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Design & Development of a 20-MW Flywheel-based Frequency Regulation Power Plant

A Study for the DOE Energy Storage Systems Program

Robert Rounds and Georgianne H. Peek

Prepared by
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Abstract

This report describes the successful efforts of Beacon Power to design and develop a 20-MW frequency regulation power plant based solely on flywheels. Beacon's Smart Matrix (Flywheel) Systems regulation power plant, unlike coal or natural gas generators, will not burn fossil fuel or directly produce particulates or other air emissions and will have the ability to ramp up or down in a matter of seconds. The report describes how data from the scaled Beacon system, deployed in California and New York, proved that the flywheel-based systems provided faster responding regulation services in terms of cost-performance and environmental impact. Included in the report is a description of Beacon's design package for a generic, multi-MW flywheel-based, regulation power plant that allows accurate bids from a design/build contractor and Beacon's recommendations for site requirements that would ensure the fastest possible construction. The paper concludes with a statement about Beacon's plans for a lower cost, modular-style substation based on the 20-MW design.

Contents

Figures

Tables

BACKGROUND

One of the requirements for safe and reliable grid operation is the need to closely balance power supply with power demand on a minute-to-minute and even second-to-second basis. When the supply of power exceeds demand, frequency rises above 60 Hz and, when supply is less than demand, frequency drops below 60 Hz. The regulation ancillary service is used by grid operators to balance supply with demand in order to maintain grid frequency within required parameters. Figure 1 illustrates the need for constant regulation over the course of the day.

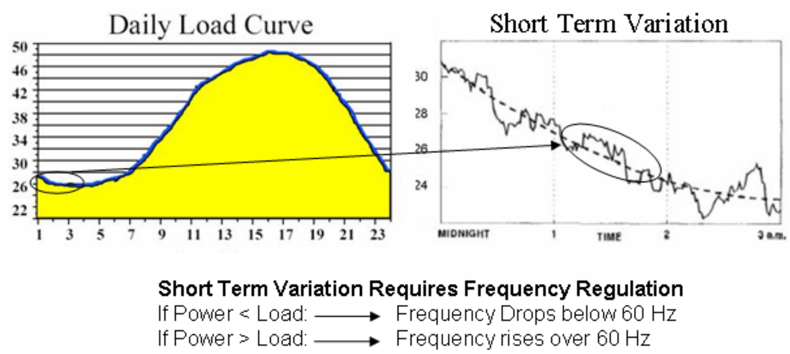

Figure 1. Regulation versus daily load changes

National demand for regulation services is relatively constant on an annual basis and equals approximately one percent of total U.S. daily peak power production. Demand for regulation is expected to rise faster than electricity growth in general, due to the effects of increasing penetration of wind and solar. While both are environmentally beneficial, wind and solar are intermittent renewable energy sources that create greater demand for regulation services on the grid.

Unlike coal or natural gas generators that provide regulation services, Beacon Power's flywheel technology does not burn fossil fuel or directly produce particulates or other air emissions. This should make it possible to permit and site a 20-MW flywheel-based plant almost anywhere on the grid that is relatively close to a transmission line – in 12-18 months. Flywheel-based regulation is also uniquely fast and can achieve a 100% "up" or 100% "down" power status in less than four seconds after receiving a command signal from an independent system operator (ISO). The California ISO (CAISO) has stated that this fast speed of response could produce at least twice the effective value of slower, incumbent, fossil-based regulation technology , which is allowed five minutes to provide a full response.[1]

Displacing existing fossil-based regulation plants with flywheel-based regulation provides another benefit: recapture of a corresponding amount of added peak generation capacity. This

[1] In its December, 2006 press release announcing the successful completion of testing for the flywheel demonstration system in California, the California Energy Commission (CEC) stated: "In addition to the environmental and transmission benefits of flywheel technology, current research at Lawrence Berkeley National Laboratories indicates that 10 megawatts of fast-responding flywheel energy could provide the grid with the equivalent energy of 20 megawatts or more of traditional, slow-responding, power plant energy."

allows the fossil plants to be run at constant load. The result is improved energy efficiency and reduced emissions.

Scale-power Smart Energy Matrix units, comprising multiple flywheel units, ancillary electronics, communications, and control software, have been built and deployed by Beacon Power on the CAISO and New York ISO (NYISO) grids (Figure 2). These scale-power units are being used to evaluate the ability of Beacon's technology to properly perform the regulation service on a large-scale basis on the grid. Data and results from both tests are available through the New York State Energy Research and Development Association (NYSERDA) and the CEC.

Knowledge gained from the scale-power test units has also been used in this contract to help design the world's first 20-MW flywheel-based regulation power plant. This stationary plant will house 200 flywheels, as well as all electrical, control, thermal and other systems necessary to perform regulation reliably, safely, and cost-effectively over a design life of 20 years. Beacon Power plans to build such plants around the U.S. and to own and operate them on an independent merchant basis.

Figure 2. Smart Energy Matrix installed at Pacific Gas & Electric (PG&E) Facility, San Ramon, Calif.

Beacon Power is in the design-build stage for a high-energy, 25-kWh/100-kW, high-speed carbon-composite flywheel optimized to perform regulation. This fourth generation, or "Gen 4" flywheel (Figure 3), will be the core flywheel device used in the regulation power plant.

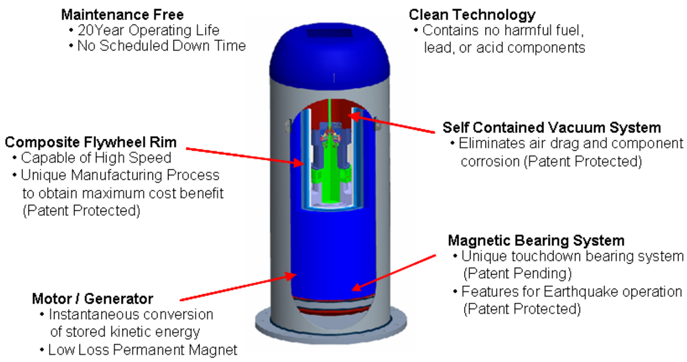

Figure 3. Flywheel cross-section

OBJECTIVES

The three main objectives for this project were:

1. Perform a technology comparison between existing plants that provide regulation and a flywheel-based plant, relative to such benefits as cost-performance, environmental impact and the benefits of faster responding flywheel regulation.
2. Produce a design specification and related drawings incorporating optimal features based on results of engineering analysis and tradeoff studies aimed at defining the ideal design characteristics of such a plant.
3. Identify criteria for selection of site locations as well as possible site locations.

TECHNOLOGY COMPARISON

Emissions Analysis

KEMA Inc. was commissioned by Beacon Power to evaluate various performance aspects of the Beacon Power 20-MW flywheel-based regulation power plant, including its emissions characteristics. To support the emissions evaluation, a detailed model was created to compare the emissions of carbon dioxide (CO_2), sulfur dioxide (SO_2), and nitrous oxides (NO_x) for a Beacon Power flywheel plant versus three types of commercially available power generation technologies.

The comparison of generation technologies included a typical coal-fired power plant, a natural gas combustion turbine, and a pumped -hydro storage system. Emissions from the coal and natural-gas-fired generation technologies result directly from their operation because they burn fossil fuels. In contrast, emissions for the flywheel and pumped hydro energy storage systems occur indirectly because they use some electricity from the grid to compensate for energy losses during operation. The emissions characteristics for these losses are based on the emission characteristics for the specific ISO area where the flywheel and pumped storage system are being used.

The mix of power generation technologies and average system heat rates for fossil-based power generation systems varies across regions in the U.S. To obtain a regionally adjusted emissions comparison, system data specific to three ISO regions was examined: Mid-Atlantic (Pennsylvania, New Jersey, Maryland or PJM), CAISO, and ISO New England (ISO NE). Data for each of these ISOs was extracted from the Department of Energy (DOE) Energy Information Administration (EIA) and Environmental Protection Agency (EPA) eGRID databases. Model calculations assumed typical heat rate and efficiency data for each type of generation.

For coal- and natural-gas-fired generation, KEMA's research found that providing regulation results in increased fuel consumption on the order of 0.5 to 1.5%.[2] This finding is supported in estimates made by a U.S. DOE National Lab, information obtained from the ISOs, and from a

[2] A 0.7% increase in fuel consumption due to frequency regulation was assumed in the model for this study.

European study that evaluated electricity producers to determine whether power plants providing regulation had an increase in fuel consumption and maintenance requirements. This effect was reflected in the model.

Based on the above data, model analysis showed that flywheel-based regulation can be expected to produce significantly less CO_2 for all three regions and all of the generation technologies, as well as less NO_x and SO_2 emissions for all technologies in the CAISO region. The flywheel system resulted in slightly higher indirect emissions of NO_x and SO_2 in PJM and ISO NE for gas-fired generation. This is because PJM and ISO NE's generation mix includes coal-fired plants, and make-up electricity used by the flywheel and pumped-hydro systems reflects higher NO_x and SO_2 emissions from electricity generated in those areas. This effect was greatest in PJM because it has proportionally more coal-fired plants than ISO NE.

When the flywheel system was compared against "peaker" plants for the same fossil generation technologies, the emissions advantages of the flywheel system were even greater. Model results for each of the ISO territories are summarized in

Table 1. Emissions Comparison for PJM.

Flywheel Emission Savings Over 20-year Life: PJM					
	Coal		Natural Gas		Pumped Hydro
	Baseload	Peaker	Baseload	Peaker	
CO_2					
Flywheel	149,246	149,246	149,246	149,246	149,246
Alternate Gen.	308,845	616,509	194,918	224,439	202,497
Savings (Flywheel)	159,599	467,263	45,672	75,193	53,252
Percent Savings	52%	76%	23%	34%	26%
SO_2					
Flywheel	962	962	962	962	962
Alternate Gen.	2,088	5,307	0	0	1,305
Savings (Flywheel)	1,127	4,345	-962	-962	343
Percent Savings	54%	82%	n/a	n/a	26%
NO_x					
Flywheel	259	259	259	259	259
Alternate Gen.	543	1,381	105	154	351
Savings (Flywheel)	284	1,122	-154	-105	92
Percent Savings	52%	81%	-148%	-68%	26%

Table 2. Emissions Comparisons for CAISO.

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%

Table 3. Emissions Comparisons for ISO-NE.

Flywheel Emission Savings Over 20-year Life: ISO-NE					
	Coal		Natural Gas		Pumped Hydro
	Baseload	Peaker	Baseload	Peaker	
CO_2					
Flywheel	106,697	106,697	106,697	106,697	106,697
Alternate Gen.	304,759	608,354	197,359	227,249	144,766
Savings (Flywheel)	198,062	501,657	90,662	120,552	38,070
Percent Savings	65%	82%	46%	53%	26%
SO_2					
Flywheel	270	270	270	270	270
Alternate Gen.	1,300	3,303	0	0	367
Savings (Flywheel)	1,030	3,033	-270	-270	96
Percent Savings	79%	92%	n/a	n/a	26%
NO_x					
Flywheel	115	115	115	115	115
Alternate Gen.	416	990	58	85	157
Savings (Flywheel)	301	875	-58	-31	41
Percent Savings	72%	88%	-101%	-36%	26%

The emissions estimates under the scenarios listed above show highly favorable comparisons for the flywheel across all generation technologies. Figure 4 graphically displays the emissions savings for a flywheel plant versus other technologies.

The remaining sections of the report provide the assumptions that were used in the modeling as well as further insights and analysis.

A full summary of the emission comparisons is provided in Appendix A. The final data was based on the operation of a "typical" power plant for each of the categories. Analysis using known heat rates for a specific generating plant performing regulation would improve the accuracy of model comparisons relative to that specific plant.

From KEMA study: 20 MW of Regulation over 20-year operating life

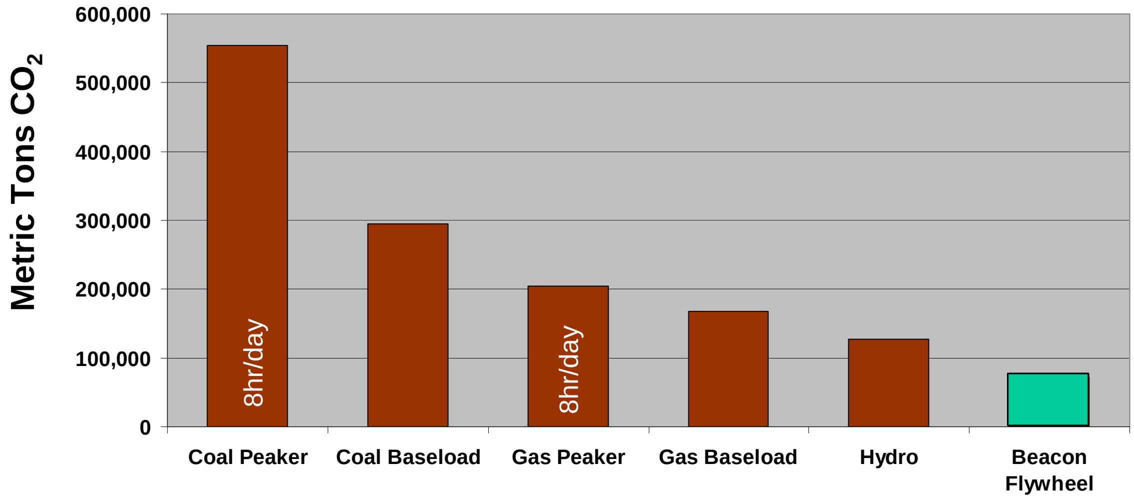

Figure 4. Emissions over 20-year operating life.

Cost-performance Analysis

KEMA, Inc., was commissioned by Beacon Power, with a contract funded by the U.S. DOE through Sandia National Laboratories, to evaluate various performance aspects of the Beacon Power 20-MW flywheel-based regulation power plant, including its life-cycle cost (LCC) to perform the regulation ancillary service in three ISO markets. To support this evaluation, KEMA created a model to compare the LCC of the Beacon Power flywheel plant with four types of commercially available fossil power generation technologies used to perform the regulation service.

The flywheel system was also compared with a lead-acid battery energy storage system that could also be used to perform the regulation ancillary service, similar to the flywheel system.

The analysis included preparing an LCC model using net present value (NPV) analysis that reflected fixed and variable costs for regulation. As shown in Figure 5, Beacon Power's flywheel is capable of delivering the regulation services at the lowest LCC.

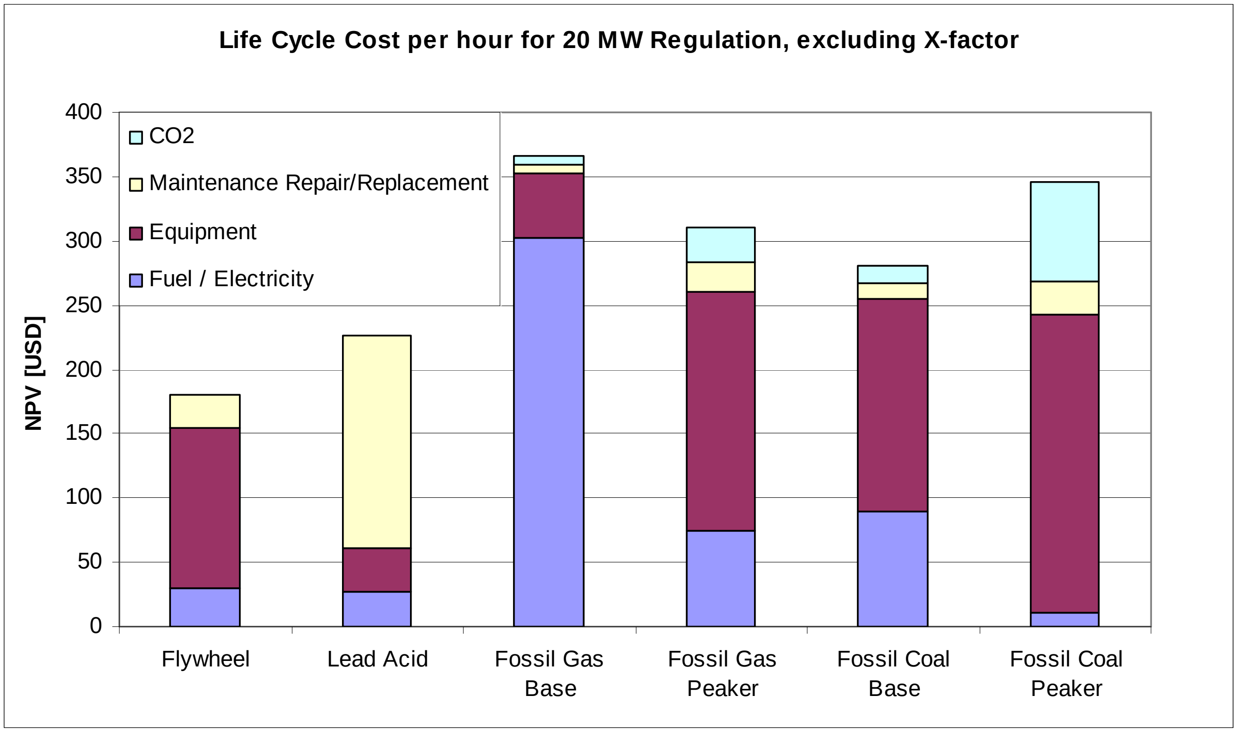

Figure 5. LCC per hour for 20-MW regulation in the PJM region.

The model calculated hourly LCC for flywheel regulation and for the competing technologies. Results of the analysis show that flywheel-based regulation can be expected to have significantly lower LCC compared to all of the competing technologies in the ISO regions studied.

Within the PJM interconnection, LCC for a base-loaded, gas-fired plant ("Fossil Gas Base" in Figure 5) doing the same amount of regulation as a flywheel plant was estimated to be $49 million more than a flywheel plant, or just over 104 percent greater.

For a base-loaded, coal-fired plant, the additional LCC versus a flywheel plant was $27 million, or more than 56 percent greater. Similarly, the LCC increment for a lead-acid battery system was estimated to be over $12 million, more than 26 percent greater compared to a flywheel plant.

Comparisons between the flywheel plant and gas- and coal-fired peaker plants were based on an equivalent cost basis. This equivalent cost was based on the NPV cost-per-regulation cycle, multiplied by the total amount of regulation cycles in the reviewed timeframe of 30 years. The amount of regulation cycles was the same for all technologies.

A gas-fired peaker plant would, therefore, require an additional $34 million in LCC, representing more than 73 percent greater effective LCC. For a coal-fired peaker plant, the comparative values were around $44 million and almost 92 percent higher, respectively. Though a CO_2 market does not yet exist in the U.S., a section was added to show the effects that a CO_2 market might have on the cost analysis.

The graph in Figure 5 also notes the exclusion of an X-factor. The X-factor is the need for fewer total regulation resources due to fast response, which could effectively decrease the LLC by a factor of 50 percent (assuming X = 2). While the X-factor is supported by study,[3] it has not yet been empirically confirmed with a full-scale plant for either the flywheel or battery technologies.

Cost Components in this analysis include:

1. Capital Cost for installing the equipment,
2. Operational Costs:
    a. Fuel (or energy losses in case of flywheels and lead-acid batteries)
    b. Carbon Credit: cost of CO_2 emissions
    c. Maintenance and repair
    d. Periodic reinvestment
    e. Staff
3. Reduction in operating life for thermal plants caused by providing regulation, and
4. Loss of availability for thermal plants due to providing regulation

Critical assumptions were verified by industry experts and, where available, public data. The cost evaluation under the scenarios listed above shows favorable comparisons for the flywheel across all generation technologies. The remaining sections of the report provide the assumptions used in the modeling, as well as further analysis and insights.

Data used in the report is based in part on average parameters for power plants considered "typical" for each of the comparison technology categories. Analysis using known historical cost components for a specific generating plant performing regulation can be expected to provide quantitatively different results relative to that plant. However, KEMA believes that use of representative plant data accurately portrays the costs for each *category* of technology.

DESIGN FOR A GENERIC 20-MW FACILITY

Beacon Power produced a design package for the multi-MW flywheel-based regulation power plant that can be used to obtain accurate bids from a design/build contractor. The design package includes conceptual designs and layout drawings based on minimizing cost, optimizing performance and decreasing build time. The goal was to develop a design concept in which 70% of the details of any plant would be based on this "core" design and 30% would be customized in response to specific site conditions, local codes, and building requirements.

[3] Makarov, Y. *Relative Regulation Capacity Value of the Flywheel Energy Storage Resource*. Consultant Report for CAISO, November 2005. *Simple Algorithms to be Tested First at San Ramon Test Facility*. A study for CAISO, October 2005.

Plant Layout and Design

The first step in plant design was to develop the base building block for the plant. Several modeling exercises were undertaken to minimize the amount of space between flywheels while allowing space for preventative maintenance and inspection. Figure 6 illustrates the relative distance between each flywheel, electronic control module (ECM), and process cooling, as well as power and communication wiring.

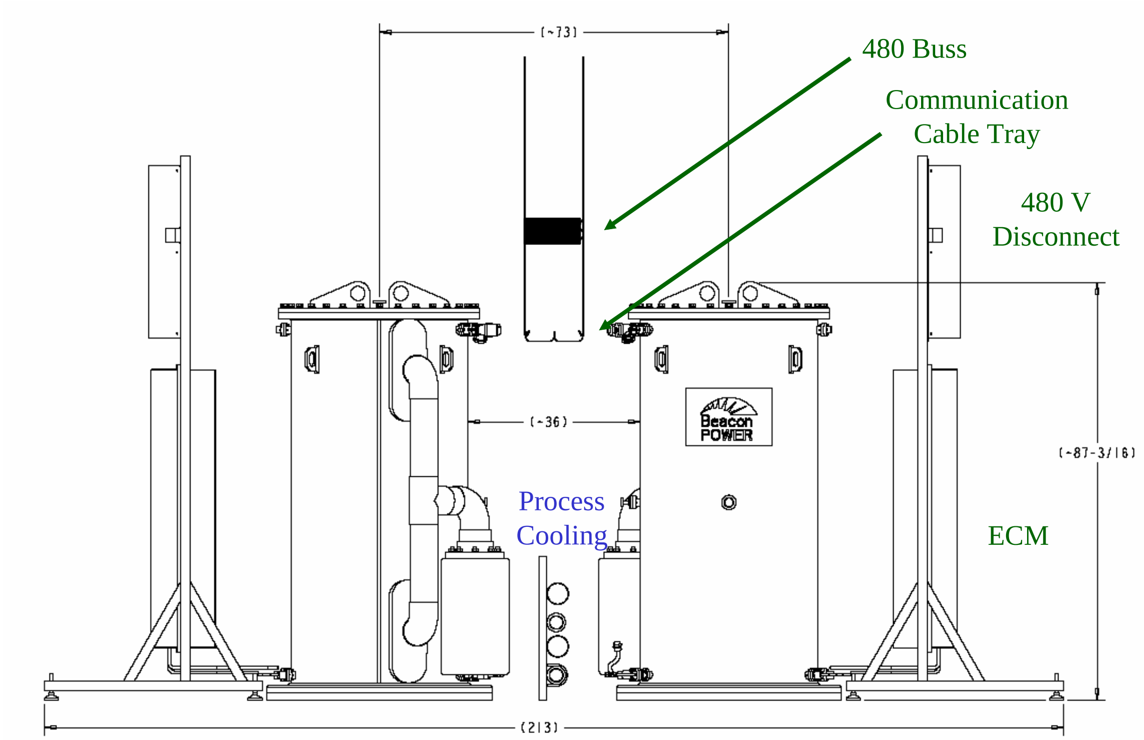

Figure 6. Side view of flywheel layout.

Process cooling for the flywheels and ECM is run down the center of the aisle between the flywheels, which minimizes piping and connection lengths. The motor leads from the flywheel are attached to the base of the ECM, thus minimizing the length, reducing cost and simplifying connection. Power then exits the ECM at the top of the unit through a 480-V disconnect to a 480-V bus duct. This routing minimizes electrical interference as it keeps the power wiring away from the communication wiring, which leaves the top rear section of the flywheel and is routed into the cable tray.

A four flywheel block layout was used to ensure proper spacing between the flywheels and ECMs along the length of the row, as pictured in Figure 7.

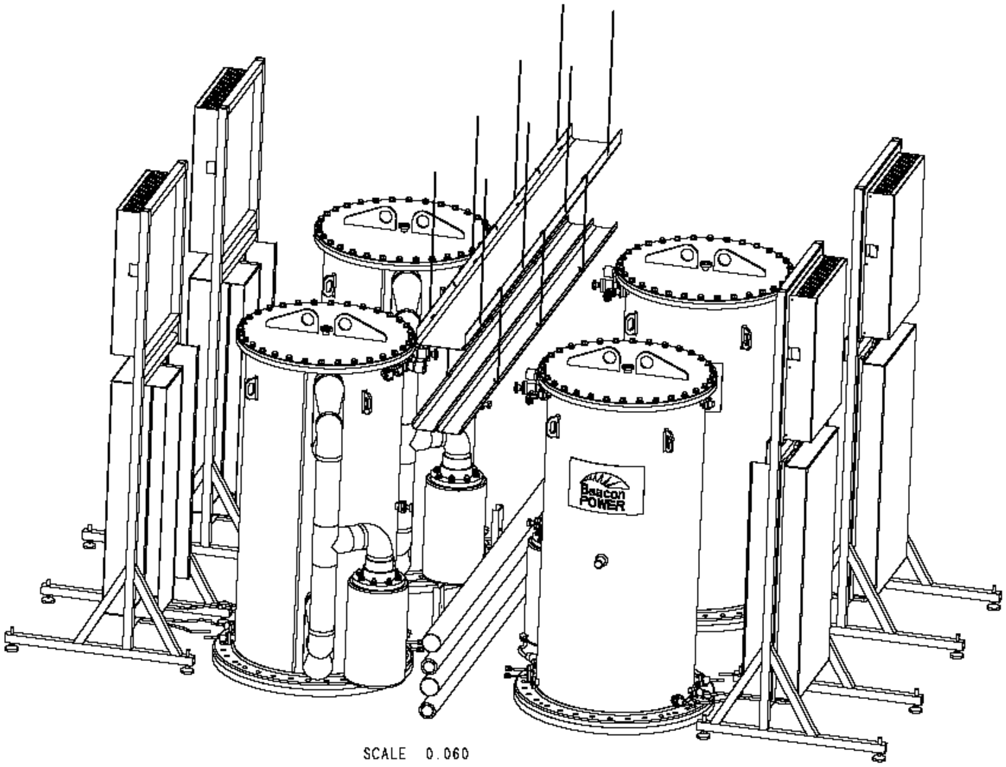

Figure 7. Four block isometric view.

Using this as the baseline configuration, four-flywheel blocks were combined to form 2-MW blocks of twenty flywheels, as shown in Figure 8. Each 2-MW block is replicated ten times, as shown in Figure 9, to produce a flywheel plant capable of providing 20 MW of power.

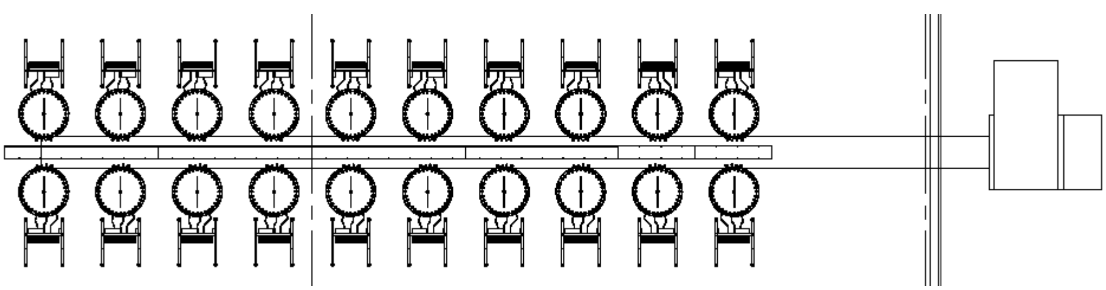

Figure 8. 2-MW block.

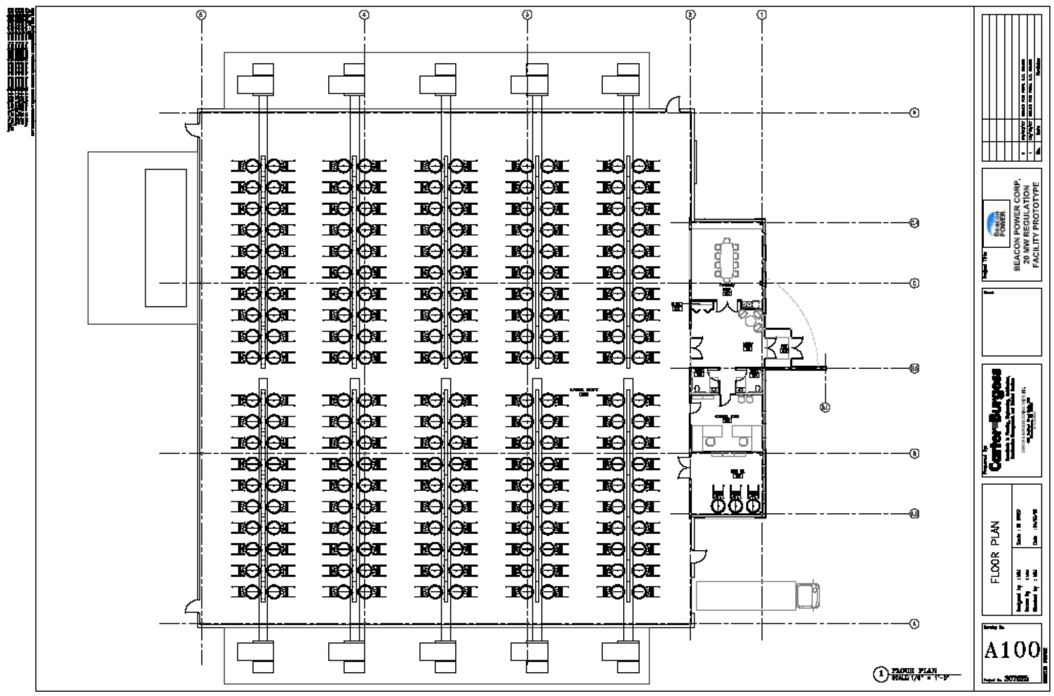

Figure 9. 20-MW flywheel plant layout.

Electrical System Design

Working with the interconnection consultant, Richard Gross PE, Inc., a reliability versus cost analysis was performed on the power wiring and transformers. Table 4 summarizes certain tradeoffs between reliability and cost. Our initial baseline design consisted of two 115- to 13.8-kV transmission transformers to ensure the most reliable plant operation. Based on the minimal impact on reliability and improvement in cost, it was subsequently determined that a single 20-MVA transmission transformer would be sufficient.

Table 4. Power System Option Comparison

Option	Layout	Reliability	Potential Savings
1 – Outdoor	2 x 12/16/20 MVA 115kV-13.8kV XFMR 4 x 13.8 kV Ckts. Loop Feed w/ Feeder Ties 20 x 1250/1438 kVA outdoor dist. XFMRs	Best	Baseline
2 – Indoor Units	2 x 12/16/20 MVA 115kV-13.8kV XFMR 4 x 13.8 kV Ckts. Loop Feed w/ Feeder Ties 20 x 1250/1438 kVA indoor XFMRs (no 13.8 kV ties)	Good (Equivalent To Option 1 w/13.8 kV Feeder Ties)	~+$0.25M
3 – Option 1 w/	1 x 12/16/20 MVA 115kV-13.8kV XFMR 2 x 13.8 kV Ckts. Loop Feed w/ Feeder Ties 20 x 1250/1438 kVA outdoor distribution XFMRs (no 13.8 kV ties)	Susceptible to 115kV-13.8kV XFMR Outage	~$0.75M
4 – Option 3 w/	1 x 12/16/20 MVA 115kV-13.8kV XFMR 2 x 13.8 kV Ckts. Loop Feed w/ Feeder Ties 10 x 1250/1438 kVA outdoor distribution XFMRs	Susceptible to 115kV-13.8kV XFMR Outage	~$1.00M

Table 5. Benefit-to-failure Rate Comparison.

Difference	Benefit	Typical Failure Rate	Repair Time	Mitigation
Redundant 115kV–13.8 kV transformers	100% operation with the loss of one transformer	115kV-13.8kV 0.01 per unit-year	6 – 9 months if factory repair or new transformer	24 hours w/spare or mobile
1 MW per transformer instead of 2MW	Loss of only 1 MW of generation for a transformer fault or 480 volt cable fault	Distribution XFMR 0.005 per unit-year	6 months for new transformer	24 hours with spare

Based on the cost savings and ability to mitigate the failure, Option 4 above was selected: one transmission level transformer, two 13.8-kV circuits, loop feeds, and ten 2.5-MVA transformers.

Carter Burgess then designed the one-line diagram for the plant, as shown in Figure 10.

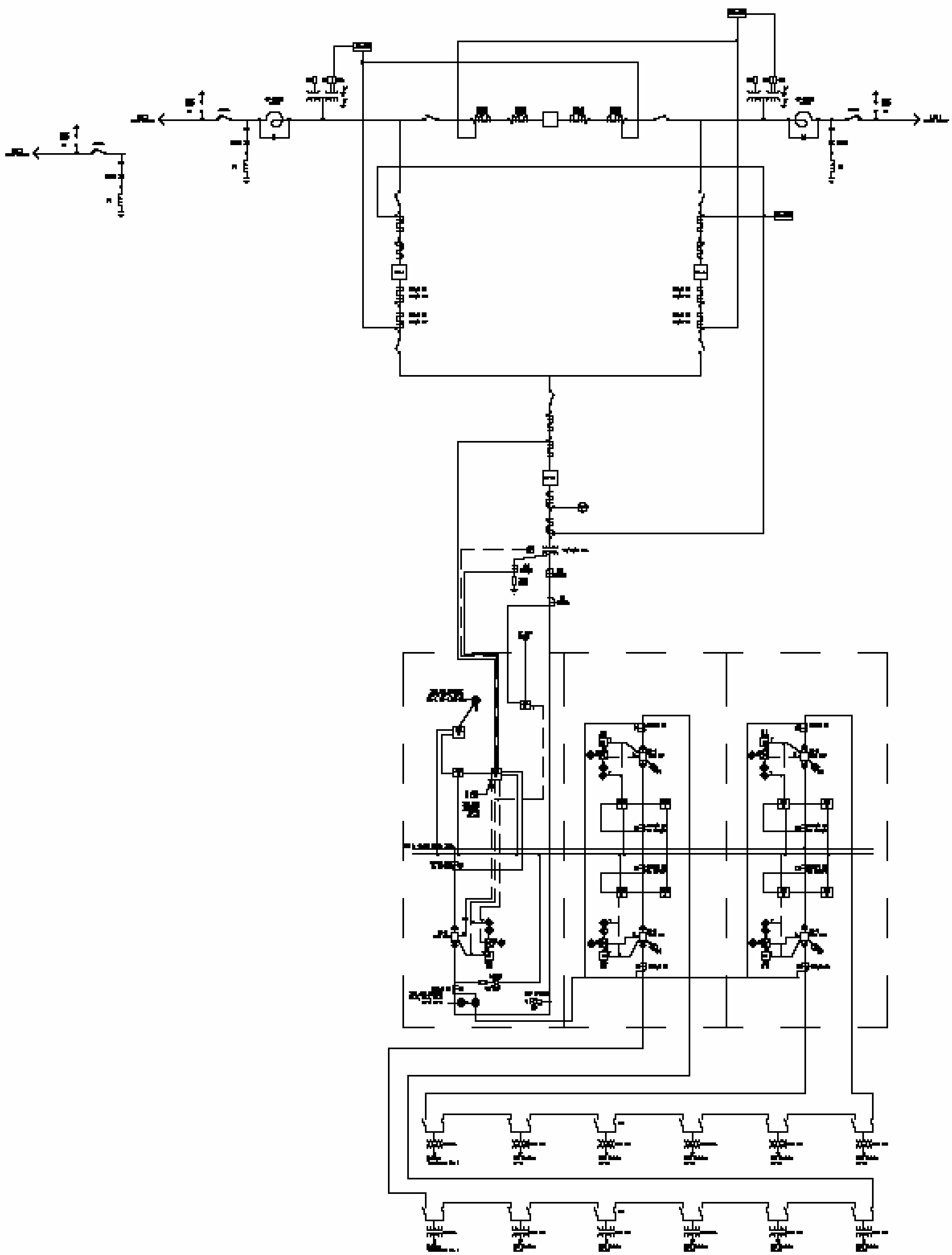

Figure 10. Electrical one-line diagram.

Process Cooling System Design

The plant utilizes two process cooling loops, one for the ECMs and another for the flywheels (Figure 11). The ECM cooling loop is a higher temperature cooling loop, in which the inlet water temperature must remain below the ambient dew point temperature to prevent condensation on the cold plate of the ECM. The flywheel cooling loop requires less flow and lower temperature.

Two plumbing systems were compared for use with the plant: a centralized system with two large chillers located within the plant versus a decentralized system. For similar cost, the decentralized system, while a little less efficient, offers greater reliability due to its higher level of redundancy.

The flywheel loop requires a refrigeration cycle chiller to achieve the lower temperatures required. A closed-loop system with a heat exchanger, located outside of the building, provides adequate cooling for the ECMs. In addition to cooling the ECMs, the closed-loop heat exchanger system provides cooling for the indoor chillers that cool the flywheels. With this setup, there is a minimal amount of heat being released into the building.

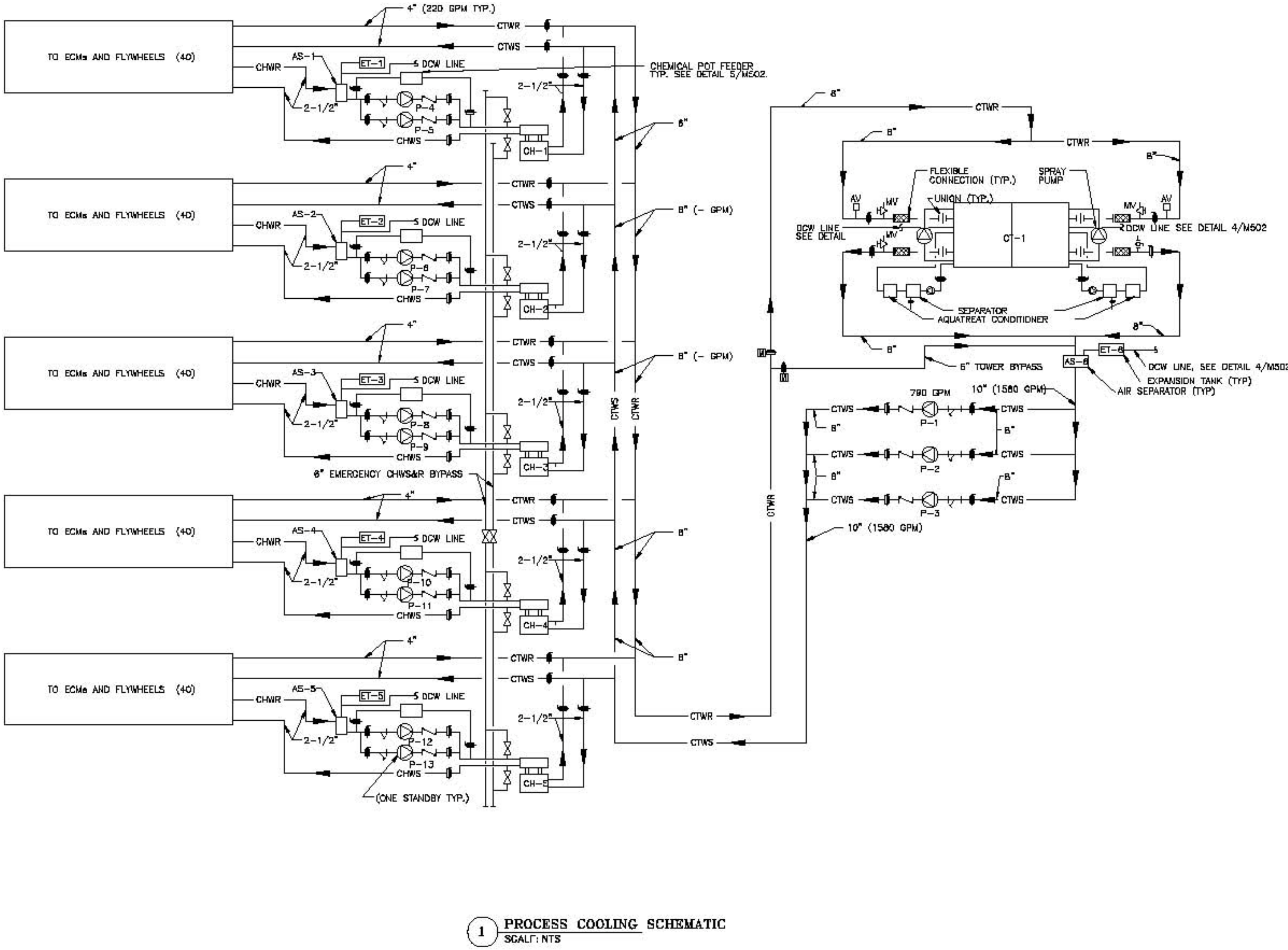

Figure 11. Process cooling P&ID.

Building Heating, Ventilation & Air Conditioning (HVAC)

To reduce initial and operating costs, one of the primary design considerations was not to air condition the space in the flywheel portion of the plant. Based on Carter Burgess calculations, air conditioning in the building will not be required. At times, however, there will be a need to move air through the building to reduce the temperature. To accomplish this, a series of motorized windows and ventilation fans were designed into the front and rear of the building, as shown in Figure 12.

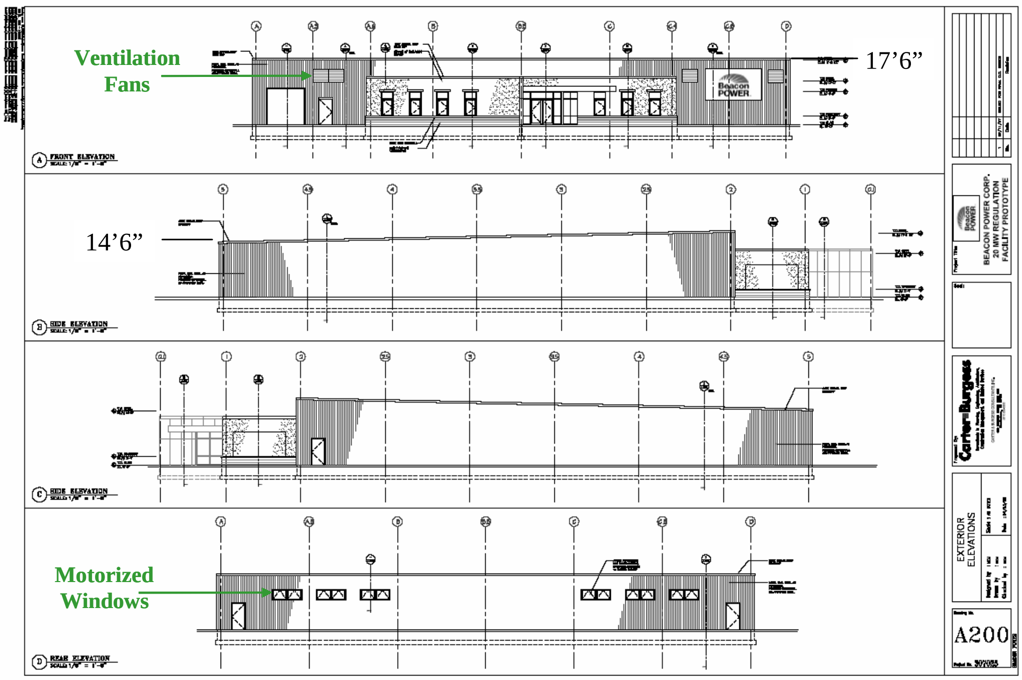

Figure 12 Plant elevation detailing ventilation.

Recommendations for Fast Track Site Selection

To ensure the widest applicable design, the starting site assumption was a rural area with little to no city services and a 115-kV transmission line nearby. These assumptions, therefore, required the design of a substation and a storm water management area, and also drove setback requirements. Based on this design, Carter Burgess developed a series of site requirements to ensure the fastest possible build (Figure 13).

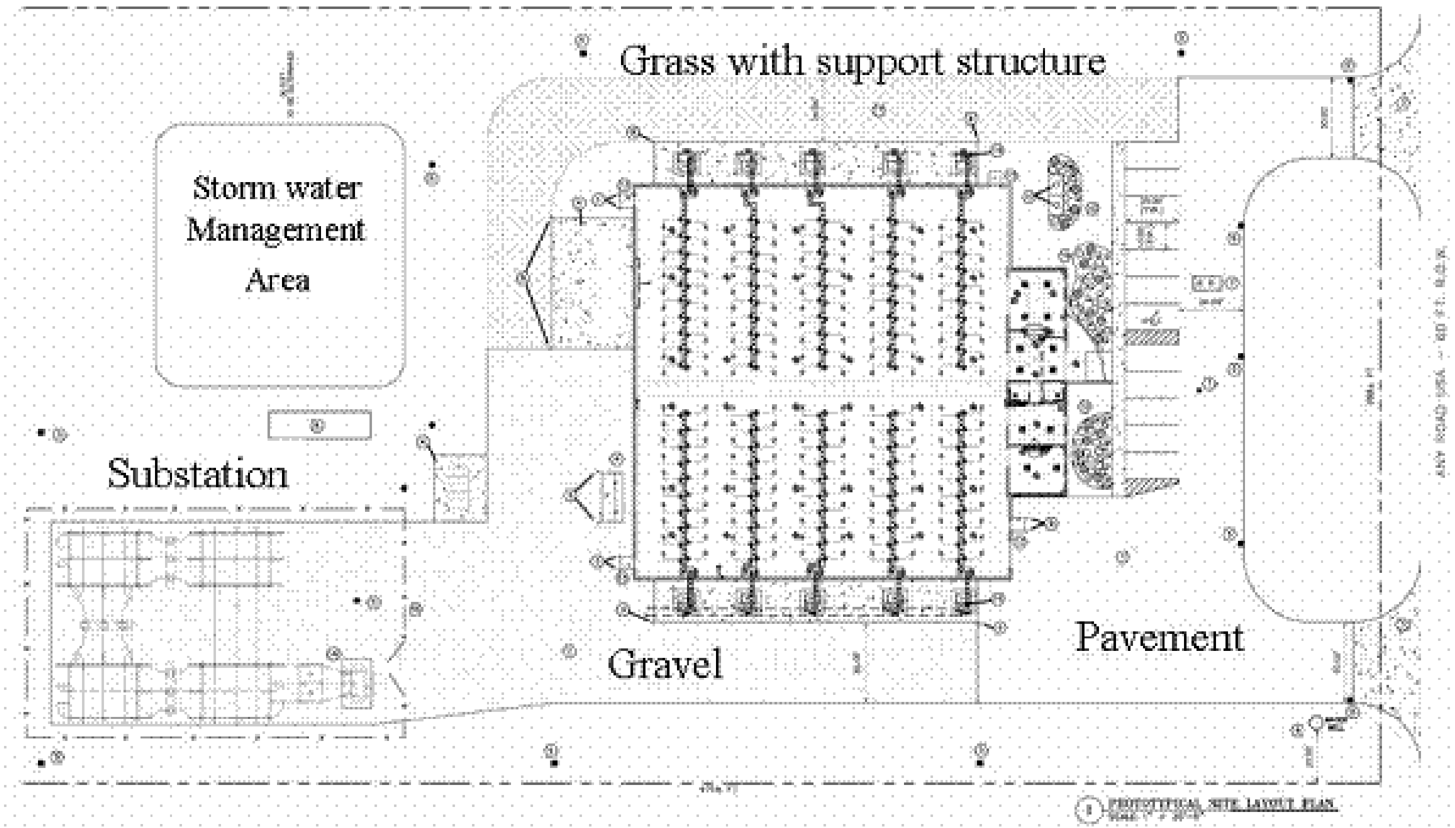

Figure 13. Plant site layout.

Site Selection & Permitting

Based on the above design for optimum site criteria, ensuring the fastest build would require the site selection criteria provided in Table 6.

Table 6. Site Selection Criteria.

Site Topography	Minimal grade change throughout site.
Available Utilities	Public storm drain. Public sanitary connection. Public water connection. Telephone.
Electrical	Substation site with 20-MW capacity available.
Parcel	Vacant. No demolition/site preparation required.
Geotechnical	Suitable bearing capacity without “over cutting”. Material could also allow for infiltration of storm water if acceptable my municipality.
Municipal Requirements	Minor relative to landscaping, screenings, building materials, etc.
Zoning	Industrial/light manufacturing–typical. Allow for construction of facility without requiring rezoning, variances, etc. In some situations, zoning might only require administrative review by municipality.

Construction

The plant is designed to minimize the amount of construction time necessary. The flywheel area was designed to be as compact as possible, while allowing for space to work on the units when required. The flywheel section of the building was designed to allow for construction with a pre-engineered building. This building would be built off site, which will reduce cost and construction time.

Renewable Energy Assessment

Sandia National Laboratories performed a renewable energy assessment for two sites, one in Southern California and the other in Central Massachusetts that focused on benefits of installing photovoltaic (PV) modules on the roof of the power plant to offset the daily energy losses of the plant (Table 7).

Table 7. Potential PV savings.

	Fixed Array	Single Axis
Southern California	1.8%	2.3%
Central Massachusetts	1.5%	1.8%

LEED-NC Assessment

Carter Burgess reviewed the building design and determined that the flywheel regulation plant can achieve a silver Leadership in Energy and Environmental Design (LEED) rating (Figure 14). The full analysis is located in Appendix A.

LEED for New Construction v2.2
Registered Project Checklist

	Potential Points	Yes	?	No
Sustainable Sites	14 Points	8	1	5
Water Efficiency	5 Points	3	2	0
Energy & Atmosphere	17 Points	6	1	10
Materials & Resources	13 Points	6	3	4
Indoor Environmental Quality	15 Points	9	3	3
Innovation & Design Process	5 Points	1	0	4
Project Totals (pre-certification estimates)	69 Points	33	10	26

LEED-NC Ratings	
Platinum:	52-69 points
Gold:	39-51 points
Silver:	33-38 points
Certified:	26-32 points

Figure 14. LEED-NC rating summary.

RESULTS

The cost for the flywheel plant, as designed, is estimated to be $10-12 million. The target goal for plant cost was $5 million. Due to the difference, Beacon Power designed a substation-style modular flywheel system that is expected to meet the target cost.

Similar to the design process for the 20-MW plant, a two-flywheel view was used to determine general relationships in the design of the substation system. All transferable functionality of the building was used in the substation design, albeit without the building. The ECMs, disconnects, and a good portion of the process cooling piping and bus duct were installed in a factory-built container that makes up the MW module, as shown in Figure 15.

Instead of pouring a foundation on site, pre-cast forms would be delivered to the site. After installation of the concrete forms, the MW module would be delivered to the site and installed. These design changes are expected to decrease the cost of the system and speed up the site build.

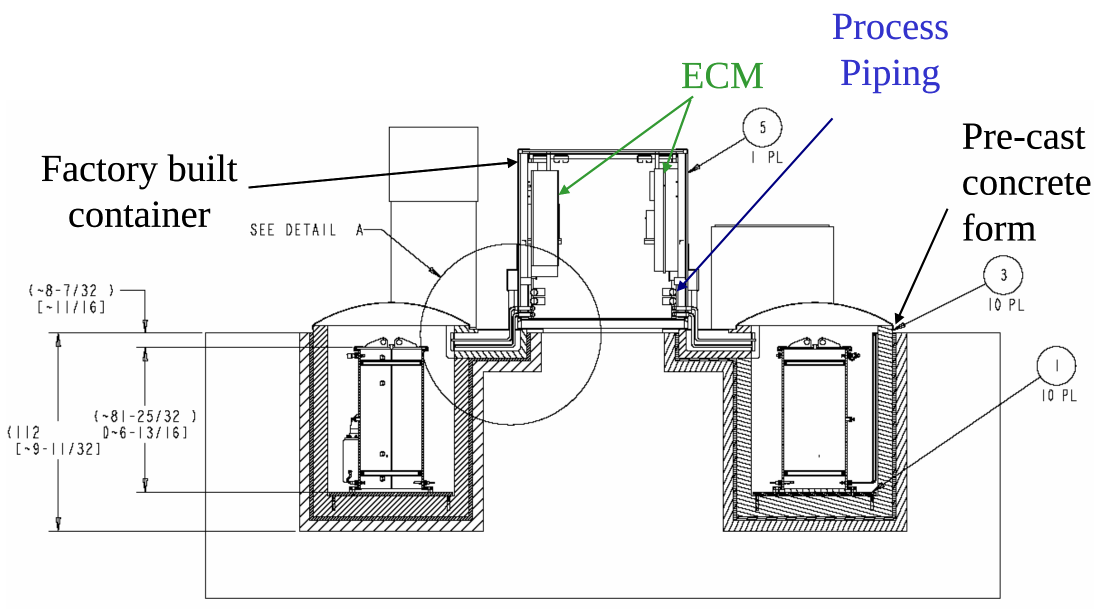

Figure 15. Cross-section of substation-style design.

As with the building design, the side (or cross-section) view was expanded into a base, building block size. With a standard shipping container, this became a 1-MW block. Figure 16 shows the 1-MW substation design with a transformer and cooling system components.

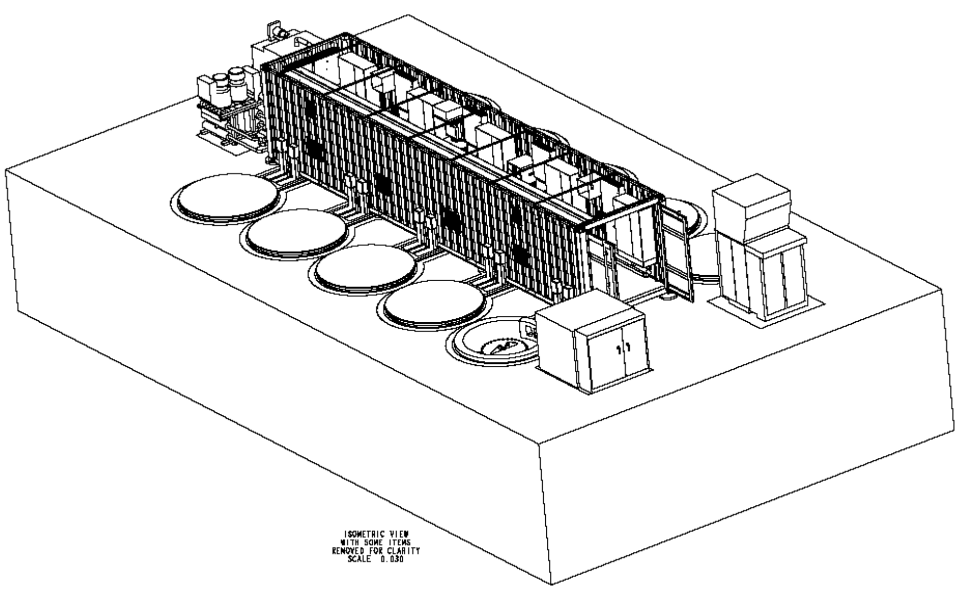

Figure 16. Substation style MW block.

Information developed for the building design funded by DOE was used as the baseline for the substation plant. Using the layout from the building design as a guide, and keeping the majority of the electrical and process cooling development, Beacon developed a 20-MW plant (Figure 17).

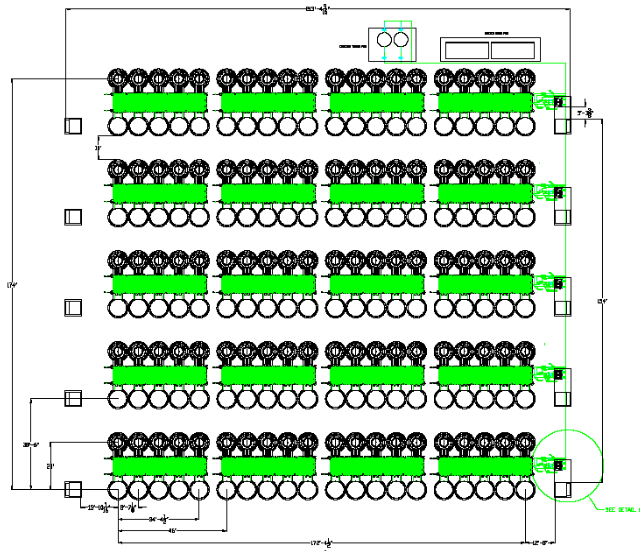

Figure 17. 20-MW substation-style plant.

APPENDIX A

EMISSIONS COMPARISON FOR A 20-MW FLYWHEEL-BASED FREQUENCY REGULATION POWER PLANT

KEMA

Emissions Comparison for a 20 MW Flywheel-based Frequency Regulation Power Plant

Beacon Power Corporation

KEMA Project: BPCC.0003.001

May 18, 2007

Final Report with Updated Data

Emissions Comparison for a 20 MW Flywheel-based Frequency Regulation Power Plant

Final Report with Updated Data

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Under Beacon Power Contract Number: 12952 of October 13, 2006

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Table of Contents

List of Exhibits

EXECUTIVE SUMMARY

KEMA Inc. was commissioned by Beacon Power to evaluate various performance aspects of the Beacon Power 20 MW flywheel-based frequency regulation power plant, including its emissions characteristics. To support the emissions evaluation, a detailed model was created to compare the emissions of CO_2, SO_2 and NO_x for a Beacon Power flywheel plant versus three types of commercially available power generation technologies used in the market to perform frequency regulation ancillary services.

The comparison of generation technologies included a typical coal-fired power plant, natural gas combustion turbine, and pumped storage hydro system. Emissions from the coal and natural gas-fired generation technologies result directly from their operation because they burn fossil fuels. In contrast, emissions for the flywheel and pumped hydro energy storage systems occur indirectly because they use some electricity from the grid to compensate for energy losses during operation. The emissions characteristics for these losses are based on the emission characteristics for the specific ISO area where the flywheel and pumped storage system are being used.

The mix of power generation technologies and average system heat rates for fossil-based power generation systems varies across regions in the United States. To obtain a regionally adjusted emissions comparison, system data specific to three Independent System Operator (ISO) regions were examined: PJM (Mid-Atlantic), California ISO (CAISO), and ISO New England (ISO NE). Data for each of these ISOs was extracted from the Department of Energy (DOE) Energy Information Administration (EIA) and Environmental Protection Agency (EPA) eGRID databases. Model calculations assumed typical heat rate and efficiency data for each type of generation.

For coal and natural gas-fired generation, KEMA's research found that frequency regulation results in increased fuel consumption on the order of 0.5 to 1.5%.[1] This finding is supported from estimates made by a U.S. DOE National Lab, information obtained from the ISOs, and from a European study that evaluated electricity producers to determine whether power plants providing frequency regulation had an increase in fuel consumption and maintenance requirements. This effect was reflected in the model.

Based on the above data, model analysis showed that flywheel-based frequency regulation can be expected to produce significantly less CO_2 for all three regions and all of the generation technologies, as well as less NO_x and SO_2 emissions for all technologies in the CAISO region. The flywheel system resulted in slightly higher indirect emissions of NO_x and SO_2 in PJM and ISO NE for gas-fired

1 A 0.7% increase in fuel consumption due to frequency regulation was assumed in the model for this study.

generation. This is because PJM and ISO NE's generation mix includes coal-fired plants, and make-up electricity used by the flywheel and hydro systems reflects higher NO_x and SO_2 emissions from electricity generated in those areas. This effect was greatest in PJM because it has proportionally more coal-fired plants than ISO NE.

When the flywheel system was compared against "peaker" plants for the same fossil generation technologies, the emissions advantages of the flywheel system were even greater. Model results for each of the ISO territories are summarized in Table 1, Table 2, and Table 3 on the following pages.

Table 1: Emissions Comparison for PJM

Flywheel Emission Savings Over 20-year Life: PJM					
	Coal		Natural Gas		Pumped Hydro
	Baseload	Peaker	Baseload	Peaker	
CO2					
Flywheel	149,246	149,246	149,246	149,246	149,246
Alternate Gen.	308,845	616,509	194,918	224,439	202,497
Savings (Flywheel)	159,599	467,263	45,672	75,193	53,252
Percent Savings	52%	76%	23%	34%	26%
SO2					
Flywheel	962	962	962	962	962
Alternate Gen.	2,088	5,307	0	0	1,305
Savings (Flywheel)	1,127	4,345	-962	-962	343
Percent Savings	54%	82%	n/a	n/a	26%
NOx					
Flywheel	259	259	259	259	259
Alternate Gen.	543	1,381	105	154	351
Savings (Flywheel)	284	1,122	-154	-105	92
Percent Savings	52%	81%	-148%	-68%	26%

Table 2: Emissions Comparisons for CAISO

Flywheel Emission Savings Over 20-year Life: CA-ISO					
	Coal		Natural Gas		Pumped Hydro
	Baseload	Peaker	Baseload	Peaker	
CO2					
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%
SO2					
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%
NOx					
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%

Table 3: Emissions Comparisons for ISO-NE

Flywheel Emission Savings Over 20-year Life: ISO-NE					
	Coal		Natural Gas		Pumped Hydro
	Baseload	Peaker	Baseload	Peaker	
CO2					
Flywheel	106,697	106,697	106,697	106,697	106,697
Alternate Gen.	304,759	608,354	197,359	227,249	144,766
Savings (Flywheel)	198,062	501,657	90,662	120,552	38,070
Percent Savings	65%	82%	46%	53%	26%
SO2					
Flywheel	270	270	270	270	270
Alternate Gen.	1,300	3,303	0	0	367
Savings (Flywheel)	1,030	3,033	-270	-270	96
Percent Savings	79%	92%	n/a	n/a	26%
NOx					
Flywheel	115	115	115	115	115
Alternate Gen.	416	990	58	85	157
Savings (Flywheel)	301	875	-58	-31	41
Percent Savings	72%	88%	-101%	-36%	26%

The emissions estimates under the scenarios listed above show highly favorable comparisons for the flywheel across all generation technologies.

The remaining sections of the report provide the assumptions that were used in the modeling as well as further insights and analysis.

A full summary of the emission comparisons is provided in Section 4.3. The final data was based on the operation of a "typical" power plant for each of the categories. Analysis using known heat rates for a specific generating plant performing regulation would improve the accuracy of model comparisons relative to that specific plant.

1. Introduction

Beacon has requested that KEMA perform a two-phased technology evaluation of a 20 MW flywheel technology contrasting flywheel-based frequency regulation with conventional fossil, hydro and lead acid solutions with respect to:

Phase I: Environmental impact evaluation of the flywheel system with other commercially utilized frequency regulation technologies, bidding into the ancillary services market.

Phase II: Benefits of fast response to grid frequency regulation management, updated life-cycle environmental impacts and cost-performance analysis of the flywheel.

This report addresses Phase I, evaluating the environmental impact of the flywheel, compared to other existing commercially available technologies for frequency regulation as an ancillary service.

2. Scope of Work and Work plan

2.1 Technologies

KEMA evaluated the following technologies for frequency regulation at three locations. One in the CAISO service area, one in the PJM service area and one in the ISO New England service area:

a) Beacon Flywheel (Nominal power at 20MW plant)

b) Conventional coal-fired fossil generating plants (Base Load and Peaker plants)

c) Conventional gas-fired fossil generating plants (Base Load and Peaker plants)

d) Pumped Hydro Storage

2.2 Environmental Impact Evaluation

The Beacon flywheel is evaluated against other generation for the purpose of frequency regulation based on emissions and includes the following:

a) Impact of the operation of the storage system to the environment - Quantified in tons of CO_2, NO_x, and SO_2.

b) Assumptions are provided to Beacon and collectively accepted before the analysis commences.

c) As part of the assignment a proprietary environmental evaluation tool was developed by KEMA.

d) The deliverable for the Phase I task is this report on the possible emissions savings.

3. Assumptions and Approach

3.1 General Assumptions Emissions Calculations

For coal and natural gas, a simplified approach was used to characterize whether plant efficiencies at altering loads have a large impact on actual emissions output. For coal and natural gas, emissions can vary depending on other factors. For coal, it can depend on the type of coal and firing conditions, while natural gas has efficiency variances around not only loading but also temperature factors. Hence, for the analysis, the following simplified assumptions were used:

(i) Comparisons of the natural gas and coal plant emissions were made against units that did not have emission reduction equipment in the case of NO_2 and SO_2.

(ii) For coal and natural gas base loaded plants, cycles were conducted around a 95% capacity factor with up and down ramping of +/- 5% of capacity. Cycling can be adjusted to occur around another factor by adjusting the Heat Rate factors for each of the charging and discharging inputs per the worksheet heat rate vs. capacity output table.

(iii) ISO related "System-wide" emission outputs were used in calculating the emissions from the flywheel and hydro pumped storage options associated with the losses. This data was taken from EPA eGRID [1] and DOE Energy Information Administration (EIA) [2] databases. System-wide ISO emissions do take emission control technology into account.

(iv) Coal emission factors are typically calculated based on loads of 80% or greater. Although the emissions generated at a given heat rate or efficiency are influenced by additional factors related to fuel type, the actual plant output has a more significant impact on the overall emissions, which allows the use of the simple calculation.

(v) Because the data was taken for one cycle and extrapolated over an entire year for the base load configurations, the focus of the model is on operations during that single cycle.

(vi) For coal and natural gas-fired generation, KEMA's research found that frequency regulation results in increased fuel consumption on the order of 0.5 to 1.5%. For this study 0.7% is used as the increased fuel consumption. This finding is supported from estimates made by a U.S. DOE National Lab, information obtained from ISOs, and from a European study [9, 10] that evaluated electricity producers to determine whether power plants providing frequency regulation had an increase in fuel consumption and maintenance requirements. This effect was reflected in the model.

3.2 Flywheel Charging and Discharging Cycles

For frequency regulation, the first general assumptions that were used were the number of cycles that occurred for each day. A cycle was defined as 15 minute ramp up or charging period, a 15 minute ramp down or discharging period, and 30 minutes of maintaining steady state or normal operations. For a complete day, 24 cycles were examined. The model uses a build-up approach that focuses on a single cycle, then extrapolates that data into a single day, a single year, and finally to a 20-year lifetime. Partial charges and discharge cycles were not considered. The flywheel was modeled as a system and emissions where calculated for all equipment and operations included in the entire system.

3.3 Flywheel Operation

For the flywheel to operate in frequency regulation mode, four separate modes of operation were taken into account. These include: ramp-up (charging), ramp down (discharging), steady state period where the voltage level is being maintained in the flywheel, and an accommodation for the percentage of time when the flywheel system is unavailable for frequency regulation because it has run out of energy. KEMA utilized Beacon data for this percentage. In the scale power test unit in California, Beacon determined the flywheel was available 98.3% of the time for frequency regulation. Hence, a factor of 1.7% was used to account for the percent of time that the unit was unavailable. The emissions are created during these operating scenarios by the flywheel using power from the grid to make up for the estimated 10% load losses on ramp up and ramp down, 1% energy required to maintain the flywheel, and the remaining unavailability utilization factor.

These idling losses (1%) of the flywheel can be absorbed from the grid or they can be compensated with renewable energy resources (solar or wind plant). In these calculations all flywheel losses are compensated by the generation mix of the specific ISO. Emissions rates used in these calculations use standard area fossil emission factors and "system" average heat rates and reflect the generation mix of the ISO region.

It was estimated that the flywheel system plant is able to provide only regulation during the availability period (assumed 98.3%) and that the overall charge - discharge efficiency of the flywheel is assumed at 80% (10% for ramp-up and 10% for ramp-down).

3.4 Coal-fired Plant Operation

The coal-fired plant emission data is calculated under two scenarios:

a) The first scenario is a base-load operation. Under this scenario, the coal plant is deemed to be a large power plant (400MW), base-loaded, and participating in a steady energy market. Hence, as the plant is considered to be already on-line, the emissions calculations above normal operations only occur when the plant is asked to increase its output (ramp-up) or decrease its output (ramp-down).

Summarizing:

i. A large power plant was used (400 MW) to represent a base-loaded coal plant that would be supplying wholesale energy to the market.

ii. Plant size was selected in order to allow a plant that could supply 20 MW around its rated 95 % capacity.

iii. Heat rates were used from a "general" coal plant without emissions reduction equipment [5]. General estimates of heat rate fluctuations off the 100% operation were obtained through an estimated heat rate curve.

iv. A cycle was determined by a ramp-up, increasing output to the grid, and ramp-down decreasing output of the power plant.

b) A second operating scenario is in "peaker" operation. Under this scenario, the emissions of the coal plant are estimated in a "peaker" operating mode. In a "peaker" operating mode the plant is only operating to participate in the frequency regulation market. In this case, the ramp up and ramp down emissions are calculated, as well as idling emissions, where the emissions for the output while idling are compared against the same output that would have been produced by a plant running at full rated capacity. Data for typical emission rates were taken from the EPA eGRID [1] and DOE EIA [2] databases on ISO emission factors. It is assumed that these plants operate only for a limited time during the day and year.

Summarizing:

i. The power plant operates for a limited number of hours per day (typically 6-12 hours per day). In this calculation 8 hours was used.

ii. A size of 75 MW plant size was assumed in order to allow power plant output to swing from + 20 MW to – 20 MW around an idling situation.

iii. Model assumes plant is in idling model of operation to respond to frequency regulation, emissions for idling condition (supplying power to market) is counted towards emission. Amount of emissions is calculated by comparing the emissions of the idling power plant to that of a power plant providing the equivalent amount of output (MW) while operating at its full rated capacity. The emission of the plant operated at full capacity is used as a plant would otherwise be supplying that power and output to the grid (100% base loaded operation).

iv. Ramp up and ramp down cycles are measured against output swings around the idling capacity of 50%.

v. For peaking plants, a decrease in output of plant has a more dominant effect on the results than the rising heat rate. Ramp-down cycles act as an offset to the ramp-up cycle.

vi. Fuel content for CO_2, SO_2, and NO_x were based on coal power generation data from 2004 EPA eGRID [1], and the 2000 DOE EIA [2] databases for the specific regions examined. (PJM, ISO NE, CA ISO).

3.5 Natural Gas Fired Combustion Turbines

Like the coal-fired power plants, the natural gas turbines are operated in the same modes of operation – Base-load and "Peaker" operation as discussed in Section 3.4. Heat rate data from a typical natural gas fired plant was utilized for the study. As the emission factors for the natural gas plants are lower than for coal, estimated emissions were correspondingly less than those produced by coal-fired plants. Lifetime emissions savings for a flywheel regulation plant replacing a base-load natural gas-fired plant were calculated to be 23-53% for CO_2, depending on the ISO region.

The analysis showed the flywheel to have greater emission than the natural gas plant for SO_2 and NO_x. These differences are accounted from the fact the flywheel creates its emissions indirectly from an average of all generation sources on the system. These system averages were taken from EPA eGRID [1] and DOE EIA [2] databases. This is the main driver to the natural gas power plant producing less NO_x and SO_2 emissions versus the flywheel-based system.

KEMA believes that a significant amount of frequency regulation is conducted with natural gas combustion turbines. Operation of the base loaded and peaker power plants were similar to the coal units. The main differences between the two technologies are in the size of the efficiency fluctuations and a higher minimum load level used for gas generation compared to coal. The analysis only varied heat rate based on partial loading. Natural gas turbine efficiencies are also typically subject to variations such as temperature. However, for this analysis, only efficiency fluctuations were included.

3.6 Hydro Pump Storage

Pump-storage scenarios were similar to the flywheel scenario insofar as like the flywheel regulation, hydro regulation does not produce emissions directly. The indirect emissions that were calculated were based on the inefficiencies of the system and the extra energy that is required to make up for the losses. The losses associated with ramping up and ramping down are larger than that of the flywheel since the efficiency of a hydro pump storage facility is lower. Thus the overall emissions for hydro pump storage are greater than those for the flywheel. It was estimated that a pump hydro plant is able to provide regulation 100% of time. The overall charge - discharge efficiency of the hydro system was estimated at 70%.

3.7 Assumptions on ISO Generation Mix

The mix of power generation technologies and average system heat rates for fossil-based power generation systems varies across regions in the United States. To obtain a regionally adjusted emissions comparison, system data specific to three Independent System Operator (ISO) regions were examined: PJM (Mid-Atlantic), California ISO (CAISO), and ISO New England (ISO NE). The year 2004 data in the EPA eGRID [1] and year 2000 DOE EIA [2] databases were used to assume the different generation mixes in the different ISOs investigated. Model calculations assumed typical heat rate and efficiency data for each type of generation.

The flywheel emissions were compared to the emissions of the generators that are currently actively bidding into the frequency regulation ancillary services market. These are mainly natural gas, coal and oil power plants. A summary of the year 2004 generation mixes for each of the ISO territories used in the analysis is shown below in Table 4.

Table 4: Assumed Generation Mix in Different ISOs

Territory	Fuel Type	Fuel Mix (%)
	Coal Power Plant	58.9%
	Natural Gas	5.4%
PJM	Oil	2.5%
	Nuclear	31.0%
	Hydro	1.1%
	Wind	0.1%
	Biomass	.9%
	Coal Power Plant	15.7%
	Natural Gas	38.4%
ISO-NE	Oil	8.2%
	Nuclear	28.0%
	Hydro	5.0%
	Wind	0%
	Non-Hydro Renew	4.7%
	Coal Power Plant	6.9%
	Natural Gas	49.3%
CA ISO	Oil	.8%
	Nuclear	15.9%
	Hydro	16.4%
	Wind	2.2%
	Biomass	3.2%
	Geothermal	5.2%

4. Developed Emissions Evaluation Tool

4.1 Description of Emission Tool

To support the evaluation, a detailed model was developed to compare the emissions of CO_2, SO_2 and NO_x for one of Beacon Power's planned 20 MW flywheel plants versus the three major types of conventional power generation technologies used today to perform frequency regulation. A spreadsheet based tool has been developed as part of this phase of the project. The tool has variable inputs on the different assumptions, discussed above. These inputs are used to calculate the emissions comparison per ISO region.

4.2 Variable Inputs to Emission Tool

An example of the different variable inputs is shown in Table 5. The input variables are shown for the flywheel. Similar input tabs are used for the different generator types. The table shows how the operation of the application is defined and where losses are accounted for during operation. In the model, these inputs are set up for each of the technologies being analyzed.

Table 5: Variable Input Page for Flywheel

Variables		
Max Cycles per day	24	cycles
Size	20,000	kW
Heat Rate(PJM)	10,128	btu/kWh
Charge/Discharge Time	0.25	hr
Total System Losses	14%	Percentage
Percentage Regulation Compliance	98.3%	Percentage
Cycle Time with No Load	0.5	hr
Solar System Providing No Load Power Toggle	No	

4.3 Output of Emission Comparison Tool

Table 6 is a summary of the emissions data obtained from modeling the operation of the Beacon Power flywheels against the other options for frequency regulation - a base-loaded coal plant, a "peaker" coal plant, base-loaded natural gas plant, a "peaker" gas plant and hydro pump storage are compared with the flywheel emissions output.

Table 6: Comparison of Emissions Output Data

Comparison	CO_2				SO_2				NOx			
	Per Cycle	Per Day	Per Year (tons)	Per Lifetime (tons)	Per Cycle	Per Day	Per Year (tons)	Per Lifetime (tons)	Per Cycle	Per Day	Per Year (tons)	Per Lifetime (tons)
PJM	lbs		tons		lbs		tons		lbs		tons	
Fly Wheel	1,704	40,889	7,462	149,246	11	263	48	962	3	71	13	259
Coal Baseload	3,526	84,615	15,442	308,845	24	572	104	2,088	6	149	27	543
Coal Peaker	3,814	168,907	30,825	616,509	26	1,454	265	5,307	7	378	69	1,381
Natural Gas Baseload	2,225	53,402	9,746	194,918	0	0	0	0	1	29	5	105
Natural Gas Peaker	1,188	61,490	11,222	224,439	0	0	0	0	1	42	8	154
Pump Storage	2,312	55,479	10,125	202,497	15	357	65	1,305	4	96	18	351
ISO-NE	lbs		tons		lbs		tons		lbs		tons	
Fly Wheel	1,218	29,232	5,335	106,697	3	74	14	270	1	32	6	115
Coal Baseload	3,479	83,496	15,238	304,759	15	356	65	1,300	5	114	21	416
Coal Peaker	3,764	166,672	30,418	608,354	16	905	165	3,303	3	271	50	990
Natural Gas Baseload	2,253	54,071	9,868	197,359	0	0	0	0	1	16	3	58
Natural Gas Peaker	1,203	62,260	11,362	227,249	0	0	0	0	0	23	4	85
Pump Storage	1,653	39,662	7,238	144,766	4	100	18	367	2	43	8	157
CA ISO	lbs		tons		lbs		tons		lbs		tons	
Fly Wheel	1,040	24,953	4,554	91,079	1	23	4	63	1	18	3	64
Coal Baseload	3,676	88,222	16,100	322,009	13	302	55	1,103	6	137	25	499
Coal Peaker	3,977	176,106	32,139	642,789	14	768	140	2,803	6	348	63	1,269
Natural Gas Baseload	2,221	53,297	9,727	194,534	0	0	0	0	1	22	4	80
Natural Gas Peaker	1,186	61,369	11,200	223,997	0	0	0	0	0	32	6	118
Pump Storage	1,411	33,857	6,179	123,577	1	23	4	85	1	24	4	87

These evaluation results are also summarized for each of the ISO territories in Table 7, Table 8, and Table 9 for the 20 year life cycle of the application.

Table 7: Emissions Comparison for PJM

Flywheel Emission Savings Over 20-year Life: PJM					
	Coal		Natural Gas		Pumped Hydro
	Baseload	Peaker	Baseload	Peaker	
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Flywheel	149,246	149,246	149,246	149,246	149,246
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Savings (Flywheel)	284	1,122	-154	-105	92
Percent Savings	52%	81%	-148%	-68%	26%

Table 8: Emissions Comparisons for CAISO

Flywheel Emission Savings Over 20-year Life: CA-ISO					
	Coal		Natural Gas		Pumped Hydro
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CO2					
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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%
SO2					
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%
NOx					
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%

Table 9: Emissions Comparisons for ISO-NE

Flywheel Emission Savings Over 20-year Life: ISO-NE					
	Coal		Natural Gas		Pumped Hydro
	Baseload	Peaker	Baseload	Peaker	
CO2					
Flywheel	106,697	106,697	106,697	106,697	106,697
Alternate Gen.	304,759	608,354	197,359	227,249	144,766
Savings (Flywheel)	198,062	501,657	90,662	120,552	38,070
Percent Savings	65%	82%	46%	53%	26%
SO2					
Flywheel	270	270	270	270	270
Alternate Gen.	1,300	3,303	0	0	367
Savings (Flywheel)	1,030	3,033	-270	-270	96
Percent Savings	79%	92%	n/a	n/a	26%
NOx					
Flywheel	115	115	115	115	115
Alternate Gen.	416	990	58	85	157
Savings (Flywheel)	301	875	-58	-31	41
Percent Savings	72%	88%	-101%	-36%	26%

4.4 Discussions of the Emission Comparison Results

The emissions comparisons estimates showed highly favorable results for the flywheel for reduction of CO_2. The developed model and analysis shows that the flywheel-based frequency regulation can be expected to create significantly less CO_2 for all of the generation technologies in every region, as well as less NO_x emissions for all technologies in the CAISO region.

Lifetime CO_2 savings for a flywheel-based regulation plant displacing a coal-fired plant in the PJM Interconnect area were estimated to be 159,599 tons for a base loaded coal plant and 467,263 tons for a peaker coal plant. This translates to projected reductions of 52% and 76%, respectively. In the ISO NE region, CO_2 reduction versus base loaded and peaker coal plants were projected to be 65% and 82%, respectively.

Lifetime CO_2 savings for a flywheel-based regulation plant displacing a base loaded natural gas-fired plant in California were estimated to be 103,455 tons, while CO_2 savings for a peaker gas plant were 132,917 tons. This translates to a projected savings of 53% and 59% in CO_2 emissions, respectively.

Lifetime CO_2 savings for a flywheel-based regulation plant displacing a pumped hydro plant were 26% in all three regions.

The flywheel system resulted in slightly higher indirect emissions of NO_x and SO_2 in PJM and ISO NE for gas-fired generation. This is because PJM and ISO NE's generation mix includes coal-fired plants as well as the low SO_2 emissions from natural gas power plants. The make-up electricity used by the flywheel and hydro systems reflects higher NO_x and SO_2 emissions from electricity generated in those areas.

5. Conclusions

In this report, KEMA compared the emissions from different frequency regulation generator technologies that actively participate in the ancillary services market, with the equivalent emissions associated with a 20 MW flywheel plant. A detailed model was developed to compare the emissions of CO_2, SO_2 and NO_x for a Beacon Power flywheel plant versus three types of commercially available power generation technologies used in the market to perform frequency regulation ancillary services.

The generation technologies compared included a typical coal-fired power plant, natural gas combustion turbine, and pumped storage hydro system. Emissions from the coal and natural gas-fired generation technologies result directly from their operation because they burn fossil fuels. In contrast, emissions for the flywheel and pumped hydro energy storage systems occur indirectly because they use some electricity from the grid to compensate for energy losses during operation.

The mix of power generation technologies and average system heat rates for fossil-based power generation systems varies across regions in the United States. To obtain a regionally adjusted emissions comparison, system data specific to three Independent System Operator (ISO) regions were examined: PJM (Mid-Atlantic), California ISO (CAISO), and ISO New England (ISO NE). Data for each of these ISOs was extracted from the most recent DOE EIA, and EPA eGrid databases. Model calculations assumed typical heat rate and efficiency data for each type of generation.

For coal and natural gas-fired generation, KEMA's research found that frequency regulation results in increased fuel consumption on the order of 0.5 to 1.5%. In this study 0.7% increased fuel consumption is used.

Based on the above data, model analysis showed that flywheel-based frequency regulation can be expected to produce significantly less CO_2 for all three regions and all of the generation technologies, as well as less NO_x and SO_2 emissions for all technologies in the CAISO region. The flywheel system resulted in slightly higher indirect emissions of NO_x and SO_2 in PJM and ISO NE for gas-fired generation. This effect was greatest in PJM because it has proportionally more coal-fired plants than ISO NE.

When the flywheel system was compared against "peaker" plants for the same fossil generation technologies, the emissions advantages of the flywheel system were even greater.

6. Recommendations

- All the data of this study was based on publicly available data from DOE, EPA and the different ISO sites. Some of the data may be dated in terms of the generation mix and generating efficiencies and heat rates. These results should be validated with direct ISO involvement in a future study.

- The assumed generation data is of a generic plant. It is thus limited in the details of specific frequency regulation plant efficiencies under different operating scenarios. It is proposed that a more in-depth analysis is performed based on specific coal or gas-fired generators. This should be done to calculate the specific emission savings that the flywheel installation can achieve at a specific installation in a certain ISO region.

- The frequency regulation control signal from a specific ISO could not be integrated into the current simplistic model. When a specific site is selected for frequency regulation, it is recommended to use specific generation data and integrate the relevant ISO frequency regulation control signal. This will be valuable to investigate the impact of partial discharge cycles on the lifetime emissions savings of the flywheel system compared to other generation technologies.

- The flywheel system has a much faster dynamic response compared to other frequency regulation generation technologies. The faster response or ramp-rate of the flywheel system can provide better frequency regulation results compared to conventional generation units. For comparison this improved performance could not be evaluated.

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APPENDIX B

COST COMPARISON FOR A 20–MW FLYWHEEL-BASED FREQUENCY REGULATION POWER PLANT

Cost Comparison for a 20 MW Flywheel-based Frequency Regulation Power Plant

Beacon Power Corporation

KEMA Project: BPCC.0003.002

September, 2007

Final Report

Cost Comparison for a 20 MW Flywheel-based Frequency Regulation Power Plant

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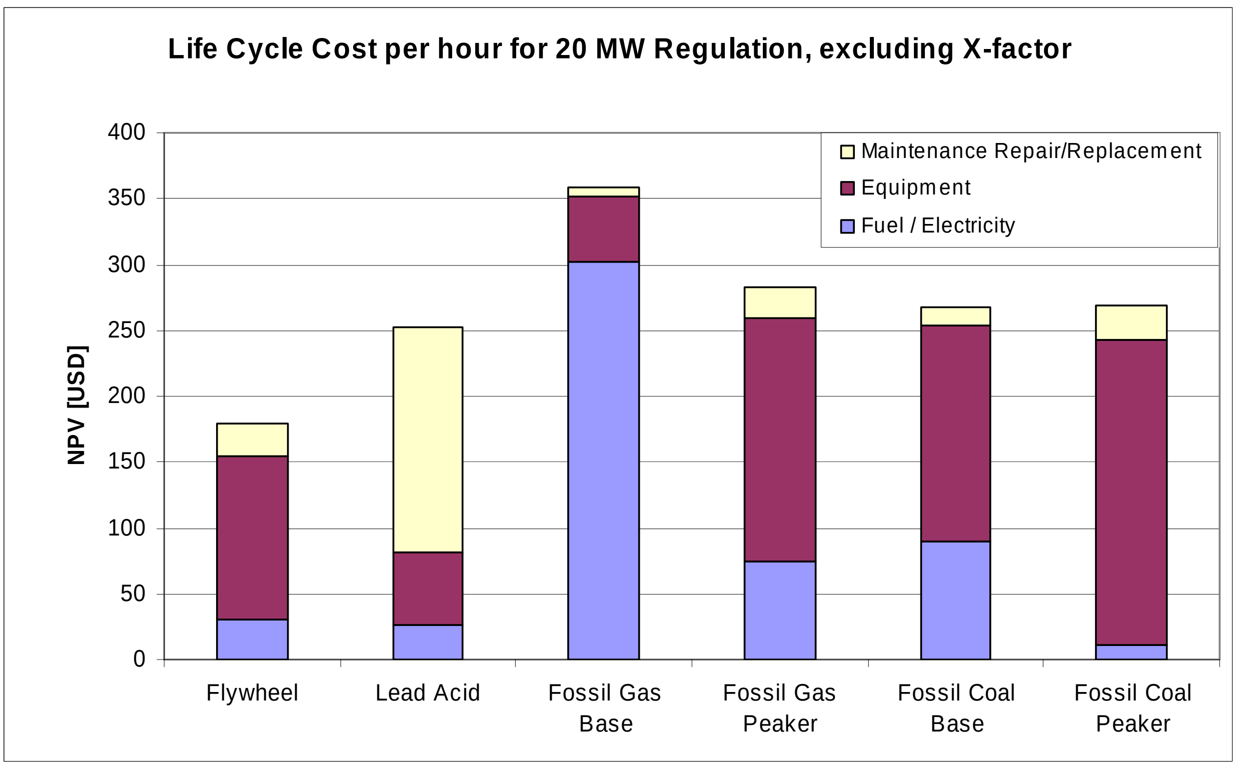
Table of Contents

List of Exhibits

EXECUTIVE SUMMARY

KEMA, Inc. was commissioned by Beacon Power, with a contract funded by the US DOE through Sandia National Laboratories, to evaluate various performance aspects of the Beacon Power 20 MW flywheel-based frequency regulation power plant, including its life cycle cost to perform frequency regulation ancillary services in three Independent System Operator (ISO) markets. To support this evaluation, a model was created by KEMA to compare the life-cycle cost of the Beacon Power flywheel plant with four types of commercially available fossil power generation technologies used to perform frequency regulation services. The flywheel system was also compared with a lead acid battery storage system that could also be used to perform frequency regulation ancillary services, similarly to the flywheel system.

The analysis included preparation of a Life Cycle Cost model using Net Present Value analysis that reflected fixed and variable costs for regulation. As can be seen in **Error! Reference source not found.**, Beacon Power's flywheel is capable of delivering the regulation services at the lowest life cycle cost. Though a CO_2 market does not yet exist in the U.S., a section has been added to show the effects that a CO_2 market might have on the cost analysis. The graph also notes that it has excluded an X-factor. The



X-factor is the need for less

Figure 1: Life Cycle Cost per hour for 20 MW Regulation in the PJM region

total regulation resources due to fast response which could effectively decrease the LLC by a factor of 50 percent (assuming X = 2). While the X-factor is supported by several ISO studies, it has not yet been empirically confirmed with a full-scale plant for either the flywheel or battery technologies.

The model calculated hourly life cycle costs for flywheel regulation and for the competing technologies. Results of the analysis show that flywheel-based regulation can be expected to have significantly lower life cycle costs (LCC) compared to all of the competing technologies in the ISO regions studied. Within the PJM Interconnection, LCC for a base loaded gas-fired plant ("Fossil Gas Base" in **Error! Reference source not found.**) doing the same amount of regulation as a flywheel plant was estimated to be $47 million more than a flywheel plant, or just over 100 percent greater. For a base loaded coal-fired plant the additional LCC versus a flywheel plant was $23 million, or more than 49 percent greater. Similarly, the LCC increment for a lead acid battery-based system was estimated to be over $19 million, more than 41 percent greater compared to a flywheel plant.

Comparisons between the flywheel plant and gas and coal-fired peaker plants have been based on an equivalent cost basis. This equivalent cost is based on the NPV cost per regulation cycle, multiplied by the total amount of regulation cycles in the reviewed timeframe of 30 years. The amount of regulation cycles is the same for all technologies.

A gas-fired peaker plant would therefore require an additional $27 million in LCC, representing more than 57 percent greater effective life cycle cost. For a coal-fired peaker plant the comparative values were around $23 million and almost 50 percent higher, respectively.

Cost Components included in this analysis include:

1. Capital Cost for installing the equipment.
2. Operational Costs
    a. Fuel (or energy losses in case of flywheels and lead acid batteries)
    b. Maintenance and repair
    c. Periodic reinvestment
    d. Staff

e. Carbon Credit: Cost of CO_2 emissions, though there is not a market for CO_2 in the U.S., we have included a section that shows cost impacts for the various technologies if a CO_2 market existed in the U.S.

3. Reduction in operating life for thermal plants caused by providing regulation

4. Loss of availability for thermal plants due to providing regulation

Critical assumptions have been verified by industry experts and, where available, public data.. The cost evaluation under the scenarios listed above show favorable comparisons for the flywheel across all generation technologies. The remaining sections of the report provide the assumptions used in the modeling as well as further analysis and insights.

Data used in the report is based in part on average parameters for power plants considered "typical" for each of the comparison technology categories. Analysis using known historical cost components for a specific generating plant performing regulation can be expected to provide quantitatively different results relative to that plant. However, KEMA believes that use of representative plant data accurately portrays the costs for each *category* of technology.

1. Introduction

Beacon Power Corporation retained KEMA to perform a technology and cost evaluation of a 20 MW flywheel-based regulation plant and to compare the results against commercial fossil-based and pumped hydro solutions as well as a potential lead acid battery solution. The content of each phase was as follows:

Phase One: Emissions impact evaluation of the flywheel system compared to commercially utilized frequency regulation technologies bidding into the ancillary services market, and

Phase Two: Benefits of fast response to grid frequency regulation management and the regional grid; cost-performance analysis of the flywheel versus other commercially utilized frequency regulation technologies; and updated life-cycle emissions impacts incorporating the most recent emissions data from the US Environmental Protection Agency (EPA).

The balance of this Phase Two report is contained in the following sections:

Section 2: Benefits of Fast Response Regulation – discussion of the potential system-wide benefits of fast response, including both common and differential benefits for fast regulation tied into the grid at transmission and distribution levels.

Section 3: Cost Performance Analysis – evaluation of lifecycle cost-performance of flywheel-based regulation compared to commercially available technologies and lead acid batteries.

Section 4: Assumptions and Approach – listing of critical assumptions.

Section 5: Life Cycle Cost Evaluation – description of the model and output results.

Section 6: Conclusions – summary of major findings.

Section 7: References – sources for supporting data.

Appendix: Assumptions and Model Inputs – listing of model inputs for all the technologies.

2. Benefits of Fast Response Regulation

This section discusses the potential benefits of fast response regulation. These benefits are based on the findings of the California Independent System Operator (CAISO) and the California Energy Commission (CEC) with respect to the expected ability of fast response regulation to allow a reduction in the total system-wide capacity of regulation resources. This reduction is accomplished by using a mix of both fast response and slower conventional regulation generators. The section then reviews other possible benefits of fast regulation, some of which would be common to regulation resources integrated at either transmission or distribution voltages, and some of which would be specific to one or the other.

2.1 Reduction of System-wide Regulation Resources

In 2005 CAISO agreed to participate with Beacon Power in a contract awarded to Beacon by the CEC to demonstrate the value of frequency regulation using fast response flywheel energy storage. The CAISO supported the integration of the flywheel demonstration unit to its Energy Management System (EMS) and also helped determine the best way to optimize dispatch of the unit in order to take maximum advantage of the uniquely fast response capability of flywheel regulation.

2.1.1 CAISO's ACE Smoothing Algorithm

With the objective of fully exploiting the fast speed-of-response characteristics of flywheel technology, CAISO assigned Dr.Yuri Makarov of the CAISO to develop a new algorithm that would maximize system-wide benefits to the ISO. In particular, the new algorithm was designed to create maximum synergy between fast response flywheel-based regulation, and slower response conventional generation resources.[1]

ISO dispatching algorithms typically dampen the rapidly moving signal as determined by the instantaneous Area Control Error (ACE) in order to better match generator transient response capability and minimize the movement and directional changes of participating regulation generators. This helps reduce generator wear and tear and tripping events to levels considered acceptable by the owners of those resources as well as the ISO. However, signal damping can also have the effect of increasing the amount of regulation resources, and associated costs, needed for regulation.

[1] Dr. Makarov's work on frequency regulation, including frequency regulation algorithms and the 2X performance factor is referenced in several CAISO internal reports, as follows: "Suggested Algorithms to be Tested at San Ramon Test Facility," a California ISO document published 10/25/05, researched and written by Dr. Makarov; and "Relative Regulation Capacity Value of the Flywheel Energy Storage Resource," also researched and written by Dr. Makarov.

Given their relatively slow speed-of-response, conventional regulation resources sometimes provide regulation in the wrong direction – after conditions have completely changed – and the grid is calling for regulation in the opposite direction. This occurs when the inertia of the slower responding generators does not allow power output to completely reverse in response within the intervals between ISO signals, which are typically every 4 to 6 seconds. A related undesirable effect of slow response resources is that they can sometimes partially cancel each other by simultaneously regulating in opposite directions. Both of these effects occur due to the inertial lag of conventional generators and the consequent necessity of signal dampening, and both contribute to the need for more system-wide regulation resources than would otherwise be required to maintain proper frequency limits on the grid.

After CAISO developed and compared alternative methods for implementing frequency regulation, the best of these methods, termed the "ACE Smoothing Algorithm," was selected for the flywheel regulation demonstration tests that were subsequently performed over a period of 18-months in California. The "ACE Smoothing Algorithm" was specifically designed to extract maximum synergy between the faster, but energy limited flywheel regulation and slower but unlimited energy duration conventional generation resources. This was done by allowing the faster flywheel to regulate the most extreme high frequency regulation requirements which demand a faster ramp rate, while leaving the filtered lower frequency remainder to be handled by the conventional generating resources.

Figure 2 on the following page was provided as part of a February 2005 presentation by CAISO to the CEC. It graphically shows CAISO's goal to correct the majority of the ACE with faster responding regulation to make it easier for slower ramping regulators to follow the smooth orange line. As noted in Figure 2, the expected advantages of this control method include a reduction in the number of direction reversals of the conventional generators, greater ability to operate those slower units closer to their preferred operating point (POP), and a consequent reduction in the total amount of regulation resources needed for the total ISO system.

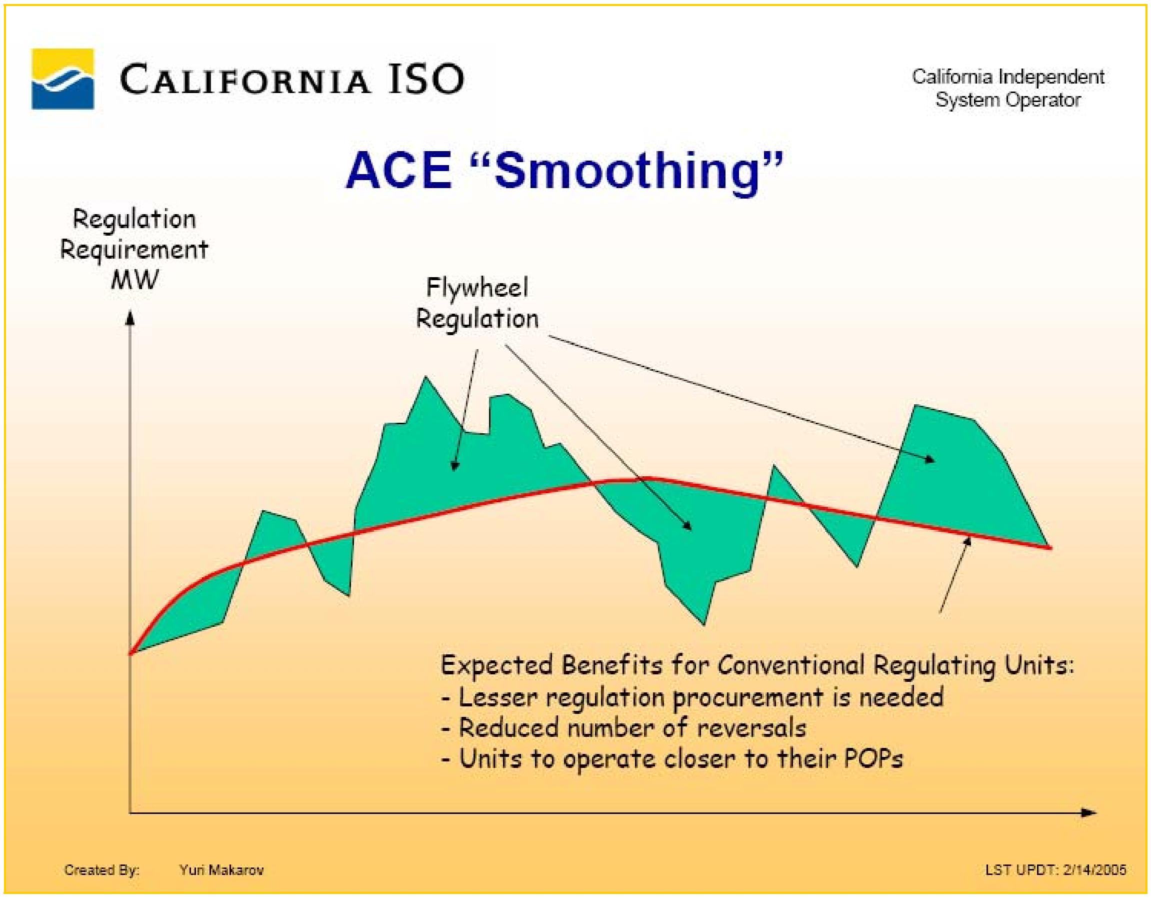


Figure 2: CAISO "ACE Smoothing"

The CAISO modeled the expected system-wide performance of the ACE Smoothing Algorithm assuming that fast regulation resources comprised one-fourth of total regulation assets based on regulating power. The model showed this combination would provide twice the regulation benefit compared to conventional automatic generation control (AGC) resources driven by traditional dispatching algorithms.[2] The CEC also supports the position that fast ramp rate regulation can be expected to have a higher value to the grid compared to slower regulation.[3]

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[2] In an April 12, 2007 meeting at the CAISO, Dave Hawkins of the CAISO confirmed CAISO's view that fast responding flywheel regulation, if operated using the ACE Smoothing Algorithm may be twice as effective compared to conventional regulation resources operating alone. Other meeting attendees included Mike Gravely of the CEC and Bill Capp, Jim Arseneaux and Chet Lyons of Beacon Power Corporation.

[3] In its December, 2006 press release announcing the successful completion of testing for the flywheel demonstration system in California, the CEC stated: "In addition to the environmental and transmission benefits of flywheel technology, current research at Lawrence Berkeley National Laboratories indicates

To understand the potential impact of faster regulation on comparative costs for all the technologies, KEMA's model was developed to represent this effect. The results are shown in Section 5.2.4 with the impact on the Life Cycle Cost (LCC) shown in Figure 8 These results use the same assumptions underlying the cost summary model, except that 1 MW of flywheel regulation is assumed to displace 2 MW of conventional regulation. This effect is referred to in this report as the "2X factor." Since lead acid batteries would have a possible response rate as fast as that for flywheels due to a similar power electronics interface, a similar result is shown for lead acid batteries in Figure 8. Figure 8 also assumes that lead acid batteries would displace twice as much conventional regulation resource.

For the purpose of this report, the comparative cost scenario modeled in Section 5.2.4. and shown in Figure 8 is regarded as an as-yet unproven possibility since the 2X factor has not yet been tested and validated with a full-scale commercial plant operating in the required proportions with other conventional regulation resources. Nevertheless the results in Section 5.2.4 present an intriguing potential picture of comparative costs for regulation technologies if the 2X factor is confirmed with a full-scale plant.

Beacon's flywheel technology can be integrated into the grid at either the transmission or distribution level. For 20 MW plants, integration will likely take place at or near transmission level to minimize the risk of grid disturbances. For smaller capacities, e.g., 5 MW and below, distributed regulation resources can be placed in the distribution level without much concern for disturbances. The sub-sections below identify and discuss other potential benefits of fast response regulation deployed at either the transmission or distribution level on the grid.

2.2 Reduced CO_2 Greenhouse Gas Emissions

As presented and discussed in the Phase I Report [1], KEMA's model analysis shows that flywheel-based frequency regulation can be expected to produce significantly less CO_2 for all three ISO regions that were modeled and compared to all of the conventional fossil and pumped hydro generation technologies. This benefit will apply to flywheel resources as well as Lead Acid Storage system resources integrated on either the transmission or distribution level.[4]

that 10 megawatts of fast-responding flywheel energy could provide the grid with the equivalent energy of 20 megawatts or more of traditional slow-responding power plant energy."

[4] For a detailed discussion of CO_2 reduction benefits, see: "Emissions Summary Comparison for a 20 MW Flywheel-based Frequency Regulation Power Plant," KEMA, Inc., published in December, 2006.

2.3 Reduced Dependence on Fossil Fuel

In order for fossil-based plants to perform frequency regulation they must cycle up and down. For coal and natural gas plants, KEMA has found that the thermal cycling that fossil-based regulation plants undergo while performing frequency regulation reduces efficiency for the entire plant and causes them to consume in the range of 0.5 to 1.5% more fuel compared to what they would otherwise use if operated on a steady state basis. Adoption of flywheel-based regulation can reduce the amount of fossil fuel used by society to accomplish the regulation function, and that in turn would reduce national dependence on supplies of foreign fossil fuel from unfriendly and unreliable parts of the world.

2.4 Increased Peak and Base Load Generation Capacity

In its 2006 Long Term Reliability Assessment, the North American Electric Reliability Council (NERC) identified a looming shortage of peak generating capacity as a major concern requiring decisive action. Flywheel-based frequency regulation can be sited in the grid next to the existing installed base of fossil-based regulation plants. Where relevant, installing additional flywheel-based frequency regulation allows the recapture of the fraction of generation capacity that must otherwise be reserved to perform frequency regulation. This regained base load capacity will not require permitting or incur long construction cycles and delays since those fossil plants are already in place. In effect, the use of flywheel-based regulation would increase regional peak and base load generation capacity in proportion to the plants it displaces. In some regions, flywheel and battery-based regulation might conceivably qualify for some form of "capacity credit" which is paid by some ISOs to resource providers whose technology has the effect of increasing regional capacity. This estimated increase in capacity has not been quantified in this study.

2.5 Increased Transmission Capacity and Reduced Congestion

Flywheel systems sited in the distribution grid at medium voltage levels place the regulation service closer to the loads being regulated. Transmission and transformation losses associated with injecting regulating power on the transmission system could therefore be reduced or eliminated. This in turn would free up transmission line capacity, resulting in reduced or avoided congestion. However, the value of this benefit can only be quantified for specific locations by considering location-specific constraints. This estimated increase in transmission capacity has not been quantified in this study.

2.6 Additional Reduction of Grid Losses

The fluctuations of power flow in the transmission grids can be reduced due to the fact that the flywheel system is taking care of the fast fluctuations at the distribution level, while the average power is delivered by the generator/transmission system. The grid losses are much lower if the fluctuating power is not transmitted through the transmission system, but compensated directly at the source in the distribution system. Effectively, regulation plants embedded in the distribution system can reduce grid losses compared to more centrally located resources requiring greater allocation of transmission capacity. This estimated reduction in grid losses has not been quantified in this study.

2.7 Other Potential Grid benefits of Flywheel Systems

2.7.1 Provision of Grid Backup and 'Black Start' Ancillary Services

Once the flywheels are charged, they could also be used to supply selected critical loads or part of a grid in the event of a grid outage or interruption. Once an outage occurs, it will not be possible to supply regulation to the main grid anymore, so the system would be available for alternative applications. Even if the flywheels were partially empty before the outage, the flywheels could be charged with a smaller diesel generator than normally required to be used as a Black Start facility. This estimated benefit in Black Start has not been quantified in this study.

2.7.2 Support of Reactive Current / Voltage Control

The power electronics of the flywheel system have the ability to generate or absorb reactive power within the power range of the converters while performing regulation ancillary services. The control of reactive current may benefit grid operators since this allows the control of voltage – which in turn can help improve the quality of electricity delivered to end-users. This estimated benefit of VAr regulation and voltage support has not been quantified in this study.

3. Cost Performance Analysis

This section explains the rationale for KEMA's approach to structuring the cost comparison model. It also defines a regulation cycle and provides other background on key aspects of the cost model.

3.1 Life Cycle Cost Comparison Model

To simplify the 30-year cost comparison model, all of the technologies were assumed to be capable of generating equal annual revenues for the same 20 MW capacity of regulation resource. With the annual revenue for each technology thus fixed, the technology with the lowest combined present value for capital and operating costs can be considered the preferred technology. As explained below, this cost-centric approach to modeling probably underestimates the comparative advantage of the lowest cost technology.

In practice, low cost regulation resources are accepted into the ISO bid stack more often, thus maximizing their participation in the market and making it likely that annual revenues of a low cost bidder will be greater compared to bidders with higher life cycle costs who must bid higher prices. Limiting the model comparison to costs is a practical necessity because there is no reasonable way to make an accurate predictive determination of market-based revenue streams for each of the competing regulation technologies. Doing so would require an ISO system-wide model incorporating the operating characteristics for every regulation resource competing in a given market. This type of information is generally unavailable because it is considered proprietary to each of the regulation bidders.

Since revenues for higher cost regulation resources are probably lower relative to the revenues of bidders with lower life cycle cost, the conclusion that flywheel regulation technology has the lowest life cycle cost understates the comparative economic advantages of flywheel regulation.

3.2 Definition of the Hourly Regulation Cycle

The life cycle cost approach assumes the same regulation service for all technologies as defined in this paragraph. For modeling frequency regulation, the following regulation cycle is assumed: a cycle is defined as a 15 minute ramp up or charging period, a 15 minute ramp down or discharging period, and 30 minutes of maintaining steady state or normal operation. For a complete day, 24 cycles are examined. Partial charges and discharge cycles are not considered here. During the charge up as well as during the discharge phase, 20MW power is assumed. This defined cycle allows the creation of a relatively simple cost evaluation model that contains both full power range and high cyclic content. In practice, for real-life regulation a more volatile power profile will be evident, but the simplified cycle assumed in this report captures operating costs with reasonable accuracy while being easier to work with.

3.3 Technologies

KEMA evaluated the Life Cycle Cost for the technologies listed below providing frequency regulation at three locations: CAISO service area, PJM service area and the ISO New England (ISONE) service area. The technologies evaluated within these ISO regions were:

a) Beacon flywheel (nominal power at 20MW plant)

b) Conventional coal-fired fossil generating plants (base load and peaker units)

c) Conventional gas-fired fossil generating plants (base load and peaker units)

d) Lead acid battery storage

3.4 Approach

The Beacon flywheel was evaluated against the other generation technologies for the provision of frequency regulation. The following boundary assumptions were made:

a) Both the service profile and amount of regulation provided were considered identical for all the technologies

b) Cost factors for the different technologies were identified from literature where available. In certain cases KEMA made assumptions on the cost factors and benchmarked these assumptions with internal KEMA experts, external experts, and input from Beacon.

c) Assumptions for the key figures for all the technologies were provided to Beacon and collectively accepted before the analysis commenced.

d) The results of the Phase I - KEMA CO_2 emission analysis (see Reference 1) are incorporated in this Life Cycle Cost analysis as a cost for emitting carbon dioxide

e) As part of the assignment, a dedicated Life Cycle Cost evaluation tool was developed by KEMA. This proprietary tool is for internal Beacon Power use only.

f) The dedicated Life Cycle Cost tool is based on Net Present Value (NPV) calculations and incorporates costs that are either the direct result of providing the regulation service or additional costs incurred for providing the regulating service.

g) The results of these Life Cycle Cost calculations for providing regulation service are quantified both as a total NPV as well as in cost per hour.

4. Assumptions and Approach

This section identifies the cost components that are relevant to the regulation application. Each cost component is explained, and the numbers used in the model are given.

4.1 Cost Components

A dedicated NPV model is used to quantify the relevant costs allocated to regulation. The NPV model uses various costs that are captured on an annual basis.

The captured costs in the model include:

1. Capital Cost
2. Operational Costs
    a. Fuel (or electricity losses in case of Flywheels and Lead Acid Batteries)
    b. Maintenance
    c. Periodic reinvestment
    d. Staff
    e. Carbon Credit: Costs associated with CO_2 emissions were added in a final section to show the potential impact of carbon costs for each of the technologies assuming a CO_2 market emerges in the U.S. in the future
3. Lifetime reduction for thermal plants due to providing Regulation
4. Loss of availability for thermal plants due to providing Regulation
5. Depreciation

These costs are further discussed in the following paragraphs.

Where applicable, care has been taken to keep the assumptions between the emission analysis (Reference 1) and this cost comparison study as consistent as possible.

4.2 Capital Cost

Generally speaking, capital cost is the cost of installing a complete system. While that can be applied to the flywheel and the lead acid system, it is not a usable approach for the fossil systems since the total power plant is used only partially for regulation. Therefore, an alternative approach is taken. Only a fraction of the total power plant capital cost is allocated as regulation capital cost. The fraction is calculated by taking the ratio of the regulation power (in the case of this study, 20MW) compared to the nominal power plant rating (e.g., 400 MW for a base plant or 75 MW for a peaker plant).

Capital cost for the flywheel and lead acid systems is the total cost of the initial installment of the complete system, building, storage (flywheel or batteries) power electronics, monitoring & control, grid connection etc.

Table 1 below shows the data that is used in the Life Cycle evaluation for capital cost.

Table 1: Capital Cost for Each Technology

Technology	Capital cost [USD/kW]
Flywheel	1,630
Lead Acid	729
Gas Base	600
Gas Peaker	800
Coal Base	2,000
Coal Peaker[5]	1,000

[5] Note that currently only a few coal peakers are being constructed, so peaker capital cost was estimated.

4.3 Operational Costs

All costs occurring after the initial installment were allocated under operational costs. These are captured in the NPV cost model as annual costs and include fuel, cost due to CO_2 emissions, maintenance, reinvestments, staff, lifetime reduction and loss of availability. For the fossil plants, items under operational cost indicate that fraction of the cost that can be fairly *allocated* to the regulation service. For example, under maintenance, only the additional maintenance due to the fact that the plant is providing regulation service was included in the analysis.

4.3.1 Fuel for Fossils and Electricity Losses for Flywheels and Lead Acid Batteries

A fossil plant that is providing regulation services will have different fuel consumption compared to the same plant that is not providing regulation. The increased fuel cost is captured in this model. The increase in fuel consumption will lead to a higher cost for electricity generated by the power plant. This increased cost is allocated to regulation as fuel cost. The cause for the increased fuel consumption is two fold:

First, a plant providing regulation must reduce its output in order to both ramp up and ramp down during regulation. The reduced output will result in reduced efficiency of the plant, which increases fuel cost for the bulk power that is being generated by the plant. This means that all of the bulk power that is generated is actually generated at a higher fuel cost. Not all plants will always run at maximum optimal output, due to market schemes, portfolio use, rescheduling or other causes. Therefore increased fuel use due to running at partial load can only be allocated to regulation in a fraction of the total operating hours. Here a fraction of 50% of the total operating hours is chosen for the generators providing regulation services.

Second, a power plant that is cycling 20 MW above and below a given set point will have slightly increased fuel consumption. Measurements have shown that this increased fuel use ranges from 0.5% to 1.5%. In this study, an increase of fuel consumption of 0.7% is assumed for all fossil plants. This is considered conservative. Note that when this 0.7% factor is applied against the entire plant, the additional fuel consumption attributable to performance of the regulation function becomes a significant cost factor.

Assumed base and increased fuel costs for the fossils is as shown in Table 2 on the following page. The table shows increased fuel consumption as a percentage that includes both of the effects discussed above.

Table 2: Fuel Cost Allocated to Regulation for Fossil Power Plants

Type of Power Plant	Fuel Cost		
	Base Cost [USD/kWh]	Increased Fuel consumption allocated to regulation [%]	Additional Fuel Cost allocated to regulation [USD/MWh]
Coal Base	0.0196	2.7	0.5292
Coal Peaker	0.0300	2.7	0.8100
Gas Base	0.0480	3.7	1.7760
Gas Peaker	0.0732	3.2	2.3424

These values are based on average power plants in the existing USA generation portfolio, and assuming a 5-6 USD/MMBTU energy price. As Flywheels and Lead Acid batteries also consume energy from main stations, the electricity cost for flywheels and Lead Acid Systems is assumed to be .05 USD/kWh.

4.3.2 Carbon Credit: Cost Associated with CO_2 Emissions

The cost for carbon emissions is calculated by multiplying tons of CO_2 emitted for each type of plant (from the emission study) by an assumed cost per ton for carbons emission. The cost per ton for carbon emissions is not set in the United States since there is currently no CO_2 market mechanism. However, it appears likely that a CO_2 market will emerge in the U.S. or else the U.S. will join the international market before too long. In Europe, a CO_2 market is in place. The CO_2 cost in the model of 17 USD/ton of CO_2 is the 2008 forward market value/cost on the EU emission markets for emitting an additional ton of CO_2.

Carbon Cost is only allocated to the fossil plants, since only these generate direct emissions. The flywheel and lead acid systems have zero direct CO_2 emissions because they do not consume fuel. Hence, for the purposes of this model they have no direct CO_2 related costs.

As a CO_2 market in the U.S. does not currently exist, calculations of total cost excluded $CO_{2.}$ However, in section 5.2 “Output of Cost Model”, an additional section was added to show the impacts that such a market might have on the cost calculations for each of the technologies.

4.3.3 Maintenance

A line item in the model for annual maintenance cost is identified for each technology. This represents the additional maintenance above and beyond regular maintenance due to the fact that a plant is providing regulation. Since the lead-acid and flywheel systems are installed specifically for regulation, all maintenance is allocated to regulation. Cost data used was obtained from the following sources:

- **Flywheel system**: annual maintenance cost provided by Beacon Power.

- **Lead acid system**: allocated annual maintenance is 2% of the initial installation or capital cost. This number is an estimate based on lead-acid systems described in the EPRI/DOE Handbook (see Reference 2) and has been validated by Sandia National Labs' experts (Reference 3)

- **Fossil systems**: 0.5% additional maintenance is used. This number is based on limited empirical data available on this topic (Reference 5). The data does not allow differentiating between the different fossil plants. Therefore, 0.5% is used for the base and peaker plants, gas as well as coal.

4.3.4 Periodic Reinvestment

This item includes all costs for equipment made after the initial installation and includes items such as new battery cells, new bearings, etc. This item is most relevant for the flywheel and lead acid systems, as similar costs have already been captured under maintenance for the fossil technologies. For the flywheel system, the model incorporates data provided by Beacon Power.

For the lead acid system, the lifetime of the battery cells is evaluated based on amp-hour counting. This results in a 1.14 yr lifetime, meaning a replacement of the full battery pack every 7th year. The cost of this battery pack replacement is allocated under periodic investments.

For the fossil-based generating plants, no periodic reinvestments were allocated to regulation.

4.3.5 Staff

This cost item includes the staff responsible for operations of the systems allocated to regulation. Again, this means for fossil generators only the additional staff due to the regulation service, and is estimated to be 1 FTE (full-time-equivalent) for all fossil systems.

For flywheel systems, the staff requirement as provided by Beacon power is 1.25 FTE.

Based on larger battery systems, such as the utility installation for PREPA, Metlakatla and GVEA, a total of 3 FTE is assumed for the lead acid system (see Reference 3).

4.4 Lifetime Reduction for Thermal Plants Due to Regulation

Thermal plants are subject to unplanned outages or trips. Each trip will cause the plant to go off-line, which results in increased maintenance, inspection and repair. Each trip will also result in a reduction of remaining lifetime due to increased stresses and loading of the components in the plants, such as the boiler or the turbine blades.

Typically, a trip results into 10-20 hours of lifetime reduction. Empirical data has shown that the amount of unplanned trips is directly related to how often and how fast the output of a plant changes (Reference 7). Regulation causes the output and rate of change (in output) to change a great deal. Trips caused by the performance of regulation by thermal plants also contribute to decreased system availability and loss of regulation revenue for thermal plants

The referenced empirical data shows that the amount of unplanned trips a generator experiences annually increases to approximately 15 trips due to regulation services. See

Figure 3 on the following page.

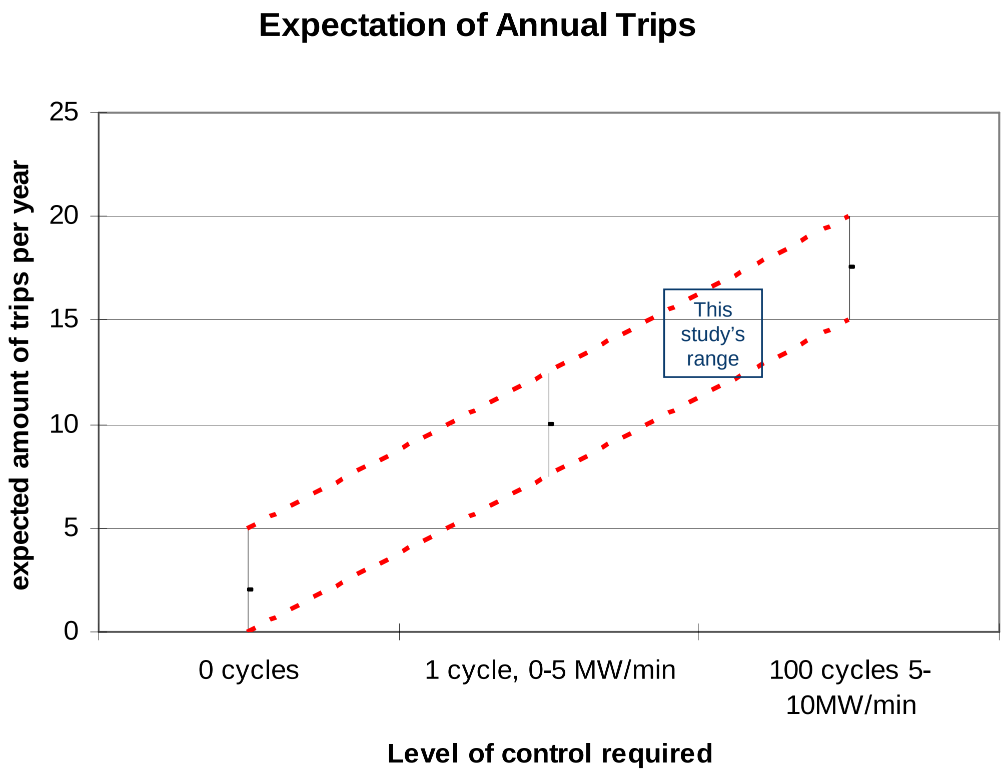

Figure 3: **Increase in annual unplanned trips based on level of control required by power plant**

The resulting lifetime reduction is in the range of 150-300 hours annually, or 4,500-9,000 hours in a 30 year evaluation frame, equaling up to 1 year reduction in life due to the fact that the plant is performing regulation services. The model assumes a 1 year reduction in lifetime. In the NPV model a reinvestment is made in the 30th year, equal to 1/30 of the original capital investment. (References 4, 5 and 7.)

4.5 Loss of Availability of Thermal Plants Due to Regulation

During scheduled maintenance a power plant is not available for power generation or regulation services until the unit is brought back on-line. Depending on the issues at hand, this downtime can be hours, days or even weeks if repairs are required. This translates into a reduced availability and has an associated cost.

Limited empirical data shows that a plant providing regulation will have a reduced annual availability of 500 hours (from about 8,500 hours operation annually down to about 8,000 hours). This equates to a reduction of availability of 6%. See

Figure 4.

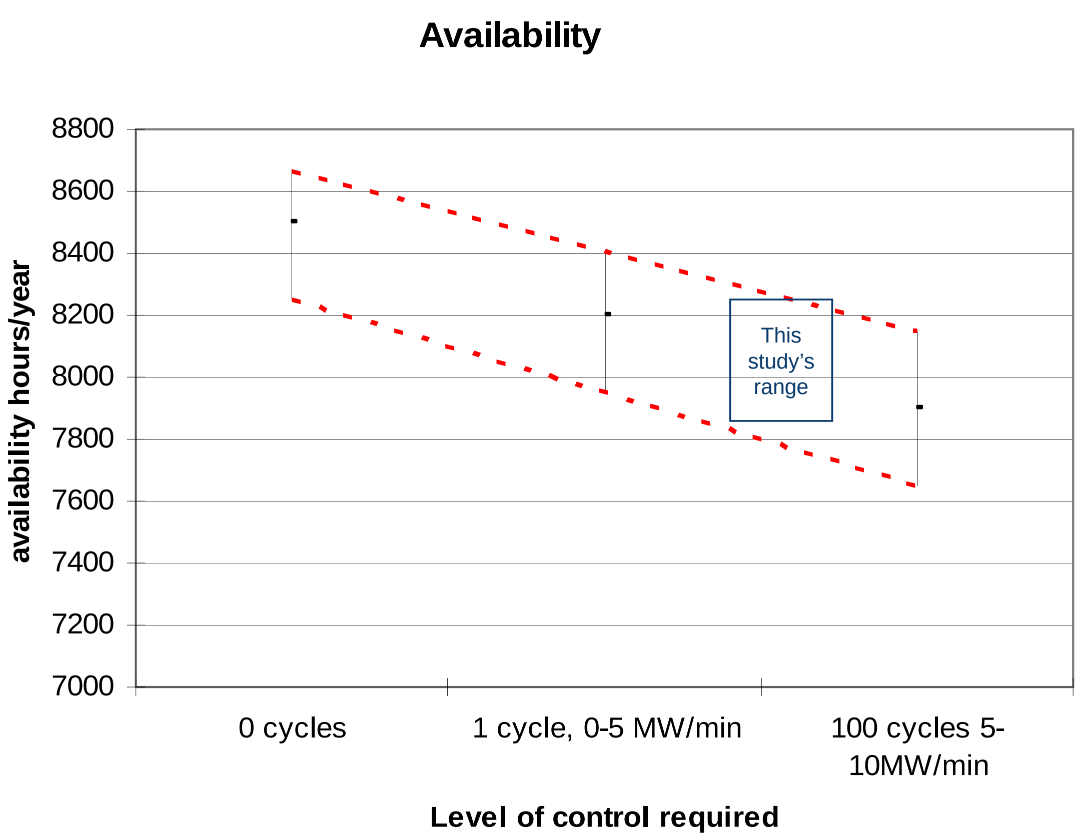
Availability
8800
8600
8400
8200
8000
7800
7600
7400
7200
7000
availability hours/year
This study's range
0 cycles
1 cycle, 0-5 MW/min
100 cycles 5-10MW/min
Level of control required

Figure 4: Loss of availability due to the level of control on a power plant

Note that this estimated additional costs associated with the loss of availability of the plants due to regulation are currently not reflected in the model. For the purpose of this study it is assumed that the loss of regulation service due to tripping or other maintenance issues associated with thermal plants will be filled in by other plants because there are enough other plants in the ISO's control area to make up any shortfall. In the cost model for this study no costs due to tripping are levied against the thermal plants. In practice, tripping will reduce revenue from regulation, but such reduction is not reflected in this study since all the technologies are assumed to develop the identical revenue per year for identical nameplate capacity. The error this introduces is not considered significant enough to warrant a different modeling approach. (References 4, 5 and 7.)

4.6 Depreciation

While federal and state depreciation has an influence on the financial modeling of capital intensive investments with long lifetimes, including the technologies compared in this study, this KEMA LCC model results do not incorporate the effects of depreciation tax shield. This was due to the uncertainty of selecting the correct depreciation schedule for each of the assets and the impossibility of selecting a set of typical tax circumstances for assumed owners of the technologies. For example, an asset owner with limited corporate earnings might pay little or no taxes, whereas a highly profitable corporation could be subject to high taxation on net plant revenues. Owners who pay high taxes would benefit comparatively more from the income tax shield – which would artificially skew the comparison between technologies. In short, since financial performance can be heavily driven by tax treatment, KEMA's life cycle cost model excluded such tax effects in order to develop an accurate comparative cost-based life cycle financial analysis.

In practice, the depreciation tax schedules for the technologies being compared probably vary considerably since they reflect Federal policy which has as one of its objectives the encouragement of advanced new technologies. For example, the tax schedule for a standard fossil-based thermal power plant might be 20 or 30 year straight line depreciation, whereas for advanced energy storage technologies like flywheels and batteries – accelerated 5 or 7-year Modified Accelerated Cost Recovery System (MACRS) depreciation might well apply. If the tax shield effects of those shorter depreciation schedules can be captured they can effectively reduce the capital cost by 15 percent or more, so differences in tax treatment are worth noting.

4.7 Learning Curve and Cost Changes

Over the years, some of the cost components will change. Today, we do not have the knowledge of future costs for items such as fuel, maintenance, capital cost, etc. For "what if" analysis, the Developed Dedicated Life Cycle Cost model includes, for relevant cost components, a line item for "annual cost increase," which is set to zero. The argument for this assumption is that it avoids skewing results in favor of the most extravagant claims about expected future cost breakthroughs for given technologies. The counterargument is equally valid. Not projecting cost breakthroughs, especially for the newest technologies, artificially inflates future costs. For example, the amount of energy stored in one of Beacon's 4th generation flywheels is about four times greater than one of its 3rd generation flywheels, but it does not cost four times as much. Advances in battery technology are also occurring at a rapid rate. Nevertheless, since the thrust of this cost comparison study is aimed at providing a fair cost comparison of these technologies as they stand today, no annual cost decrease due to performance improvements is assumed. The effect of cost reduction due to volume production was, however, included in the model. The cost calculation of the flywheel was based on volume-driven cost reductions achieved by the 10th plant.

5. Life Cycle Cost Evaluation

5.1 Description of Cost Tool

To support the evaluation, a detailed model was developed to compare the life cycle cost of providing the same regulation service. Technologies compared included a flywheel system, a lead-acid system, and fossil generators using either gas or coal (both base load and peaker plants). A spreadsheet tool has been developed with variable inputs for key assumptions, as discussed above. These inputs are used to calculate and compare cost for each of the technologies for each of three ISO regions.

This model assumes a 30 year life and costs for the 10^{th} plant. The primary cost driver for the flywheel technology is the cost of the flywheel itself. The cost of the 10^{th} plant is projected as $1,630 USD / MW. of capacity, which includes all ancillary systems.

An example of the input section of the model is shown in Table 3 on the following page. These parameters can be changed in the general section of the inputs or in the technology specific sections for each technology. Assumptions are on a single page, allowing quick and consistent modeling of the technologies and cost components. The model may also be used to perform further "what-if" analysis. The losses for the complete flywheel system are included.

			unit	
general	evaluation timeframe	30	year	
	initial year for NPV calculations	2,007		
	nr of cycles in 1 year	8,760		
	nr of cycles in 30 year	262,800	cycles	
	FTE cost	80,000	USD/a	
	electricity cost - station power	0.05	USD/kWh	
	electricity cost - transaction power	0.07	USD/kWh	
	annual price increase for station power electricity cost	0.0%	/yr	
	annual price increase for transaction power electricity cost	0.0%	/yr	
	nominal power of Regulation unit	20	MW	
	corporate tax	35%		
	Cost of Debt	7.5%		
	Cost of Debt (incl Tax Shield)	4.9%		
	Cost of Equity	7.5%		
	Equity	40%		
	Debt	60%		
	Discount Rate for Cash Flow	7.50%		
	Regulation revenu per service hour	52.50	USD/MW service hour	
	revenue for Regulation	9.2	MUSD/a	
	CO2 emissions	17	USD/ton	
	annual price increase for CO2 emissions	0.0%	/yr	
	X-factor: multiplier for fast Flywheels	2	X	
	X-factor: multiplier for fast Lead acid	2	X	
	region selection for emmissions	numeric average		
	nominal rating for base case fosil plants	400	MW	
	nominal rating for peaker fosil plants	75	MW	

Flywheel				unit		
	operating hours per day		24			
Investments	Flywheel (complete) system					
	10th plant		1630	USD/kW		
	value to use in cost model	10th plant	1630	USD/kW		
operational costs	maintenance					
	general annual maintenance		11,600	USD/MW		
	annual price increase for maintenance		0.0%	/yr		
	annual price increase for replacements		0.0%	/yr		
	losses					
	Total Losses		12,421,680	kWh /year		1
	required staff for operation		1.25	FTE/yr		
CO2 emissions	PJM		7,462	ton/a		
	CAISO		4,554	ton/a		
	ISO NE		5,335	ton/a		
	numeric average		5,784	ton/a		
	no emission		0			
	value to use in cost model		numeric average		5,784 ton/a	
other	depreciation scheme for plant		MACRS 20 Years			

Table 3: Example of Model Input Page

5.2 Output of Cost Comparison Tool

The model is set up in a modular and flexible way. This allows the output to be presented in different ways. This paragraph will show the results in several graphs. Each will be explained and summarized.

5.2.1 Total Life Cycle Cost of the Technologies

Figure 5 shows the total Life Cycle Cost (LCC) for the PJM area over the complete lifetime of a 20 MW regulating plant in Million 2007 US dollars. While the graph seems to indicate that both peaker plants are able to provide regulation for less money, peaker plants are assumed to be operational only 8 hours per day, not 24. This means that the peakers deliver one-third of the service per 24-hour period compared to the non-peaker thermal plants or the storage technologies. Thus they cannot be directly compared to the other technologies without a cost adjustment shown on the following page.

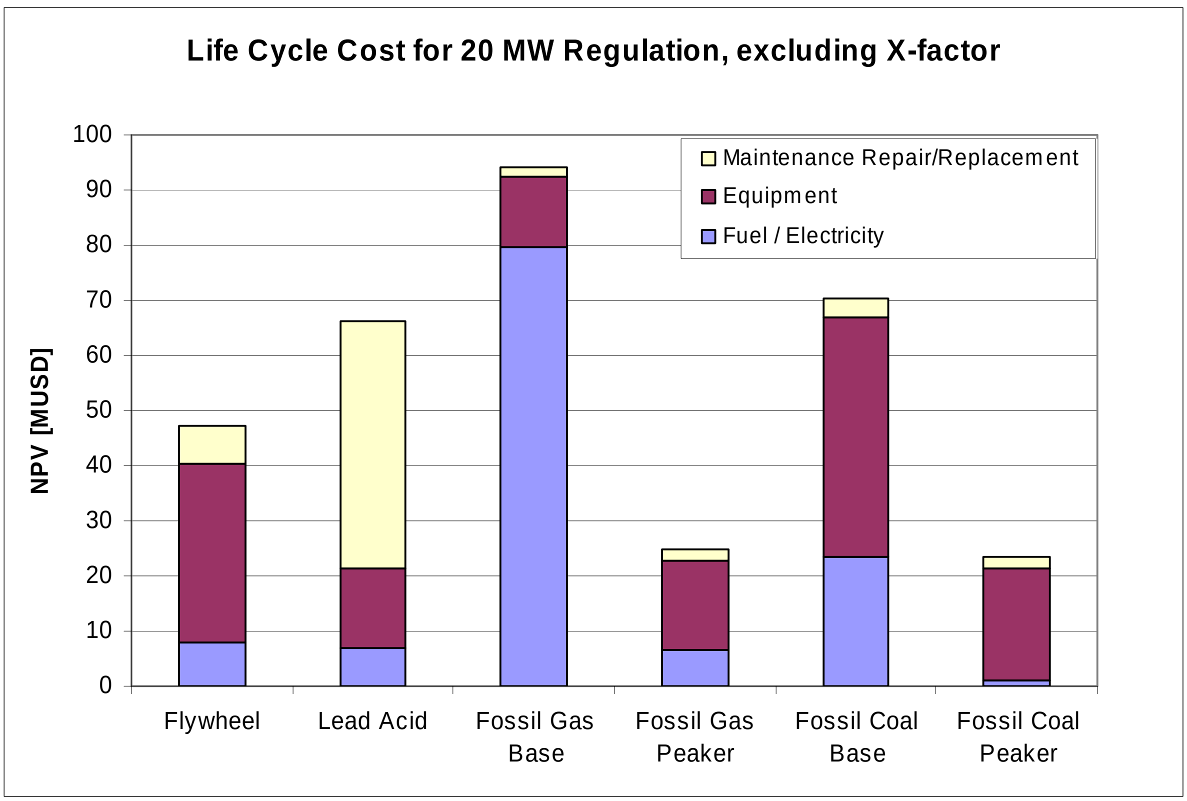

Figure 5: Life Cycle Cost for Regulation does not reflect the total cost picture as peaker plants are operational only 8 hour per day

From this figure the life cycle cost (LCC) for a base loaded gas-fired plant ("Fossil Gas Base" in Figure 5) doing the same amount of regulation as a 20 MW flywheel plant was estimated to be $47 million more than a flywheel plant. For a base loaded coal-fired plant the additional LCC compared to a flywheel plant was estimated as $23 million. Similarly, the LCC increment for a lead acid battery-based system was estimated to be $19 million greater compared to a flywheel plant. These values are calculated in the KEMA developed LCC tool and can be visually verified in Figure 5.

5.2.2 Hourly Life Cycle Cost Comparison

As mentioned in the previous paragraph, the cost comparison needs to compensate for the effect that peaker plants actually only operate on an 8 hour per day basis while the other technologies are operational 24/7. The compensation is achieved by standardizing the LCC to "cost per hour" for providing Regulation. This provides a fair and equitable comparison as shown below in Figure 6 below. The LCC per hour to provide 20 MW of regulation is presented in 2007 US dollars.

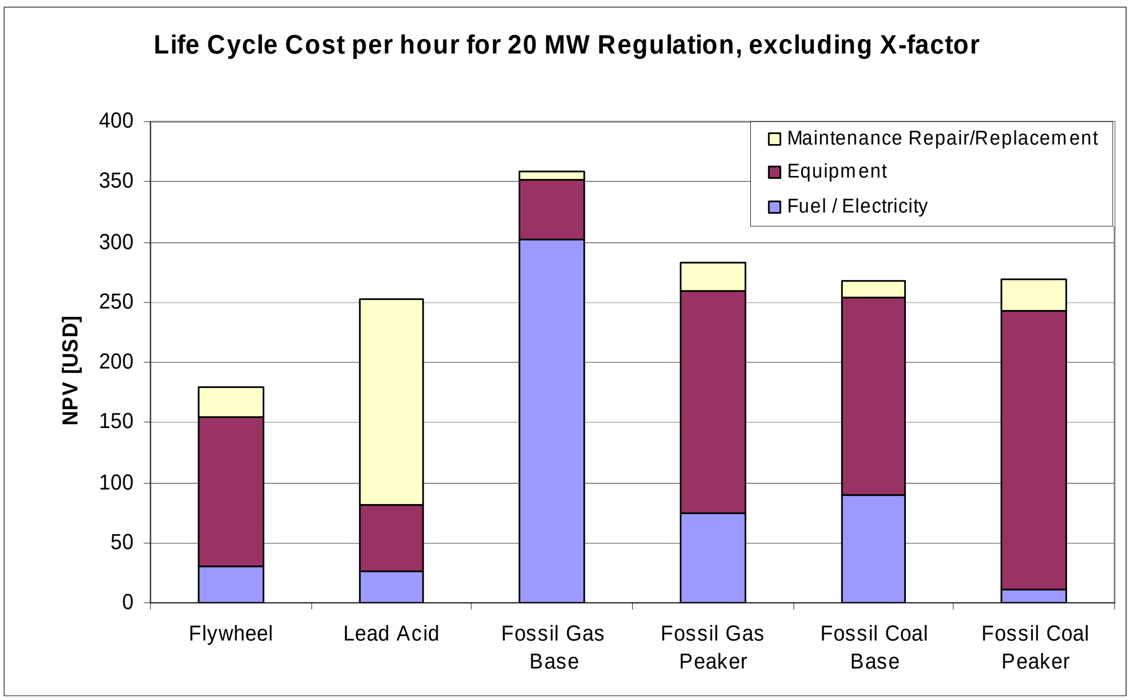

Figure 6: Hourly LCC allows for a sound comparison between technologies

Figure 6 clearly shows that the Beacon Flywheel systems have the lowest hourly life cycle cost for regulation, reflecting both initial capital costs and operational costs. The graph also shows that cost for regulation service for the peaker plants is significantly less compared to the base plants. The main reason for this is the lower fuel cost for the peaker plants. Since a base plant has a higher rating, the increased fuel consumption for the entire 380MW plant (400-20) is allocated to regulation, while for the peaker this cost component is only calculated over 55MW (75-20).

Comparisons between the flywheel plant and gas and coal-fired peaker plants have been based on an equivalent cost basis. This equivalent cost is based on the NPV cost per regulation cycle, multiplied by the total amount of regulation cycles in the reviewed timeframe of 30 years. The amount of regulation cycles is the same for all technologies. A gas-fired peaker plant would therefore require an additional $27 million in LCC, representing more than 57 percent greater effective life cycle cost. For a coal-fired peaker plant the comparative values were around $23 million and almost 50 percent higher, respectively. This 30 year LCC result is calculated for providing 24/7 regulation services.

5.2.3 Region Independent Results for Evaluated Regions

Regions will differ in technology life cycle costs only if CO_2 markets exist. This is because regions have different generation mixes and hence, different emission profiles. In the absence of CO_2 markets, little differences in projected costs exist across regions. This is shown in Figure 7 below:

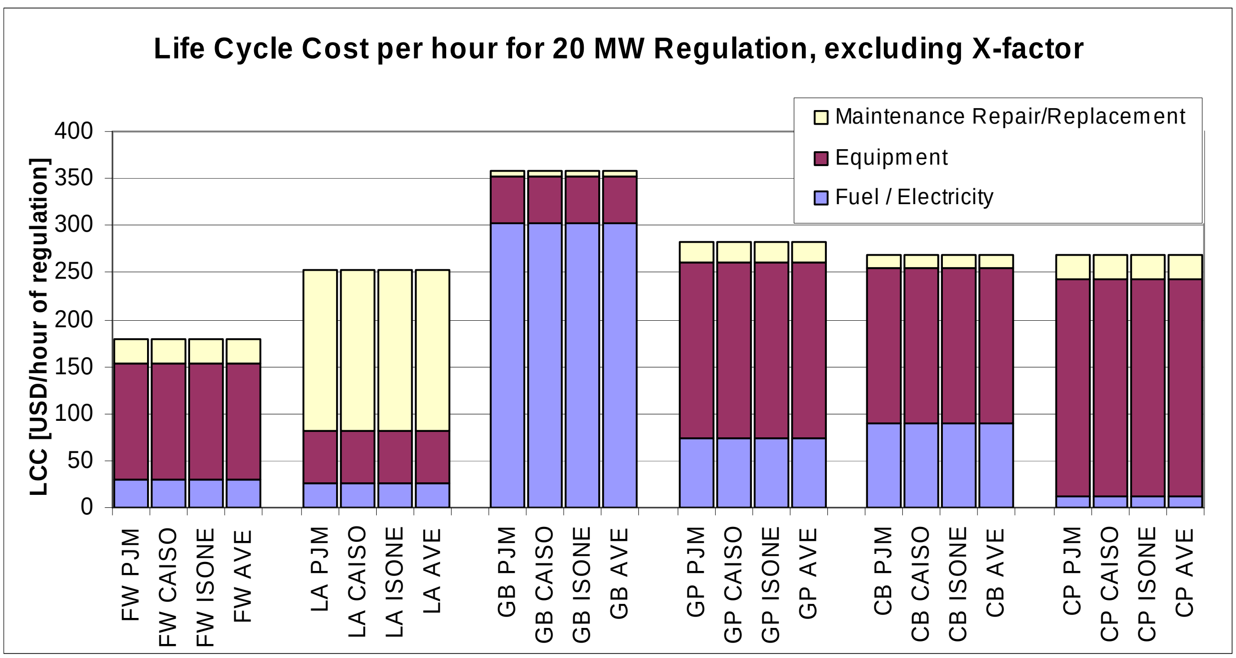

Figure 7: Comparison of the hourly LCC over the PJM, CAISO and ISONE regions shows little deviation in cost

Figure 7 [6] shows that hourly LCC cost is identical for all three regions. Therefore, we conclude that hourly LCC costs are comparable for the three regions and can be fairly represented either by a numerical average of the three or by any one of the three.

5.2.4 Effect of X-factor on Hourly LCC

While the efficacy of the X-factor is supported by several ISO studies, the X-factor has not yet been empirically confirmed with a full-scale plant for either the flywheel or battery technologies. Nevertheless, for illustrative purposes, Figure 8 shows that should the flywheel and/or battery technologies obtain higher regulation revenues from ISOs in consideration of potential X-factor regulation advantages (primarily the need for less total regulation resources due to fast response), costs for those technologies could effectively decrease by a factor of 50 percent (assuming X = 2).

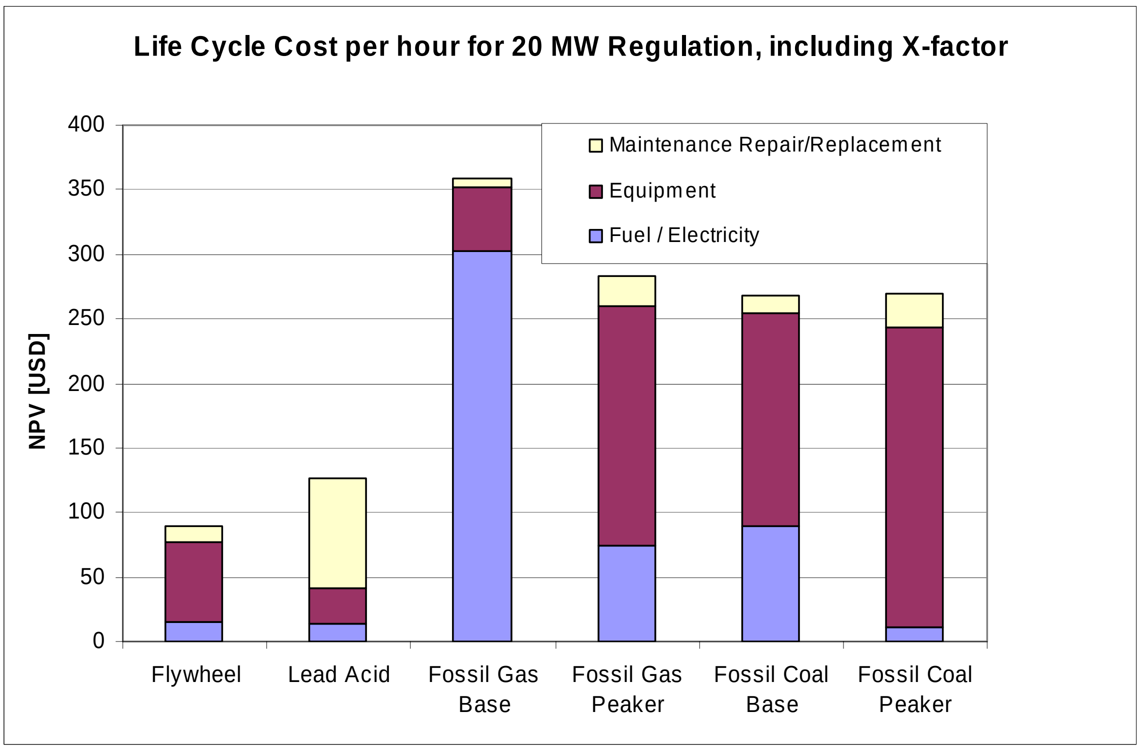

Figure 8: Illustrative results for an X-factor

[6] FW = Beacon's Flywheel; LA = Lead Acid system; GB = Gas Base-load Fossil plant; GP = Gas Peaker plant; CB = Coal Base-load fossil plant; CP = Coal peaker plant; AVE = numerical average of PJM, CAISO and ISONE area.

5.2.5 Total Life Cycle Cost of the Technologies with CO_2 Included

Though a CO_2 market does not exist in the U.S., it is likely that one may soon exist. Hence, for each of the cost calculations shown in the previous section, the model was also run with the assumption that a market existed. In this scenario, the value of CO_2 was set to $17 USD/ton. The results of the analysis are shown for each of the cases examined in the previous sections of the "Model Output."

1. Total Life Cycle Cost of the Technologies

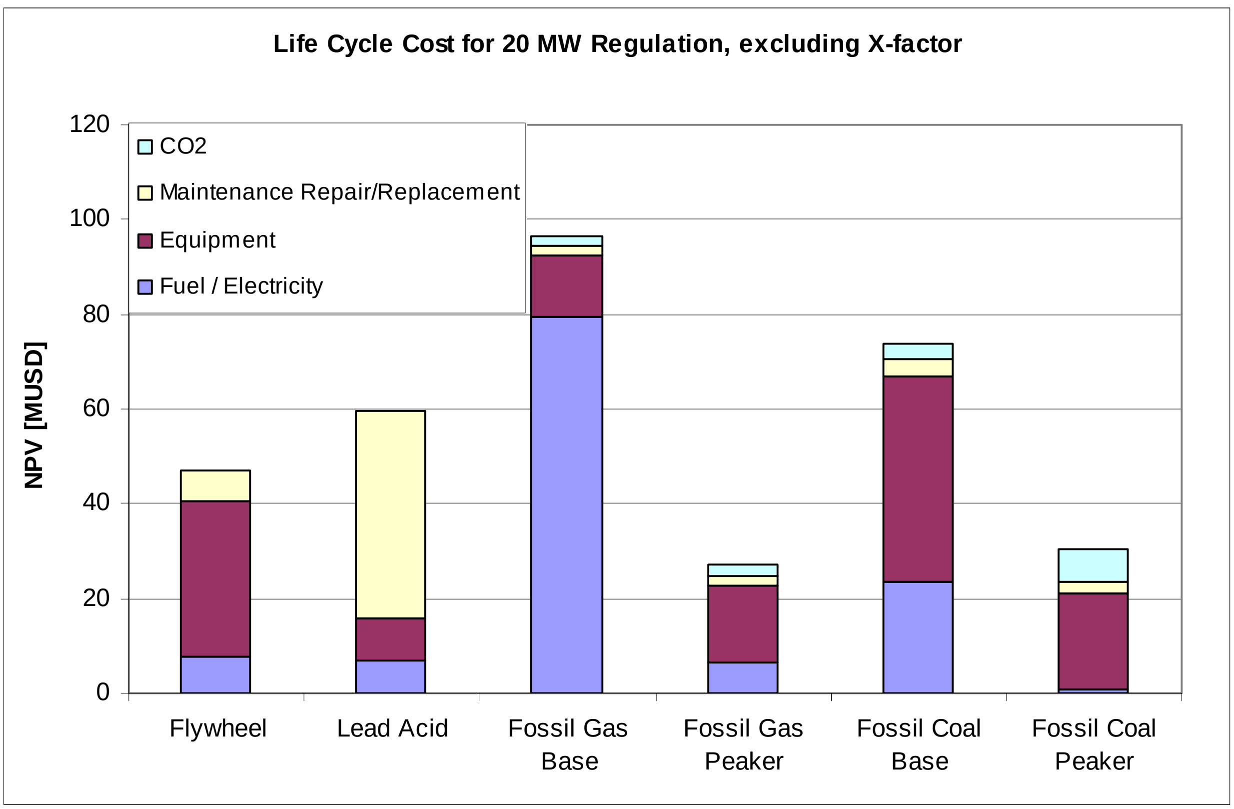

Figure 9: Life Cycle Cost for Regulation does not reflect the total cost picture as peaker plants are operational only 8 hour per day

From this figure the life cycle cost (LCC) for a base loaded gas-fired plant ("Fossil Gas Base" in Figure 9) doing the same amount of regulation as a 20 MW flywheel plant was estimated to be $49 million more than a flywheel plant. For a base loaded coal-fired plant the additional LCC compared to a flywheel plant was estimated as $27 million. Similarly, the LCC increment for a lead acid battery-based system was estimated to be $19 million greater compared to a flywheel plant. These values are calculated in the KEMA developed LCC tool and can be visually verified in Figure 9.

2. Hourly Life Cycle Cost Comparison

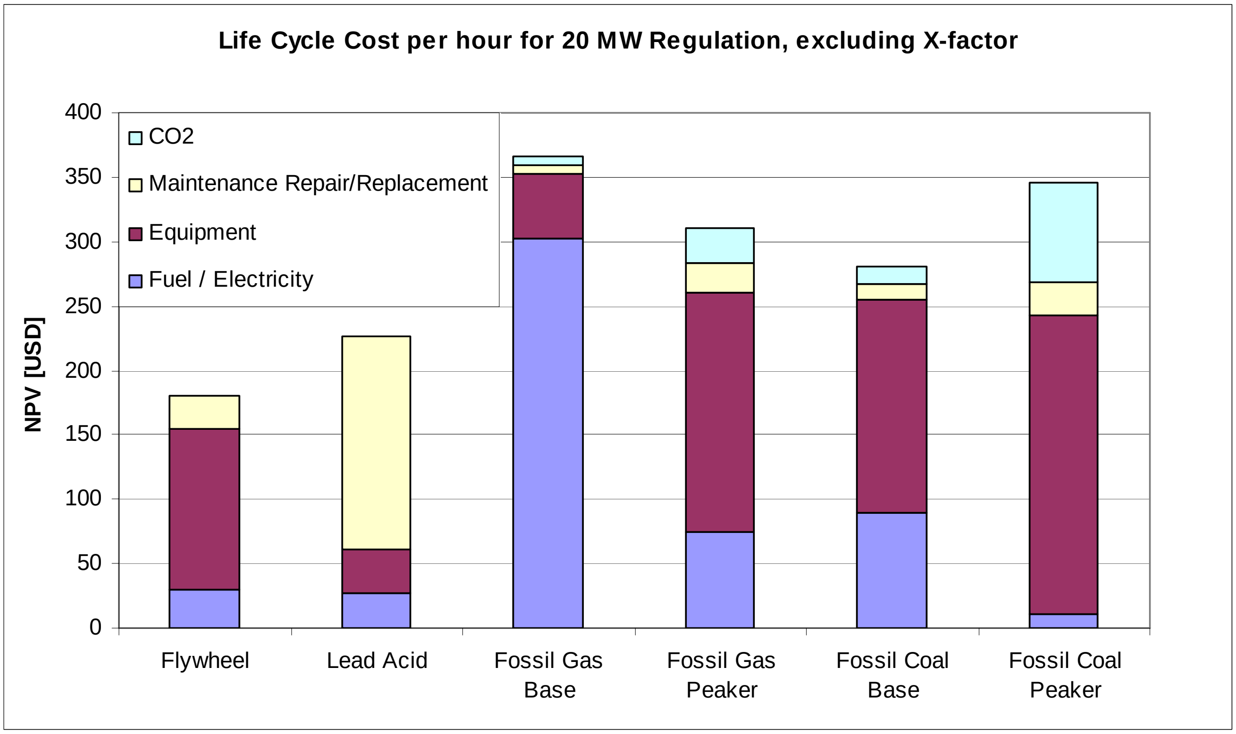

Figure 10: Hourly LCC allows for a sound comparison between technologies

With an active CO_2 market, a gas-fired peaker plant would require an additional $34 million in LCC, representing more than 73 percent greater effective life cycle cost. For a coal-fired peaker plant the comparative values were around $44 million and almost 92 percent higher, respectively. This 30 year LCC result is calculated based on the provision of 24/7 regulation services.

3. Region Independent Results for Evaluated Regions

When comparing the different ISO regions, the CO_2 cost component would have an impact because of the different generation mixes in each region and is represented in the graph shown below in Figure 11.

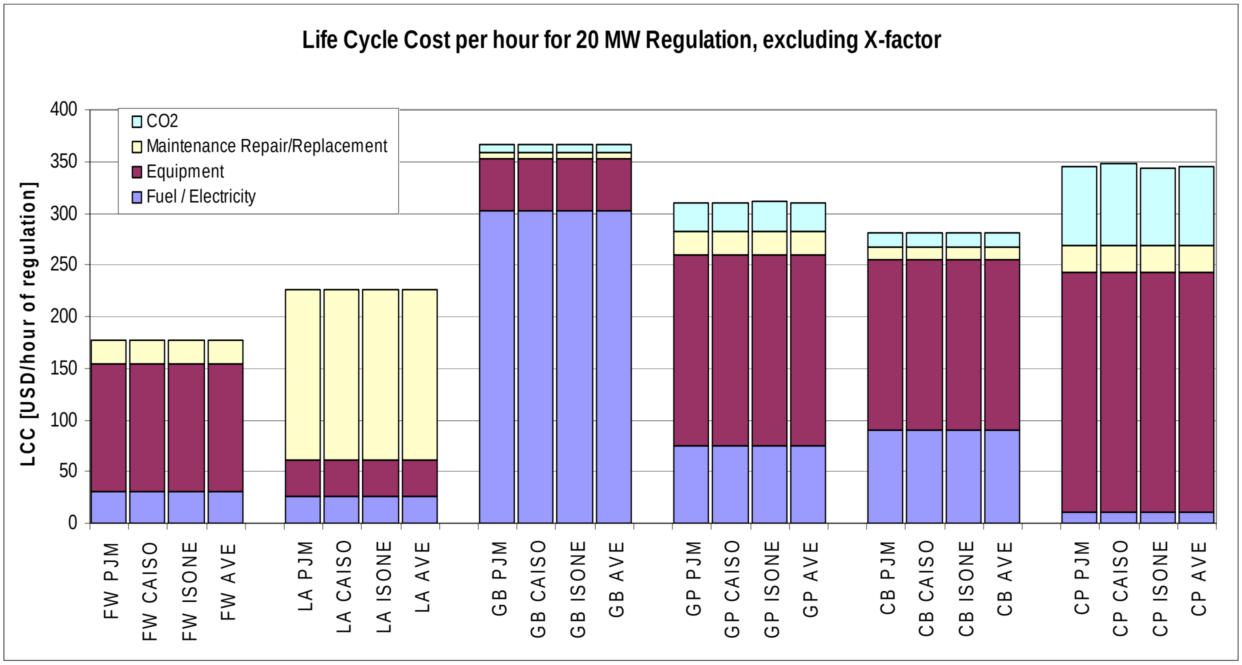

Figure 11: Comparison of the hourly LCC over the PJM, CAISO and ISONE regions shows little deviation in cost

4. Effect of X-factor on Hourly LCC

While the efficacy of the X-factor is supported by several ISO studies, the X-factor has not yet been empirically confirmed with a full-scale plant for either the flywheel or battery technologies. Nevertheless, for illustrative purposes, Figure 12 shows that should the flywheel and/or battery technologies obtain higher regulation revenues from ISOs in consideration of potential X-factor regulation advantages (primarily the need for less total regulation resources due to fast response), costs for those technologies could effectively decrease by a factor of 50 percent (assuming X = 2).

In Figure 12 on the next page, CO_2 costs are included in the totals.

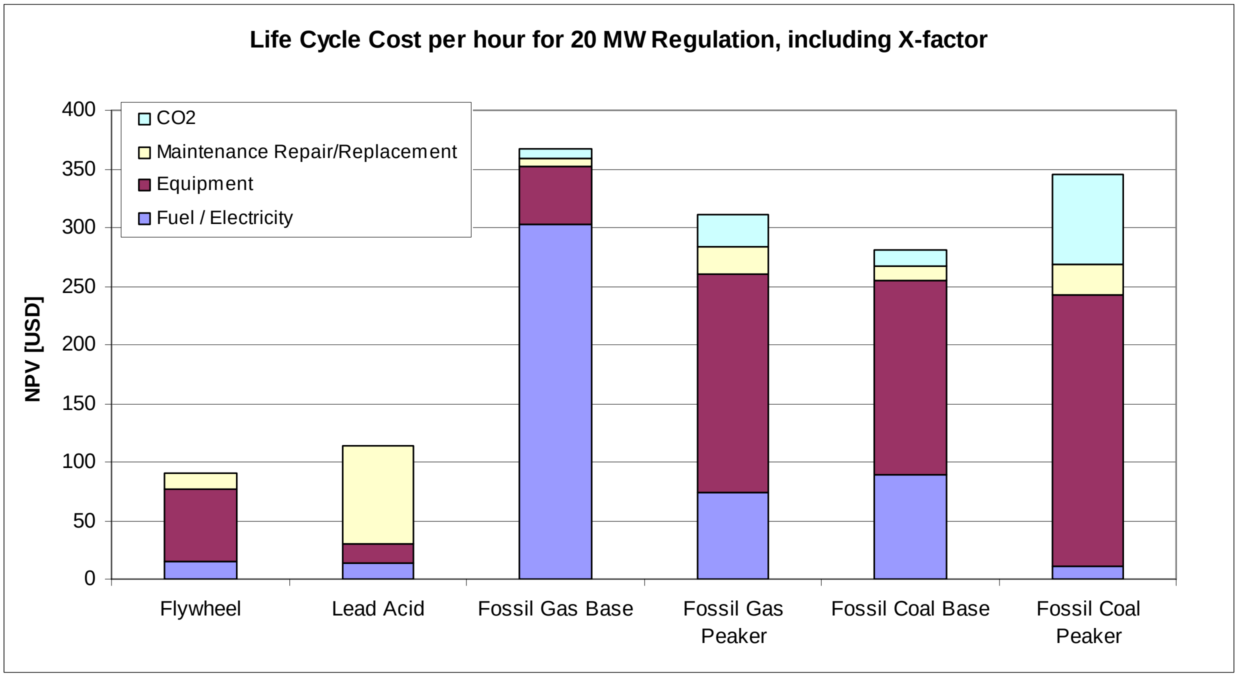

Figure 12: Illustrative results for an X-factor

6. Conclusions

In this report, KEMA compared the life cycle cost (LCC) for different regulation technologies. A model was developed to compare the cost of regulation service for a Beacon Power flywheel-based plant versus four types of commercially available power generation technologies and a lead acid storage system.

The model calculated the hourly LCC for regulation for all evaluated technologies. The results show that flywheel-based frequency regulation can be expected to show significantly lower life cycle costs for all of the competing regulation technologies in all of the ISO regions studied.

The generation technologies evaluated included typical base loaded and peaker coal-fired and natural gas combustion turbine plants. For the flywheel and the lead acid battery systems, 100 percent of costs are direct costs, since these systems provide only regulation service. For the fossil plants, relevant cost components required for the performance of regulation were identified and allocated to the regulation function. Model calculations assumed typical heat rate and efficiency data for each type of generation.

While the additional benefits of fast response is supported by several ISO studies, the X-factor performance multiplier has not yet been empirically confirmed with a full-scale plant for any fast responsive technology. Therefore the LCC comparisons summarized below do not incorporate any potential future cost reduction benefit due to the 2X factor.

Most regions show similar LCC comparisons due to the fact that only the cost associated with CO_2 emissions are differentiating the different regions, all other costs are assumed to be similar. Within the PJM Interconnection for example, the LCC for a base loaded gas-fired plant doing the same amount of regulation as a flywheel plant was estimated to be $47 million more than a flywheel plant, or just over 100 percent greater. For a base loaded coal-fired plant the additional LCC versus a flywheel plant was $23 million, or more than 49 percent greater. Similarly, the LCC increment for a lead acid battery-based system was estimated to be over $19 million, more than 41 percent greater compared to a flywheel plant.

Comparisons between the flywheel plant and gas and coal-fired peaker plants have been based on an equivalent cost basis. This equivalent cost is based on the NPV cost per regulation cycle, multiplied by the total amount of regulation cycles in the reviewed timeframe of 30 years. The amount of regulation cycles is the same for all technologies.

A gas-fired peaker plant would therefore require an additional $27 million in LCC, representing more than 57 percent greater effective life cycle cost. For a coal-fired peaker plant the comparative values were around $23 million and almost 49 percent higher, respectively.

If the impact of a potential future CO_2 market is included, cost differences increase even more favorably for the flywheel power plant.

In summary, the flywheel regulation plant has a significantly lower LCC compared to all of the competing technologies studied for all of the ISO regions considered, both with or without consideration of any possible future cost impacts due to the emergence of a domestic CO_2 market and related costs

7. References

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7. Expert views on generator behavior as function of fluctuating loads, including Regulation, Henk Koetzier and Valerio Serrotti, KEMA Consulting, Arnhem, Netherlands

Appendix – Assumptions and Model Inputs

			unit
general	evaluation timeframe	30	year
	initial year for NPV calculations	2,007	
	nr of cycles in 1 year	8,760	
	nr of cycles in 30 year	262,800	cycles
	FTE cost	80,000	USD/a
	electricity cost - station power	0.05	USD/kWh
	electricity cost - transaction power	0.07	USD/kWh
	annual price increase for station power electricity cost	0.0%	/yr
	annual price increase for transaction power electricity cost	0.0%	/yr
	nominal power of Regulation unit	20	MW
	corporate tax	35%	
	Cost of Debt	7.5%	
	Cost of Debt (incl Tax Shield)	4.9%	
	Cost of Equity	7.5%	
	Equity	40%	
	Debt	60%	
	Discount Rate for Cash Flow	7.50%	
	Regulation revenu per service hour	52.50	USD/MW service hour
	revenue for Regulation	9.2	MUSD/a
	CO2 emissions	17	USD/ton
	annual price increase for CO2 emissions	0.0%	/yr
	X-factor: multiplier for fast Flywheels	2	X
	X-factor: multiplier for fast Lead acid	2	X
	region selection for emmissions	numeric average	
	nominal rating for base case fosil plants	400	MW
	nominal rating for peaker fosil plants	75	MW

Flywheel				unit			
	operating hours per day		24				
Investments	Flywheel (complete) system						
	10th plant		1630	USD/kW			
	value to use in cost model	10th plant	1630	USD/kW			
operational costs	maintenance						
	general annual maintenance		11,600	USD/MW			
	annual price increase for maintenance		0.0%	/yr			
	annual price increase for replacements		0.0%	/yr			
	losses						
	Total Losses		12,421,680	kWh /year			1
	required staff for operation		1.25	FTE/yr			
CO2 emissions	PJM		7,462	ton/a			
	CAISO		4,554	ton/a			
	ISO NE		5,335	ton/a			
	numeric average		5,784	ton/a			
	no emission		0				
	value to use in cost model		numeric average		5,784	ton/a	
other	depreciation scheme for plant		MACRS 20 Years				

Figure 13: General and Flywheel Assumptions and Model Inputs

Lead Acid				unit	
	operating hours per day		24		
Investments	Batteries		150	USD/kWh	
	shipping		0	USD/kWh	
		batteries	3.75	MUSD	
	Power electronics to grid		165	USD/kW	
	Balance of plant		100	USD/kW	
operational costs	maintenance				
	general annual maintenance		2%	of original investment	
	annual price increase for maintenance				
	annual price increase for replacements		0.0%	/yr	
	losses				
	battery losses charging		5.0%	of actual charge load	
	battery losses discharging		5.0%	of actual discharge load	
	station losses		10%	of actual load	
	interconnection losses		0%	of actual load	
	energy	battery losses charging	2190000	kWh /year	
		battery losses discharging	2190000	kWh /year	
		station losses	8760000	kWh /year	
		interconnection losses	0	kWh /year	
		total losses	13,140,000	kWh /year	
	required staff for operation		3	FTE/yr	
sizing	Cell voltage		2	V	
	Amp hour rating		100	Ah per cell	
	DC voltage		700	V	
	nr of cells in series (per string)		350.0		
	installed capacity per string		70	kWh	
	cycle depth		20%		
	energy per regulation cycle		5,000	kWh	
	required nameplate capacity		25,000	kWh	
	nr of strings		357.1		
	total nr of cells		125,000		
lifetime	nameplate cycle life time		2,000	cycles	
	nameplate Ah life		200,000	Ah	per cell
	nameplate Ah life		71,428,571	Ah	for total installed system
	Ah per regulation cycle		7,143	Ah	
	life time in regulation cycles		10,000		
	life time in years		1.14	yrs	
CO2 emissions		PJM	7,894	ton/a	
		CAISO	4,817	ton/a	
		ISO NE	5,643	ton/a	
		numeric average	6,118	ton/a	
		value to use in cost model	numeric average		6,118 ton/a
other	depreciation scheme for plant		MACRS 20 Years		
	depreciation scheme for battery		linear 1 Year		

Figure 14: Lead-acid Assumptions and Model Inputs

Fossil power plant Coal Base Load			unit	
Investments	fossil plant system cost	2000	USD/kW	
	nominal rating of fossil plant	400	MW	
	operating hours per day	24		
	Annual capacity Factor	100%		
operational costs	maintenance			
	general annual maintenance	0.5%	of original investment	
	annual price increase for maintenance and replacements	0.0%	/yr	
	increased fuel consumption due to regulation	0.7%	of all bulk power being generated	
	increased fuel consumption due to lower efficiency	2%	of all bulk power being generated	
	base fuel cost	0.0196	USD/kWh	
	annual price increase for fuel (coal)	0.0%	/yr	
	required staff for operation	1	FTE/yr	
lifetime				
	shelf life time	30	year	
	life time reduction due to regulation	1	yr/30 years	
		97%		
CO2 emissions	PJM	15,442	ton/a	
	CAISO	16,100	ton/a	
	ISO NE	16,100	ton/a	
	numeric average	15,881	ton/a	
	value to use in cost model	numeric average	15,881	ton/a
other	control band for Regulation	5%	of nominal power	
	reduction in availability	6%	of time	
	derating' due to required control band	1.00		
	depreciation scheme for plant	linear 30 Years		

Fossil power plant Coal peaker			unit	
Investments	fossil plant system cost	1000	USD/kW	
	nominal rating of fossil plant	75	MW	
	operating hours per day	8		
	Annual capacity Factor	33%		
operational costs	maintenance			
	general annual maintenance	0.5%	of original investment	
	annual price increase for maintenance and replacements	0.0%	/yr	
	increased fuel consumption due to regulation	0.7%	of all bulk power being generated	
	increased fuel consumption due to lower efficiency	2%	of all bulk power being generated	
	base fuel cost	0.013	USD/kWh	
	annual price increase for fuel (coal)	0.0%	/yr	
	required staff for operation	1	FTE/yr	
lifetime				
	shelf life time	30	year	
	life time reduction due to regulation	1	yr/30 years	
		97%		
		8	hr	
CO2 emissions	PJM	30,825	ton/a	
	CAISO	32,139	ton/a	
	ISO NE	30,418	ton/a	
	numeric average	31,128	ton/a	
	value to use in cost model	numeric average	31,128	ton/a
other	control band for Regulation	27%	of nominal power	
	reduction in availability	6%	of time	
	derating' due to required control band	1.00		
	depreciation scheme for plant	linear 30 Years		

Figure 15: Coal Fossil Assumptions and Model Inputs

Fossil power plant base load gas			unit	
Investments	fossil plant system cost	600	USD/kW	
	nominal rating of fossil plant	400	MW	
	operating hours per day	24		
	Annual capacity Factor	100%		
operational costs	maintenance			
	general annual maintenance	0.5%	of original investment	
	annual price increase for maintenance and replacements	0.0%	/yr	
	increased fuel consumption due to regulation	0.7%	of all bulk power being generated	
	increased fuel consumption due to lower efficiency	3%	of all bulk power being generated	
	base fuel cost	0.048	USD/kWh	
	annual price increase for fuel (gas)	0.0%	/yr	
	required staff for operation	1	FTE/yr	
lifetime				
	shelf life time	30	year	
	life time reduction due to regulation	1	yr/30 years	
		97%		
CO2 emissions	PJM	9,746	ton/a	
	CAISO	9,727	ton/a	
	ISO NE	9,868	ton/a	
	numeric average	9,780	ton/a	
	value to use in cost model	numeric average	9,780	ton/a
other	control band for Regulation	5%	of nominal power	
	reduction in availability	6%	of time	
	derating' due to required control band	1.00		
	depreciation scheme for plant	linear 30 Years		

Fossil power plant gas peaker			unit	
Investments	fossil plant system cost	800	USD/kW	
	nominal rating of fossil plant	75	MW	
	operating hours per day	8		
	Annual capacity Factor	33%		
operational costs	maintenance			
	general annual maintenance	0.5%	of original investment	
	annual price increase for maintenance and replacements	0.0%	/yr	
	increased fuel consumption due to regulation	0.7%	of all bulk power being generated	
	increased fuel consumption due to lower efficiency	2.5%	of all bulk power being generated	
	base fuel cost	0.07319	USD/kWh	
	annual price increase for fuel (gas)	0.0%	/yr	
	required staff for operation	1	FTE/yr	
lifetime				
	shelf life time	30	year	
	life time reduction due to regulation	1	yr/30 years	
		97%		
CO2 emissions	PJM	11,222	ton/a	
	CAISO	11,200	ton/a	
	ISO NE	11,362	ton/a	
	numeric average	11,261	ton/a	
	value to use in cost model	numeric average	11,261	ton/a
other	control band for Regulation	27%	of nominal power	
	reduction in availability	6%	of time	
	derating' due to required control band	1.00		
	depreciation scheme for plant	linear 30 Years		

Figure 16: Gas Fossil Assumptions and Model Inputs

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