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# Assessment of Energy Storage Alternatives in the Puget Sound Energy System

## Volume 2: Energy Storage Evaluation Tool

**December 2013**

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Chunlian Jin  
Patrick Balducci  
Michael Kintner-Meyer



Prepared for the U.S. Department of Energy  
under Contract DE-AC05-76RL01830

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Pacific Northwest National Laboratory  
Richland, Washington 99352



# Executive Summary

This volume presents the battery storage evaluation tool developed at Pacific Northwest National Laboratory. The tool is used to run a one-year simulation to evaluate the benefits of battery storage for multiple grid applications, including energy arbitrage, balancing service, capacity value, distribution system equipment deferral, and outage mitigation. This tool is based on the optimal control strategies to capture multiple services from a single energy storage device. In this control strategy, at each hour, a look-ahead optimization is first formulated and solved to determine the battery base operating point. The minute-by-minute simulation is then performed to simulate the actual battery operation.

The development of this tool was motivated by the need for the distribution planning community to have a tool to analyze energy storage with its multitude of services. The tool described in this report enables distribution system planning engineers to model the dispatch of an energy storage system to meet multiple objectives while estimating the economic value of the system as a grid asset when optimally operated.

This volume provides background and a manual for this evaluation tool. Volume 1 of this report presents the findings of the financial feasibility study for energy storage systems in the Puget Sound Energy system, and also documents the optimization tool's structure and application.



## **Acknowledgments**

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## Acronyms and Abbreviations

ESS	energy storage system(s)
PNNL	Pacific Northwest National Laboratory
PSE	Puget Sound Energy
SOC	state of charge



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# 1.0 Introduction

A battery storage device can be operated to provide multiple services. Considering the cost of energy storage systems (ESS), capturing value streams from multiple applications is extremely important for financial viability. This volume presents the ESS evaluation tool and the optimal control strategy developed at Pacific Northwest National Laboratory (PNNL) for its evaluation of energy storage in the Puget Sound Energy (PSE) system.

## 1.1 Background

There are different ways to charge and discharge an energy storage device over time. The total value from various applications depends on how the battery is operated. It is, therefore, desirable to control the battery in an optimal manner such that total benefits are maximized. In the evaluation method developed at PNNL, we simulate how the battery system is scheduled and operated. In order to evaluate this practical value, two steps are used. At each hour, a look-ahead optimization is formulated based on energy and balancing prices and on the power requirements for capacity and distribution deferral services. The duration of the look-ahead window used here is 24 hours. The optimization problem is solved to determine the base operating point (power exchange between battery and grid on the AC side) and balancing service capacity on an hour-by-hour basis. These optimal solutions (provided in hourly increments) together with balancing signals and outage information are used to simulate minute-by-minute battery charging and discharging operation through the operating hour. This process repeats every hour, resulting in a rolling window. A discussion of the optimization formulation and minute-by-minute simulation process can be found in Section 3.2.6 of Volume 1 of this report. The evaluation process is illustrated in Figure 1.1. The methodologies used to estimate the values associated with various ESS services are described Sections 3.2.1 through 3.2.5 in Volume 1.

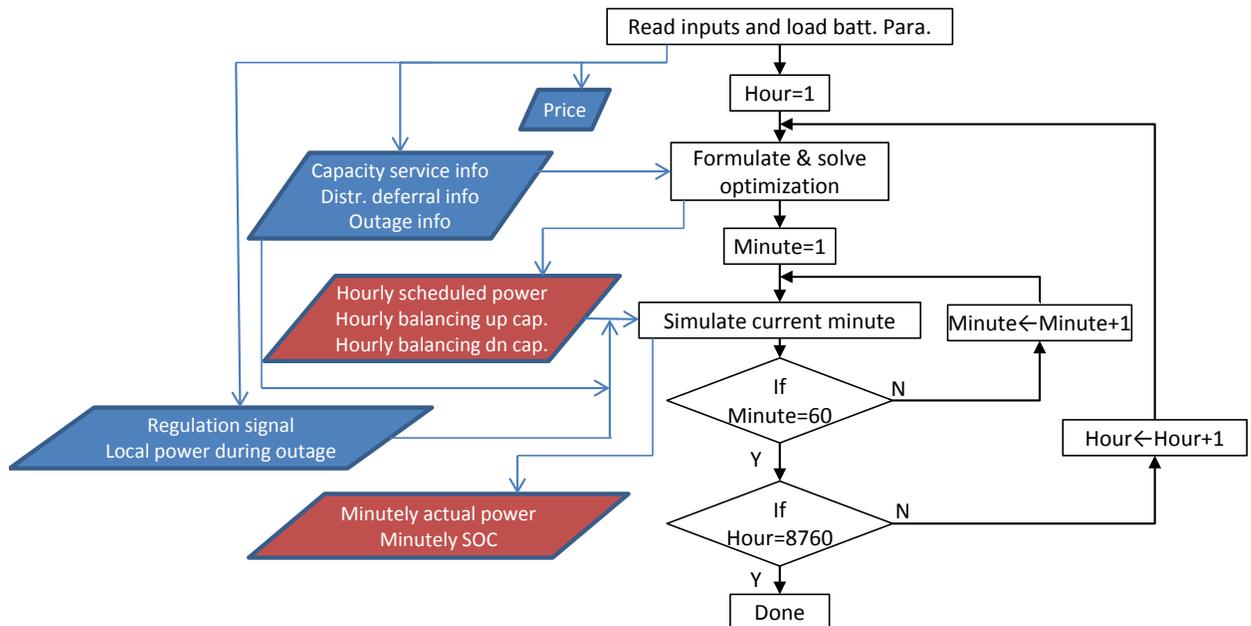


Figure 1.1. Flowchart of Battery Optimization Tool

## 1.2 Purpose of the Evaluation Tool

The evaluation tool automatically uses input data to repeatedly formulate and solve the optimization problem at each hour of the evaluation period, and to simulate the actual power exchange on a minute-by-minute basis. The input information includes battery parameters, energy and balancing prices, balancing signals, power requirements from capacity and distribution deferral services, and outage information. Users have the option to run the simulation for different locations (Bainbridge Island or Baker River) and differently bundled services. Users can also choose from among 50 balancing price scenarios. Model output monetizes the annual value obtained by providing each service (e.g., capacity, distribution deferral) and identifies the number of hours for which the ESS is used to provide each service.

The development of this tool was motivated by the need for the distribution planning community to have a tool to analyze energy storage with its multitude of services. The tool described in this report enables distribution system planning engineers to model the dispatch of an energy storage system to meet multiple objectives while estimating the economic value of the system as a grid asset when optimally operated.

## 2.0 Instructions for Using the Energy Storage System Optimization Tool

### 2.1 System Requirements

The ESS evaluation tool currently only runs on Microsoft® 64-bit Windows® operating systems. It was developed using MATLAB®, and the stand-alone executable file was generated using the Deploy Tool of MATLAB version 7.16 (R2011b). The tool can be run outside the MATLAB environment and users need not have a licensed copy of MATLAB. Before using the tool, users must first make sure that the MCR installer file, MCR7.16, is available on the target computer where the executable file will be run.

### 2.2 Installation

1. Decompress BattEvaluation.zip file:
  - *Input* folder: Default input files for the Bainbridge Island and Baker River cases
  - *Output* folder: Directory for output files
  - *BattEvaluation.exe*: Battery benefits evaluation tool
  - *MCRInstaller.exe*: MCR7.16.
2. Ensure you have installed MCR7.16 first. If the MCR is not installed, running *BattEvaluation.exe* will generate the error message shown in Figure 2.1.

 Input	11/18/2013 9:57 AM	File folder	
 Output	11/18/2013 9:57 AM	File folder	
 BattEvaluation.exe	12/9/2013 10:49 AM	Application	2,146 KB
 MCRInstaller.exe	8/14/2011 4:58 AM	Application	423,277 KB

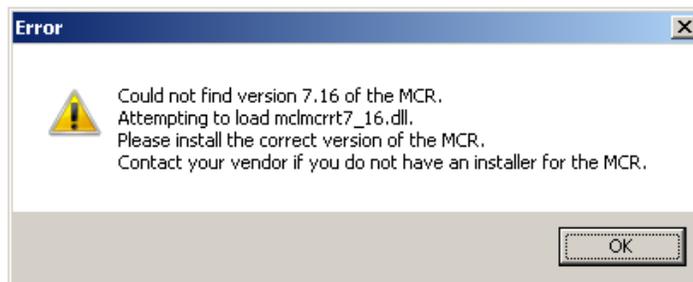
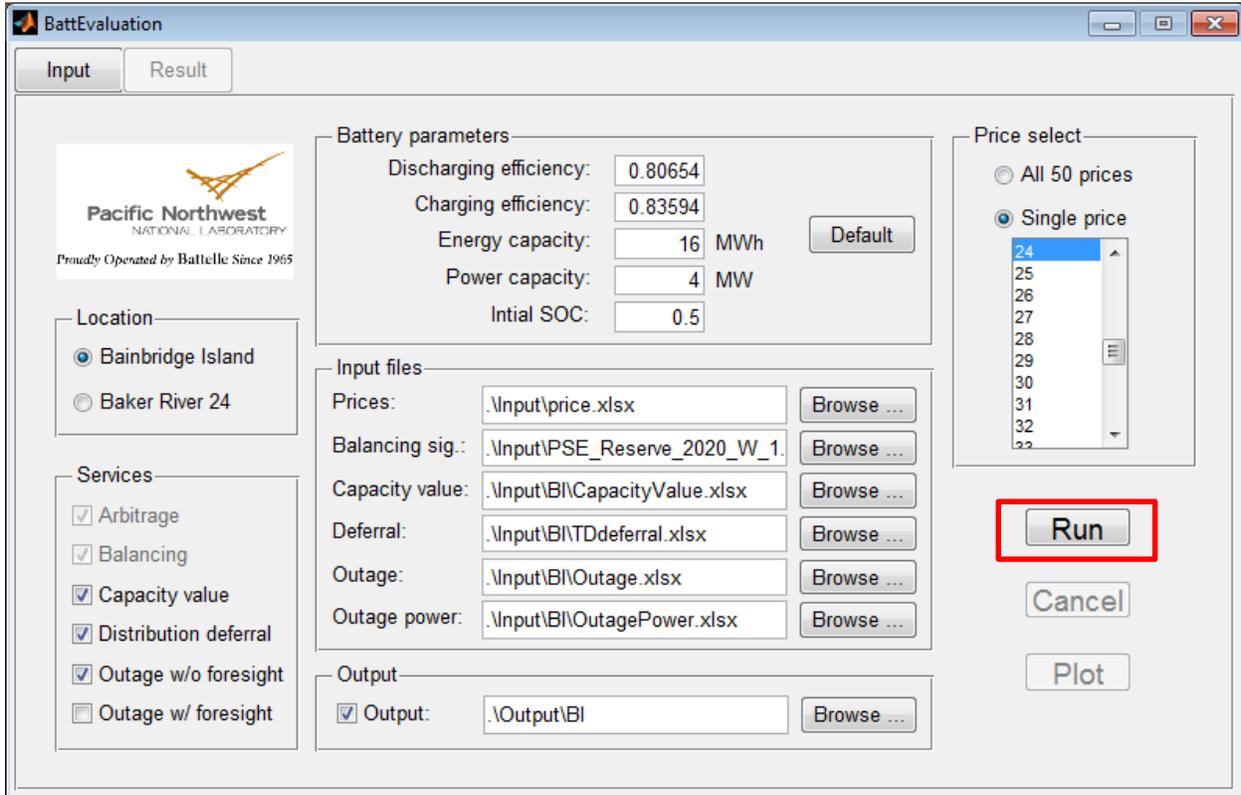


Figure 2.1. Error Message Displayed when MCR is not Installed

### 2.3 Running a Simulation

The primary functionality of the ESS evaluation tool is to formulate and solve the battery operational optimization and simulation over a 1-year period to evaluate the benefits from various applications.

Left-double-click *BattEvaluation.exe* to open the tool. By default, the *Input* tab will display, as presented in Figure 2.2. The *Result* tab is not enabled until a simulation has been run and results are available.



**Figure 2.2.** Battery Evaluation Tool Graphical User Interface

Click the *Run* button to start a simulation with default settings for 1) location, 2) services, 3) battery parameters, 4) input files, 5) output path, 6) and price. There are three phases in the simulation: a) reading input files; b) running the optimization; and c) writing solutions (if the *Output* check box is toggled on). The second phase is the most time consuming one. The progress bar indicates the status of the optimization, as shown in Figure 2.3. Once the optimization starts, users can terminate the simulation by clicking the *Cancel* button.

**Note:** Whenever the tool does not function properly or fails to respond, close and restart the tool.

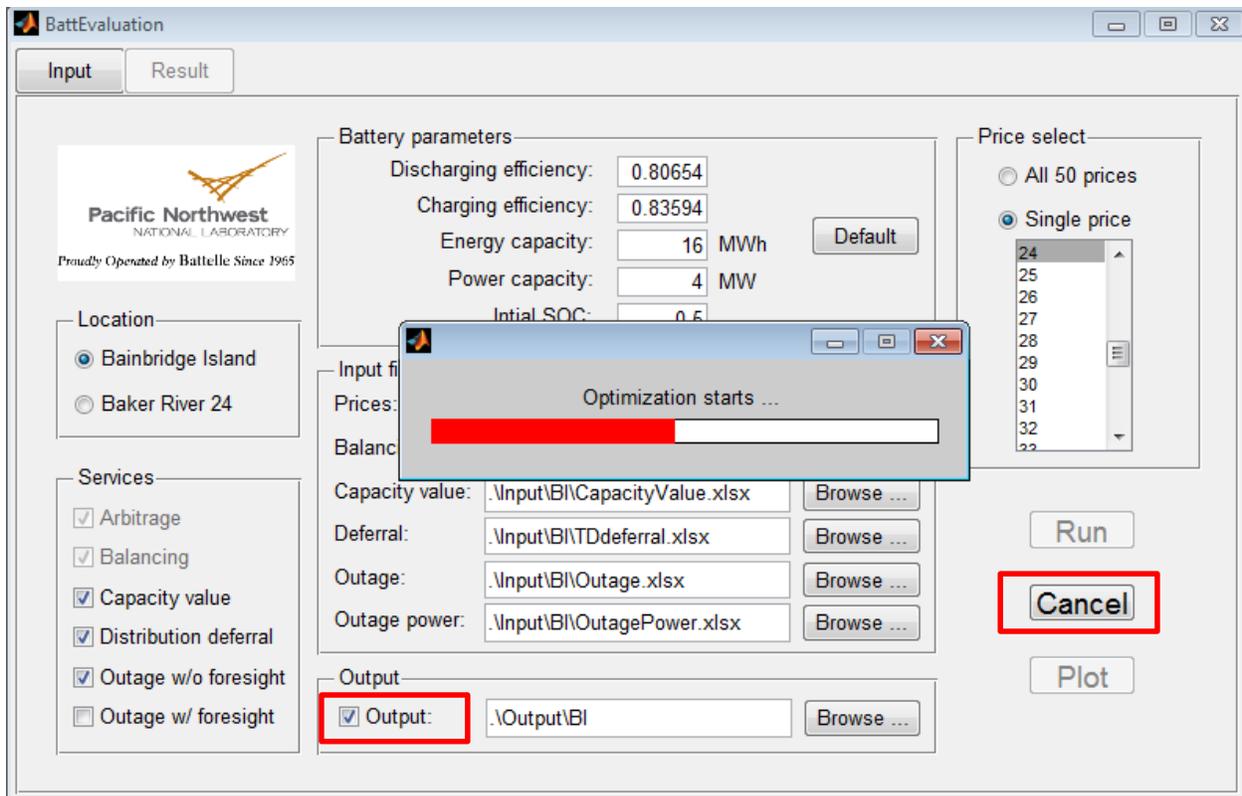


Figure 2.3. Running a Simulation with Default Settings

## 2.4 Viewing Simulation Results

When the simulation is finished, the user can 1) view results summary, 2) plot the minute-by-minute state of charge (SOC) and power output together with input prices, and 3) view the detailed results on their hard disk in the selected output location. The first two functions are only available when a single price is selected for simulation. If users elect to run simulations for 50 prices, the first two functions are not available and results need to be exported to a hard disk.

### 1. View results summary

Users can view summarized results by clicking the *Result* tab after a simulation is finished. Annual value derived from each service and the hour distribution from different services will be displayed, as shown in Figure 2.4.

### 2. Plot results

Users can also plot results by clicking the *Plot* button. Minute-by-minute SOC and power output together with input prices (hourly) will be plotted, as shown in Figure 2.5. The axes of three plots are linked together so that a zoom operation on the time axis in one subplot will automatically be applied to all three sub-figures. In addition, the time axis labels are automatically adjusted, as illustrated in Figure 2.6.

3. View results on hard disk

When the *Output* check box is toggled on, results are exported onto a hard disk. Description of the output files is provided in Section 3.5.

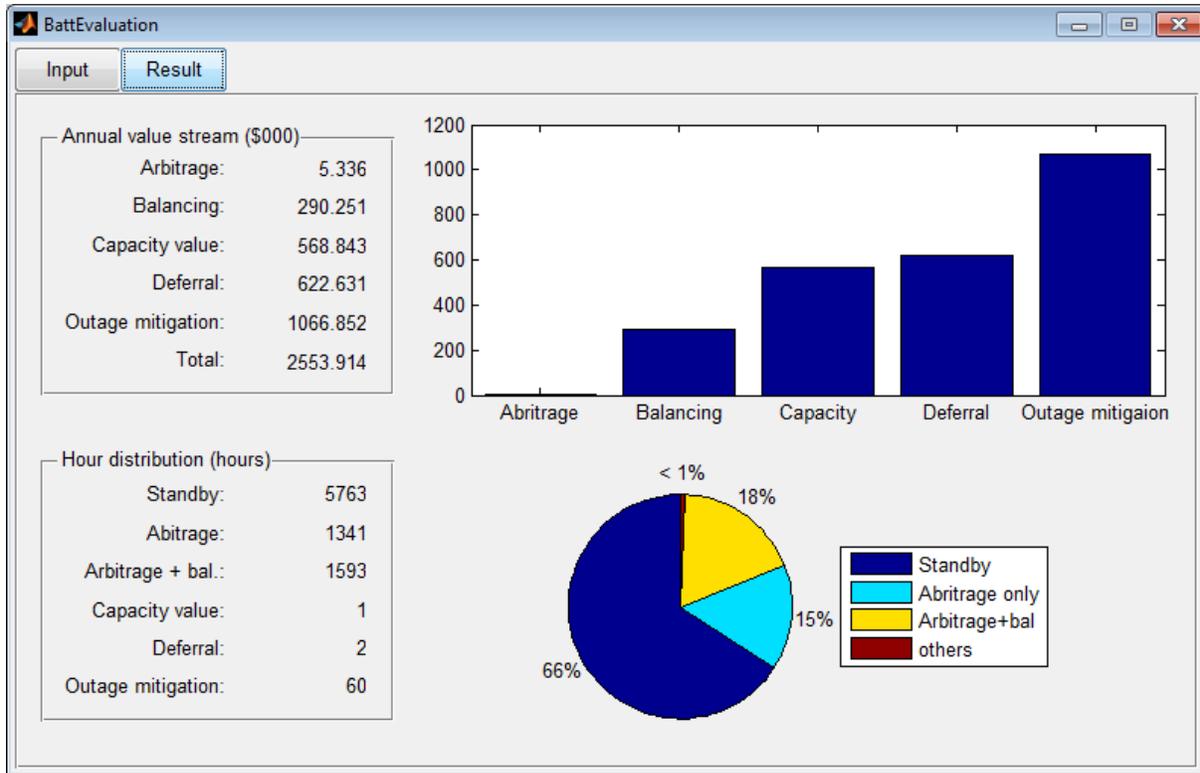


Figure 2.4. Results Summary

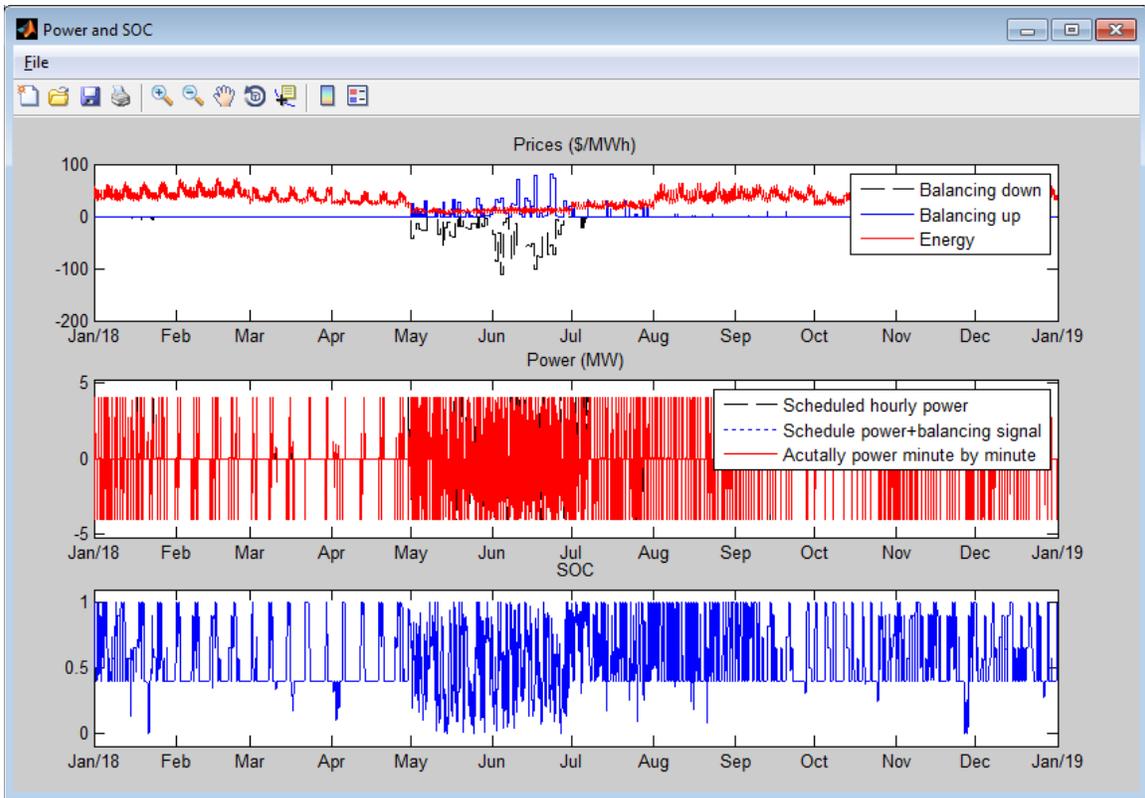
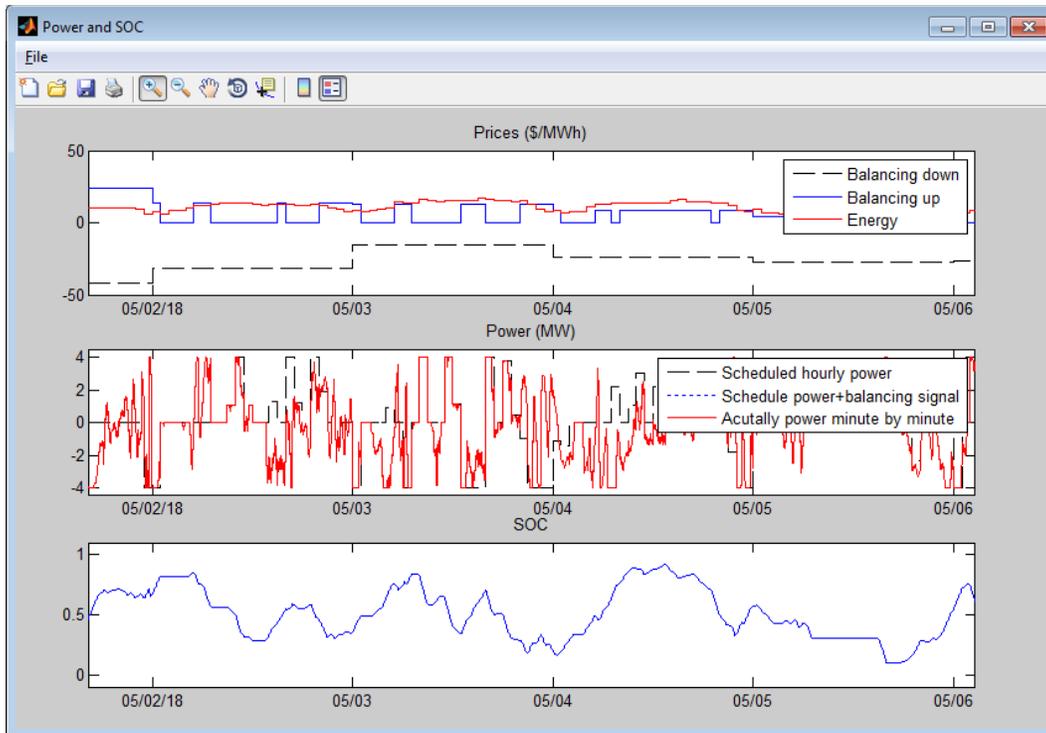


Figure 2.5. SOC and Power Output



(a)



(b)

**Figure 2.6.** SOC and Power Output: (a) Zoomed in to Day-Level Display; (b) Zoomed in to Hour-Level Display

## 3.0 Modifying Input Data and Settings

### 3.1 Location Panel

Two locations are available: Bainbridge Island and Baker River. These are two locations where PSE is considering ESS deployment, and are defined in detail in Section 3.1, Volume 1 of this report. When a location is changed, the default battery parameters, input files, and output folder change automatically.

### 3.2 Services Panel

There are four service bundles considered in this tool:

1. Arbitrage + balancing service
2. Arbitrage + balancing service + capacity value & distribution deferral
3. Arbitrage + balancing service + capacity value & distribution deferral + outage without foresight
4. Arbitrage + balancing service + capacity value & distribution deferral + outage with foresight

In the last two cases, all applications are considered. However, different assumptions are used to evaluate the value of mitigating outages. In the outage-without-foresight scenario, battery operation is scheduled without any foreknowledge of outages built into the optimization process. Therefore, the optimization proceeds the same as it would without outages. When an outage occurs, the battery immediately responds to address the local load until the battery is fully discharged or the system recovers from the outage. In the outage-with-foresight scenario, it is assumed that the battery is scheduled with foresight of outages. The battery is operated to obtain a full SOC before outages occur, and therefore may mitigate more of the outage. This scenario provides an upper bound of outage mitigation value.

#### *Notes:*

- Arbitrage and balancing service are considered in each of these four cases. Therefore, they are disabled from deselecting.
- Capacity value and distribution deferral services always appear together in the four bundled cases. Therefore, they are coded to be selected/deselected simultaneously. In other words, selecting or deselecting one check box will automatically execute on the other.
- Because scenarios of *Outage w/o foresight* and *Outage w/ foresight* are exclusive to each other, selecting one check box will automatically deselect the other.
- When outage mitigation is considered, capacity value and distribution deferral services are also considered. Hence, selecting *Outage w/o foresight* (or *Outage w/ foresight*) will automatically make *Capacity value* and *Distribution deferral* selected.
- Input files are automatically enabled and disabled as different services are toggled on and off.

### 3.3 Battery parameters Panel

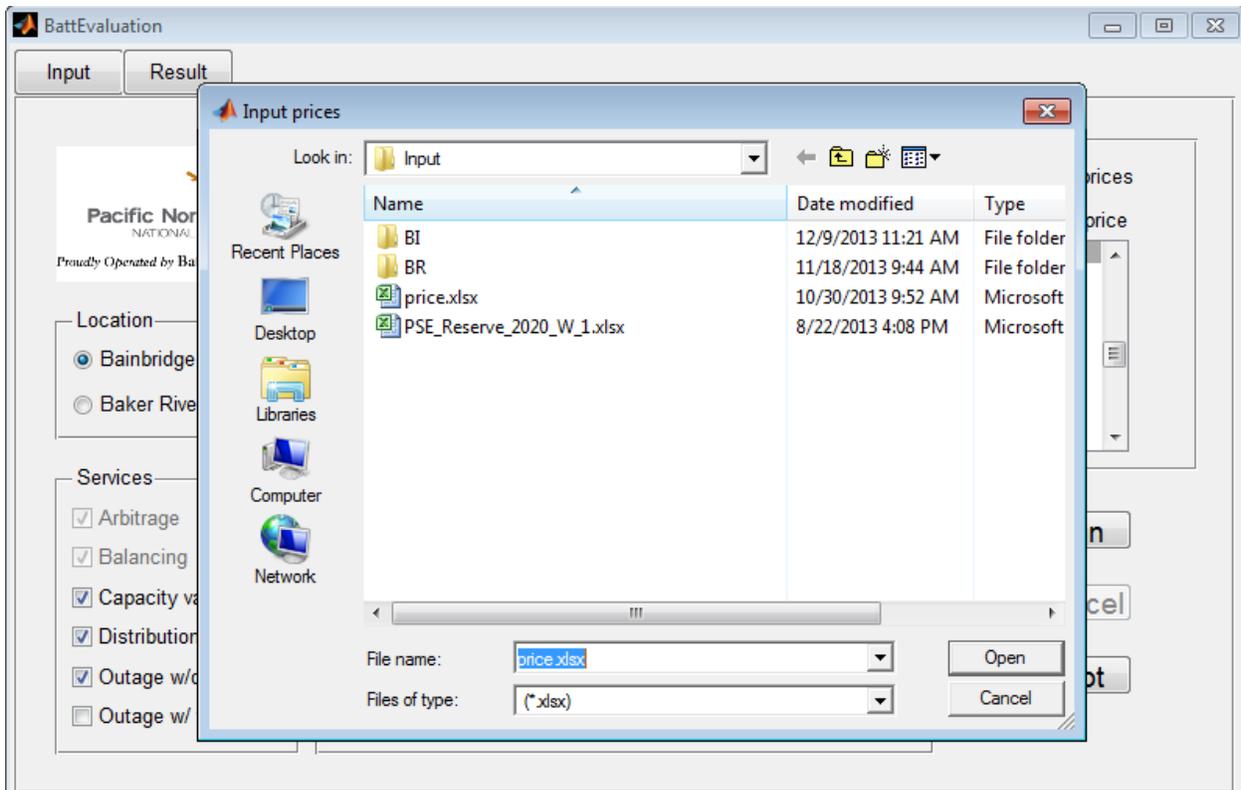
The evaluation tool starts with default battery parameters for each location. Users can easily modify battery parameters by typing in the desired values for power and energy capacity, as well as charging and discharging efficiencies. The *Default* button is used to reset battery parameters to default values.

### 3.4 Input files Panel

In order to evaluate the battery storage benefits, the following data are needed to run the optimization and simulation: i) minute-by-minute system balancing signal, ii) hourly energy and balancing prices, iii) power requirement for capacity value and distribution deferral, and iv) outage information.

- Balancing signals: The *Balancing Sig.* input file contains minute-by-minute balancing signals through a year. In this work, the system reserve requirement and balancing signals in the PSE system are determined stochastically based on one-minute system load data, wind generation data, and statistics of current load and wind forecast errors. There are 30 series of balancing signals. However, it has been found that evaluation results are not sensitive to balancing signals. Hence, the balancing signal nearest the median value was used as an input.
- Energy and balancing prices: The price forecasting model Aurora was used by PSE to minimize production costs and generate corresponding energy prices. Fifty Monte Carlo simulations were performed in order to capture uncertainties. Based on the results from Aurora and system reserve requirements generated by PNNL, PSE's internal mixed-integer linear programming model is used to determine the balancing services and prices. It has been found that evaluation results vary with input prices. Therefore, all 50 groups of prices are used as inputs. In the *Price select* panel, users have the option to either run simulation using all 50 groups of prices, or select one price for simulation. When *Single price* is chosen, a price index needs to be selected. By default, price No. 24 is selected, which provides results closest to the mean value of the 50 prices.
- The capacity value and distribution deferral input files contain information for power requirements during different hours of the year for the two services. The numbers in the default input files are obtained using forecast load information and available system/local resource capacity for Bainbridge Island and Baker River.
- Outage and outage power: The *Outage* input file contains a series of outage values, including date, start time, duration, and outage cost for different durations. The *Outage power* input file contains the power requirement from the local system during outages. In the default input files, outage information is generated by selecting the average annual number of outages over multiple years.

Users can easily select other files as input by directly typing the entire (or relative) file path, or clicking the *Browse* button to select a file. If the second method is used, the tool will display a modal dialog box through which users can select the desired input file, as shown in Figure 3.1. In this case, users should have input files ready first. These can be created by modifying the default input files; only the cells in red font need to be modified.

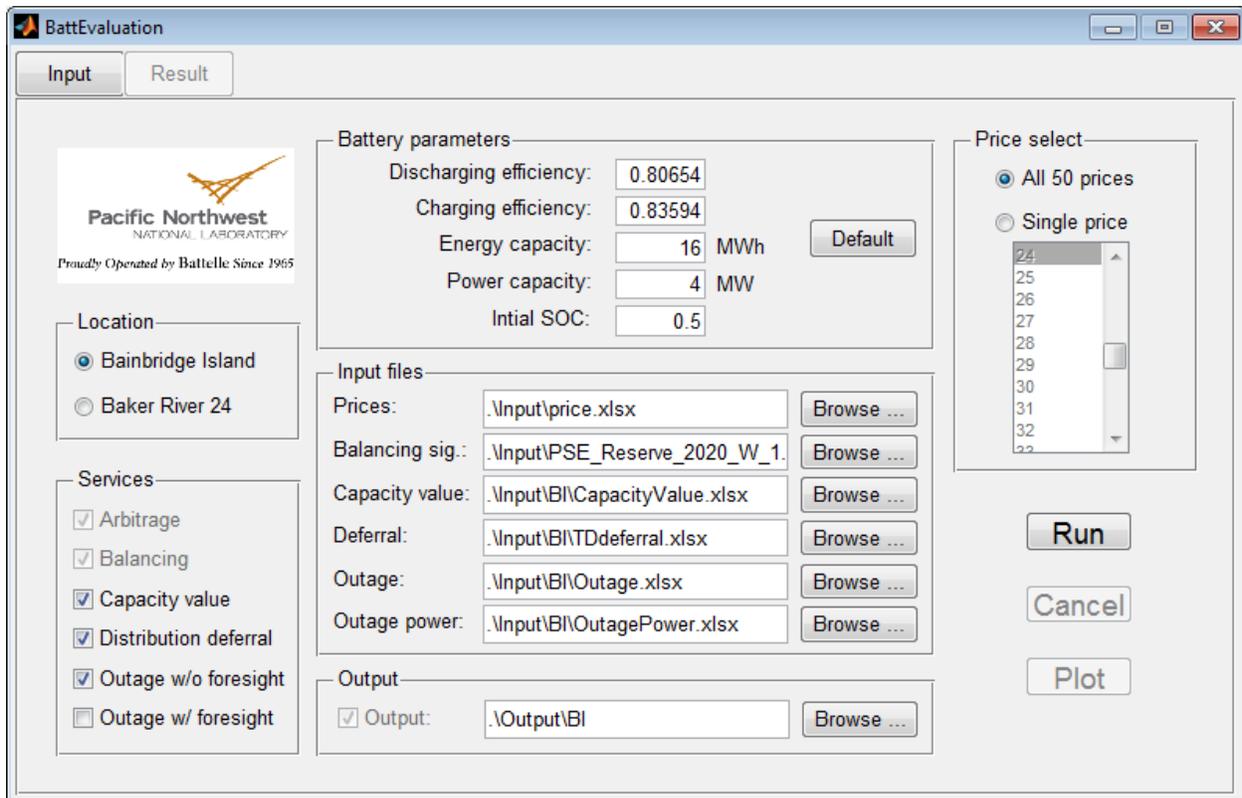


**Figure 3.1.** Browse Input Files

### 3.5 Output Panel

When a single price is selected to run a simulation, in addition to viewing and plotting results within the evaluation tool, one can also choose to export results to hard disk by checking the *Output* box. The default output path is the output folder that is in the same directory as *BattEvaluation.exe*. Users can change the output path by 1) directly typing the desired path, or 2) pushing the *Browse* button to select a file, similarly to modifying an input file.

When all 50 prices are selected, viewing and plotting results within the evaluation tool are not supported. Users can only view results through exporting them to their hard disk. Therefore, selecting *All 50 prices* in the *Price select* panel will disable the output box from deselecting, as shown in Figure 3.2.



**Figure 3.2.** Output Check Box is Disabled from Deselecting When *All 50 prices* is Chosen

For each price and each bundle of services, output files include: *BattOpti\_j.csv*, *BattSimi\_j.csv*, *HourStati\_j.csv*, *Outagei\_j.csv* (when outage mitigation is included), and *Resultsi\_j.csv*, where *i* represents price index (from 1 to 50), and *j* represents service bundle ID (from 1 to 4). Please refer to Section 3.2 for description of service bundles. The description of each output file is provided below.

- *BattOpt*: results from hourly optimization, including base operation point and balancing up and down service
- *BattSim*: minute-by-minute battery output and SOC from simulation
- *HourStat*: hour distribution for different applications
- *Outage*: Outage summary
- *Results*: Value stream from each application and total benefits

### 3.6 Price select Panel

Since all 50 groups of prices are used as price inputs, users have the option to run simulation for all 50 groups of prices or select only one price for simulation. When *Single price* is chosen, a price index needs to be selected. By default, it is price No. 24 because it provides results closest to the mean value of the 50 prices.

## 4.0 Conclusions

In order to evaluate different ESS value streams, which are at times in competition with one another, an optimization tool was developed to simulate battery operation. The scheduling (hourly) and actual operation (minute by minute) of a battery was simulated for a one-year period and a control strategy defined. An executable file was developed with a simple user interface. The user can choose from 50 balancing price signals, two locations, and five services. The battery parameters can also be modified for the run. The executable file is accompanied by a series of Excel®-based input files, which can easily be modified for site-specific conditions. The model takes approximately one minute to run. The output includes annual values by service and the number of hours the ESS is used for each service.

PNNL has plans to modify the tool to enable analysis of additional battery chemistries, additional services, and even additional energy resources (e.g., demand response programs). Furthermore, PNNL is currently developing an ESS sizing algorithm that has the potential to also be integrated into the tool. Through additional applications and tests, PNNL plans to adapt and expand the tool to address additional analytical needs. In the coming months, PNNL plans to make the executable file publically available and will seek industry input in modifying and advancing the tool.







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