The Economic Case for Bulk Energy Storage in Transmission Systems with High Percentages of Renewable Resources

Final Project Report

Power Systems Engineering Research Center

Empowering Minds to Engineer the Future Electric Energy System
The Economic Case for Bulk Energy Storage in Transmission Systems with High Percentages of Renewable Resources

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Power Systems Engineering Research Center

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Executive Summary

As the penetrations of variable renewable generation increase, the uncertainty and variability of wind and solar require more resources to follow the variations. Energy storage technologies may become an increasing part of the resource mix for following renewables. This final report addresses several aspects of the economics of using energy storage, optimized for multiple objectives, including cost, congestion, and emissions, for increasing levels of renewable resource penetration. The report is presented in three parts.

Part I: Optimal Generation Expansion Planning with Integration of Variable Renewables and Bulk Energy Storage Systems

Pumped-hydroelectric energy storage has proven to be valuable as bulk energy storage for energy arbitrage coordinating with conventional thermal generators. New storage technologies, including compressed air and batteries, are in various stages of development and commercialization. In the future grid there are uncertainties in terms of modeling and optimization in assessing the value of bulk energy storage coordinating less with thermal generators and more with wind and solar. Moreover, the price of natural gas is predicted to have large variations in the next several decades and new environmental regulations may cause the retirement of some coal fired generators. A generation planning model is therefore needed that comprehensively models wind, solar and energy storage under multiple scenarios of energy and environmental policies and natural gas prices.

Part I of this report presents such an optimal planning model using a multi-period optimization formulation that is implemented in MATPOWER’s open source extensible optimal power flow structure. Storage, wind, and several types of energy storage are available as resources in the generation expansion model. Storage at multiple locations is co-optimized in hourly simulations using four representative weeks for the four seasons.

Policies are modeled as prices and limits to CO2 emissions and subsidies to renewable generation. In a cap-and-trade scenario, CO2 prices begin at 36.94 $/ton and rise to 60.18 $/ton over a 20-year planning horizon. Subsidies for wind and solar were modeled as 22 $/MWh. An emissions cap of 1,000 lbs/MWh was modeled for new generation. A low natural gas price scenario has the price rising from 2.5 $/MBtu to 5.86 $/MBtu over a 20-year planning horizon. A high gas price scenario rises to 14 $/MBtu.

The planning model was first tested and verified on a 3-bus test system. This model was then applied to a 20-year planning horizon on a reduced 240-bus model of the Western Electric Coordinating Council (WECC) system. The planning model developed in this work is now available for use on other systems by system planners and researchers.

The implementation of the planning model on the WECC system yielded some interesting results:

- In every case simulated except the case with high natural gas prices, no renewable subsidies, and no price or limit on CO2 emissions, coal-fired generation is retired. Retirements are greatest for the low gas price case with CO2 price and renewable incentives.
• Significant natural gas fired generation is retired in every case. New gas-fired generation is built in the low gas price cases with CO₂ price and renewable incentives, and with no incentives or CO₂ price.
• Nuclear generation is built in all of the high-gas-price cases.
• A significant amount of new wind generation is installed in every case except the case with low natural gas prices, no renewable subsidies, and no price or limit on CO₂ emissions.
• Solar generation is installed in the cases with a CO₂ price, regardless of gas price, and in the high-gas-price case when there is a limit on CO₂ emissions for new generation.
• Energy storage is installed in every case except the low-gas-price case when there is a limit on CO₂ emissions for new generation.
• Average production costs, which includes fuel, O&M, emissions, and subsidies, increase in all cases over the first ten years. They then decrease over the second ten years for the cases with high gas prices. They remain approximately constant for the low gas price cases with either a price or limit on CO₂ emissions. Average production costs continue to increase for the case with low gas prices and no price or limit on CO₂ emissions.
• CO₂ emissions only decrease over the 20-year horizon in the cases with a price on CO₂ emissions.

Future research will revise the environmental regulations to those that have been proposed by the US Environmental Protection Agency in 2014. Transmission expansion will be added to the planning model. Unit commitment, ramp rates, and market models will also be added, along with a corresponding reductions from one-hour to shorter simulation time steps.

**Part II: The Cost and Benefit of Bulk Energy Storage in the Arizona Power Transmission System**

This research project addresses the issue of making an economic case for bulk energy storage in electric power systems. Bulk energy storage has often been suggested for large scale electric power systems in order to levelize load; store energy when it is inexpensive and discharge energy when it is expensive; potentially defer transmission and generation expansion; and provide for generation reserve margins. As renewable energy resource penetration increases, the uncertainty and variability of wind and the diurnal variation of solar energy may be alleviated or even eliminated through the utilization of bulk energy storage technologies. The research considers the utilization of **pumped hydro storage** as the main, credible, and economically feasible energy storage technology. The focus in this report is on pumped hydro energy storage.

The research describes how pumped hydro storage can improve (reduce) operating costs. The intent is to partially justify the commission of large scale pumped hydro energy storage through the reduction of operating costs. Note that the design of large scale storage is done in the long term, typically longer than five years, and economic operation of power systems is done in real time. These are disparate time horizons. The proposal described in
this report is for the design of large scale energy storage using the benefits of economic operation as a partial justification of the project.

From a technical approach, the quadratic programming function in MATLAB termed QUADPROG is used to simulate an economic dispatch that includes energy storage. A program is created that utilizes quadratic programming to analyze various cases using a 2010 summer peak load from the Arizona transmission system, part of the Western Electricity Coordinating Council (WECC). The MATLAB program is used to test the Arizona test bed with a low level of energy storage to study how the storage power limit affects several optimization outputs such as the system wide operating costs. Very high levels of energy storage (e.g., up to 13.6 GW) are then augmented to see how high level energy storage affects peak shaving, load factor, operating costs and other system applications. Various constraint relaxations are made to analyze why the applications tested eventually are limited by the facilities available. That is, the transmission and storage assets that are the operational constraints are identified. Pumped hydro energy storage has two main specifications: power (i.e., MW) and energy (i.e., MWh). The ratio of these two quantities, E/P, is discussed in the report and levels of E/P from 1.0 to 10.0 are discussed and evaluated.

The authors identify strengths and weaknesses of the quadratic programming approach. The main strength is that the software needed for the analysis of efficacy of pumped hydro is readily available and no special data requirements are present. Also, results indicate that the quadratic programming approach gives an accurate answer within the bounds of approximate modeling of active power losses in the transmission system (e.g., about 3 – 5%). The ‘DC power flow study’ assumption is made for the analysis and the report assesses the accuracy of this approach: there is good / excellent agreement with alternative analyses which use more elaborate models. Advice and experience in the use of QUADPROG are given in an appendix for potential users of these software tools.

A main conclusion of the study is that bulk energy storage using pumped hydro, even in a desert environment such as Arizona, may offer an economically feasible technology to levelize the system load, and thereby reduce operating costs. The analysis includes published data on the costs of development of pumped hydro. Typical figures for Arizona are found to be a reduction of operating costs in the 4 to 8% range is feasible.

The documentation and test cases focus on the potential for six pumped hydro sites in Arizona and adjacent southern California and Nevada:

- Longview Pumped Storage located in Big Chino Valley, Yavapai county, southeast of Seligman, AZ
- Table Mountain Pumped Storage located in Mohave county near the towns of Peach Springs and Kingman, AZ
- Eagle Mountain Pumped Storage located in San Bernardino county, northeast of Palm Springs, CA
- Lake Mead located in Clark county Nevada and Mohave county Arizona, near Boulder City, NV
- Glen Canyon in Coconino county Arizona near Page, AZ
- Horse Mesa in Maricopa county near Globe, AZ.
A discussion of the non-electrical issues in the development of these sites is given. These include regulatory, environmental, and sociological issues. The logical next step in bringing this technology to fruition would be a full scale study of both the economic dispatch and unit commitment of a large scale system with pumped hydro as bulk energy storage. The analysis contained in this study is considered to be preliminary because the following issues are modeled and considered only in approximate terms: the cost to develop a site for pumped hydro; national and international issues relating to water usage (e.g., from the Colorado River); accounting for water losses; accounting for long term environmental phenomena (e.g., drought); approvals required from Native American communities; public acceptance of such proposals (which are by their nature large-scale and publically visible); availability of funds from commercial, private, and state and national sources for the required investment.

From a technical point of view, the detailed inclusion of active power losses in the transmission system were modeled only in an approximate way, and this too deserves greater scrutiny. Suggestions for further work are given in Chapter 6 of the report.

**Part III: Economic Assessment of Energy Storage in Systems with High Levels of Renewable Resources**

Part III of the final report evaluates the attractiveness of bulk energy storage technologies under high renewable penetration levels. Different energy storage technologies are studied to assess the economic case of energy storage in systems with high renewable penetration levels and identify their appropriate applications.

This report reviews the different types of bulk energy storage technologies. The characteristics of different energy storage technologies, such as power and energy capacities, ramping capabilities, and other characteristics are described. Based on the characteristics and costs, the appropriate applications are identified and summarized for each type of energy storage technology.

To study the economical case for bulk energy storage in transmission system with high renewable penetration, a stochastic unit commitment model is proposed to identify the impact of increasing renewable penetration on the attractiveness of bulk energy storage in comparison to conventional generators. By using a stochastic unit commitment model, both the energy shifting and fast ramping capabilities of energy storage technologies are captured endogenously. The results show that conventional generators will see lower profits and, hence, produce lower returns on investments as the renewable penetration levels increase. However, by integrating energy storage into the system, the average costs of conventional generators decrease, while fewer generators are dispatched in the system with higher capacity factors compared to the cases without energy storage. As such, energy storage improves the utilization of the conventional generators in the system.

Besides providing bulk energy management services, the benefits of energy storage in procuring regulation services in real-time operation are also evaluated in this report. A two-stage optimization framework is used to demonstrate the attractiveness of energy storage in providing high quality of regulation services. By having energy storage in the
system, the system reliability and the capability to integrate high penetration levels of renewable energy are enhanced.

While most forms of energy storage are still considered to be too expensive and not competitive with conventional generators, it is shown in the report that the attractiveness of conventional generators decreases as the renewable penetration levels increase whereas the attractiveness of energy storage increases with the increase in renewable resources. As a result, with new energy storage technologies, it is expected that there will be a break point where energy storage becomes competitive with conventional generating resources, resulting in increased deployment of energy storage technologies.

**Project Publications:**

N. Li and K. W. Hedman, “Economic assessment of energy storage in systems with high levels of renewable resources,” *IEEE Transactions on Sustainable Energy*, accepted for publication.


**Student Theses:**
