The Requirement for Variable Electricity from Base-Load Nuclear Power Plants: Role of Heat Storage

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The electricity market is changing with decreasing markets for base-load electricity. Changes in nuclear power plants are required to match changes in markets. 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 design to enable variable electricity output to maximize revenue while operating the nuclear reactor at base load to minimize energy production costs.

There are three classes of heat storage options coupled to reactors. Six types of heat storage can be integrated into steam cycles coupled to light-water reactors and other nuclear reactors. There are two types of heat storage that couple to high-temperature Brayton cycles coupled to High-temperature Gas-cooled Reactors (HTGRs), Fluoride-salt-cooled High-temperature Reactors (FHRs) and molten salt reactors (MSRs). Three types of heat storage can be incorporated into the intermediate heat transfer loops employing sodium, molten salt, or lead.

Heat storage can enable the power plant to operate as a battery or pumped hydro station. At times of low electricity prices there is the option to divert heat from the reactor 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. The low-value electricity from the plant and added low-value electricity from the grid can be used to electrically resistance heat the heat storage media. When electricity prices increase, heat from the reactor and storage goes to the turbine for peak electricity production to maximize revenue. At all times the reactor operates at full load.

The limitation of storage is that it is not assured generating capacity because storage systems can be depleted. In markets with large capacity payments, adding natural gas, oil, biofuels or hydrogen heaters can provide added heat which enables the plant at any time to produce at peak electric capacity: base load plus the peaking capability from heat storage.

INTRODUCTION

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 capacity, the cost of energy doubles. Wind and solar output depends upon local conditions. With the large-scale use of solar, by the time solar is producing 15% of the total electricity needs over a year, solar output at times of good solar conditions exceeds electricity needs and the price of electricity collapses to zero. The resources society used to build the solar poqwe systems are wasted at such times. The same occurs with wind as wind output approaches 30% and nuclear as nuclear approaches 70%.

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 and higher operating costs. Fossil fuel plants with low capital costs, high operating costs, and the ability to ramp up and down quickly become the preferred generating option in such markets.

These market changes create large incentives for high-capital-cost low-operating-cost nuclear generating technologies to (1) operate at full capacity to minimize cost and (2) add heat storage to enable variable electricity output to maximize revenue—sell when prices are high and minimize sales when prices are low. Heat is put into storage at times of low prices to produce added electricity at times of higher prices.

There is a direct overlap between thermal storage used for nuclear and solar thermal systems. Relatively small amounts of solar can collapse prices at times of high solar input and thus destroy the economics of solar. This creates large incentives to develop solar thermal storage for solar thermal power systems to minimize electricity sales at times of high solar input.

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

OPTIONS FOR VARIABLE POWER OUTPUT

There are four options (Fig. 2) for variable power from a nuclear power plant—each with different characteristics. The market will ultimately determine which options are preferred under different market conditions.

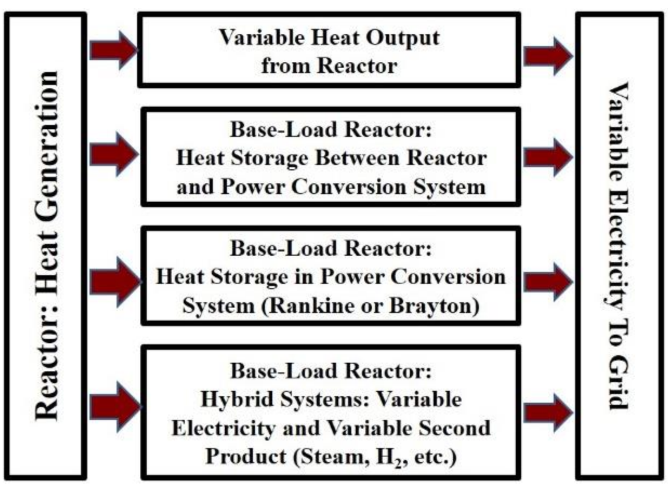

Fig. 2. Options for Variable Electricity from a Nuclear Power Plant

Vary Reactor Power Levels

Reactor power levels can be varied to match demand. In countries such as France pressurized water reactors (PWRs) have done load following for decades. If the number of hours at low electricity prices are small, this becomes the preferred option due to its low capital cost.

Integrate Heat Storage with the Power Cycle

Heat storage can be integrated into the power cycle to enable variable electricity output with base-load reactor operations.

Rankine (Steam) cycles. A recent workshop [2, 3] evaluated 6 heat storage technologies that can be coupled to light water reactor steam cycles. Steam is the input to the storage system with steam or heat in most cases returned to turbines or feed-water heaters. We have identified six types of heat storage systems that couple to steam cycles.

- *Steam Accumulators*. Heat is stored as high-pressure high-temperature water. The technology has the fastest response speed for variable power output. It is a commercial heat storage technology used in some concentrated solar thermal power systems.
- *Sensible Heat Fluid Systems*. Heat is stored in a secondary solid or liquid. This technology is commercially deployed in some concentrated solar thermal power systems. Westinghouse is developing such a system for LWRs

- *Cryogenic Air Systems*. A cryogenic air energy storage system stores energy by liquefying air at times of low electricity prices. To produce electricity, the liquid air is compressed, heated using low-temperature heat (cooling water), further heated with nuclear heat and sent through a gas turbine before being exhausted to the atmosphere. The technology has the highest peak-to-base load output of any storage option. A pilot plant coupled to a biofuels power plant is now operating in the United Kingdom. The estimated round-trip efficiency for this technology coupled to a LWR is over 70%.
- *Packed-bed Thermal Energy Storage*. Heat is stored in solid pebbles inside a pressure vessel. In principle, this technology has the highest round-trip efficiency. The technology is in the early laboratory development stage.
- *Hot Rock Storage*. Heat is stored in hot crushed rock at atmospheric pressure. This technology is expected to have the lowest incremental heat storage cost. There is significant ongoing research for solar thermal systems and limited work on applications to nuclear systems
- *Geothermal Heat Storage Systems*. Thermal energy is stored in hot rock underground. This is the only option capable of seasonal heat storage. Limited work has been done

Brayton power cycles. Sodium and salt reactors can be coupled to Brayton power cycles [4-7] with heat storage. Heat transfer from storage is to hot air (open cycle) or helium (closed cycle) which requires a different set of heat storage technologies. Some of these systems include Firebrick Resistance Heated Energy Storage (FIRES) that buys electricity when prices are low (base-load electricity plus electricity from the grid) to heat firebrick to very high temperatures and adds heat to the Brayton power cycle when prices are high to boost temperatures and power output [6]. The potential electricity-to-heat-to-electricity round trip efficiencies may exceed 70%. They are in the early stage of development.

Heat Storage between Reactor and Power Cycle

For reactors with low-pressure intermediate loops containing sodium, lead, or liquid salt, heat storage can be incorporated into the intermediate loop between reactor and power cycle [8].

- *Coolant Heat Storage*. The intermediate fluid can be used as the storage fluid. This is done for solar thermal systems with nitrate salts. The viability for use in nuclear systems depends upon the cost of the fluid and for sodium a concern about safety of large sodium storage masses.
- *Sensible Heat Storage*. Various solids can be used for storing heat where very low-cost solids are used for heat storage. In some cases the solid material is compatible with the coolant—such as storing heat in iron or steel in sodium loops where steel is less expensive than sodium.
- *Latent Heat Storage.* Heat can be stored in phase change materials—an area of much research for solar systems and limited research for nuclear systems. These systems are more complex but storage volumes are smaller and heat is stored at a defined temperature.

Hybrid Energy Systems

The reactor produces two or more products to enable variable electricity output with base-load reactor operations. The second product is produced in variable amounts and could be steam to industry, hydrogen, clean water (desalination) or some other product. This has large long-term potential but is a longer term option in most cases because it requires co-siting of facilities.

HEAT STORAGE ECONOMICS

The drive for heat storage in nuclear and concentrating solar power systems 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 [9] of electricity storage technologies and their likely future costs based on such characteristics as materials of construction concluded capital 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.

The other cost is conversion of stored heat to electricity. The lowest cost strategy for converting stored heat to electricity is to dump the heat 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) with somewhat lower costs for higher temperature steam cycles. The incremental cost of an incrementally larger power conversion system will be a few hundred dollars per kilowatt. This is substantially less than the capital cost of a combined cycle natural gas plant at ~$1000/kW(e). From a capital cost perspective, heat storage has the potential to be much more economic than the competition.

For all of the storage options there is the option electric heating. In a low-carbon world there may be times of very low or negative electricity prices (Fig. 1). The nuclear plant operator could shut down the power conversion cycle and send all heat to storage with no electricity to the grid; however, one wants the turbine running to quickly go from low power to peak power when electricity prices rapidly increase. To keep the turbine running at times of low prices but minimize sales of electricity, there is the option to use low-value electricity from the turbine operating at its minimum load and cheap electricity from the grid to heat up the storage media—an electricity to heat to electricity storage system. The electricity-to-heat efficiency is near 100%; thus, the round trip efficiency will be very close to the power conversion system heat-to-electricity efficiency. In this mode the nuclear plant operates as a combined power plant and battery that buys and sells electricity.

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 these technologies. Storage systems (except geothermal heat storage) do not fix this problem because they can be depleted over time. What storage does is reduce the number of hours per year where one needs assured capacity.

The systems herein have oversized turbines and storage. Assured generating capacity for peak power production can be enabled by adding natural gas, oil, biofuels, or ultimately hydrogen combustion systems to provide the heat that would have come from storage. If the peaking capacity is 200 MWe over base-load, the combustion heaters must produce heat sufficient for 200 MWe of electricity production. Because the peak turbine capacity is already paid for (part of the storage system), the only capital cost for the extra capacity is the combustion gas heater that will be used infrequently—a fraction of the cost of a stand-alone gas turbine. Because such systems would be used infrequently, the cost of fuel is small relative to the capital cost. If the system is built with storage, a low-cost system for auxiliary heat for added capacity can be added where market capacity payments justify such an expense.

CONCLUSIONS

The electricity market is changing with decreasing markets for base-load electricity. Decreases in the relative size of the industrial sector versus other uses for energy decrease base load as a fraction of total energy demand. Large-scale deployment of wind or solar collapse electricity prices at times of high wind or solar output but often raise the price of electricity at other times. These market effects have been seen in parts of Europe, the United States, Japan and China.

Nuclear power plants with heat storage can provide variable electricity to the grid to maximize revenue while the reactor operates at base-load to minimize costs. Unlike solar thermal systems with storage, they are not limited by solar availability in terms of location (north/south with short/long days) or climate (sunny/clouds). Heat storage technologies enable nuclear to replace fossil fuels as a dispatchable electricity source enabling (1) a low-carbon electricity grid and (2) larger scale use of renewables by reducing solar and wind induced price collapse that limits the economic use of these technologies.

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