifecycle Net* Revenue ($PW)				Lifecycle B/C**			
Plant Power (kW)	Demo., Actual Availability	Demo. w/o Commu-nication-related Outages	Demo. w/o Research-related Outages	Commercial Plant, Target Availability	Demo., Actual Availability	Demo. w/o Commu-nication-related Outages	Demo. w/o Research-related Outages	Commercial Plant, Target Availability	Demo., Actual Availability	Demo. w/o Commu-nication-related Outages	Demo. w/o Research-related Outages	Commercial Plant, Target Availability
100	27,024	27,024	29,508	55,470	193,762	193,762	211,571	397,722	0.96	0.96	1.05	1.97
85.7	25,943	25,943	28,072	47,546	186,011	186,011	201,276	340,905	0.92	0.92	1.00	1.69
71.4	36,564	36,564	38,338	39,622	262,162	262,162	274,882	284,087	1.30	1.30	1.36	1.41

*Net = revenue minus operations costs and makeup energy charges.

**$PW Lifecycle Net Revenue / Plant Installed Cost.

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