



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

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

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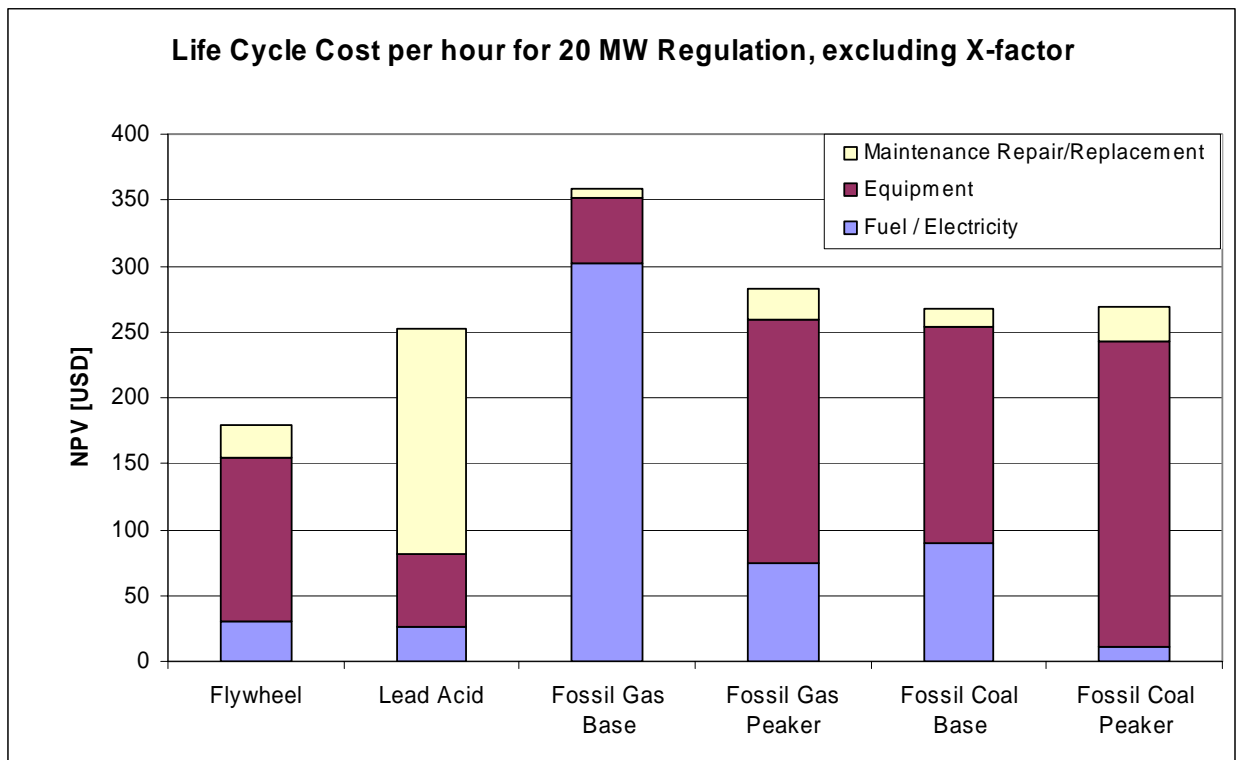
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## EXECUTIVE SUMMARY

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 Figure 1, Beacon Power’s flywheel is capable of delivering the regulation services at the lowest life cycle cost. Though a CO<sub>2</sub> market does not yet exist in the U.S., a section has been added to show the effects that a CO<sub>2</sub> market might have on the cost analysis.



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

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 Figure 1) 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. Periodical reinvestment
  - d. Staff
  - e. Carbon Credit: Cost of CO<sub>2</sub> emissions, though there is not a market for CO<sub>2</sub> in the U.S., we have included a section that shows cost impacts for the various technologies if a CO<sub>2</sub> 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

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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.

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# 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.

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## 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) system 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.<sup>1</sup>

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.

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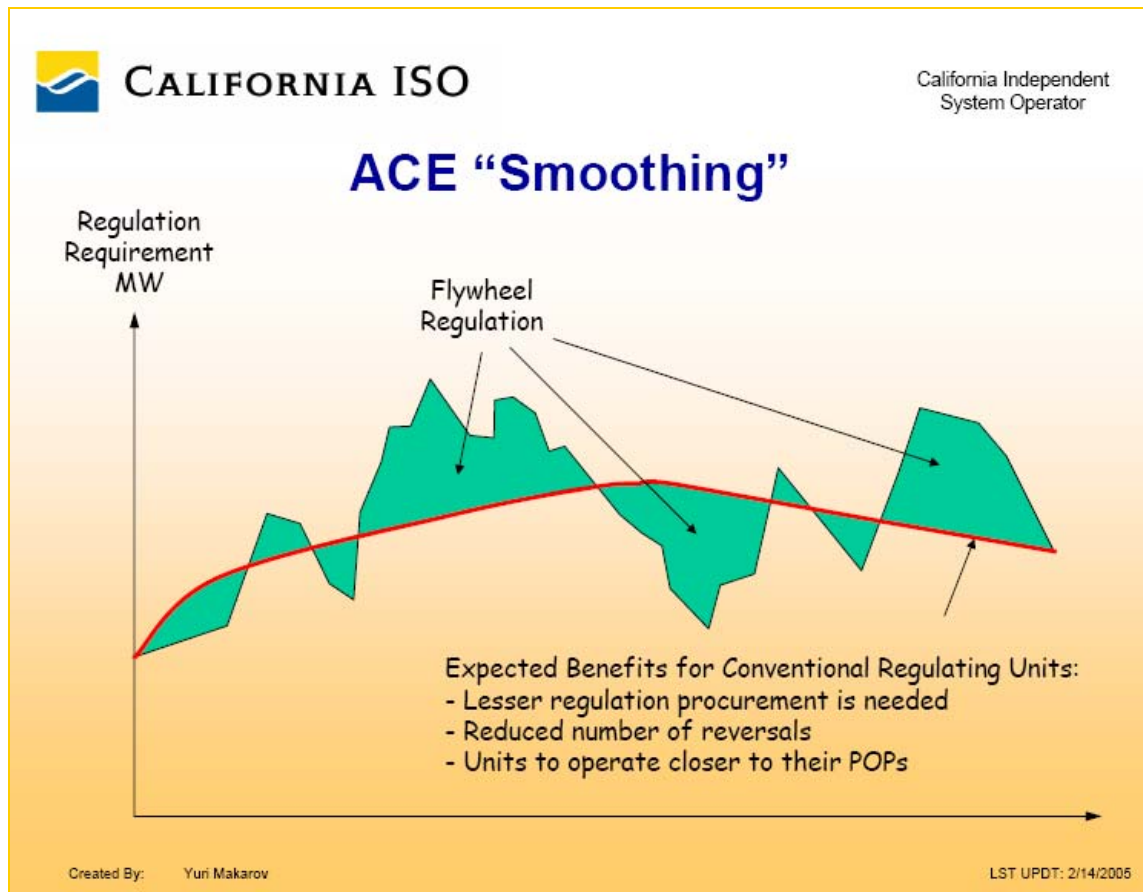
<sup>1</sup> Dr. Makarov's work on frequency regulation, including frequency regulation algorithms and the 2X performance factor is referenced in several CAISO internal reports, as follows: "Suggested Algorithms to be Tested at San Ramon Test Facility," a California ISO document published 10/25/05, researched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

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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 another 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.<sup>2</sup> 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.<sup>3</sup>

<sup>2</sup> 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.

<sup>3</sup> 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

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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<sub>2</sub> 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<sub>2</sub> 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.<sup>4</sup>

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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."

<sup>4</sup>For a detailed discussion of CO<sub>2</sub> reduction benefits, see: "Emissions Summary Comparison for a 20 MW Flywheel-based Frequency Regulation Power Plant," KEMA, Inc., published in December, 2006.

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## 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

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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.

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### **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.

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### 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<sub>2</sub> 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.

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- 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 Introduction 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. Periodical reinvestment
  - d. Staff
  - e. Carbon Credit: Costs associated with CO<sub>2</sub> emissions were added in a final section to show the potential impact of carbon costs for each of the technologies assuming a CO<sub>2</sub> market emerges in the U.S. in the future
3. Life time 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**

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

<sup>5</sup> Note that currently only a few coal peakers are being constructed, so peaker capital cost was estimated.

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## 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<sub>2</sub> 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<sub>2</sub> Emissions**

The cost for carbon emissions is calculated by multiplying tons of CO<sub>2</sub> 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<sub>2</sub> market mechanism. However, it appears likely that a CO<sub>2</sub> market will emerge in the U.S. or else the U.S. will join the international market before too long. In Europe, a CO<sub>2</sub> market is in place. The CO<sub>2</sub> cost in the model of 17 USD/ton of CO<sub>2</sub> is the 2008 forward market value/cost on the EU emission markets for emitting an additional ton of CO<sub>2</sub>.

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<sub>2</sub> emissions because they do not consume fuel. Hence, for the purposes of this model they have no direct CO<sub>2</sub> related costs.

As a CO<sub>2</sub> market in the U.S. does not currently exist, calculations of total cost excluded CO<sub>2</sub>. 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.

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### 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 Periodical 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 7<sup>th</sup> year. The cost of this battery pack replacement is allocated under periodical investments.

For the fossil-based generating plants, no periodical 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).

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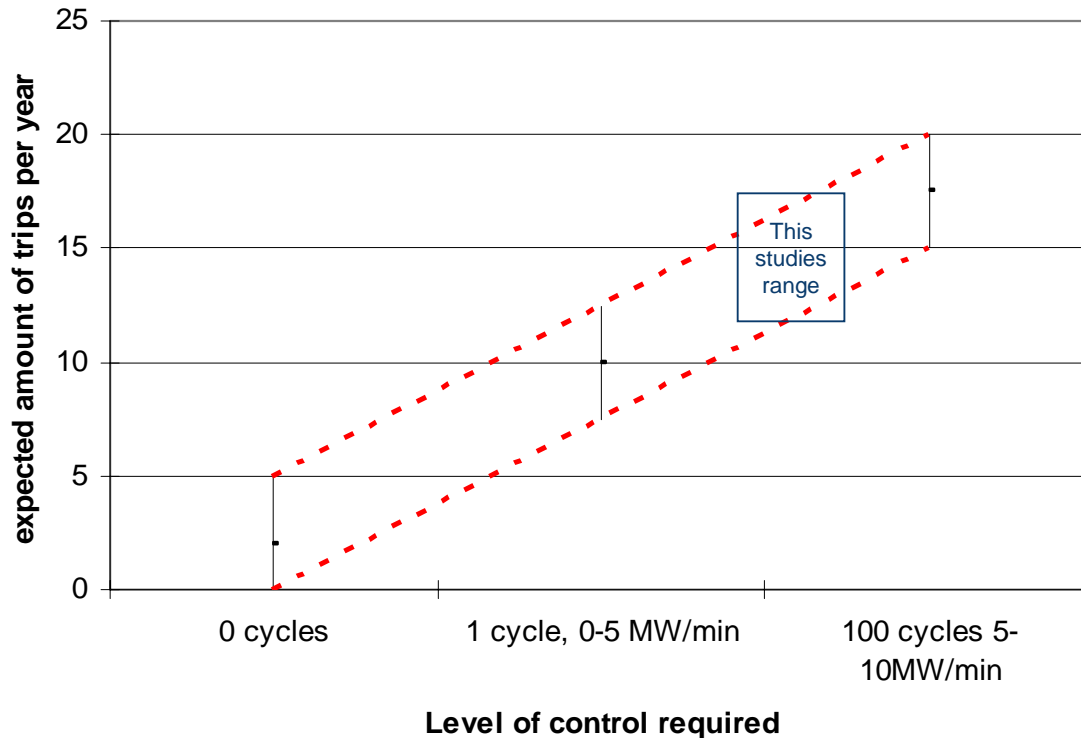
## 4.4 Life time Reduction for Thermal Plants Due to Regulation

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.

## Expectation of Annual Trips



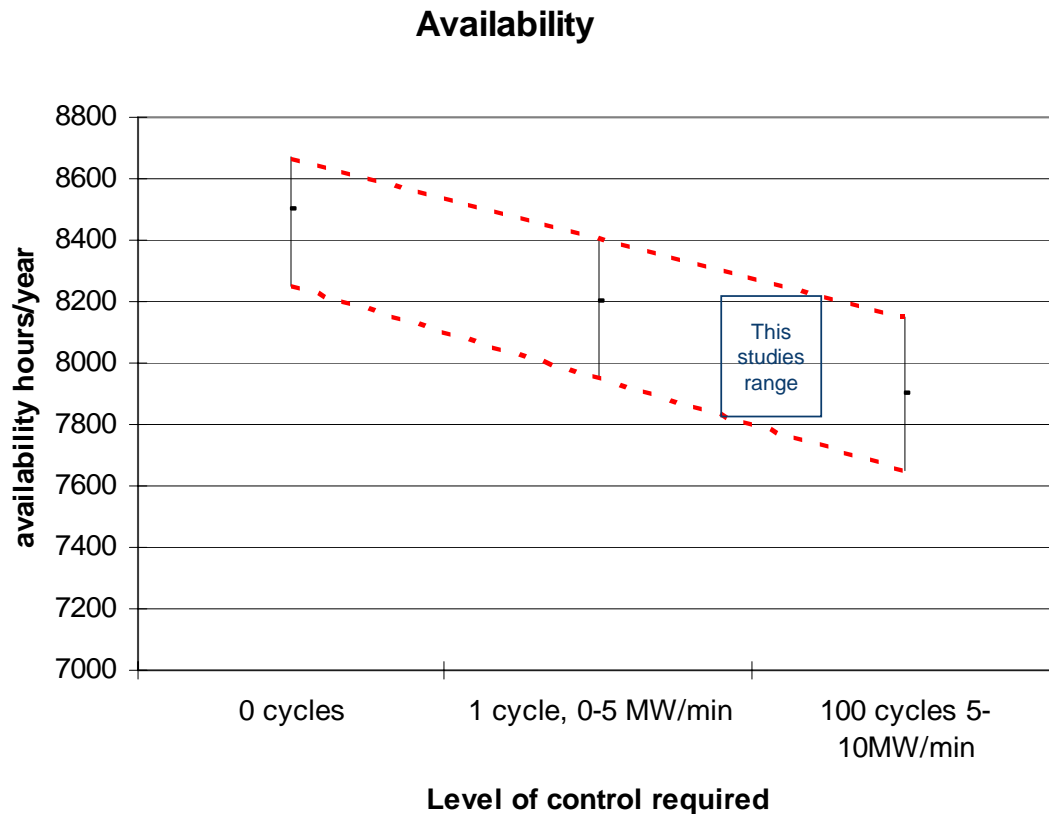
**Figure 3: Increase in annual unplanned trips based on level of control required by power plant**

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 30<sup>th</sup> 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.



**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 4<sup>th</sup> generation flywheels is about four times greater than one of its 3<sup>rd</sup> 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 10<sup>th</sup> plant.

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## 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<sup>th</sup> plant. The primary cost driver for the flywheel technology is the cost of the flywheel itself. The cost of the 10<sup>th</sup> 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	
<b>general</b>	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 revenue 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		
<b>Flywheel</b>			
		unit	
	operating hours per day	24	
Investments	Flywheel (complete) system		
	10th plant	1630 USD/kW	
operational costs	value to use in cost model	10th plant	1630 USD/kW
	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	Flywheel losses	1.20 MWh/MW day	
	Total Losses	12,421,680 kWh /year	
	required staff for operation	1.25 FTE/yr	
	CO2 emissions		
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	
other	value to use in cost model	numeric average	5,784 ton/a
	depreciation scheme for plant	MACRS 20 Years	

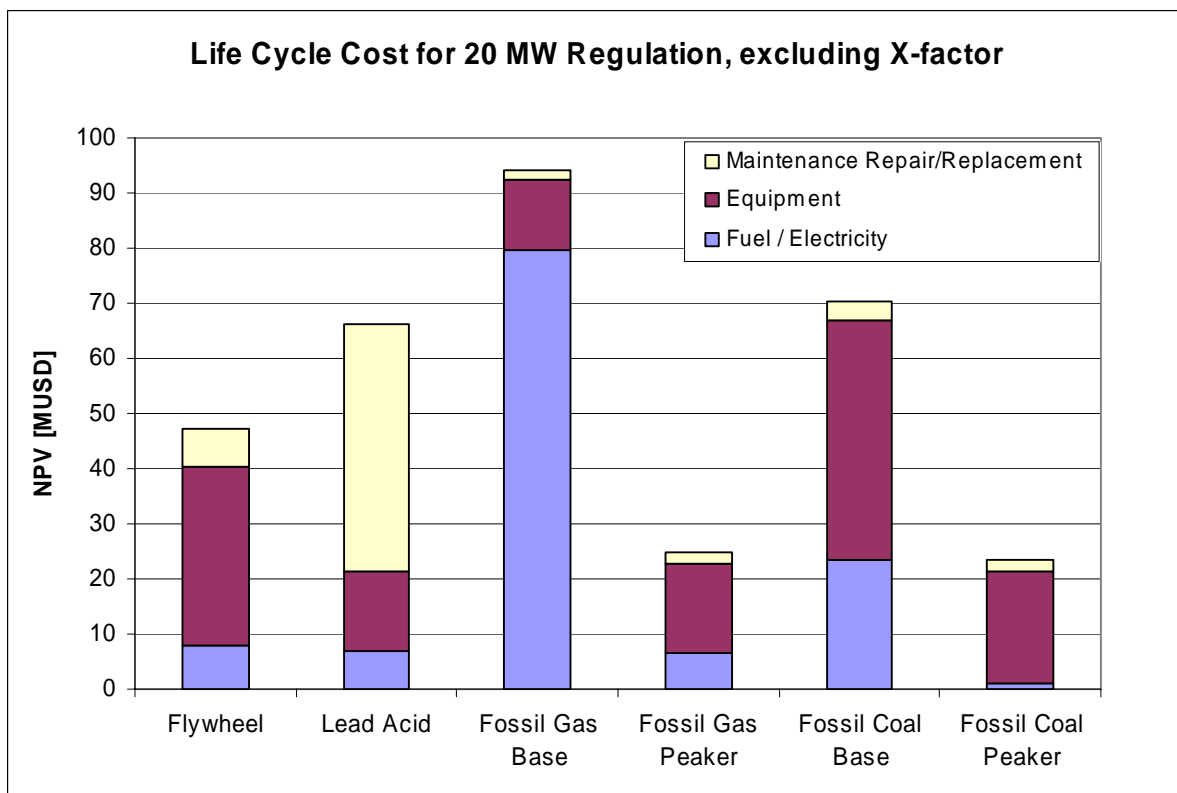
**Table 3: Example of Model Input Page**

## 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.

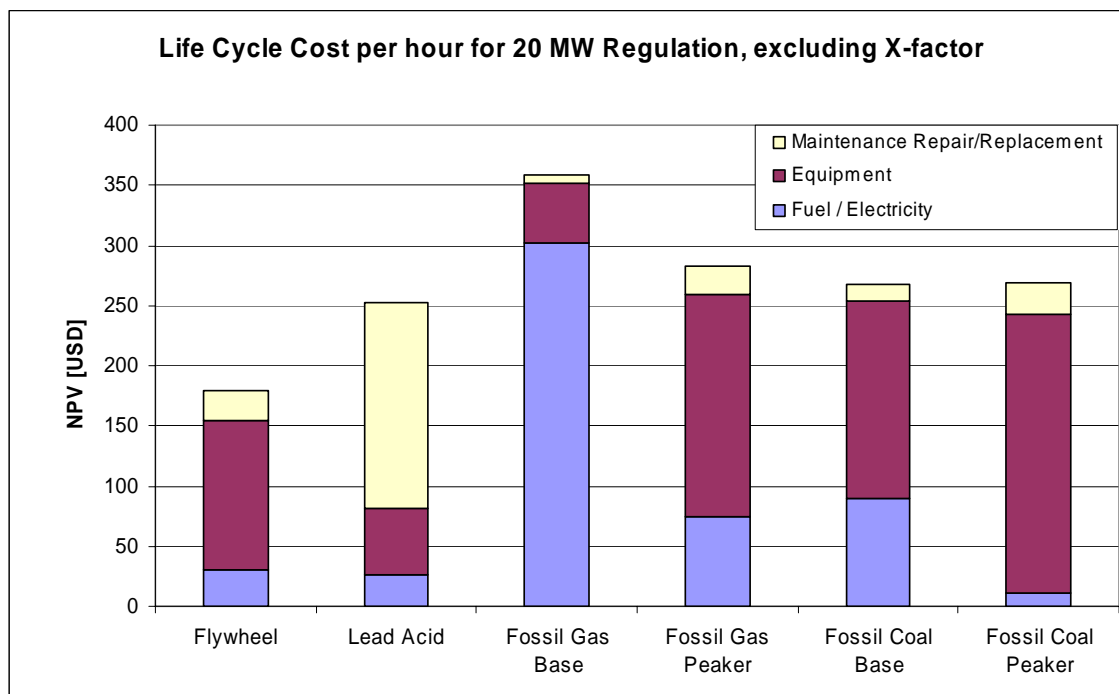


**Figure 5: Life Cycle Cost for Regulation does not reflect the total cost picture as peaker plants are operational only 8 hour per day**

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**

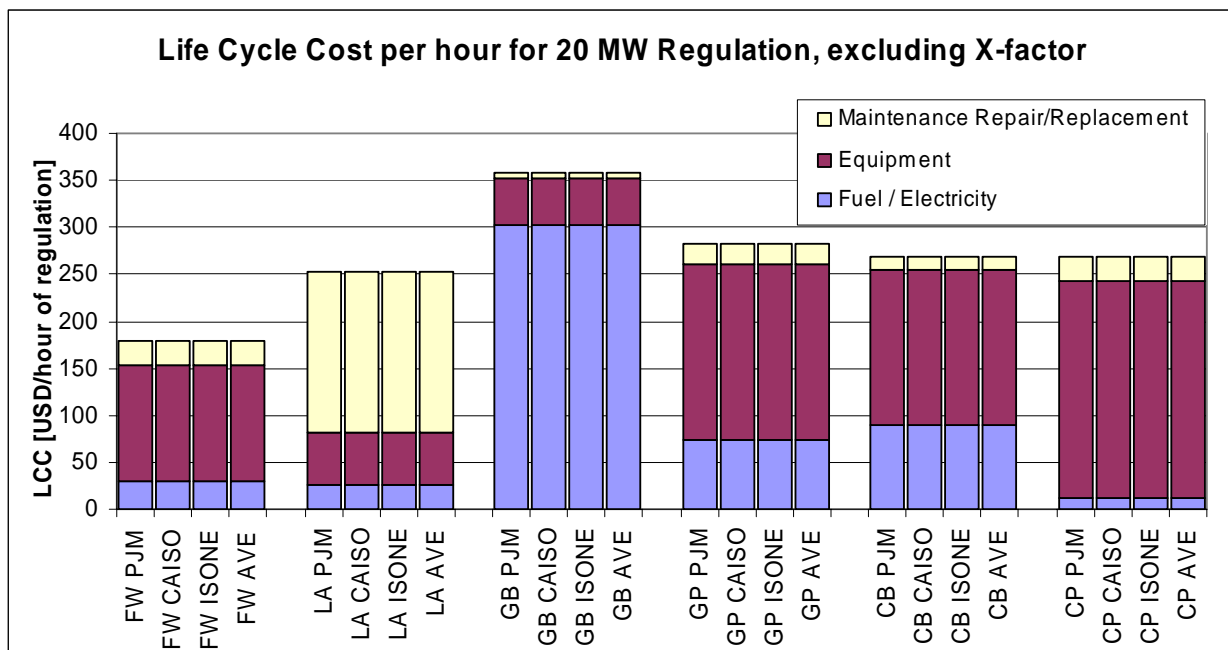
Figure 6 clearly shows that the Beacon Flywheel systems have the lowest hourly life cycle cost for regulation, reflecting both initial capital costs and operational costs. The graph also shows that cost for regulation service for the peaker plants is significantly less compared to the base plants. The 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<sub>2</sub> markets exist. This is because regions have different generation mixes and hence, different emission profiles. In the absence of CO<sub>2</sub> markets, little differences in projected costs exist across regions. This is shown in Figure 7 below:

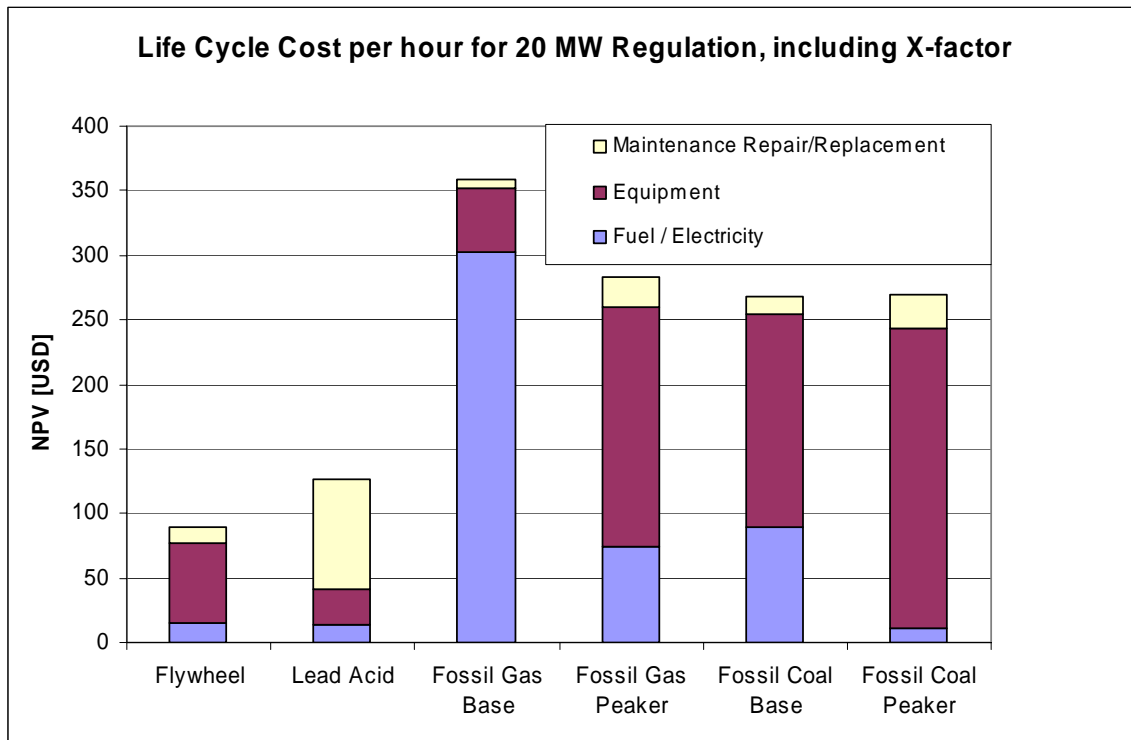


**Figure 7: Comparison of the hourly LCC over the PJM, CAISO and ISONE regions shows little deviation in cost**

Figure 7 <sup>6</sup> 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  $X = 2$ ).



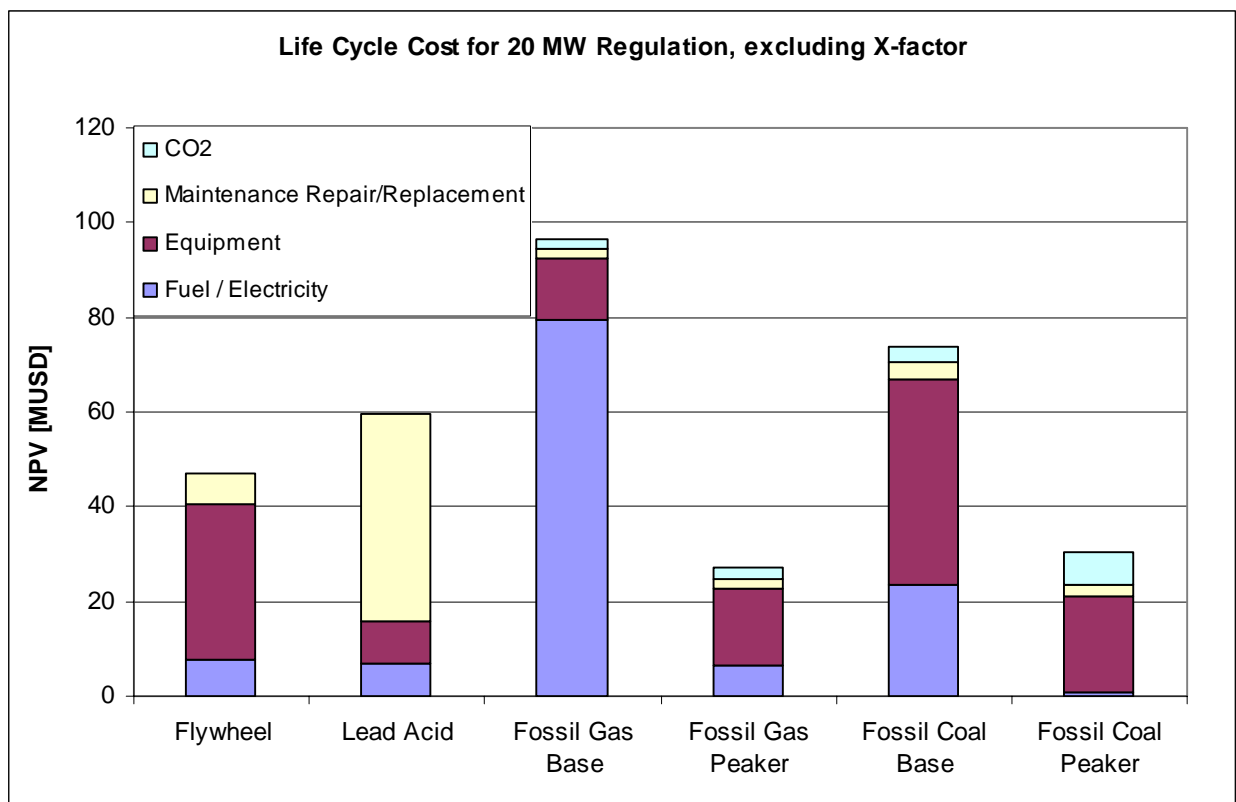
**Figure 8: Illustrative results for an X-factor = 2 replace by graph without CO2 effect.**

<sup>6</sup> 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<sub>2</sub> Included

Though a CO<sub>2</sub> 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<sub>2</sub> was set to \$17 USD/ton. The results of the analysis are shown for each of the sections examined in the previous sections of the “Model Output.”

### 1. Total Life Cycle Cost of the Technologies

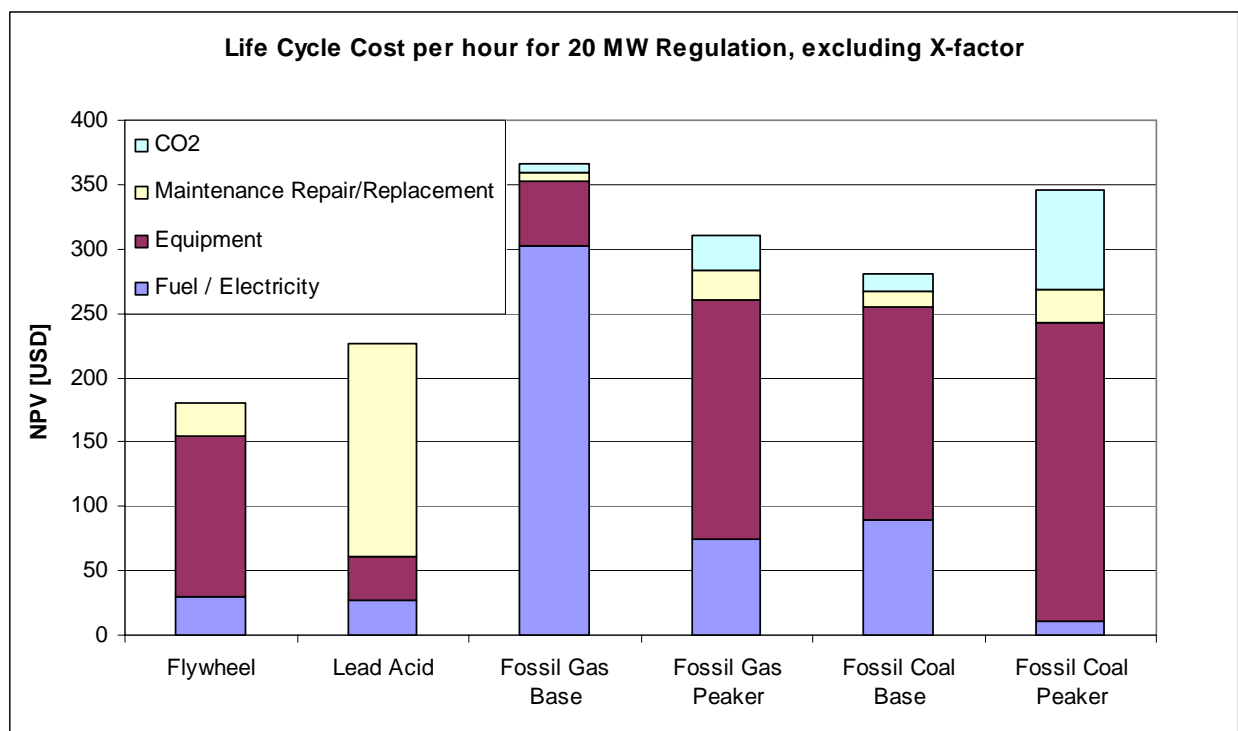


**Figure 9: Life Cycle Cost for Regulation does not reflect the total cost picture as peaker plants are operational only 8 hour per day**

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

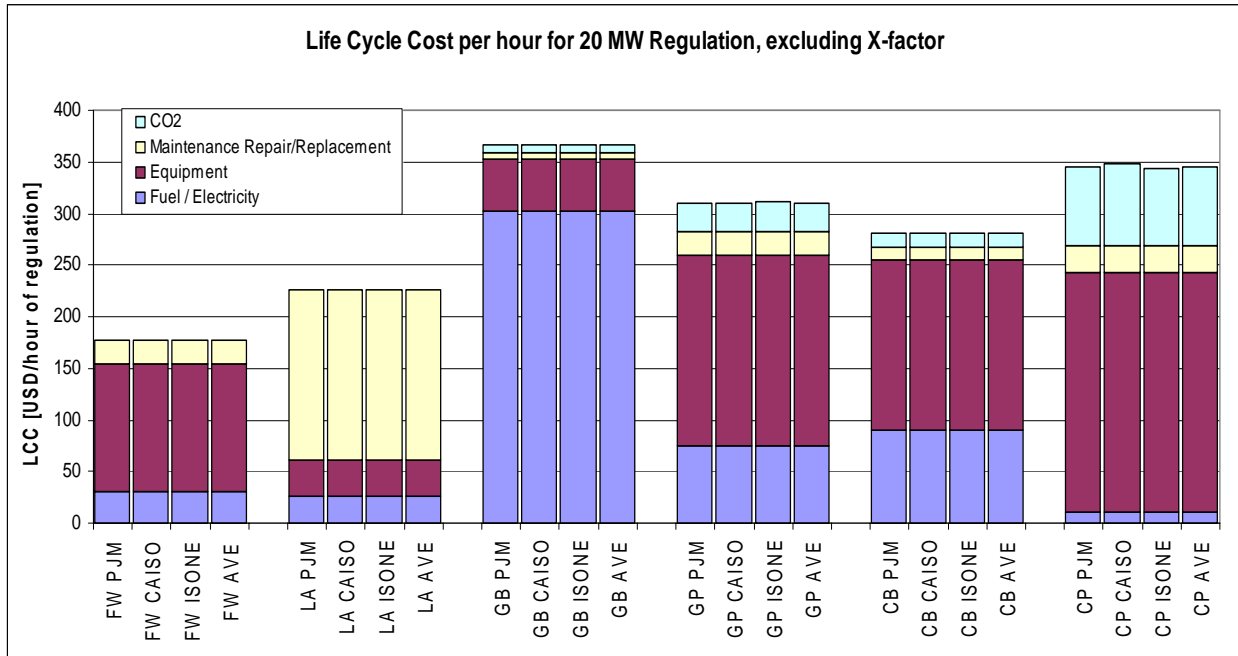


**Figure 10: Hourly LCC allows for a sound comparison between technologies**

With an active CO<sub>2</sub> 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<sub>2</sub> 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.

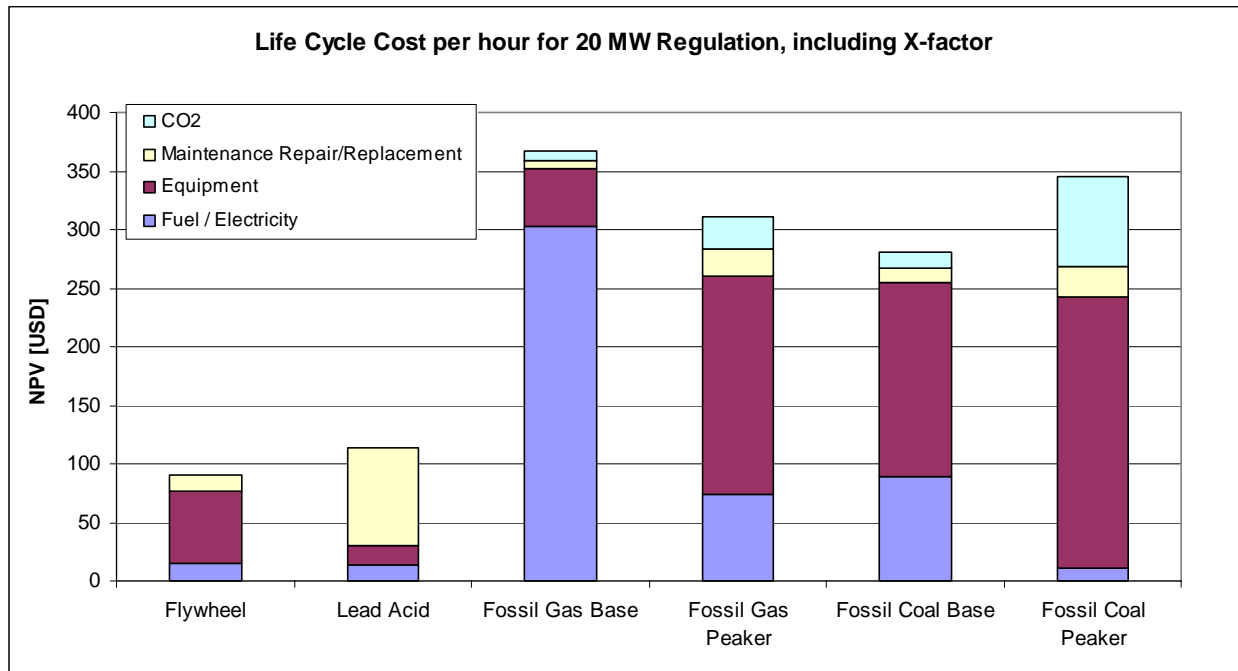


**Figure 11: Comparison of the hourly LCC over the PJM, CAISO and ISONE regions shows little deviation in cost**

#### 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<sub>2</sub> costs are included in the totals.



**Figure 12: Illustrative results for an X-factor**

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## 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<sub>2</sub> 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.

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If the impact of a potential future CO<sub>2</sub> 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<sub>2</sub> 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	
<b>general</b>	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 revenue 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 emissions		numeric average
	nominal rating for base case fossil plants		400 MW
nominal rating for peaker fossil plants		75 MW	
<b>Flywheel</b>		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		
	Flywheel losses		1.20 MWh/MW day
	Total Losses		12,421,680 kWh /year
	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
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	
	nameplate Ah life	71,428,571 Ah	
	per cell		
	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**

<b>Fossil power plant Coal Base Load</b>		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
lifetime	required staff for operation	1 FTE/yr
	shelf life time	30 year
CO2 emissions	life time reduction due to regulation	1 yr/30 years 97%
	PJM	15,442 ton/a
	CAISO	16,100 ton/a
	ISO NE	16,100 ton/a
	numeric average value to use in cost model	15,881 ton/a 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

<b>Fossil power plant Coal peaker</b>		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
lifetime	required staff for operation	1 FTE/yr
	shelf life time	30 year
CO2 emissions	life time reduction due to regulation	1 yr/30 years 97%
		8 hr
	PJM	30,825 ton/a
	CAISO	32,139 ton/a
	ISO NE	30,418 ton/a
other	numeric average value to use in cost model	31,128 ton/a numeric average 31,128 ton/a
	control band for Regulation	27% of nominal power
other	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**

<b>Fossil power plant base load gas</b>		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
lifetime	required staff for operation	1 FTE/yr
	shelf life time	30 year
CO2 emissions	life time reduction due to regulation	1 yr/30 years 97%
	PJM	9,746 ton/a
	CAISO	9,727 ton/a
	ISO NE	9,868 ton/a
	numeric average value to use in cost model	9,780 ton/a 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

<b>Fossil power plant gas peaker</b>		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
lifetime	required staff for operation	1 FTE/yr
	shelf life time	30 year
CO2 emissions	life time reduction due to regulation	1 yr/30 years 97%
	PJM	11,222 ton/a
	CAISO	11,200 ton/a
	ISO NE	11,362 ton/a
	numeric average value to use in cost model	11,261 ton/a 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**