PNNL-32513

Long-duration Energy Storage Technology Analysis and Development

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U.S. DEPARTMENT OF ENERGY

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

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

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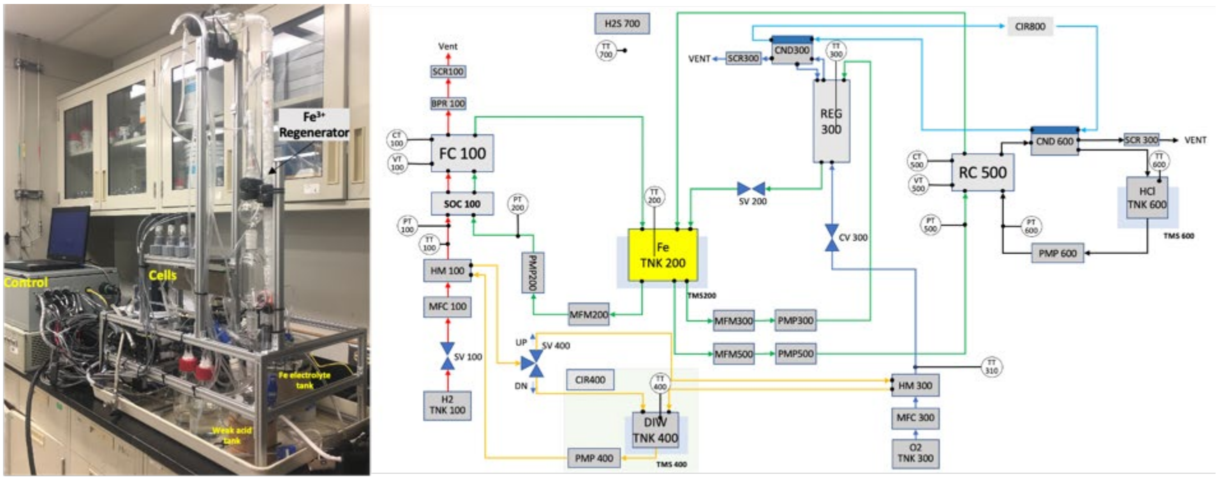
Summary

This project develops a new low-cost and flexible long-duration energy storage (LDES) technology based on simultaneous regeneration technology. In lieu of the technology development, the project team also conducts a complete cost analysis for LDES based on various currently available technologies, as well as grid economic and environmental benefits analysis for LDES. There are three tasks in this project: Task 1. Fe-H_2 flow cell fabrication, testing, demonstration. Task 2. Dynamic modeling, simulation and control architecture of power system. Task 3. Cost and grid analysis.

1.0 Fe-H_2 flow cell fabrication, testing, demonstration

The task is to develop a small (25 cm^2) test bench of long-duration energy storage of Fe/H_2 flow cells with regeneration, and to demonstrate continuous (~one week) operation.

Fe-H_2 flow cell test bench with regeneration



(a) Fe-H_2 Flow cell with Regeneration

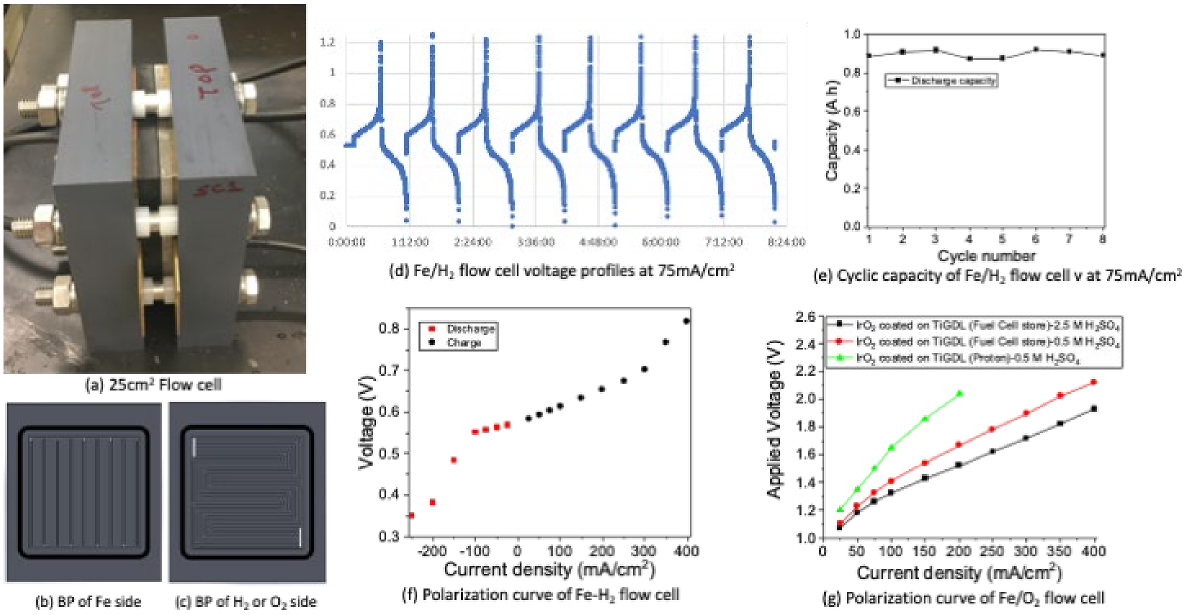
(b) System Plumbing and Instrumentation Diagram (P&ID)

Fig. 1 Fe-H_2 flow cell, image and flow chart.

Integrated Fe-H_2 flow cell system with regeneration was fabricated (Fig. 1). The system includes flow cells, H_2 and air supply, pumps for liquid circulation, and controls.

Flow cells

Two 25cm^2 flow cells (Fig. 2a~c) for Fe/H_2 and Fe/O_2 were fabricated and evaluated. Fe/H_2 flow cell exhibits stable voltage profiles and capacities, > 96% coulombic efficiency at charging and discharging current densities up to 75 mA/cm^2 (Fig. 2d,2e). Fe/H_2 flow cell includes Nafion 211, Pt/C GDE (SGL28BC), and Elat-H electrodes. Fe/O_2 flow cell includes N212, IrO_2 coated Ti GDE, and Elat-H electrodes. The electrolyte for Fe/H_2 flow cell test is 1M $FeCl_2$ + 4.5M HCl, the flow rate is 40mL/min, the electrolyte temperature is 60 ^{0}C, H_2 flow rate and its bubbler temperature are 30mL/min and 80 ^{0}C. Charging polarization behavior of Fe/O_2 cell with 1M $FeSO_4$ + 2.5M H_2SO_4 electrolyte is shown in Fig. 2g.



(a) 25cm² Flow cell

(b) BP of Fe side

(c) BP of H_2 or O_2 side

(d) Fe/H_2 flow cell voltage profiles at 75mA/cm²

(e) Cyclic capacity of Fe/H_2 flow cell v at 75mA/cm²

(f) Polarization curve of Fe-H_2 flow cell

(g) Polarization curve of Fe/O_2 flow cell

Fig. 2 Flow cell testing

Coupled operation of flow cells

Continuous H_2 production with coupled Fe/H_2 and Fe/O_2 flow cells was demonstrated (Fig. 3). Though short demonstration of 30 min, flat voltage of the Fe/H_2 flow cell indicates that Fe solution is well regenerated.

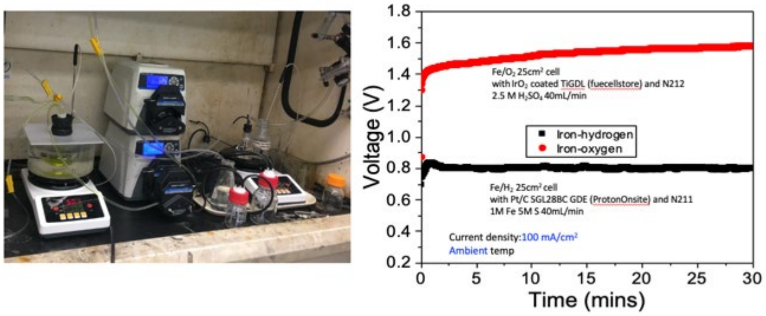


Fig. 3 Integrated flow cells for continuous operation

Catalytic regeneration of Fe (III)

Fe^{3+} regeneration cell demonstrated that equivalent conversion rate of 0.28 A/cm^2 was achieved using pure Fe^{2+} sulphate solution (1.0 M $FeSO_4$ + 2.5M H_2SO_4) for 1 hour (Fig. 4). Through the optimization of cell design and operation conditions, the rate will be improved.

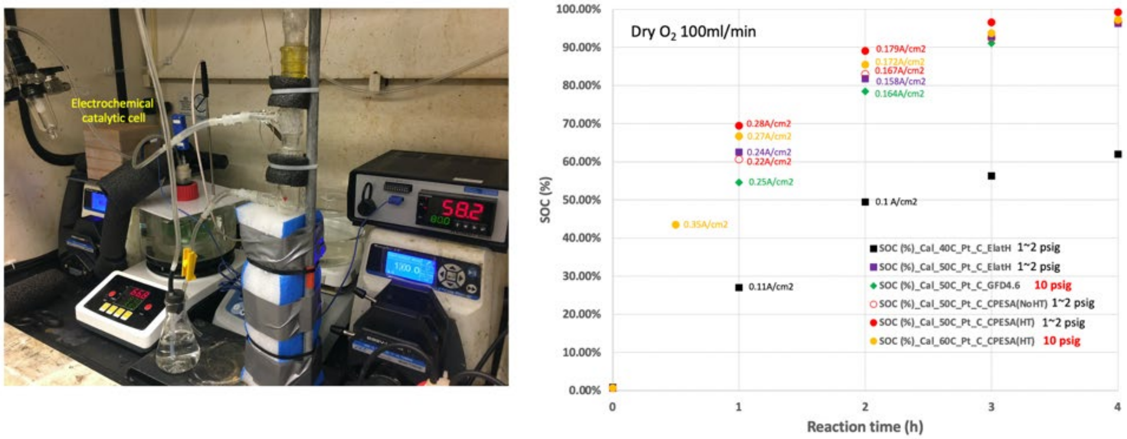


Fig. 4 Catalytic regeneration of Fe(III)

System debugging and operation

System debugging is under way. Pump is operating and temperature sensors are well working. Pressure sensors will be checked. Water flooding of membrane humidifier in the hydrogen side is identified that sealant is not sufficient between the membrane module and housing, which will be fixed by RTV silicone. Lab SOP was approved for safe operation of the bench top system. System level operation will be expected in early 2022.

2.0 Dynamic modeling, simulation, and control architecture of power system

An increasing share of inverter-based resources (IBRs) will soon lead to an IBR-dominated power system with potentially millions of IBR devices. Along with traditional grid-following (GFL) control, grid-forming (GFM) control of IBRs is also emerging to provide grid support and services, conventionally provided by synchronous machines. Therefore, it becomes pertinent to study the impact of high IBR presence with a mix of GFL and GFM inverter technologies in the system and gain insights for developing a system-wide control architecture of IBRs.

In this work, we addressed one major hurdle in these studies by developing a transmission & distribution (T&D) co-simulation tool that can perform dynamic simulation of large T&D power system networks with 10,000+ of IBRs. This tool enables the impact investigation and control development for an IBR-dominated power system. The test results are presented here on a minni-WECC transmission system connected with the Institute of Electrical and Electronics Engineers (IEEE) 8500 node distribution system at all load buses.

Second, through simulation we identify the minimum percent share of GFM inverters required to keep the system stable under disturbance for incremental levels of total IBR penetration. The study reveals that for the 100% IBR penetration scenario without any synchronous machine, only 12% of GFMs (rest 88% GFL) is needed to guarantee a stable frequency response, and the nadir point of the 12% GFM for 100% IBR penetration scenario is much higher than the base case with 100% synchronous machines.

Third, we envisioned and discussed a hierarchical control for an IBR-dominated power system with three control layers, namely primary, secondary, and tertiary controls that provide different services to the grid at multiple timescales. The implementation of the control architecture and development of specific controls remains a scope for future studies.

There are several other factors and challenges with high IBR penetration that need to be studied in detail, such as headroom management given intermittent nature of resources, ownership and policy issues, incentive for services provided by IBRs, coordination among different control objectives, etc. The development of tools and encouraging insights from the case study facilitates the future exploration of various aspects of IBR-dominated power system.

3.0 Cost and grid analysis

The benefits of an LDES system for grid applications depend on how it is operated. Modeling and optimal dispatch methods are required to define technically achievable benefits from an LDES system. Many existing optimal scheduling methods assume perfect price and load forecast. Few other studies consider the uncertainties associated with forecasts when determining bids for the day-ahead market with a look-ahead window up to 24 hours. Such a look-ahead window is long enough for the BESS deployed today with a duration of less than 8 hours. For LDES, however, the 24-hour look-ahead window is generally not long enough to optimally utilize the long-duration storage capabilities, considering the needs and opportunities for interday energy shifting. This task aims to develop an advanced scheduling method for LDES considering price forecast uncertainties and understand the potential impacts of different factors on the benefits of an LDES system, such as the duration of energy storage and round-trip efficiency.

To address the challenge in LDEs scheduling, we proposed a multi-resolution optimal scheduling method with a look-ahead window beyond 24 hours, considering the price forecast uncertainties. The proposed method employs varying time resolution, with coarser resolutions for periods farther into the future. Forecast uncertainties are explicitly modeled and used for LDES scheduling through stochastic programming.

Price forecasting with an hourly resolution is difficult for a time window beyond two days. It is relatively easier to predict prices beyond 24 hours with a lower time resolution because the number of data points to be predicted and associated uncertainties are reduced. The hour-to-hour price fluctuations in future days will not affect optimal scheduling in a short term. Therefore, average prices over longer windows are enough for scheduling that involves interday energy shifting. Based on such a multi-resolution look-ahead strategy, we formulated the optimal scheduling problem as a two-stage stochastic programming problem that maximizes the expected gain over the entire look-ahead window. The optimization is performed daily to generate the day-ahead market bids. The decisions to make in the first stage problem are the charging/discharging power for the next 24 hours. The second stage optimizes recourse actions, i.e., the operation schedule beyond 24 hours, given the settled prices in Hours 1 to 24.

The proposed method has been tested and validated using the wholesale energy price in New York City in 2020. In particular, we used an hourly resolution for the first 6 hours, a 6-hour resolution for hours 7-24, a daily resolution for days 3-7, and a weekly resolution beyond up to 8 weeks. It was found that the potential annual revenue from energy arbitrage using 6-day look-ahead windows is $15,461 with a 1MW/48MWh battery, representing a 56% increase compared to $9,936 obtained using a conventional method with a 24-hour look-ahead window. Operating schedules with 24-hour and 6-day look-ahead windows on a sampled week are plotted in Figure 5. A longer look-ahead window enables the exploration of interday energy arbitrage opportunities with the long-duration capability optimally utilized.

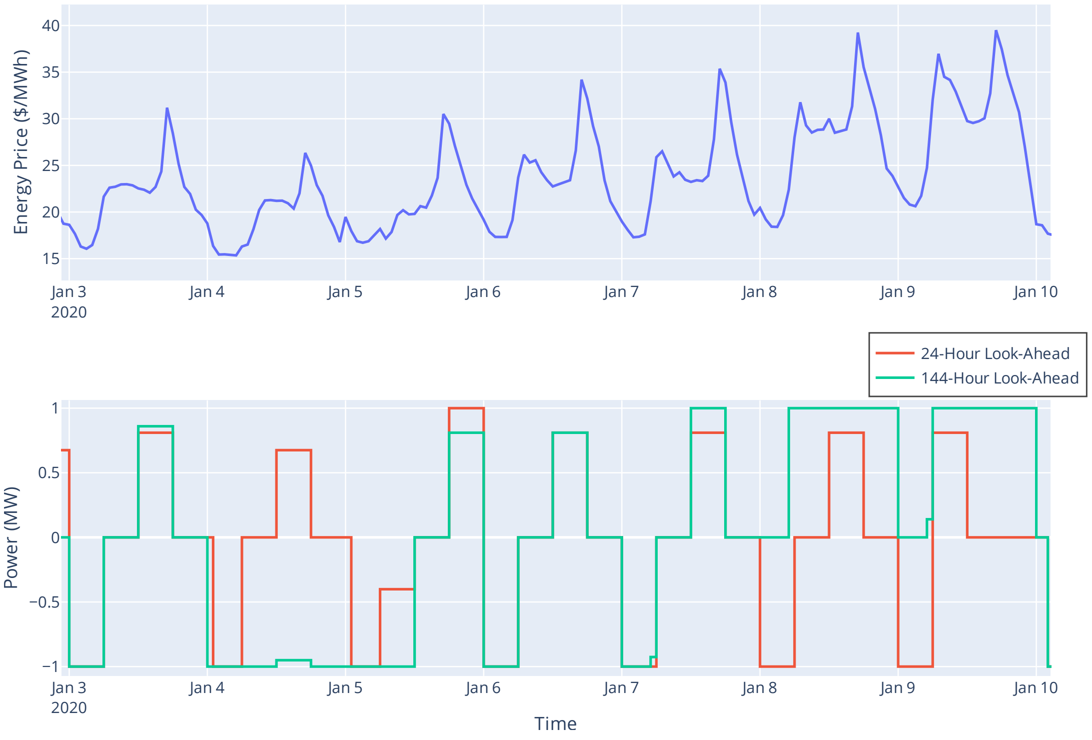
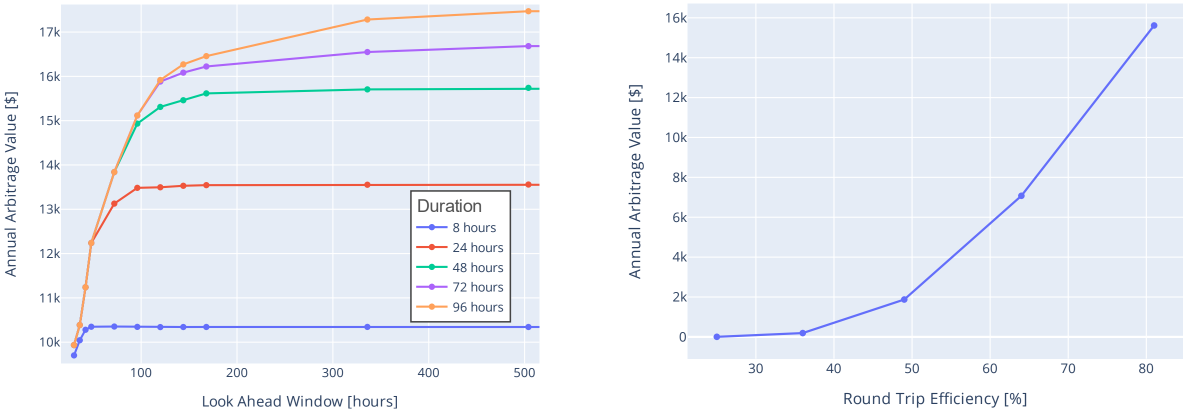


Fig. 5 Example energy prices and optimal operations of a 1MW/48MWh battery with different look-ahead window lengths. Positive power means discharging and negative power means charging.

Comprehensive analyses have been performed to understand the impacts of various factors, including duration, efficiency, length of the look-ahead window, on the economic benefits of an LDES system. Figure 6a shows that the value of an LDES system is closely related to its duration as well as the look-ahead window length. It was found that the look-ahead window needs to be at least twice the duration of energy storage to realize 95% of the potential benefits. Figure 6b shows that the round-trip efficiency also significantly affects the benefits.



(a)

(b)

Fig. 6 Impact of look-ahead window length and round-trip efficiency on annual benefits from energy arbitrage

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