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Coupling heat storage to nuclear reactors for variable electricity output with baseload reactor operation

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ABSTRACT

Nuclear reactors produce heat and thus can couple to heat storage systems to provide dispacthable electricity while the reactor operates at full power. Six classes of heat storage technologies couple to light-water reactors with steam cycles. Firebrick Resistance-Heated Energy Storage (FIRES) converts low-price electricity into high-temperature stored heat for industry or power. FIRES and brick recuperators coupled to nuclear brayton power cycles may enable high-temperature reactors to buy electricity when prices are low and sell electricity at higher price.

1. Introduction

Global energy systems are changing with limits on greenhouse gas emissions and the large-scale introduction of non-dispatchable wind and solar generators. In this article we examine options for future large-scale heat storage systems to enable baseload nuclear reactors to provide economic variable electricity to the grid and variable heat to industry. These heat storage technologies can be deployed with storage capacities measured in megawatt-days to gigawatt-years. The market requirements are first examined followed by examination of the three categories of heat storage technologies and their different capabilities from the perspective of the electricity grid. Heat storage creates a parallel set of energy storage options to electricity (work) storage technologies (pumped hydro, batteries, etc.)

2. Market requirements

Mankind has had the same energy policies for 300,000 years: match production with variable energy demand by throwing a little more carbon on the fire. While the technology has changed from the cooking fire to the gas turbine, the economics have not. The cost of the cooking fire (stone or brick) and the gas turbine are low. Most of the labor and capital resources are in gathering the fuel (wood, natural gas, etc.) and bringing it to the fire. These are low-capital-cost, high-operating-cost technologies. As a consequence, it is economical to produce energy at a variable rate to match variable energy needs by operating the fire at partial load.

Nuclear power has high capital costs and low operating costs. Consequently when it was introduced into systems with fossil generating capacity, it operated at base load with variable electricity demand met by fossil units. However, we are now transitioning to a low-carbon world where the available energy sources are nuclear, wind, and solar. These technologies have high capital costs and low operating costs. If these energy production facilities are operated at half capacity, the bus-bar cost of electricity approximately doubles. Because energy is about 8% of the global economic output, operating these technologies at part load significantly increase energy costs with large impacts on global standards of living.

No combination of nuclear, wind, or solar matches energy demand. Solar and wind are non-dispatchable energy sources whereas nuclear is dispatchable. However, meeting all energy demands with variable nuclear power would be expensive (Denholm et al., 2012) because it implies low capacity factors for many nuclear plants.

One way to understand the challenge is to look at electricity markets. In deregulated wholesale electricity markets, electricity generators bid a day ahead to provide electricity to the grid. The grid operator accepts the lowest bids to meet electricity demands. All of the winning bids are paid the electricity price ($/MWh) of the highest-priced winning electricity bid required to meet the electricity demand for that hour. Nuclear, wind, and solar bid their marginal operating costs, which are near zero. Fossil plants bid their marginal costs, which are close to the cost of the fossil fuels that they burn.

In a market with nuclear and fossil plants, the fossil plants set the hourly price of electricity. If one adds large quantities of solar or wind,

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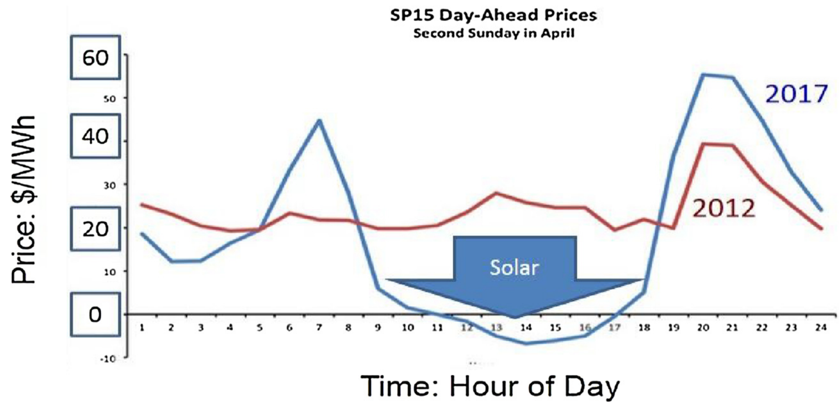

Fig. 1. Impact of added solar on California electricity prices for second Sunday in April: 2012 and 2017.

their low operating costs set market prices at times of high wind or solar production. Fig. 1 shows the impact of solar additions between 2012 and 2017 on California electric prices on a spring day with high solar production and low electricity demand. Electricity prices collapse at times of high solar production (California ISO, 2017; MIT, 2015) to zero or negative under certain circumstances. The price increases as the sun goes down because solar electricity production stops and peak demand occurs in the early evening. This market behavior has resulted in new utility-scale concentrated solar power plants to include heat storage to better match electricity output to need and avoid selling electricity when prices are low. The same effect occurs with wind except on a multiday cycle that reflects weather patterns.

All high-capital-cost low-operating-cost technologies will collapse the price of electricity at certain times if deployed on a sufficiently large scale (Haratyk, 2017; Bistline, 2017; Hirth, 2013, 2015). This economically limits deployment of any low-carbon technology and favors complementary deployment of low-capital-cost/high-operating-cost fossil plants (gas turbines) to provide electricity when prices are higher—unless there are restrictions on the use of fossil fuels. This change in the market from low-capital-cost/high-operating-cost fossil plants to high-capital-cost/low-operating-cost nuclear, wind, and solar creates the economic incentive to deploy energy storage systems to consume low-price energy (raise its price) and provide energy at times of higher demand.

2.1. Market designs

There are three sources of revenue for any energy storage system. Energy markets pay per unit of electricity delivered to the grid. The figure above show the variation in prices in selected energy markets versus time, which creates the economic case for all energy storage systems: store energy when prices are low to sell when prices are high.

Capacity markets assure sufficient generating capacity to meet demand, that is, to avoid blackouts. There are two strategies. The first strategy is to have no capacity market and allow energy prices to go to very high levels ($1000s/MWh or more) at times of scarcity. Plants will be built whose revenue depends upon incomes during the sale of electricity for tens or hundreds of hours per year when prices are very high.

The second strategy is for the electricity grid to have contracts (Joskow, 2008) for assured electricity capacity to accommodate multiday periods of low solar production, month-long periods of low wind (such as January 2017 in Europe), or extreme weather events (United States). Most electricity markets have capacity markets, where the grid operator pays a fixed value in dollars per megawatt of assured capacity. In effect, the grid operator pays to lower the risks of blackouts and avoid the high costs of such blackouts in terms of economics, public health risks (cold houses, summer heat exhaustion, etc.) and social disruption. The addition of wind and solar generators has increased the use of capacity markets because these energy sources cannot assure production of electricity given their intermittency. Depending upon the market, some storage technologies can obtain capacity payments

Auxiliary service market refers to other electricity grid services such as frequency control, load following, black start (system restart after power outage) and reserves for rapid response to grid emergencies such as another electrical generator failing. However, revenue from such services represents a small fraction of the overall power system revenue in all regions of North America and Europe.

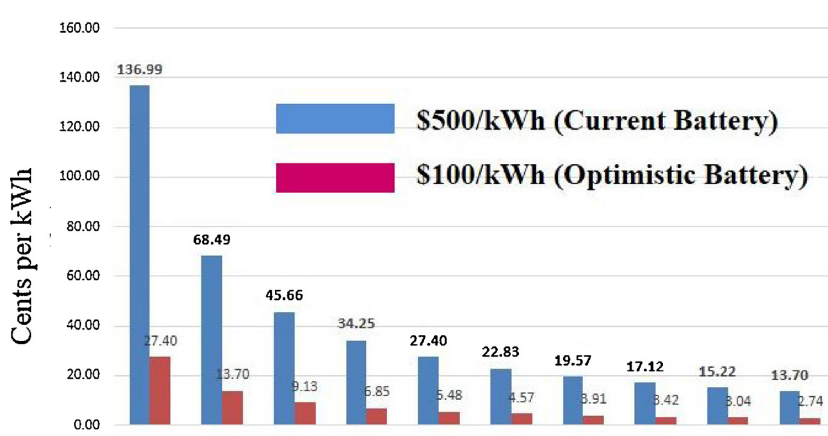

Fig. 2. Electricity storage cost versus utilization rate for existing and optimistic battery costs.