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Levelized cost of energy and sensitivity analysis for the hydrogen–bromine flow battery

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HIGHLIGHTS

- Evaluated the effect of complexing agents on H_2–Br_2 battery cost.
- Complexing agents are not economically competitive for >15 min discharge times.
- Battery levelized cost of electricity too high for grid-scale electricity storage.
- Sensitivity analysis shows lifetime is largest factor in H_2–Br_2 system cost.
- Extending lifetime of electrocatalysts is needed for the H_2–Br_2 system.

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ABSTRACT

The technoeconomics of the hydrogen–bromine flow battery are investigated. Using existing performance data the operating conditions were optimized to minimize the levelized cost of electricity using individual component costs for the flow battery stack and other system units. Several different configurations were evaluated including use of a bromine complexing agent to reduce membrane requirements. Sensitivity analysis of cost is used to identify the system elements most strongly influencing the economics. The stack lifetime and round-trip efficiency of the cell are identified as major factors on the levelized cost of electricity, along with capital components related to hydrogen storage, the bipolar plate, and the membrane. Assuming that an electrocatalyst and membrane with a lifetime of 2000 cycles can be identified, the lowest cost market entry system capital is 220 $\$$ kWh^{-1} for a 4 h discharge system and for a charging energy cost of 0.04 $\$$ kWh^{-1} the levelized cost of the electricity delivered is 0.40 $\$$ kWh^{-1}. With systems manufactured at large scales these costs are expected to be lower.

1. Introduction

Global prosperity requires a reliable and low-cost sustainable supply of energy. Forty percent of the United States' energy consumption is electricity and its production results in 30% of all US greenhouse gas emissions [1].

Forty percent of electricity use is from baseload facilities operating under efficient, steady-state conditions [2]. Time-varying usage and the peak demands of consumers is provided by a combination of load following plants, with capacity factors of 30–40% [2], short start-up times, and lower efficiencies than baseload facilities, and peaker plants, which have capacity factors of 10–15%. The price of electricity produced by a peaker is more expensive than off-peak energy, due to low capacity factors [3] and efficiencies. Incorporation of renewable power generation from wind and photovoltaic power stations to combat emissions will only cause more fluctuations in supply, resulting in the need for more peaker plants.

Electrical energy storage of lower cost and higher efficiency fossil fuel and nuclear baseload power, and intermittent renewables to match supply and demand through load-leveling might be an alternative to fossil fuel-based load following and peaker plants, Fig. 1. Currently, stored electrical energy provides only 2% of the electricity used in the US [4]. The relatively small fraction reflects the relatively high cost of widely available electrical energy storage compared to peak and load following power generation. If electrical energy storage can deliver electricity for a lower price than

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producing it on demand, or if there are other reasons a power generation system cannot be deployed (noise pollution, etc.), energy storage will be used rather than peaker or load following plants.

The US DOE has set cost targets for economic grid-scale energy storage systems of 150 \$ kWh^{-1} installed with 1 h discharge [5], and ARPA-E has a target of 100 \$ kWh^{-1} [6]. The lifetime of the energy storage system plays a large role in the economic feasibility of the system [7], thus, metrics incorporating the system cycle lifetime are also used, such as the capital cost per charge–discharge cycle (\$ kWh^{-1} $cycle^{-1}$) or the levelized cost of electricity. The levelized cost of electricity is calculated by amortizing the capital cost over the lifetime of the system, and including the cost of the electricity needed to charge the system. The levelized cost of electricity allows for direct comparison of different energy systems, including primary generation systems such as natural gas peakers. A discussion of the levelized cost and the method used here to calculate it are included in the Supplementary Information. The DOE target for energy storage systems is a levelized cost of 0.10 \$ kWh^{-1} $cycle^{-1}$ [5].

Grid-level energy storage is an enormous potential market now only addressable cost-effectively by pumped hydroelectric energy storage (PHES) and to a lesser extent compressed air energy storage (CAES), Fig. 2 [8,9]. PHES provides 99% of U.S. bulk energy storage capacity with enormous peak power potential, 128,000 MW [4]. PHES round-trip energy efficiencies are typically 70–80% [10], due to losses during pumping of water to an elevated reservoir (charge) and in recovery of the gravitational energy by a turbine (discharge). CAES is nearly as cost-effective as PHES in certain locations [11], and has a round-trip efficiency of approximately 70% [12], with inevitable losses due to compression and expansion. Geographical limitations and environmental concerns limit the capacity of both PHES and CAES. Markets for higher-cost, smaller-scale energy storage exist and are discussed in several publications [4,9]. Because of the higher levelized cost of electricity of electrochemical systems, currently they are relegated to these higher value markets (see Table S1 for examples), rather than grid-scale storage.

The most widely used rechargeable electrochemical energy storage systems are solid electrode batteries such as lithium ion, nickel cadmium, lead acid, and sodium sulfur which store energy as electrochemical potential energy in solid electrodes. Automotive and portable electronics applications use lead acid and lithium ion batteries while most stationary applications use lead acid and molten salt (sodium sulfur) battery systems. The limitations of solid electrode batteries include energy storage density of their electrodes and the mass transfer limited rates of reaction at the electrodes.

In electrochemical flow batteries the energy is stored in the electrochemical potential of redox active species in the electrolyte itself rather than the solid electrodes. The electrochemical reaction rates can be higher than solid electrode batteries facilitated by convective mass transport in the flowing reactant streams allowing higher power density and energy density and decreasing the costs (\$ kW^{-1}, \$ kWh^{-1}) [13]. Flow battery systems can undergo full charge and discharge cycles at a lower cost per kWh per cycle than non-flow batteries [7] and have long cycle lifetimes because they do not rely on the stability of a repetitively stressed solid electrode structure.

Importantly, in flow batteries the power and energy functionalities are decoupled; the electrochemical potential in the electrolyte can be stored in arbitrarily large vessels separate from the power generating electrodes. For typical applications, 4 h of storage is required for a ratio of power to energy of 1 kW–4 kWh. Hybrid flow batteries have one electrode where energy is stored in a solid electrode and thus do not decouple power and energy. Examples of flow and hybrid flow batteries include all-vanadium, zinc-bromide and hydrogen–bromine systems, typically operated at 60–80% round trip energy efficiency. Tables S2-4 summarize advantages and disadvantages of some solid electrode, hybrid, and flow batteries.

The hydrogen–bromine flow battery has been investigated as a potentially low-cost electrical storage option [14,15], however

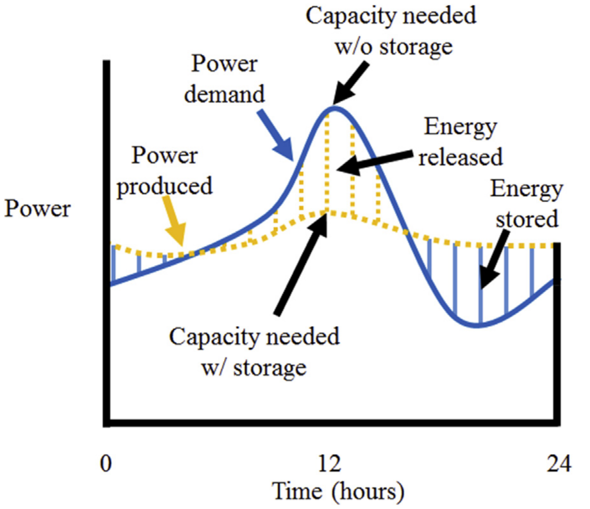

Fig. 1. Power demand (blue curve) and power produced if storage is used (orange curve) as a function of time. Without electricity storage, the power produced must equal power demand, therefore the maximum power production capacity must match the maximum power demand. With energy storage, energy can be stored (blue shaded areas) when power generation exceeds power demand, then released (orange shaded area) when power demand exceeds supply. The maximum power capacity without storage is much higher than with storage. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

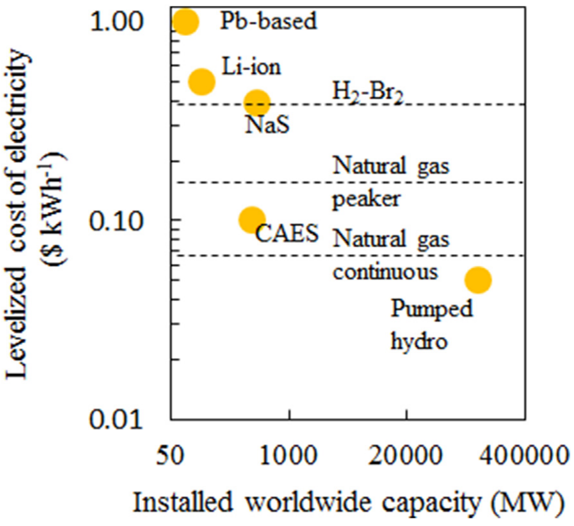

Fig. 2. Installed capacity for electrical energy storage systems (2012) [4] vs. levelized cost of electricity estimates [11,55,56] for Pb-based (lead acid-based batteries), Li-ion (lithium ion batteries), NaS (sodium sulfur batteries), CAES (compressed air energy storage) and pumped hydro (pumped hydroelectric energy storage). Levelized costs of electricity [11] are for 20 years lifetime unless otherwise indicated, (H2–Br2 system lifetime assumed to be ~5 years). NaS battery cost based on recent data [57]. Levelized costs of electricity calculated in this work for H2–Br2 flow battery and natural gas peaker (4 h operation per day) and continuously operated plants (23.5 h operation per day) are included as dotted lines. Detailed calculations included in the Supplementary information.