COMPLEMENTARY ROLES OF POWER-TO-GAS-TO-POWER AND BATTERIES IN A 100% RELIABLE WIND AND SOLAR ELECTRICITY SYSTEM

Jacqueline A. Dowling, California Institute of Technology, 1-626-395-4575, jdowling@caltech.edu
Mengyao Yuan, Carnegie Institution for Science, 1-650-319-8904, myuan@carnegiescience.edu
Fan Tong, Carnegie Institution for Science, 1-650-319-8904, ftong@carnegiescience.edu
Nathan S. Lewis, California Institute of Technology, 1-626-395-6335, nslewis@caltech.edu
Ken Caldeira, Carnegie Institution for Science, 1-650-319-8904, kcaldeira@carnegiescience.edu

Overview
Affordable energy storage is critical to achieving a highly reliable and low-cost electricity systems based primarily on wind and solar generation. While electrochemical batteries are useful for smoothing daily variations of solar generation, they would not provide cost-effective seasonal storage even at drastically lower battery costs. Nevertheless, much research and investment resources have been focused on the improvement of batteries for grid-scale storage. Power-to-Gas-to-Power (PGP) is an alternative storage technology that stores energy in the form of hydrogen fuel and uses electrolyzers and fuel cells for electricity/fuel conversion on demand. Traditionally, less attention has been given to PGP due to its low efficiencies compared to batteries.

We uncover the complementary functional roles of PGP and battery storage in a least-cost electricity system relying solely on wind and solar electricity generation. We optimize capacity and dispatch to meet 100% of hourly demand using a simple electricity model for the contiguous United States (CONUS). We perform analyses across a wide range of systems and technoeconomic assumptions. Our simple model allows results to be more easily interpreted and fundamental system behavior to be explored. In the interest of transparency and reproducibility, we provide a link to model code, input data, and model results: https://github.com/jacquelineDowling/SEM-pgp-batt.

Methods
The model in this study allows evaluation of system cost and performance, with 100% reliability as a strict constraint, at a high temporal resolution (one hour) over a multi-year time period (1980-2015). The simple model has been shown to be in qualitative agreement with more complex multi-nodal electricity models where comparisons can be made. Added complexity would change the precise values of our results but would not be expected to affect our qualitative results. We have built upon an assessment of the hourly averaged wind and solar resources based on a reanalysis data set. We consider a limiting best case that minimizes variability of wind and solar generation by assuming lossless transmission from generation to load over all of CONUS. The simple electricity model thus represents an agglomerated single generation source at a given time, connected losslessly at that same time to a single agglomerated load (i.e. the load balancing region is CONUS). Least-cost solutions were found for installed capacities and dispatch schedules for wind and solar generation, battery storage, and PGP, subject to the constraint that demand must be met 100% of the time. A range of battery and PGP costs were considered, with cost and technical assumptions for the base case (current costs) available at the github link. Wind and solar cost and efficiency values used for the base case were obtained from the U.S. EIA’s 2018 Annual Energy Outlook. Capacity costs (fixed costs) and lifetimes for all storage technologies were taken from Davis et al. Davis et al does not provide PGP energy-related costs, so these were evaluated from the H2A model data compiled by the National Renewable Energy Laboratory (NREL).

Results
Even at current costs, introduction of PGP would lower total system costs in a system relying on wind and solar electricity generation and battery storage (Figure 1). In a least-cost electricity system, batteries are used primarily for intra-daily storage (capacity of 2.2 h of mean CONUS demand), whereas PGP is used primarily for inter-seasonal storage (capacity of 26 days of mean CONUS demand). Fundamentally, this is because energy storage and conversion in PGP are decoupled, allowing PGP to have large energy storage capacities (e.g., in underground reservoirs) at much lower storage costs than batteries. Our analysis also shows that addition of PGP technology at current costs would reduce costs of 100% reliable electricity systems supplied by variable renewable generation (wind and solar PV) and battery storage (Figure 2). Increasing the number of years considered in the optimization increases the amount of PGP deployed in a least-cost system. In addition, we investigated the system’s sensitivity to future storage technology innovations (cost reductions). Less costly batteries lead to a higher penetration of solar electricity, whereas less costly PGP leads to a higher penetration of wind electricity. Overall system costs decreased more with reductions in PGP costs than with reductions in battery costs (Figure 3).
Figure 1. Base case dispatch curves. Electricity sources to the grid (positive values) and electricity sinks from the grid (negative values) are balanced at each hour of 2015. (a) Annual results with 5-day averaging; (b) 5-day period with maximum battery discharge (starting at 07:00AM CST); (c) 5-day period with maximum PGP discharge (starting at 09:00AM CST). The black area represents end-use demand (as does the black line). At each hour, generation from wind and solar plus dispatch from PGP and battery storage is balanced by end-use demand and charging of PGP and battery storage. PGP primarily provides inter-seasonal storage whereas batteries provide intra-day storage.

Figure 2. System costs with different technology combinations. In the left-most three bars, generation is by solar only; in the middle three bars, by wind only; and in the right-most three bars a combination of solar and wind. Within each group of three bars, the left-most bar represents a system with PGP storage only, the middle bar represents a system with battery storage only, and the right-most bar allows both storage technologies to compete. Stacked areas in each bar represent the cumulative contribution of each technology to total system cost over the optimization period (2015). In all cases, introduction of PGP reduces overall system costs compared to a system with only batteries.

Figure 3. Sensitivity of system cost to PGP and battery costs. PGP and battery costs are independently reduced from base case assumptions (1x) to free (0x), and total system costs for the optimization period (2015) are plotted as contour lines. Capacity and dispatch of each technology, including wind and solar, were optimized in response to each combination of PGP and storage costs. The system costs are much more sensitive to reductions in PGP costs than to reductions in battery costs.

**Conclusions**

Our results indicate that Power-to-Gas-to-Power (PGP) technology at current costs would reduce system costs in a 100% reliable electricity system supplied by variable renewable generation (wind and solar PV) and battery storage. Due to its low energy storage costs, PGP would be used primarily for seasonal storage and would reduce the need to overbuild wind and solar generation capacity to obtain high reliability over multi-year time periods. Batteries are useful for hourly and daily storage because of their relatively low conversion costs and high round-trip energy efficiencies but would not provide cost-effective seasonal storage due to their high energy-storage capacity costs. As a consequence, PGP is favored to compensate for the seasonal and weather-related variability of wind, whereas batteries are favored to compensate for daily variations in solar insolation. Although battery storage at present receives the vast majority of attention, investment, incentives, and mandates designed to promote carbon-neutral grid storage technologies, relative to current costs, reductions in PGP costs would reduce system costs in a reliable wind and solar electricity system to a much greater extent than equivalent relative reductions in battery costs. These results suggest that improvements in Power-to-Gas-to-Power systems may have a high impact on lowering the cost of future near-zero-emissions electricity systems. Given the relevance of our findings to current discussions of energy transition pathways and transparency of our modeling approach, we believe our paper will be of interest to a wide range of energy scholars, utilities, policymakers, and the general public.

**References**