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Optimization of Utility-Scale Wind-Hydrogen-Battery Systems

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OPTIMIZATION OF UTILITY-SCALE WIND-HYDROGEN-BATTERY SYSTEMS

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ABSTRACT

Traditional utility-scale wind energy systems are not dispatchable; that is, the utility cannot instantaneously control their power output. Energy storage, which can come in many forms, is needed to add dispatchability to a wind farm. This study investigates two options: batteries and hydrogen.

To integrate batteries into a wind farm, a power conversion device is required to convert the direct current from the battery to alternating current for the power grid. Many wind turbines are variable speed and thus contain power conversion equipment to interface the turbine to the grid. This conversion equipment can be used to integrate the battery with the grid and to control the battery's power.

Some researchers have proposed that a hydrogen system might be used for the same purpose. Wind power would be used to electrolyze water to create hydrogen, the hydrogen would be stored, and then either a combustion device or a fuel cell would be used to convert the hydrogen back into electricity. Such a system is feasible, but suffers from much lower round-trip efficiency than a battery.

Hydrogen can also be used as a fuel at remote locations and in vehicles, so a wind farm could produce hydrogen for sale rather than for energy storage.

This paper will demonstrate that a hybrid system that involves wind, batteries, and hydrogen production for fuel use is an optimal combination. The hydrogen system is too inefficient for on-grid energy storage. A wind-hydrogen fuel only system is too expensive. A wind-battery system is attractive, but adding hydrogen production for fuel use makes the grid and fuel systems more cost effective.

APPROACH

Measured wind farm output from the Lake Benton wind farm in Minnesota was combined with grid load data from the California ISO to simulate a system in which traditional generation and energy storage were added to create a complete power grid. Simple control systems, which operated on the hourly data, were developed to control these elements in such a way as to minimize cost and maintain grid power balance. The battery was used to make up for the control system performance of the other elements because it can respond faster than the other elements.

At the conclusion of the simulation, the battery size was computed by determining the difference between the maximum and minimum annual battery charge levels. Overall cost of energy (COE) was then determined by combining the battery cost with the costs of the other elements, dividing by energy produced, and adding an assumed operations and maintenance (O&M) cost.

For hydrogen production, two cases had to be run to determine hydrogen cost – a "with hydrogen" and a "without hydrogen, with battery" case. By computing the marginal cost between the two cases, dividing by the hydrogen produced, and adding an assumed O&M cost, a final cost of hydrogen was computed.

BATTERIES FOR GRID FIRM-UP

Batteries are usually designed for limited use in portable applications. As such, most popular designs are too small and too short lived to be used as grid firm-up devices. For a battery to be successful as an energy storage element in a wind farm, it must be able to store enough energy, accept and release energy at a sufficient rate (power), and be low in initial and O&M costs. Since even one cycle per day for 20 years amounts to more than 7,300 cycles, long cycle lifetimes are also required. Several battery technologies have the potential to meet these requirements, but here we will focus on two: nickel-hydrogen and vanadium-redox.

Vanadium-redox batteries can be built to have sufficient energy and power, and cycle lifetimes have been reported at more than 10,000 cycles[1]. The cost of these batteries is reportedly about $280/kWh of storage[1].

Nickel-hydrogen batteries work similarly to the popular nickel-metal-hydride batteries except that the hydrogen, instead of being stored in an electrode, is stored externally to the electrochemical portion of the battery. These batteries have been used for many years in space applications where cycle lifetime is crucial. For this application, the hydrogen the battery produces and consumes is assumed to be stored at low pressure in the wind turbine tower, which is a potentially very low-cost approach (capital cost of $88/kg)[2]. Projected costs for these batteries are $70–$280/kWh.

RESULTS – ADDING DISPATCHABILITY TO WIND

To parameterize the term *dispatchability*, a parameter called "capacity reduction" was determined. On a real grid, the generation system must have equal capacity to the grid load (ignoring reserves) during the hour of the year in which maximum load is drawn. For a wind farm to contribute to the size of the generation system, it must be able to provide power during these peak times. Hence, the maximum output of the "traditional generation" part of the simulation was set to the maximum load during the year minus a percentage of the wind farm rated capacity. For example, if a 100-MW wind farm were used and capacity reduction were set to 60%, the traditional generation capacity would be set to the maximum load minus 60 MW.

All parameters except battery size were set at the beginning of the simulation. Therefore, many parameters were swept over a range of values with simulations determined for each case. Some parameters were held constant for all simulations. These are hydrogen storage cost ($88/kg[1]), O&M cost ($0.008/kWh), levelized replacement cost ($15/kW/year), fixed charge rate (10.60%), and the wind production tax credit (PTC = $0.020/kWh over wind farm lifetime). Some representative results are in Figures 1 and 2. Results indicate that significant dispatchability can be added to wind for a marginal cost of only $0.005–$0.020/kWh over the wind-only cost of $0.024/kWh.

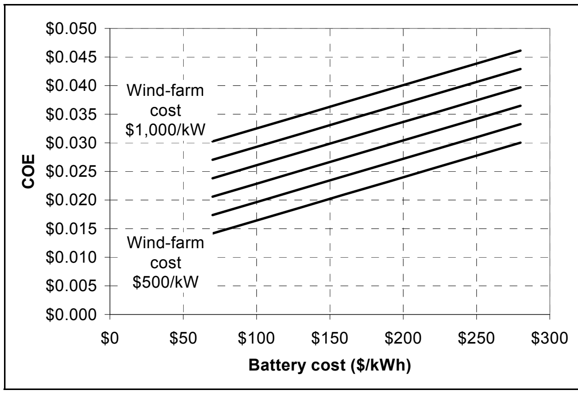

Figure 1 - 50% capacity reduction case

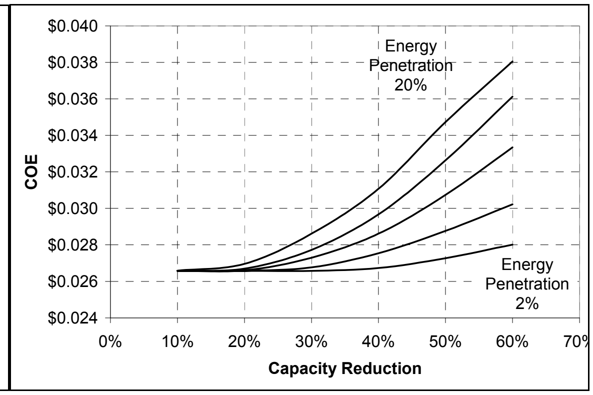

Figure 2 - $1,000/kW wind farm case

To generate the data for these plots, the simulation was run many times as parameter values were swept. For each case, Excel Solver was used to optimize the control parameters and the parameters that were not set, in such a way as to minimize COE. In all cases, the electrolyzer and fuel cell were both optimized to zero size. To investigate the cause of this, the cost of each of these elements was set to zero and new cases were run. Even with the cost of the hydrogen systems at zero, the optimizer reduced their sizes to zero in favor of the battery even though the cost of hydrogen storage ($88/kg is about $3/kWh) is much lower than the cost of the battery ($70–$280/kWh).

The cause of this seeming discrepancy is the difference in closed-cycle efficiency of the two systems. The electrolyzer efficiency was set to 75% and the fuel cell efficiency was set to 50%. The closed-cycle efficiency involves the electricity going though the electrolyzer and the resultant hydrogen going through the fuel cell. This means the closed-cycle efficiency for the hydrogen electricity storage system is 37.5%. The battery has a charge efficiency of 95% and a discharge efficiency of 90%. This equates to a closed-cycle efficiency of 85.5%. The energy lost in the hydrogen system relative to the battery system outweighs the cost savings of having a zero-cost system. Of course, in reality the hydrogen system would not be zero cost, which would lend further support to the battery system for on-grid energy storage.

RESULTS – HYDROGEN PRODUCTION

For the system to produce hydrogen for sale, an electrolyzer size had to be set so the optimizer would not optimize it to zero. This size is parameterized as a percentage of wind farm rated capacity. For example, a 5% electrolyzer is a 5-MW electrolyzer if the wind farm rated capacity is 100 MW. Parameters that were fixed for this part of the simulation were wind farm cost ($1,000/kW), battery cost ($70/kWh), hydrogen storage cost ($88/kg), O&M cost for wind ($0.008/kWh), O&M cost for hydrogen ($0.05/kg), levelized replacement cost for wind ($15/kW/year), and fixed charge rate (10.60%). Some representative results are in Figures 3 and 4.

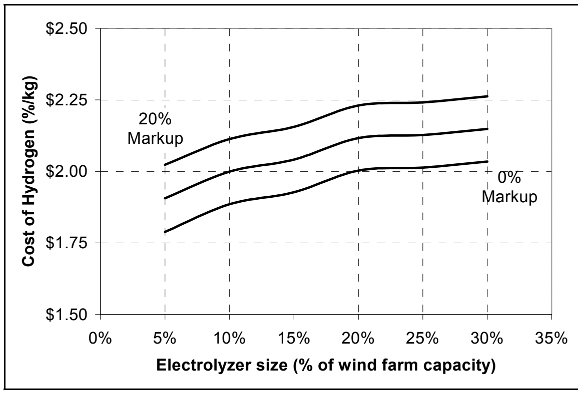

Figure 3 - Hydrogen production costs

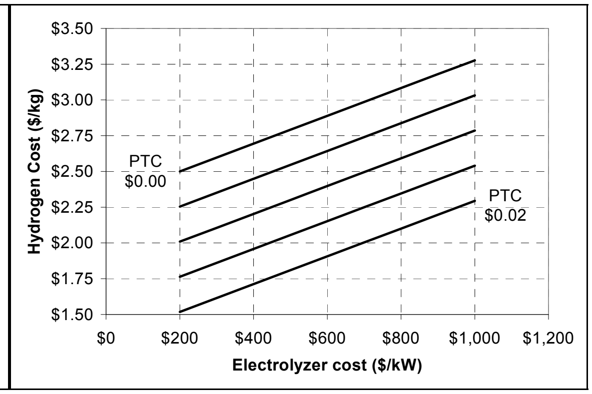

Figure 4 - Hydrogen cost for various PTCs

A wind farm operator who is seeking to produce hydrogen for sale does not receive free electricity to generate the hydrogen. That electricity would otherwise have been sold at a profit. Thus, a markup was added to the cost of the electricity that was consumed in the hydrogen-making process.

As seen in Figure 3, hydrogen cost increases with electrolyzer size because a larger electrolyzer does not have to work as hard to help prevent battery overcharge during periods of excess energy. This leads to slightly lower electrolyzer capacity factors. Figure 4 shows how hydrogen cost varies with electrolyzer cost and the value of the PTC for an electricity markup of 10% over COE. Figure 5 shows how hydrogen production volume varies with electrolyzer size, and Figure 6 shows potential pipeline transportation costs for this hydrogen, as developed by another NREL researcher[2].

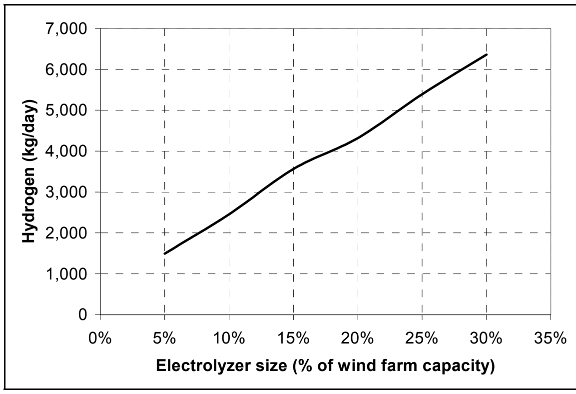

Figure 5 - Hydrogen production volume

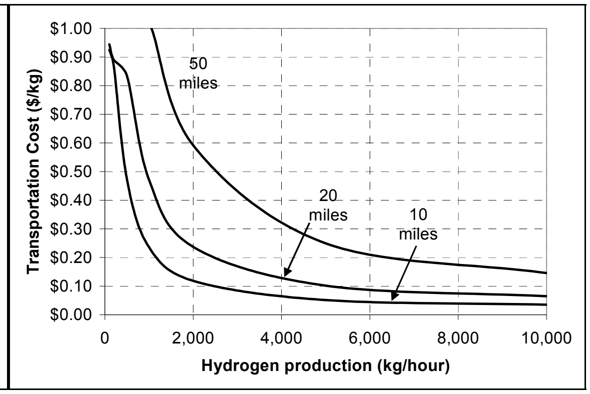

Figure 6 - Hydrogen transportation cost

CONCLUSION

With a well-integrated system of wind, batteries, and hydrogen components, wind farms might provide energy to the grid with dispatchability and provide hydrogen fuel at a reasonable cost. Batteries, because of their much higher closed-cycle efficiency, are better than hydrogen systems for grid firm-up. A combined wind, battery, and hydrogen system can provide hydrogen fuel at a lower cost than a wind-hydrogen system alone because the combined system allows the electrolyzer to operate at higher capacity factor. Lastly, hydrogen produced at prices shown in this paper can successfully fuel advanced vehicles of the future.

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