Energy Research and Development Division
FINAL PROJECT REPORT

THE VALUE OF ENERGY STORAGE AND DEMAND RESPONSE FOR RENEWABLE INTEGRATION IN CALIFORNIA

Prepared for: California Energy Commission

Prepared by: Lawrence Livermore National Laboratory

JUNE 2013

CEC-500-XXXX-XXX

Primary Author(s):
Thomas Edmunds
Alan Lamont
Vera Bulaevskaya
Carol Meyers
Jeffrey Mirocha
Andrea Schmidt
Matthew Simpson
Steven Smith
Pedro Sotorrio
Philip Top
Yiming Yao

Lawrence Livermore National Laboratory
7000 East Avenue
Livermore CA 94550
925-422-1100
www.llnl.gov

Contract Number: 500-10-051

Prepared for:

California Energy Commission

Avtar Bining, Ph.D.
Contract Manager

Fernando Pina
Office Manager
Energy Systems Research Office

Laurie Ten Hope
Deputy Director
Energy Research and Development Division

Robert Oglesby
Executive Director

ACKNOWLEDGEMENTS

The authors would like to thank Michael Gravely, Fernando Pina, Avtar Bining, Steven Ghadiri, and Ivin Rhyne at the California Energy Commission for their support and guidance. The authors would also like to thank the following persons for their advice, data resources, references to other works, and software support:

1. Mark Rothleder, Clyde Loutan, Shucheng Liu, Edward Lo, James Price, and John Goodman, California Independent System Operator
2. Glenn Drayton, Julian Hamilton, and David Llewellyn, Energy Exemplar, LLC
3. Wenxiong Huang, Plexos Solutions, LLC
4. Warren Katzenstein and Ralph Masiello, DNV KEMA Corp.
5. Guojing Cong, IBM Corp.
6. Sila Kiliccote, Mary Anne Piette, and Nance Matson, Demand Response Research Center
7. Benjamin Kaun, Haresh Kamath, and Robert Schainker, Electric Power Research Institute
8. Giovanni Damato, Strategen Corp. representing California Energy Storage Alliance
9. Chi-Fan Shih and Karen Gibson, National Center for Atmospheric Research
10. Alexandra von Meier, California Institute for Energy and Environment
11. Ronald Hofmann, Consultant
12. Antonio Alvarez, Alva Svoboda, and Daidipya Patwa, Pacific Gas and Electric Company

EXECUTIVE SUMMARY

Introduction

Implementation of California's goal of 33 percent renewable energy by 2020 will substantially increase the variability and uncertainty in electricity generation for the State's grid operators. Controlling demand with demand response programs could help mitigate this variability and uncertainty. In addition, new energy storage technologies could help levelize loads during the day and provide additional operating flexibility.

Project Purpose

The overall economic goal of this project is to identify policies, technologies, and control methods that could reduce the cost and improve the reliability of electric power for California ratepayers. The technical objectives of the project are:

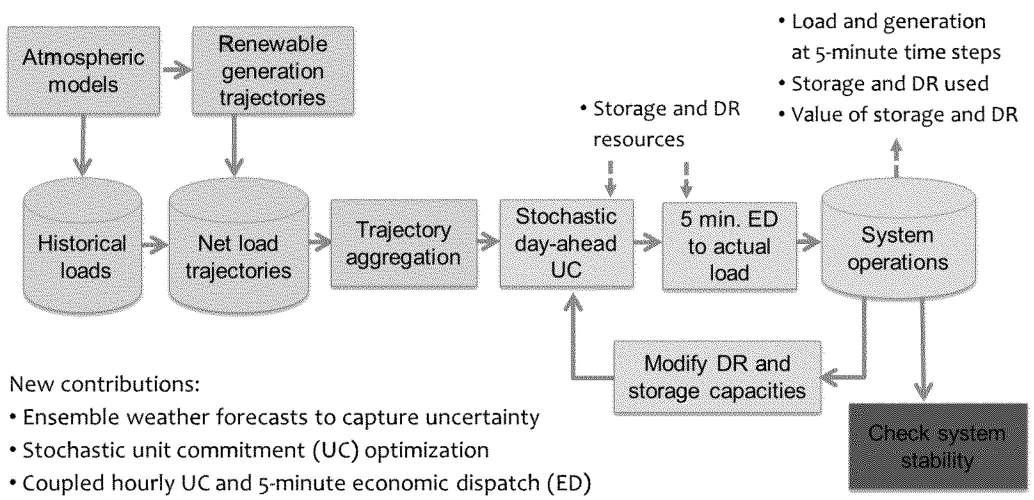
- Develop scenarios that probabilistically characterize the requirements for system control under high penetration of intermittent generation.
- Develop a simulation test bed that includes forecasting, unit commitment (scheduling resources to turn on or off), and economic dispatch (setting power levels) taking into account the scenarios.
- Characterize performance of a range of candidate demand response, energy storage, and generation technologies using the simulation test bed.

California Assembly Bill 2514 (Public Utilities Code Sections 2835-2839) enacted in 2010 directs the California Public Utilities Commission to open a proceeding to determine, if appropriate, procurement targets for energy storage by load serving entities. This study, which shows the value that different levels of energy storage capacity can provide, is intended to inform that decision.

Project Results

The models and the overall analysis process developed for this study are depicted in **Figure ES-1**. As indicated by the color coding in the figure, there are three basic components: weather and renewable generator models (blue), a stochastic production simulation model that finds the minimum-cost operating schedule (yellow), and an electromechanical simulation model that checks the stability of the system (green).

Figure ES-1: Renewable Generation, Production Simulation, and Resource Evaluation Process



The analysis approach incorporates three new capabilities:

- **Ensemble weather forecasts with uncertainty** – An ensemble is a collection of possible paths or trajectories that the weather may follow. The ensemble is produced by varying the atmospheric physics sub-models that govern evolution of weather conditions for that particular day. This approach is in contrast with current planning modeling methods that use one forecast for each day and one uncertainty value for each season.
- **Stochastic unit commitment optimization** – The production simulation model minimizes cost taking into account the stochastic or randomness of the system as represented by the ensemble of possible renewable generation trajectories produced by the weather model. Current practice is to minimize cost for a single trajectory, and to add safety factors that increase operating costs.
- **Coupled hourly and 5-minute timescales** – The production simulation model utilizes two different timescales for the unit commitment and economic dispatch to perform the optimization. Current planning models use a single timescale.

The Electric Power Research Institute, the California Energy Storage Alliance, and the Demand Response Research Center provided the data and assumptions describing energy storage and demand response resources that are used in the models. The California Independent System Operator provided the production simulation model and other supporting data.

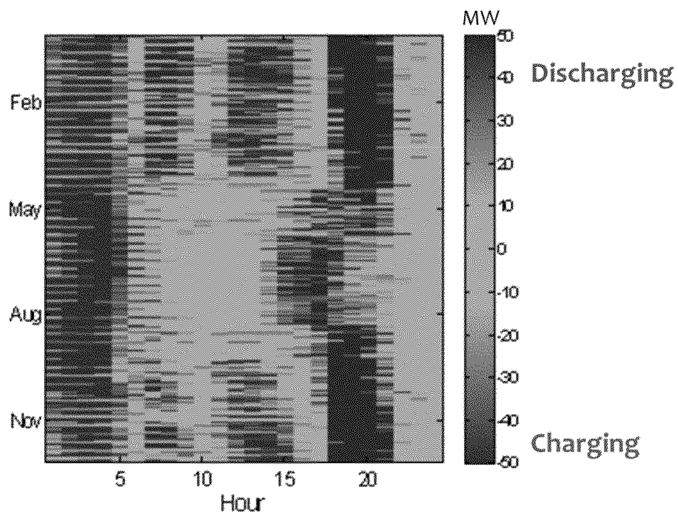
Over 3,000 days were simulated using this process under various sets of assumptions. Running the models on high performance computing systems with thousands of cores, the equivalent of thousands of personal computers, allowed us to complete results thousands of times faster. The entire analysis campaign required three million core hours of computer time – the equivalent of 342 years of continuous operation of a single personal computer.

A number of cases with different technologies and quantities of demand response and energy storage are analyzed using the stochastic production simulation model. The hourly values of regulation, load following, spinning reserve, and non-spinning reserve are computed to estimate potential revenue streams from energy storage or demand response resources that could provide these services.

Energy Storage Results

To characterize operation of Li-ion batteries with four hour discharge time, the production simulation model was run for all hours of the year. Usage patterns are shown in **Figure ES-2**. Each day of the year corresponds to a horizontal line and each hour of the day corresponds to a vertical line.

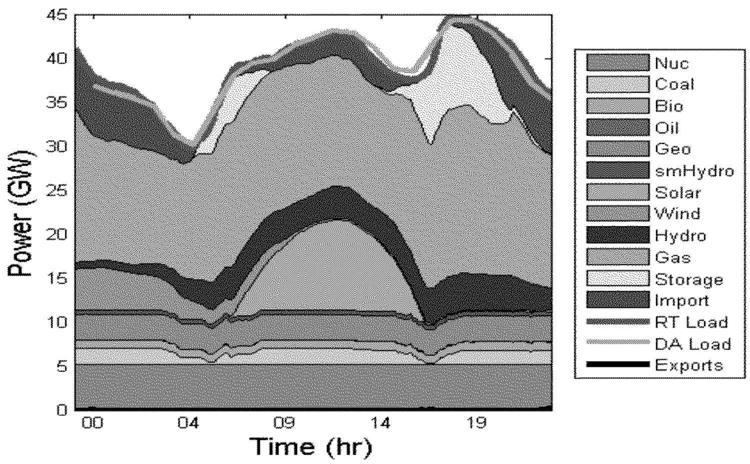
Figure ES-2: Generation and Charging for 50 MW Li-Ion Batteries



The figure shows days and times when the battery is charging (blue colors) and discharging (red colors). As indicated by the patterns in the figure, usually there are two charge-discharge cycles in the winter, spring, and fall. During the summer, the system only cycles once per day.

Li-ion, flow battery, and compressed air energy storage devices were added and the system was simulated. Conventional generation and storage usage for January 15, 2020 are shown in **Figure ES-3**.

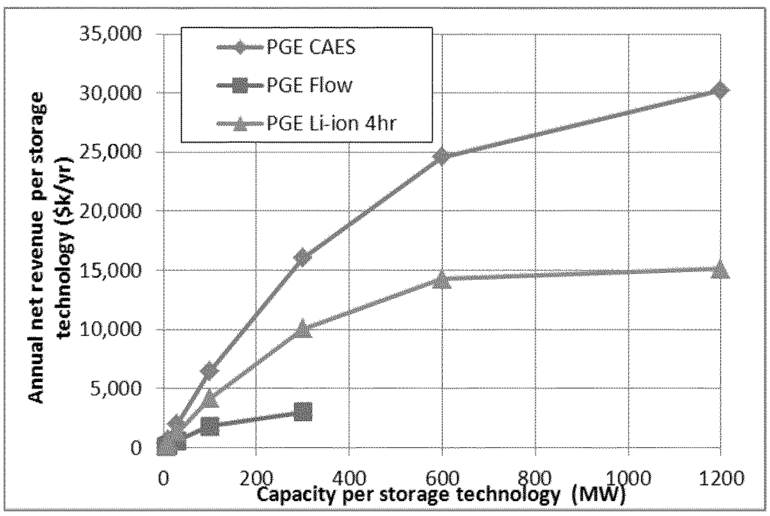
Figure ES-3: Usage of 7,200 Megawatts of Storage on January 15, 2020



As indicated by the blue area in the figure, wind is available in the early morning to charge the batteries on this day. As indicated by the gray area on the top left, energy storage is discharged during the ramp up to meet the mid-day peak. Storage is used more heavily to meet the daily peak at hour 19 (7:00 p.m.).

A sensitivity study was conducted by increasing the power of three energy storage technologies while maintaining a four-hour discharge time. Net revenues (revenue from energy discharge minus costs of energy for charging the battery) are shown in **Figure ES-4**. Net revenues for energy storage in Southern California Edison's service territory are similar.

Figure ES-4: Annual Net Revenues for Energy Storage (4 Hour Discharge)



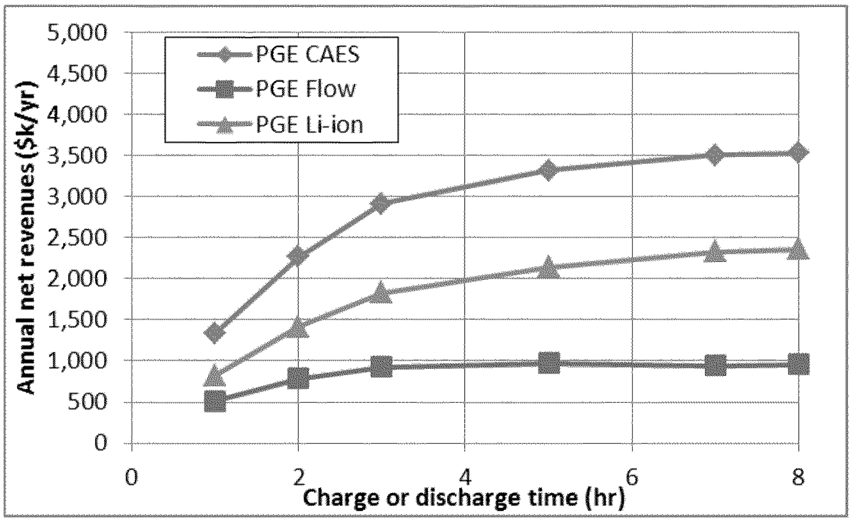
SB_GT&S_0890401

The horizontal axis shows the power for each energy storage technology. Because there are three technologies in each of two service territories, the total storage power in California is six times the value shown on the horizontal axis. The vertical axis shows the annual net revenue, or annual operating profit, from energy arbitrage for each energy storage technology. Some key results are as follows:

- Compressed air energy storage provides the highest net revenue from energy arbitrage and flow batteries provide the lowest.
- Flow batteries are no longer dispatched when 600 megawatts of each technology are deployed.
- The reduced benefits of additional capacity may suggest a goal 1,200-1,800 megawatts of energy storage capacity for the State based upon operating costs and benefits associated with energy arbitrage.
- The first kilowatt of compressed air, Li-ion, and flow battery storage provide $70, $45, and $20 per year net revenues from energy arbitrage, respectively.
- Levelized capital costs of these three storage technologies are $302, $616, and $318 per kilowatt per year, respectively. Net revenues from energy arbitrage are significantly less than levelized capital costs.
- Load following, regulation, and spinning reserve ancillary services could each provide approximately $100 of revenue per kilowatt per year.
- Using 100 megawatts of energy storage for regulation could reduce cycling of other units by 80%.
- 200 megawatts of flywheels providing regulation would save $70 million per year, which exceeds the levelized flywheel capital costs of $60 million per year.

A sensitivity study was conducted by varying the discharge time while holding the power constant at 50 megawatts per technology per service territory (300 megawatts total). Results are shown in **Figure ES-5**. As indicated in the figure, energy storage systems with discharge times less than 3 hours are significantly more valuable.

Figure ES-5: Annual Net Revenues for 50 Megawatts of Storage for Each Technology



Demand Response Results

Some key observations regarding the value of demand response are as follows:

- **Demand response for five minute load following** – Operating costs would be reduced by $84 million per year (0.7 percent of total operating costs).
- **Demand response for four second regulation** – System operating costs would be reduced by $31 million per year (0.3 percent of total operating costs).

Project Benefits

This study will benefit California ratepayers by informing policy makers of cost impacts associated with renewable generation, energy storage, demand response, and other goals for development and operation of the State power grid. Goals could be set to achieve environmental and other benefits without imposing an undue burden on California ratepayers. Given the billions of dollars in capital investments and operating costs associated with the power grid, a small improvement in decision making could provide substantial savings.