Light Water Reactors with Heat Storage and Auxiliary-Combustion Steam Generation to Maximize Electricity and Capacity Payment Revenue

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INTRODUCTION

The electricity market is changing with decreasing markets for base-load electricity. Changes in nuclear power plants are required to match changes in markets to maximize revenue. Nuclear energy produces heat that is then converted to electricity. Heat storage is cheaper than electricity storage (batteries, pumped storage, etc.); thus, there is the option to incorporate heat storage into the power plant to enable variable electricity output to maximize revenue from electricity sales while operating the nuclear reactor at base load to minimize energy costs.

Six heat storage technologies have been identified that couple to LWR steam cycles—two that have been commercialized with concentrated solar thermal power system steam cycles. At times of low electricity prices steam is diverted to heat storage while operating the power turbine at minimum load. Keeping the turbine on line allows rapid return to full electricity output to meet demand during times of high prices. When electricity prices increase, heat from the reactor and storage goes to the turbine system for peak electricity production. Many U.S. reactors are equipped with turbines that can be adapted to deliver 10 to 15% excess capability with minimal modifications so as to allow the plant to produce the added peak electricity.

There is also the option to use low-value electricity from the plant and grid to electrically resistance heat the heat storage media. There is the option to add a gas, oil, biofuels or ultimately hydrogen steam boiler to enable peak electricity production even if heat storage is depleted. If the peak capability is 100 MW(e) greater than base-load operation, added steam generation increases the assured capacity by 100 MW(e) that in markets with capacity payments increases net revenue.

MARKETS

We are in a transition [1] to a low-carbon world where the primary energy sources are nuclear, wind and solar. These systems have high capital costs and low fuel costs. If these systems are operated at half their productive capacity, the cost of energy approximately doubles. Wind and solar output depends upon local wind and solar conditions. Inherent to the large-scale deployment of solar energy, when capacity exceeds 15% or more of the total electricity needs over a year, there will be times of good solar conditions where solar output has to be curtailed and the price of electricity can collapse to zero. The resources society used to build the solar systems are wasted at such times. The same occurs with wind as wind output approaches 30% and nuclear as nuclear approaches 70%. In each system it is assumed that the rest of the system uses fossil fuels.

These market effects are now seen in Europe, the United States, Japan and China. Figure 1 is one example from the California market. Prices over a day are shown for the year 2012 and the same day in 2017 after the addition of large quantities of solar capacity. Price collapse makes all low-carbon technologies less competitive and improves the competitive position of fossil fuels, particularly natural gas plants with low capital costs, higher operating costs and the ability to ramp up and down quickly to match markets.

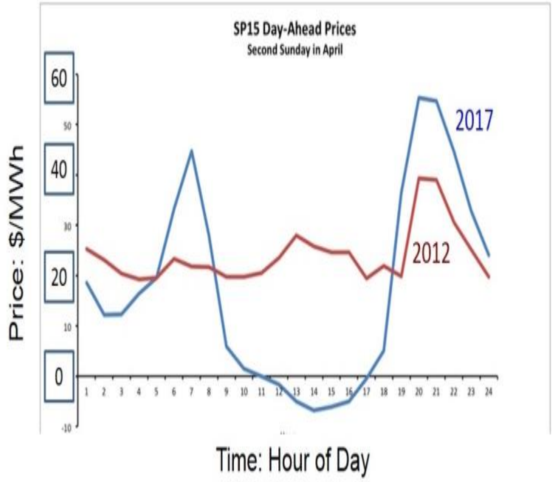

Fig. 1. Change in California Prices in April under High Solar Input

We discuss two strategies to improve LWR economics in these markets while the reactor operates at base load. The first strategy is the use of heat storage to *sell less electricity at times of low prices and more at times of high prices*. The second strategy is coupling auxiliary steam generation (gas-, oil-, biofuels-, hydrogen (future)-fired boilers) to nuclear reactors with heat storage to increase the assured peak capacity of the nuclear plant to *obtain larger capacity payments from the electricity grid*.

VARIABLE ELECRICITY OUTPUT WITH BASE-LOAD REACTOR OPERATIONS USING HEAT STORAGE

The reactor operates at base-load (Fig 2). When low electricity prices, some of the steam is diverted to heat storage while sufficient steam is sent to the main turbine to keep it on line at low power output. When electricity prices are high, all steam from the reactor is sent to the turbine and added heat from storage is sent to the turbine and/or feedwater heaters associated with the turbine to produce peak electricity output.

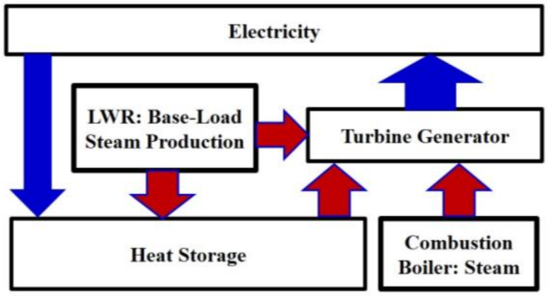

Fig. 2. Schematic of LWR with Heat Storage and Combustion Boiler for Variable Electricity

The goal is to boost revenue by selling when prices are high (Fig. 1)—with storage system capital costs significantly less than the competition—combined cycle gas turbines ($1000/kW) operating on low-price natural gas and electricity storage technologies (batteries, hydro pumped storage).

A recent review [2] of electricity storage technologies and their likely future costs based on such characteristics as materials of construction concluded costs of $340 +/-60 per kWh when deployed at the terawatt-hour storage scale. The U.S. Department of Energy long-term battery storage goal is $150/kWh for the battery—or about double that when installed with power conversion, buildings, and other required systems to couple to the grid. The DOE thermal energy storage goal is $15/kWh. Heat storage is potentially the low-cost storage option.

Heat storage has two costs: (1) the heat storage system and (2) cost to convert stored heat to electricity. The lowest cost strategy for converting stored heat to electricity is to dump the heat from storage to the main turbine or feed water heaters; that is, oversize the main turbine plant for peak power production. There are large economic incentives to use the main power conversion systems because one is then buying incremental electrical generating capacity for a somewhat larger power conversion system at half the cost of a separate power conversion system to convert stored heat to electricity. For modern LWRs, the power conversion systems are ~$500/kW(e). The incremental cost of an incrementally larger power conversion system will be a few hundred dollars per kilowatt.

For a new reactor plant, the LWR turbine system could be designed for power outputs from 30 to 130% of base-load power output. The reactor (the reactor core) would operate at nominal 100% load with variable steam to and from the storage system. For existing LWRs in the U.S., many of the existing turbines have excess capability that would allow a 10 to 15% upgrade in power output from the turbine with addition of storage and heat fed back to the turbines or feed-water heaters.

There are six classes of heat storage systems [3] that couple to steam cycles.

- *Steam Accumulators*. A steam accumulator is a pressure vessel nearly full of water that is heated to its saturation temperature by steam injection. The heat is stored as high-temperature high-pressure water. When steam is needed, valves open and some of the water is flashed to steam that is sent to a turbine producing electricity or feed-water heaters while the remainder of the water decreases in temperature. This system has faster responses than any other heat storage system. Steam accumulators for heat storage are commercially deployed in concentrated solar thermal power plants.
- *Sensible Heat Fluid Systems*. Sensible heat storage involves heating a second fluid with steam, storing that second hot fluid at atmospheric pressure, and using that fluid later to provide the heat to produce steam to then produce electricity. This technology is commercially deployed in concentrated solar thermal power systems. Westinghouse is developing a low-pressure thermal storage system that includes concrete as the primary heat storage medium (a low-cost material) and oil as a heat transfer fluid between the steam system and the concrete.
- *Cryogenic Air Systems*. A cryogenic air energy storage system stores energy by liquefying air at times of low electricity prices. The liquefied air can be stored in facilities similar to those used to store liquefied natural gas (LNG). To produce electricity, the liquid air is compressed, heated using low-temperature heat (cooling water) from the power plant, further heated with steam from the LWR and sent through a gas turbine before being exhausted to the atmosphere. This technology can be coupled to any heat source. The estimated round-trip efficiency for this technology coupled to a LWR is over 70%. The distinguishing feature of this system is that the peak electricity to base-load electricity output is higher than for other heat storage systems. A pilot

plant coupled to a biofuels power plant is now operating in the United Kingdom.

- *Packed-bed Thermal Energy Storage.* A packed-bed thermal energy storage system consists of a pressure vessel filled with solid pebbles with a steam valve at the top and water outlet at the bottom. Heat is stored as sensible heat in the pebbles. To charge the system, steam is injected into the pebble bed, condenses as the cold pebbles are heated and water exits from the bottom of the vessel. At the end of the charging cycle all pebbles are hot and there is hot water filling the voids at the bottom of the vessel. To discharge the system, water is injected into the bottom of the vessel and steam is produced by the hot pebbles. In theory, this system should have the highest round trip efficiency. The technology is in the early laboratory development.
- *Hot Rock Storage*. A hot rock energy storage system is similar in concept to a packed bed energy storage system except it operates at atmospheric pressure with air. A volume of crushed rock with air ducts at the top and bottom is created. To charge the system, air is heated using a steam-to-air heat exchanger delivering heat from the reactor, then the air is circulated through the crushed rock, heating the rock. To discharge the system, the airflow is reversed, and cold air is circulated into the crushed rock at the bottom. This discharged hot air can be used to (1) produce steam for electricity or industry or (2) hot air for collocated industrial furnaces to reduce natural gas consumption. It has the lowest incremental heat storage costs per kWt. The technology is under development for storage in solar thermal hot-air systems and is expected to be deployed in solar systems the next several years.
- *Geothermal Heat Storage Systems*. Nuclear geothermal heat storage systems combine the features of an enhanced geothermal energy facility with thermal energy storage. Thermal energy is stored by injecting hot water heated by steam from the reactor into the underground reservoir; energy is discharged by pumping hot water back to the surface for electricity production in a conventional geothermal plant. Only limited studies have been completed. This heat storage technology has different characteristics than the other heat storage options. It can provide seasonal energy storage but can only be deployed as a large system because there is no way to insulate rock deep underground. However, the surface area goes up as the square while the storage volume increases as the cube resulting in low losses for systems with more than 0.1 Gigawatt-year of heat storage.

For all of these storage systems, there is also the option to heat the storage media using resistance heaters when the price of electricity is very low (Fig. 1). The electricity can be from the turbine operating at minimum load at times of low prices and from the grid. For an LWR with 33% efficiency, electricity could be used as a heat source for storage whenever the peak price of electricity at times of high prices is more than three times the minimum price of electricity.

ASSURED PEAK CAPACITY

Depending upon the electricity market, a power generator may receive payments for assured capacity—the ability to produce electricity at any time to prevent blackouts. Historically these payments were small because fossil and nuclear plants can run on command. However, the addition of non-dispatchable wind and solar changes this. There is no assurance electricity can be produced when needed by wind or solar technologies. Storage systems do not fix this problem—except systems such as nuclear geothermal with seasonal storage. While traditional storage technologies can provide output much of time, extended low-wind or low-solar conditions will ultimately deplete storage capacity.

What storage does is reduce the number of hours per year where one needs assured capacity. If a gas turbine is used to provide assured capacity, it may be needed less than a hundred hours per year—a very expensive method to assure generating capacity.

The LWRs with heat storage have oversized turbines and heat storage. Assured generating capacity for peak power production can be enabled by adding steam boilers burning natural gas, oil, biofuels, or ultimately hydrogen to provide the heat that would have come from storage. If the difference between nominal base-load output and peak capacity with storage is 200 MWe, the steam boiler would be sized to generate steam needed to produce 200 MWe.

Because the peak turbine capacity is already paid for (part of the storage system) as well as such systems as boiler water cleanup, the only capital cost for the extra production are for the steam boilers. The incremental cost of such a steam generation system ($100 to 300/kWe) is significantly less than a simple cycle gas turbine (~$500/kWe) or a larger reactor. If the LWR has heat storage, a low-cost system for added steam production provides assured added electrical generating capacity. The fuel consumption would be very low because most of the time heat storage provides the steam for added capacity. Such an investment would be justified where (1) market capacity payments justify such an expense and/or (2) where there are sufficient hours per year where the storage system would be expected to be depleted and electricity prices will be high.

CONCLUSIONS

Historically nuclear plants have been operated to produce base-load electricity. This was the optimum economic solution in a electricity grid with nuclear and fossil plants because the nuclear plant had high capital costs and low operating costs while the fossil plants had low capital costs and high operating costs. The market is changing. The large-scale addition of wind or solar creates times of very low electricity prices because these technologies are non-dispatchable—driving prices down at times of high wind or solar inputs. This also tends to raise prices at other times.

These changes create a large incentive for nuclear plant owners to operate the reactor at base-load to minimize costs while varying electricity sales to the grid to maximize revenue. Heat storage integrated into the steam cycle is capable of accomplishing this.

The other change in the electricity system is that wind and solar can't provide assured electric generating capacity. If storage is coupled to an LWR, the turbine capacity will be larger than the base-load capacity to enable peak power production. However, stored heat may be depleted due to extended periods of low wind or solar conditions. There is the option to add steam boilers fueled by natural gas, oil, biofuels or ultimately hydrogen to provide steam for peak production from nuclear plants at such times—replacing steam that would come from storage for normal peak electricity production. This may be the lowest cost option to provide extra capacity to meet the needs for assured electricity production and provides a second source of revenue—capacity payments.

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