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

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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

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[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 increased 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 is 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 the 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	
CO2					
Flywheel	149,246	149,246	149,246	149,246	149,246
Alternate Gen.	308,845	616,509	194,918	224,439	202,497
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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
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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
	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
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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
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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.

7. References

1. EPA eGrid Database, Excel Files, Year 2004 Plant Location File, Year 2004 Plant Owner File – lists outputs for States & Regions on CO2, SO2, and NOx.
2. DOE – Energy Information Administration:
    (i) Updated State & Regional Level Greenhouse Gas Emission Factors for Electricity, March 2002
    (ii) Year 2000 State Annual Emissions & Emissions Rates for CO_2, SO_2, and NO_x
3. EPA Air Pollution & Control Division: Technology Transfer Network Clearinghouse for Inventories and emission factors. AP 42, Fifth Edition:

   (i) External Combustion Sources, Emission factors for bituminous and subbitumous coal combustion
   (ii) Natural Gas Combustions

4. "Simulating Generation Bidding Strategies in Electricity Markets with an Agent-Based Model", Argonne National Laboratory, Bottorud, Thimmapuran, and Yamakado. 2005
5. Astoria Generating Plant Data, year 2005
6. California ISO Presentation "Role of Energy Storage in California ISO Grid Operations", David Hawkins, CEC / DOE Workshop on Energy Storage. February, 2005
7. KEMA – Beacon Power previous project reports and analysis.
8. Beacon Corporation supplied flywheel material.
9. European Study: "Controlling Embedded Generation, report nr 2: Economic valuation of primary and secondary control, Evaluation of options for controlling embedded generation", W.W. de Boer and R.C.F. de Kler, Arnhem, September 28th, 2000.
10. European Study: "Technical and economic aspects of operation of thermal and hydro power systems." Thesis Norwegian University of Science and Technology. February 1997.
11. http://www.epa.gov/cleanenergy/egrid/index.htm
12. http://www.eia.doe.gov/fuelelectric.html
13. http://www.eia.doe.gov/fueloverview.html