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The Wide-area Energy Storage and Management System Phase 2 Final Report

N Lu
MR Weimar
YV Makarov

August 2010

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Related Services

Pacific Northwest National Laboratory
Richland, Washington 99352

Abstract

The higher penetration of intermittent generation resources (including wind and solar generation) in the Bonneville Power Administration (BPA) and California Independent System Operator (CAISO) balancing authorities (BAs) raises the issue of requiring expensive additional fast grid balancing services in response to additional intermittency and fast up and down power ramps in the electric power system.

The overall goal of the Wide-area Energy Storage and Management System (WAEMS) project is to develop the principles, algorithms, market integration rules, a functional design, and technical specifications for an energy storage system to cope with uncertainties and unexpected rapid changes in renewable generation power output. The resulting WAEMS system will store excess energy, control dispatchable load and distributed generation, and use inter-area exchange of the excess energy between the CAISO and BPA BAs. A further goal is to provide a cost-benefit analysis and develop a business model for an investment-based practical deployment of such a system.

Phase II of the WAEMS project consists of two tasks: the flywheel field tests and the battery evaluation. Two final reports, "Wide-area Energy Storage and Management System Phase II – Flywheel Field Tests Final Report" and "Wide-area Energy Storage and Management System – Battery Storage Evaluation", were written to summarize the results of the two tasks. The two final reports have been attached in Appendix A and Appendix B.

Keywords: energy storage, flywheel, NaS battery, regulation services, load following, real-time dispatch, balancing services, economic analysis, performance evaluation, wind integration, renewables, intermittent energy resources, ancillary services.

Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Building End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation.

This is the final report for the *Wide-Area Energy Storage and Management System Phase II* (contract number: 500-07-037, work authorization number: TRP-08-05) conducted by Pacific Northwest National Laboratory. The information from this project contributes to PIER's Energy Systems Integration Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

Executive Summary

This research was conducted by the Pacific Northwest National Laboratory (PNNL), which is operated for the U.S. Department of Energy (DOE) by Battelle under Contract DE-AC05-76RL01830, for Bonneville Power Administration (BPA), the California Energy Commission, and the California Institute for Energy and Environment (CIEE).

The higher penetration of intermittent generation resources (including wind and solar generation) in the Bonneville Power Administration (BPA) and California Independent System Operator (CAISO) balancing authorities (BAs) raises the issue of requiring expensive additional fast grid balancing services in response to additional intermittency and fast up and down power ramps in the electric supply system.

The overall goal of the Wide-area Energy Storage and management system (WAEMS) project is to develop the principles, algorithms, market integration rules, a functional design, and technical specifications for an energy storage system to cope with uncertainties and unexpected rapid changes in renewable generation power output. The resulting WAEMS system will store excess energy, control dispatchable load and distributed generation, and use inter-area exchange of the excess energy between the CAISO and BPA BAs. A further goal is to provide a cost-benefit analysis and develop a business model for an investment-based practical deployment of such a system.

There are two tasks in Phase II of the WAEMS project: the flywheel field tests and the battery evaluation.

The goal of the "**Flywheel Field Tests"** task is to minimize the balancing effort by developing a centralized control system that operates energy storage devices in conjunction with conventional generators to provide fast balancing services that can be shared among balancing authorities. The idea is based on coordination of traditional services (provided by conventional generation) and energy storage. In Phase II of the WAEMS project, a prototype WAEMS configuration consisting of a hydro electric plant and a flywheel energy storage was field tested using actual area-control-error and regulation signals provided by BPA and CAISO. The results were used to evaluate the performance and economics of the flywheel-hydro regulation service.

The performance evaluation shows an excellent performance of the WAEMS control algorithm, which separates the faster regulation effort provided by the energy storage from the slower one provided by a conventional regulating unit. The WAEMS combined service is not strictly constrained by energy storage limits because the hydro plant supports the desired flywheel's energy level. In addition, the WAEMS combined service has the same fast-response characteristic (within 6 seconds) as that provided by the flywheel energy storage alone. Furthermore, the WAEMS control algorithm reduces wear and tear on the hydro unit and allows the hydro unit to operate closer to its preferred operating point.

The breakeven price for flywheel energy storage to provide bi-directional service (1 MW regulation-up <u>and</u> 1 MW regulation-down) is \$20.37/$\pm$ MW. Because the average bi-directional regulation price of the CAISO balancing authority is \$11.95/ $\pm$ MW (Jan.-July, 2010) and that of the BPA balancing authority is \$9.38/ $\pm$ MW (2010), regulation service provided by a stand-alone flywheel energy storage will not be economical unless the regulation price will be increased or the fast regulation service will be paid at a higher rate.

Assuming that the minimum regulation price of regulation provided a hydro power plant is \$4/ $\pm$ MW, the breakeven price of the combined flywheel-hydro regulation service would be \$12.19/ $\pm$ MW; therefore, the flywheel-hydro regulation service breakeven price is found to be slightly higher than the average CAISO (\$11.95/ $\pm$ MW) and BPA (\$9.38/ $\pm$ MW) regulation prices. Because regulation prices are increasing when more renewable generation resources are integrated into the power grids, the flywheel-hydro regulation service is expected to become economical in the CAISO and BPA balancing authorities soon.

The goal of the "**Battery Storage Evaluation"** task is to investigate technical characteristics and economics of the NaS battery energy storage used for regulation and real-time dispatch (also called load following) services in the electricity market operated by the California Independent System Operator (CAISO). The results and conclusions of the battery evaluation study are summarized as follows:

- If an NaS battery is operated for 20 years at its rated output 4 MW, operating it at a lower depth of discharge (DOD) results in less cost with the existing lifecycle-DOD curve. If manufacturers can improve the NaS battery lifecycles at high DODs (>50%), the breakeven prices will drop significantly for high DOD cases.
- Under the *pay-by-capacity* scheme for regulation services, the NaS battery has a longer life and a lower cost when it runs at lower DOD. With current technology, the battery-rated power output is 4 MW. The results indicate that if the 4-MW battery provides one-directional regulation service, the high-end cost will be 26 \$/MW, and the low-end cost will be 16 \$/MW; therefore, the NaS battery was not profitable in either the CAISO or the BPA market when providing 1-directional regulation services.
- If the NaS battery power-to-energy ratio can be increased, the breakeven price for regulation or real-time dispatch services will drop significantly because the battery is capable of handling a broader range of signals. For example, the current power-to-energy ration for a 4 MW, 28 MWh NaS battery is 4:28 or 1:7. If the rated power of the NaS battery can be increased from 4 MW to 8, 12, 16, or 20 MW, while its energy storage remains at 28 MWh, the power-to-energy ratio can be increased to 2:7, 3:7, 4:7, or 5:7, respectively. However, after the rated power is raised to 12 MW, the breakeven price drop is not significant, but the life of the NaS battery is shortened dramatically. Therefore, based on the existing lifecycle-DOD curve, it may be beneficial for the manufacturer to increase the rated-power output of the NaS battery up to 8 or 12 MW, which will result in a breakeven price drop of $^1/_2$ to $^1/_3$ compared with that of the 4 MW case.

From the results, we conclude that the opportunities for flywheels or other energy storage devices lie in the following areas:

- To avoid performance problems associated with their finite energy storage capacity, provide regulation services for system operators which would agree to manage the flywheels' energy level, or participate in alternative schemes helping to co-optimize fast acting storage devices and conventional generators to provide high-quality combined regulation services.
- Operate energy storage devices in conjunction with conventional generators to improve their response time, reduce their wear and tear, and provide compatible services that do not require modifications of the existing automatic generation control and market systems.
- To increase the capacity payment, explore opportunities for sharing regulation services among two or more balancing authorities.
- Investigate methods and tariff changes so that the fast responsive and flexible resources can be compensated for additional services such as frequency response, fast ramping, voltage and reactive power support, or damping of transmission line oscillations to prevent grid angular instability.

Based on the Phase II results, it is recommended that the next phase of the WAEMS project focus on research leading to (1) practical deployment of the WAEMS that provides balancing services (including both load-following and regulation services) to the CAISO and BPA balancing authorities and (2) commercialization of the control algorithms developed in Phases 1 and 2 of the WAEMS project.

A near-term goal should be commercialization of a shared storage system between CAISO and BPA. A longer term goal should be development of methodologies for operating both fast and slow resources and sharing these resources over multiple control areas to facilitate the renewable integration and operate the power grids reliably and economically.

The next steps are to

- enhance the WAEMS controller so that it is more robust and can provide load following services;
- field test more energy storage technology options, such as Li-ion battery energy storage; and
- assist BPA and CAISO to deploy a WAEMS system between BPA (offer a hydropower plant) and CAISO (offer an energy storage device).

Another potential area of future research is the development of an energy storage evaluation toolbox that incorporates the models, algorithms, methodologies, and standardized testing signals developed or obtained in previous WAEMS tasks. This toolbox would help users find optimal configurations and assess the performance and economics of different energy storage solutions, enabling them to answer the following questions:

- Are the selected ESDs capable of providing the required services as expected?

- How much fast-regulating ESD capacity is needed for a given regulation/load-following signal?
- What is the cost of the service?

This research will provide information for power grid operators to make decisions on building an energy storage portfolio that best meets the wind-integration requirements and is most economical to implement.

Acknowledgements

This work was funded by the **Bonneville Power Administration** and the **Public Interest Energy Research (PIER) program** in renewable energy at the **California Energy Commission** and managed by the California Institute for Energy and Environment. This report was prepared with support from the California Independent System Operator.

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Acronyms

ACE	area control error
AGC	automatic generation control
APEL	Advanced Process Engineering Laboratory
BA	balancing authority
BP	base-point adjustment
BPA	Bonneville Power Administration
CAISO	California Independent System Operator Corporation
CEC	California Energy Commission
CIEE	California Institute for Energy and Environment
DOE	U.S. Department of Energy
DOT	dispatch operating target
EMS	energy management system
ESD	energy storage device
FERC	Federal Energy Regulatory Commission
ISO	Independent System Operator
NaS	sodium sulfur
NPV	net present value
NYISO	New York Independent System Operator
O&M	operations and maintenance
PDF	probability density function
PJM	Pennsylvania-New Jersey-Maryland Interconnection
PNNL	Pacific Northwest National Laboratory
POP	preferred operating point
SOC	state of charge
WAEMS	wide-area energy storage and management system

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1.0 Introduction

This research was conducted by Pacific Northwest National Laboratory (PNNL), which is operated by Battelle for the U.S. Department of Energy (DOE) under Contract DE-AC05-76RL01830, for the Bonneville Power Administration (BPA), the California Institute for Energy and Environment (CIEE), and the California Energy Commission. This section introduces the background, objectives, benefits, and tasks of Phase II of the Wide-area Energy Storage and management system (WAMES) project.

1.1 Background

The WAEMS project has three phases. Phase I (completed in 2008) was funded by BPA and supported by the California Independent System Operator (CAISO) and Beacon Power Corporation with in-kind inputs. Phase I was proof of the concept. The tasks included energy storage technology evaluation, initial WAEMS configuration design and control algorithm development, and cost-benefit analysis. Phase II (completed in 2010) was co-funded by BPA and California Energy Commission and supported by CAISO and Beacon Power Corporation with in-kind support. Phase II focused on ***Battery Storage Evaluation*** and ***Flywheel Field Tests***.

1.2 Technical Needs

This research addresses the goals and technology needs identified by CAISO and BPA in renewable energy integration and optimization of the hydro and wind resources operations.

A major operational issue associated with high renewable energy penetration (20% or even 33%) is that *ramp rates* and *magnitudes* of the regulation and load-following requirements are expected to increase significantly. Phase I and other California Energy Commission studies [1]–[6] have shown that fast-ramping balancing services could potentially reduce the regulation and load-following requirement by up to 30%. Therefore, it is important for BPA and CAISO to seek additional fast load-following and regulation resources to meet challenges of the high penetration of wind in BPA and CAISO balancing authorities.

The fast regulation and load-following services are currently provided mainly by hydro power plants or gas turbines. To meet the increasing ramp and capacity requirements, the regulating hydro plant may not be able to operate close to its preferred operating point, resulting in low efficiencies. In addition, faster load-following service puts higher mechanical stress on hydro turbines, increasing the wear and tear cost. Furthermore, due to environmental and efficiency constraints, the range within which a hydro unit can operate varies with the season and water availability. Therefore, BPA and CAISO need to consider alternative load-following and regulation resources that are economical and meet performance requirements.

Energy storage devices (ESDs) are an important part of key initiatives to integrate more renewable generation resources into the electric power grid. Traditionally, ESDs, such as battery banks, are being considered to be used as backup or used to level wind or solar outputs and shave or shift peak loads. Now, providing balancing services, including load-following and regulation, becomes a potential revenue stream for ESDs. For instance, two 20-MW flywheel facilities are being installed in New York Independent System Operator (NYISO) and Pennsylvania-New Jersey-Maryland Interconnection (PJM) balancing authorities for providing regulation services. Flywheels, NaS and Li-ion batteries, and ultra capacitors are energy storage systems having a very fast response rate but relatively limited energy storage capabilities. In Phase II, Beacon Power has conducted field tests to evaluate a hybrid system consisting of a hydro power unit and a flywheel unit to provide high-quality regulation services. NaS battery storage was evaluated for regulation and load-following services.

1.3 Goals and Tasks

The goal of this research is to investigate the technical characteristics and economics of the flywheel used for combined regulation services in the electricity market operated by CAISO and in the BPA system. The tasks addressed in Phase II are as follows:

Task 2: Design and Monitor the Flywheel Field Experiments for Existing Renewable Penetration:

- Design field experiments with the flywheel energy storage.
- Implement changes/adjustments of the flywheel energy storage, if required.
- Prepare sets of simulated control signals to control the flywheel device for regulation and frequency response using the actual data provided by BPA and CAISO.
- Monitor the experiments for the existing penetration levels.
- Depending on availability of resources and affordability of experiments, conduct studies with transactive commercial building controllers at PNNL's buildings in Richland and the Advanced Process Engineering Laboratory (APEL) Building Micro Turbine in Richland.[1]

Task 3: Design and Monitor the Flywheel Field Experiments for Future Scenarios

- In cooperation with BPA and CAISO engineers (or with BPA and CAISO wind generation forecasting service providers), prepare sets of look-ahead data for higher penetration levels of wind energy penetration in these systems (future scenarios). Design experiments to simulate these future scenarios on the flywheel utilized in Task 2.
- Monitor the experiments for the future scenarios.

[1] Note that we did not conduct experiments with transactive commercial building controllers at PNNL's buildings because of funding limitations.

Task 4: Calculate and Analyze Performance Characteristics (performance metrics) of the Flywheel Experiments (existing renewable penetration and the future scenarios) for each Regulation Resource.

- Analyze, compare, and systemize the experimental results.
- Provide a summary of results and recommendations to BPA/California Energy Commission/CIEE on continuation of the project.

Task 5: Battery Storage Evaluation.

- Study the value of the ancillary services that can be provided by the NaS battery for the following two wind energy penetration scenarios: (1) a hypothetical scenario without wind energy resource and (2) a scenario with 20% of CAISO's energy supply being provided by renewable resources, including the wind energy resource. Scenario (1) was analyzed to compare the incremental effects of wind power production.
- Evaluate technical and economical characteristics of the NaS battery when it is used to provide regulation and real-time dispatch services.
- Consider different operational conditions, find limitations, and recommend additional opportunities for the NaS battery arising in the California energy market.
- Suggest design improvements for the NaS battery physical characteristics, including energy capacity, power output, and lifetime, and help to increase the value and expand market opportunities in California.

2.0 Approach

The approach of the flywheel field tests and battery storage evaluation are briefly described in the following two sections. **Please refer to the two final reports (Appendix A: Flywheels Field Tests; Appendix B: Battery Storage Evaluation) for detailed information.**

2.1 Battery Storage Evaluation

The modeling framework of the battery storage evaluation is shown in Figure 1. The regulation and real-time dispatch[2] signals were simulated using 2006 CAISO historical data sets. The battery model was developed based on the battery depth of discharge (DOD) characteristics. The methodology used in Phase I of this project was improved by considering the physical characteristics of the NaS battery storage so that the number of battery lifecycles and the annual energy provided are realistic. The battery performance was simulated by feeding the simulated minute-to-minute regulation and real-time dispatch signals into the battery model. To evaluate the efficacy of the NaS battery storage in mitigating the intermittence brought by the higher levels of penetration of renewable energy, a scenario was studied with 20% of the CAISO load being supplied by renewable energy resources, and compared it against a scenario with zero wind generation.

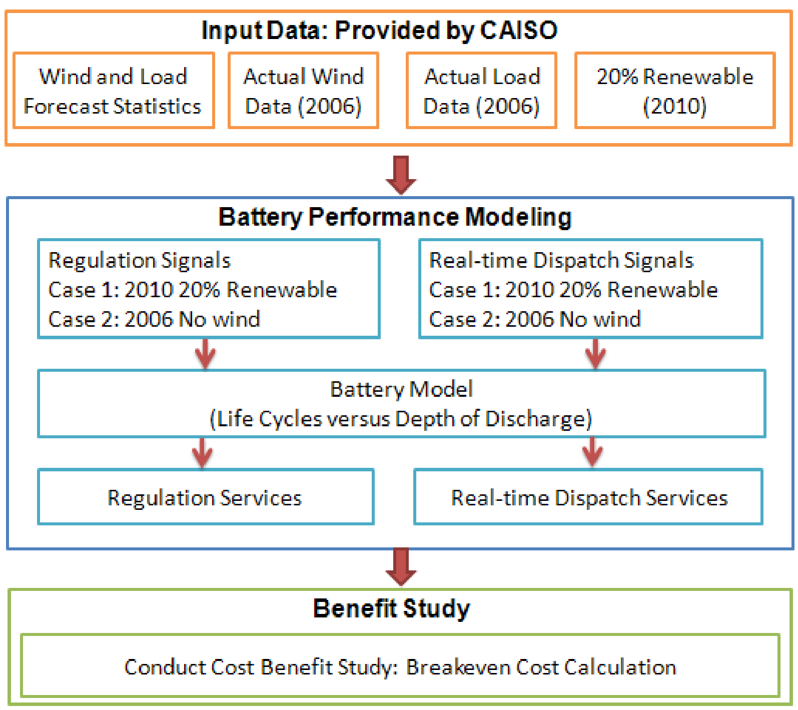


Figure 1: The modeling framework

[2] "Real-time dispatch" is also called "load following".

To provide regulation or real-time dispatch service, an NaS battery can run at either the bi-directional or one-directional mode. In the bi-directional mode, the battery responds to both "up" and "down" signals. In the one-directional mode, the battery responds to the "up" signal when it is discharging and the "down" signal when charging. The one-directional operation scheme was selected and modeled in detail in this study because the one-directional operation allows the NaS battery to have a longer service life and is easier to implement compared to bi-directional operation schemes.

In the benefit study, the economics in terms of breakeven[3] costs were evaluated and compared for different device performance characteristics and operation mechanisms to find the best options. The net present value (NPV)[4] was not calculated because the service's breakeven costs were not low enough to provide a positive NPV given assumed CAISO market prices for regulation and real-time dispatch services. Two sets of breakeven prices were considered: the high-end cost and the low-end cost. The high-end cost was obtained by applying pessimistic estimations of input variables, and the low-end cost was obtained by applying the optimistic ones.

Two payment methods were studied for the regulation service: *pay-by-capacity* and *pay-by-energy*.[5] For the real-time dispatch service, only the *pay-by-energy* method was considered.

2.2 The Flywheel Field Tests

The modeling framework of the flywheel field tests is shown in Figure 2. PNNL acquired 4-second ACE and regulation signals from BPA and CAISO, which were used as test signals in scenarios representing the <u>existing</u> level of wind generation penetration. Simulated ACE signals representing 2013 wind penetration scenarios were used for 20% renewable penetration scenarios.

The test signal was normalized to fit ±40 MW range and then fed into the WAEMS controller, which allocated the signal to the flywheel energy storage (within ±20 MW) and the hydro plant model (within ±20 MW), so that the flywheel energy storage provided the fast regulating component while the hydro plant provided the slow one. The hydro power plant was also used to help the flywheel energy storage to maintain a desired level of the stored energy. In this project, we have not conducted field tests on a real hydro plant. The hydro

[3] The break-even **Error! Reference source not found.** point for a product is the point where total revenue received equals the total costs associated with the sale of the product.

[4] Net present value (NPV) or net present worth (NPW) **Error! Reference source not found.** is defined as the total present value (PV) of a time series of revenues - costs.

[5] Pay-by-capacity means that a unit is paid by the capacity that it bids into the market regardless of the actual energy that it provides to the grid. Pay-by-energy means that a unit is paid by the actual energy that it provides to the grid.

power outputs were simulated outputs. The ±20 flywheel signal was further scaled down to ±100 kW to operate the 25-kWh, 100-kW flywheel provided for the test by Beacon Power Corporation. All field tests were conducted at the Beacon Power facility located in Tyngsboro, MA. The field tests lasted for 8 weeks (March through April, 2010.)

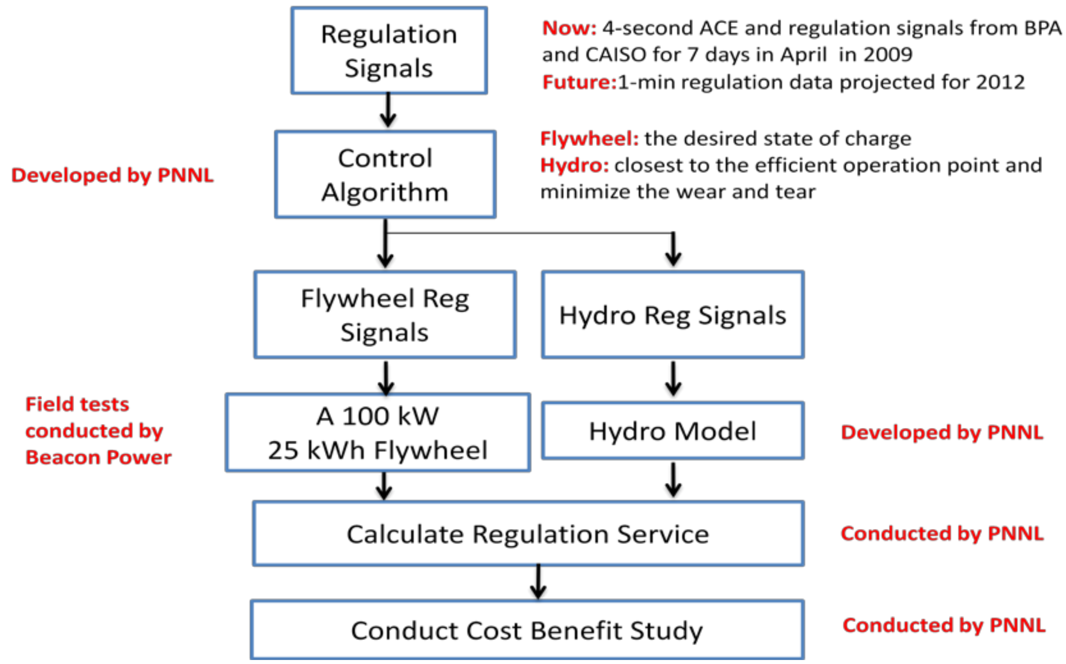


Figure 2: The experimental framework.

The performance and economic evaluations were performed by PNNL. Fade time, mileage, and utilization rate were used as performance metrics. The fade time refers to the time during which the flywheel can no longer fully respond to the regulation signal due to the energy limitations. (When a flywheel is fully charged or discharged, it cannot respond to the regulation signal.) The mileage is the sum of the power output changes, which reflects the total movements of a regulating unit within a period. The ramp-up mileage is the sum of all incremental movements and the ramp-down mileage is the sum of all decremental movements. The utilization rate is obtained as the mean absolute value of the flywheel's output, varying in response to the regulation signal, divided by its rated power.

Breakeven prices were used to evaluate the minimum market entry costs. The calculation of the breakeven prices has accounted for the installation cost, the operation and maintenance cost, the rate of return, and discount rates, as well as a few other economic parameters related with the flywheel energy storage. The pay-by-capacity payment method was studied for the regulation service. Pay-by-capacity service means that a unit is paid by the capacity that it bids into the market regardless of the actual energy that it provides to the grid.

3.0 Summary of Findings

The section briefly summarizes the main findings in Phase II of the WAEMS project. Detailed results and discussions can be found in the two final project reports attached in Appendix A and B.

3.1 Flywheel Field Tests

We conclude that a combined regulation service provided by a hydro power plant and a flywheel energy storage creates the following important benefits:

- providing additional means of mitigating the variability introduced by renewable resources,
- reducing the wear and tear of the hydro units,
- reducing the regulation requirements for BPA and CAISO balancing authorities by sharing the regulation services between them,
- providing combined service that has the same fast-response characteristic as that provided by the flywheel energy storage alone, and
- maintaining desired energy levels at the energy storage devices.

The main findings can be summarized as follows:

- The flywheel followed the regulation signal with a 6-second response delay.
- The proposed WAEMS algorithm successfully allocated the fast component of the regulation signal to the flywheel and the slow one to the hydro power plant.
- The WAEMS combined service had the same fast-response characteristic as that provided by the flywheel storage alone.
- The WAEMS combined service was not strictly constrained by energy storage limits because the hydro plant supported the desired flywheels' energy level.
- The WAEMS control algorithm provided higher utilization rates and minimized fade time.
- The WAEMS control algorithm reduced wear and tear on the hydro unit and allows it to operate closer to its preferred operating point. (A reduction in response or lesser mileage means less wear and tear for the hydro unit.)
- The breakeven price for flywheel energy storage to provide bi-directional service (1 MW regulation-up and 1 MW regulation-down) is \$20.37/$\pm$MW. Because the

average bi-directional regulation price of the CAISO balancing authority is $11.95/± MW (Jan.-July, 2010) and that of the BPA balancing authority is $9.38/± MW (2010), regulation service provided by a stand-alone flywheel energy storage will not be economical unless the regulation price will be increased or the fast regulation service will be paid at a higher rate.

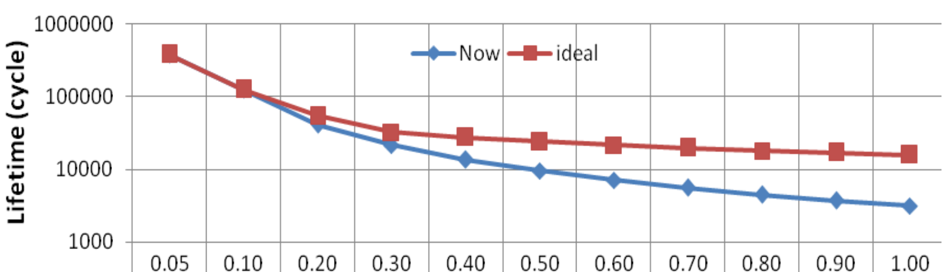
- Assuming that the minimum regulation price of regulation provided a hydro power plant is $4/± MW, the breakeven price of the combined flywheel-hydro regulation service would be $12.19/± MW; therefore, the flywheel-hydro regulation service breakeven price is found to be slightly higher than the average CAISO ($11.95/± MW) and BPA ($9.38/± MW) regulation prices. Because regulation prices are increasing when more renewable generation resources are integrated into the power grids, the flywheel-hydro regulation service is expected to become economical in the CAISO and BPA balancing authorities soon.

3.2 Battery Storage Evaluation

The results and conclusions of the battery evaluation study are summarized as follows:

- The pay-by-energy scheme for balancing services provided by a 4-MW, 28-MWh NaS battery is not economical.
- Under the *pay-by-capacity* scheme for regulation services, the NaS battery has a longer life and a lower cost when it runs at lower DOD. With current technology, the battery-rated power output is 4 MW. The results indicate that if the 4-MW battery provides one-directional regulation service, the high-end cost will be 26 $/MW, and the low-end cost will be 16 $/MW; therefore, the NaS battery was not profitable in either the CAISO or the BPA market when providing 1-directional regulation services.
- If the NaS battery power-to-energy ratio can be increased, the breakeven price for regulation or real-time dispatch services will drop significantly because the battery is capable of handling a broader range of signals. For example, the current power-to-energy ration for a 4 MW, 28 MWh NaS battery is 4:28 or 1:7. If the rated power of the NaS battery can be increased from 4 MW to 8, 12, 16, or 20 MW, while its energy storage remains at 28 MWh, the power-to-energy ratio can be increased to 2:7, 3:7, 4:7, or 5:7, respectively. However, after the rated power is raised to 12 MW, the breakeven price drop is not significant, but the life of the NaS battery is shortened dramatically. Therefore, based on the current lifecycle-DOD curve, it may be beneficial for the manufacturer to increase the rated-power output of the NaS battery up to 8 or 12 MW, which will result in a breakeven price drop of $^1/_2$ to $^1/_3$ compared with that of the 4 MW case.

- Under the *pay-by-capacity* scheme for regulation services, the battery has a longer life and a lower cost when it runs at lower DODs. With current technology, the battery's rated power output is 4 MW. The results indicate that if the 28 MWh, 4 MW battery provides one-directional regulation service, the high-end cost will be **$26/MW,** and the low-end cost will be **$16/MW**, which means that it is not economical in current CAISO ($6/MW) and BPA ($4.7/MW) balancing authorities.
- The NaS battery provides almost the same amount of regulation or real-time dispatch services for the "with 20% renewables" and "without wind" cases. Thus, the breakeven prices were similar. More batteries contribute greater ancillary service capacity and therefore, allow more intermittent generation resources to connect to the power grid. However, the amount of regulation and real-time dispatch services that an individual battery provides depends mainly on its power rating. For the "with 20% renewables" and "without wind" cases, signals sent to the NaS battery are all within its rated power output of ±4 MW. For example, although 193 MW are needed for regulation without wind, and 248 MW are needed for regulation with 20% renewable, for the 4-MW NaS battery, it provides services within ±4 MW in both cases; therefore, the amounts of energy provided in both cases are similar.
- If an NaS battery is operated for 20 years at its rated output 4 MW, operating it at a lower depth of discharge (DOD) results in less cost with the now lifecycle-DOD curve.
- If manufacturers can improve the NaS battery lifecycles at high DODs, as shown by the red line in Figure 3, the breakeven price will drop significantly for high DOD cases. The results are compared in Figure 4.



	0.05	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Now	37920	12509	41265	21569	13612	9525	7115	5560	4490	3719	3142
ideal	37920	12509	53645	32354	27224	23813	21345	19460	17960	16736	15710

Figure 3: The battery lifetime with respect to the depth of discharge

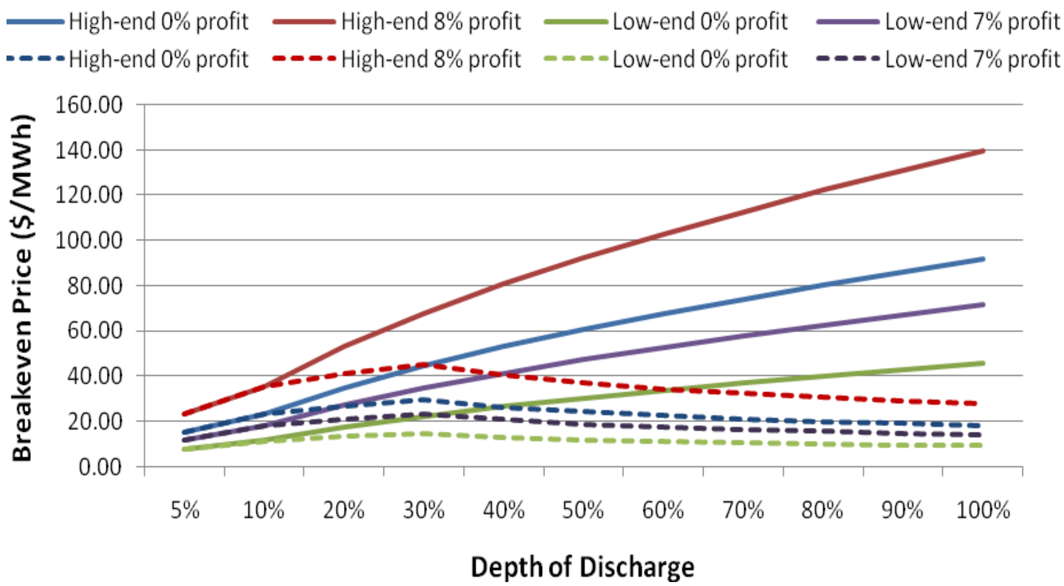


Figure 4: A comparison of high-end and low-end breakeven prices of the improved battery lifecycle case (dashed lines) and the base case (solid lines)

4.0 Recommendations and Future Works

4.1 Recommendations

From Phase I and II results, we concluded that the opportunities for flywheels or other energy storage devices lie in the following areas:

- To avoid performance problems associated with their finite energy storage capacity, provide regulation services for system operators which would agree to manage the flywheels' energy level, or participate in alternative schemes helping to co-optimize fast acting storage devices and conventional generators to provide high-quality combined regulation services.
- Operate energy storage devices in conjunction with conventional generators to improve their response time, reduce their wear and tear, and provide compatible services that do not require modifications of the existing automatic generation control and market systems.
- To increase the capacity payment, explore opportunities for sharing regulation services among two or more balancing authorities.
- Investigate methods and tariff changes so that the fast responsive and flexible resources can be compensated for additional services such as frequency response, fast ramping, voltage and reactive power support, or damping of transmission line oscillations to prevent grid angular instability.

4.2 Future Works

During Phase 2 of the Wide Area Storage and Management System (WAEMS) project

- a standalone sodium sulfur battery storage for regulation and load-following services was demonstrated to be not economical;
- the performance of a prototype WAEMS controller that operates a flywheel energy storage system in conjunction with a hydropower plant for regulation service was demonstrated to be satisfactory by field tests using actual Bonneville Power Administration (BPA) and California Independent System Operator (CAISO) regulation signals; and
- the breakeven price of the WAEMS regulation service was calculated to be slightly higher than the current average price for regulation in the CAISO market.

Based on these results, it is recommended that the next phase of the WAEMS project focus on research leading to (1) practical deployment of the WAEMS that provides balancing services (including both load-following and regulation services) to the CAISO and BPA balancing authorities and (2) commercialization of the control algorithms developed in Phases 1 and 2 of the WAEMS project.

A near-term goal should be commercialization of a shared storage system between CAISO and BPA. A longer term goal should be development of methodologies for operating both fast and slow resources and sharing these resources over multiple control areas to facilitate the renewable integration and operate the power grids reliably and economically.

The next steps are to

- enhance the WAEMS controller so that it is more robust and can provide load following services;
- field test more energy storage technology options, such as Li-ion battery energy storage; and
- assist BPA and CAISO to deploy a WAEMS system between BPA (offer a hydropower plant) and CAISO (offer an energy storage device).

Another potential area of future research is the development of an energy storage evaluation toolbox that incorporates the models, algorithms, methodologies, and standardized testing signals developed or obtained in previous WAEMS tasks. This toolbox would help users find optimal configurations and assess the performance and economics of different energy storage solutions, enabling them to answer the following questions:

- Are the selected ESDs capable of providing the required services as expected?
- How much fast-regulating ESD capacity is needed for a given regulation/load-following signal?
- What is the cost of the service?

This research will provide information for power grid operators to make decisions on building an energy storage portfolio that best meets the wind-integration requirements and is most economical to implement.

5.0 References

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Appendix A

Flywheel Field Tests Final Report

PNNL-19669

http://www.pnl.gov/main/publications/external/technical_reports/PNNL-19669.pdf

Appendix B

Battery Storage Evaluation Final Report

PNNL-18679

http://www.pnl.gov/main/publications/external/technical_reports/PNNL-18679.pdf

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