LWR heat storage for peak power and increased revenue

Heat storage is cheaper than batteries and has lower carbon emissions than gas turbines for the production of peak electricity.

By Charles Forsberg

Worldwide electricity markets are changing. In the United States, market changes are driven by (1) low-cost natural gas, (2) the addition of intermittent and often subsidized renewable generators (wind and solar), and (3) the goal of a low-carbon grid. This is reducing the demand for baseload electricity. At the same time, it has increased demand for dispatchable electricity—a market primarily served in the United States by natural gas turbines.

These changes are challenging the economics of nuclear power today but may create new opportunities for existing and new-build nuclear energy systems. Heat storage may be able to help sustain baseload reactor operation by storing heat at times of low electricity prices to produce added electricity from stored heat at times of higher electricity prices. To address these nuclear energy challenges and opportunities, the Massachusetts Institute of Technology (MIT), Idaho National Laboratory (INL), and Exelon Corporation conducted a workshop, "Light Water Reactor Heat Storage for Peak Power and Increased Revenue"[1], followed by additional assessments of heat storage options[2]. The goals were to understand the market, regulatory, and technical options for coupling heat storage to existing and future light-water reactors to improve LWR economics.

Nuclear reactors produce heat that is then converted into electricity, whereas wind and solar photovoltaic (PV) generators produce electricity. Storing heat is less expensive than storing work; that is, storing electricity using technologies such as hydro pumped storage and batteries. This order-of-magnitude cost difference between heat and electricity storage is why some new utility-scale concentrated solar thermal power systems store heat at the gigawatt-hour scale to move electricity production to times of higher wholesale electricity prices, but one does not see large-scale electricity storage coupled to wind farms or PV systems. Many of the heat storage technologies used with concentrated solar thermal systems are applicable to LWRs.

Electricity markets

Mankind has had the same energy policies for 300,000 years: meet variable energy demands 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 fireplace (stone or brick) and the gas turbine is 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, where it is economical to produce energy at a variable rate to match variable energy needs by operating the fire at partial load. In a low-carbon world, 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 busbar cost of electricity approximately doubles. The question is, what is the role of nuclear in this changing market?

Market requirements

There are two primary sources of revenue for electricity generators: selling electricity (MWh) and selling assured generating capacity (MW) to avoid blackouts. In competitive 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.

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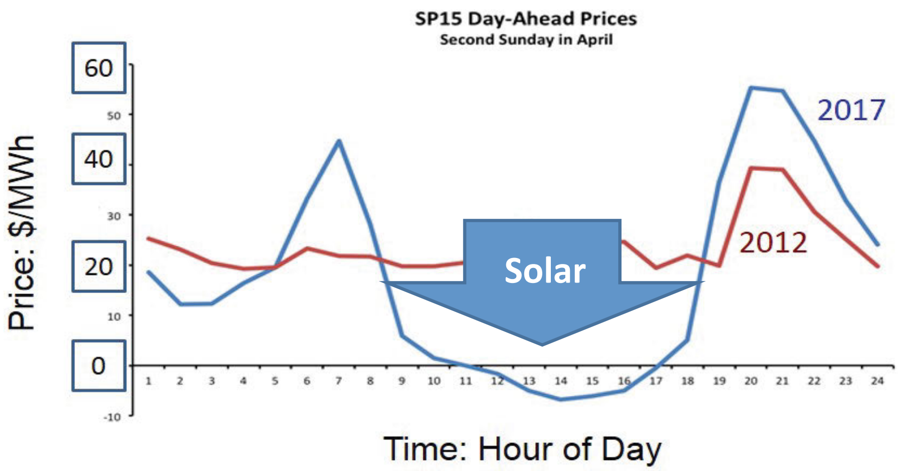

Fig. 1: Impact of added solar on California electricity prices for second Sunday in April 2012 and 2017

In a market with primarily nuclear and fossil plants, the fossil plants set the hourly price of electricity. If large quantities of solar or wind are added, their low operating costs set market prices at times of high wind or solar production.

Figure 1 shows the impact of solar additions between 2012 and 2017 on California electricity prices on a spring day. In 2012, the electricity prices were relatively flat over 24 hours and were set by the cost of fossil fuels. The small peak was in the evening, at times of peak demand. The large-scale addition of PV radically changed the market. Electricity prices collapse at times of high solar production. The price increases as the sun goes down because of lower solar electricity production and because peak demand occurs in the early evening. Similar price collapse occurs where there is large-scale deployment of wind generation. The market price of electricity has become much more volatile.

The price collapse is a consequence of adding non-dispatchable energy sources to the grid and reductions in the cost of utility wind and solar systems (Table 1). Subsidies result in the overbuilding of these technologies, but the low levelized cost is what created the new market with highly volatile wholesale electricity prices where there are good solar or wind resources. It also creates a requirement for dispatchable electricity sources (such as natural gas and nuclear) at times of low wind or solar conditions.

The other major source of generator plant revenue is capacity payments. Historically, capacity markets have not been important. A nuclear or fossil plant that generates electricity (MWh) also has assured generating capacity (MW) when electricity is needed. That is not true for wind or solar. These technologies produce electricity but can't provide assured generating capacity when the sun sets and the wind stops. Because of the growth of wind and solar, most competitive electricity markets now have capacity markets where the grid operator pays a fixed value in dollars per megawatt of assured capacity 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. Capacity payments are now a significant source of revenue for some nuclear power plants. An LWR with a heat storage system requires expanding the generating capacity over the baseload capacity to convert the heat back to electricity, increasing capacity payment revenue.

These market changes create the economic incentive to deploy heat storage systems to avoid selling low-price electricity, to sell added electricity at times of higher prices, and to sell added assured peak electricity generating capacity.

Optimized power systems

An alternative way to understand the challenge is to model the electricity system. The MIT report *The Future of Nuclear Energy in a Carbon Constrained World*[3] asked the question, What would be the optimum power system to minimize the average cost of electricity for different constraints in carbon dioxide emissions—measured in grams of carbon dioxide per kilowatt-hour of electricity generated? Carbon constraints varied from 500 g/kWh to 1 g/kWh. The average rate of emissions by utilities in the United States today is near 500 g/kWh. The study focused on Texas and New England in the United States, France, the United Kingdom, and two regions in China.

The inputs included capital costs, operating costs, and operational constraints for each technology with the electricity demand, solar conditions, and wind conditions for 8,760 hours per year. The analysis included two sets of cases: (1) all technologies and (2) excluding nuclear as an energy option.

The results showed increases in average electricity costs as carbon constraints became more limiting, with much larger increases in costs if nuclear was not allowed to be used. The specific results depended on location, with the smallest deployment of nuclear in Texas (low-cost natural gas, good wind, good solar, high-cost nuclear) and the largest deployment of nuclear in China (high-cost natural gas, low-cost nuclear).

What was also seen is that the operation of nuclear plants changed as carbon constraints became more limiting. In a low-carbon grid, there is a need for a replacement for fossil fuels to provide dispatchable electricity. The optimal generation mixture as carbon constraints increased to meet variable electricity demand includes some combination of overbuilding solar, overbuilding wind, adding storage, and operating nuclear power plants in a load-following mode. The simulations included only existing technologies and thus did not include nuclear energy with heat storage. The role of nuclear energy changed from providing baseload electricity to providing dispatchable electricity and assured generating capacity—creating the incentive to add heat storage to nuclear reactors for variable output from baseload reactor operations.

Table 1. Levelized Cost of Electricity (Lazard 2017)

Technology	LCOE: $/MWh
Solar PV: Rooftop Residential	187–319
Solar PV: Crystalline Utility Scale	46–53
Solar PV: Thin Film Utility	43–48
Solar Thermal Tower with Storage	98–181
Wind	30–60
Natural Gas Peaking	156–210
Natural Gas Combined Cycle	42–78
Nuclear	112–183

LWR heat storage

If the role of nuclear energy is changing, one must then ask the question of how to design and operate nuclear plants to match market needs. We examined the addition of heat storage—the same strategy that has been adopted by some utility-scale concentrated solar power systems.

Reactor constraints

Constant full reactor output. To minimize production costs and operational challenges, a high-capital-cost/low-operating-cost reactor should be operated at full power at all times. Steam output from the reactor is divided between the main turbine and the storage system to vary output to the grid.

Minimum electricity to the grid. For the nuclear plant to maintain its capability to rapidly send 100 percent of its rated capacity to the grid, a minimum steam flow to the turbine is maintained to allow rapid return to full power by shutting off steam going to storage. Minimum power levels for most turbines are near 30 percent. However, many existing plants have instabilities in the balance of plant that limit the minimum power to about 60 percent to 70 percent, which means 30 percent to 40 percent of the steam could go to the storage system. With new plants or changes in existing plants, the minimum power level can be lower.

Alternative methods to couple heat storage to LWRs. There are two options. The first option is a stand-alone storage system. Steam is diverted before the high-temperature turbine and sent to the heat storage system, which has its own power generation system. The condensate water returns to the main turbine condenser. The second option is to divert steam to storage at times of low demand and send heat, usually as steam, back to the turbine hall at times of high demand to produce added electricity. The main turbine is used to produce the added electricity. This has two advantages: (1) the incremental capital cost to the power cycle for added electricity output is significantly lower than with a stand-alone power system coupled to heat storage, and (2) the main turbine is always operating, thereby enabling fast response to changing electricity demand. It does require that the main turbine output be larger than the baseload capacity of the reactor.

LWR steam cycles provide multiple options on how to integrate heat storage into the power cycle. In LWRs, up to a third of the steam is diverted from the turbines to feedwater heaters to improve plant efficiency. The different feedwater heaters operate at different temperatures. Stored heat can be sent back as steam to the main turbine or to the feedwater heaters to allow more primary steam to the turbines.

Thermal storage options

There are many classes of heat storage options[2,4]. Below are two of the near-term options that are deployed today in some concentrated solar power systems. These options can provide hourly to multi-day storage. There are other technologies, such as geothermal heat storage, that can provide seasonal storage, but these technologies are early in the development cycle.

Steam accumulators. A steam accumulator is a pressure vessel nearly full of water that is heated to its saturation temperature by steam injection from the reactor when electricity prices are low. The heat is stored as high-temperature, high-pressure water. When electricity prices are high, valves open, and some of the water is flashed to steam, which is sent to a turbine producing electricity or to feedwater heaters, while the remainder of the water decreases in temperature. Steam accumulators are used in some solar thermal plants to provide heat storage to maximize sales at times of higher electricity prices. Several studies have been done on the coupling of accumulators to nuclear reactors.

Sensible heat storage. Sensible heat storage involves heating a second material with steam, storing that second material at atmospheric pressure, and using that material later to provide the heat to produce steam to then produce electricity. The heat storage material may be a liquid (oil, salt, etc.) or solid (concrete, rock, etc.). This technology is used with solar thermal power systems at temperatures near those of LWRs to enable electricity production after the sun sets.

Westinghouse has begun the development of a sensible heat storage system for LWRs (Fig. 2) in which each storage module stores sufficient heat to generate 1 MWh of electricity. Steam heats low-pressure oil, which then transfers its heat to a heat storage module in which vertical concrete plates serve as the primary heat storage medium rather than a heat transfer oil. Concrete is a less expensive heat storage medium and can be produced locally. The hot oil flows through narrow channels between slabs of concrete. To recover the heat, the direction of oil flow is reversed, and the hot oil would be used to generate steam. That steam can be (1) sent to the main reactor turbine, (2) used as a partial replacement for steam to feedwater heaters, or (3) sent to a separate power system.

Matching storage options to markets

Each heat storage technology has different characteristics: round-trip efficiency, cost to input energy into the system ($/MWt), cost of storage ($/MWh), and cost of converting heat to electricity ($/MWe). Consequently, the preferred option will depend on both the electricity market and developments in each technology. The preferred heat storage system in a grid with large solar capacity and the need for daily energy storage may be different from a system with excess wind capacity and multi-day cycles of low- and high-priced electricity.

Energy storage cost structures are different for electricity storage (pumped hydro, batteries, etc.) and heat storage systems. The capital costs for a pumped hydro facility can be divided into two parts. In a pumped hydro facility, a pump-motor system pumps the water up the hill and operates in reverse as a turbine-generator system to produce electricity. The capital cost is measured in $/kW. The rate of electricity input is about 20 percent higher than the rate of electricity output, accounting for inefficiencies. The second cost ($/kWh)

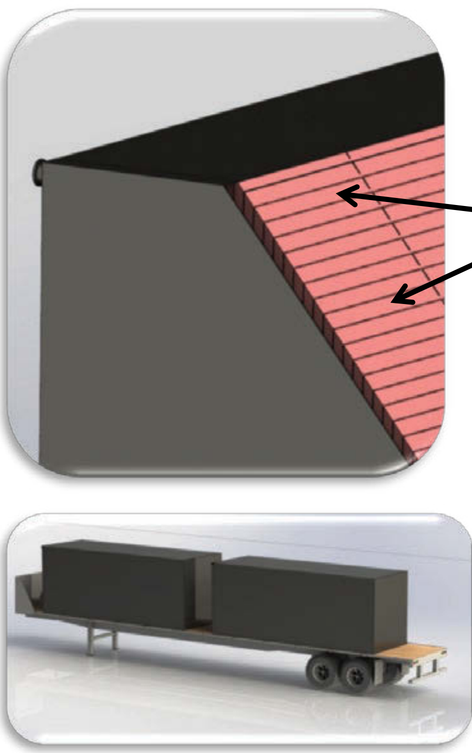

Fig. 2: Westinghouse thermal heat storage module for 1 MWh of electricity storage

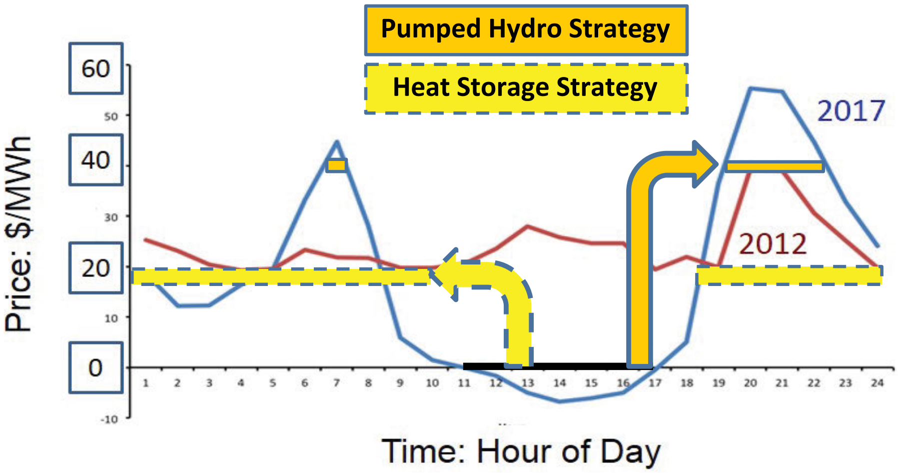

Fig. 3: Buy-and-sell strategies for pumped hydro and nuclear heat storage in California electricity market

is associated with building the two water reservoirs to provide energy storage capacity. The cost structure of these systems, where input rates are coupled to output rates, results in a business strategy of buying low-price electricity and selling only during the relatively few hours when electricity prices are very high (Fig. 3).

In heat storage systems, the heat-to-storage input power (kW), energy storage capacity (kWh), and heat-to-electricity output power (kW) are sized separately. Accumulators and some other heat storage technologies have low costs for heat addition to storage. Much of the cost is associated with the cost of converting heat to electricity. In a market with large-scale solar, the profitable strategy may be to send steam to storage six hours per day when prices are low and to produce added electricity 18 hours per day. The storage system would have high steam input rates into storage (low-cost part of system) and smaller peak electricity production rates (higher-cost part of system). This minimizes the cost of the heat storage system relative to electricity storage systems.

For existing LWRs, limited studies indicate that at many reactors, a storage system could divert 20 percent to 25 percent of the steam at times of low electricity prices, with peak power output 4 percent to 5 percent above baseload capacity, without major changes to the plant. The numbers are plant specific. For new LWRs, up to 70 percent of steam could be diverted to storage at times of low prices, with a peak output 30 percent higher than baseload. With a stand-alone turbine, the peak power output could be much larger. The actual design would depend on the specific markets and engineering trade-offs, such as turbine efficiency, as a function of load.

Storage technologies create other options. If a power reactor has heat storage, it will divert steam to storage when prices are low but keep the turbine running at minimum load to allow rapid return to full power when electricity prices increase. There is the option of using electric resistance heaters to send electricity to heat storage rather than to the grid at times of very low prices. Revenue can be increased by converting low-price electricity into stored heat and later using that heat to produce peak electricity when prices are high.

In all low-carbon electricity grids, there is the need for assured peak generating capacity. If one buys heat storage, with that heat storage comes added peak generating capacity above baseload electricity production. Storage can be depleted and thus can't assure peak generating capacity. There is the option, however, to provide a water-tube boiler to provide the extra steam for peak power production if heat storage is depleted. Most of the time, heat storage will provide the heat needed for peak power; thus, the boiler will operate for a limited number of hours per year with low fuel costs. The cost of such an auxiliary boiler is one-third to half the cost of a gas turbine. If batteries or pumped storage are used for electricity storage, these can become depleted. Gas turbines are the backup technology for electricity storage (batteries, pumped storage) to provide assured peak electricity generating capacity. In many areas, current capacity payments for assured peak generating capacity would cover the cost of such a backup boiler.

Observations

Commercialization requires a strong business case, near-commercial technology, and appropriate institutional structures. The business case for heat storage for variable power output did not exist five years ago. It only appeared with the large-scale deployment of wind and solar that drives wholesale electricity prices to very low levels at times of large wind or solar electricity production. The market impact of wind and solar depends on the quality of local wind and solar resources. It will be large in some parts of the country and small in others. If the number of hours per year with low-price electricity is small, load following will be the preferred option. As the number of hours of low-price electricity increases, however, the economics will favor heat storage to enable the reactor to operate at higher capacity factors.

The cost of peak electricity ($/MWh) from peaking gas turbines (Table 1) is greater than the levelized cost of electricity from nuclear power plants, even with relatively low natural gas prices. This creates an opportunity for competitive nuclear power to add heat storage for variable electricity output with baseload reactor operations to increase revenue.

The near-term heat storage options are at the point where demonstration projects at scale are required. The United States should implement a joint government-utility demonstration program for multiple heat storage technologies where the utility chooses the heat storage technology and manages the project with joint government-private funding[4]. Economic dispatchable nuclear power with heat storage can improve the economics of nuclear, wind, and solar.

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References

1. C. W. Forsberg et al., *Light Water Reactor Heat Storage for Peak Power and Increased Revenue: Focused Workshop on Near Term Options*, MIT-ANP-TR-170, Massachusetts Institute of Technology, Cambridge, Mass., July 2017. <http://energy.mit.edu/2017-canes-light-water-reactor-heat-storage-for-peak-power-and-increased-revenue>

2. C. W. Forsberg, "Variable and Assured Peak Electricity Production from Base-Load Light-Water Reactors with Heat Storage and Auxiliary Combustible Fuels," *Nuclear Technology*, March 2019. <https://doi.org/10.1080/00295450.2018.1518555>

3. D. Petti et al., *The Future of Nuclear Energy in a Carbon Constrained World*, Massachusetts Institute of Technology, Cambridge, Mass., Sept. 2018. <http://energy.mit.edu/wp-content/uploads/2018/09/The-Future-of-Nuclear-Energy-in-a-Carbon-Constrained-World.pdf>

4. C. W. Forsberg, "Commentary: Nuclear Energy for Economic Variable Electricity: Replacing the Role of Fossil Fuels," *Nuclear Technology*, March 2019. <http://doi.org/10.1080/00295450.2018.1523623>

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