Massachusetts Institute of Technology (MIT): Coupling Heat Storage to Base Load Nuclear Reactors

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The coupling of base load nuclear power plants to large-scale heat storage enables a new dimension for nuclear flexibility to enable nuclear plants to provide economic variable electricity to the grid. The economics of a low-carbon world are different than a world built on fossil fuels. The capital costs of fossil power plants, furnaces, and other power conversion systems are low relative to the cost of fossil fuels. The cost of fossil fuel storage is low. These characteristics make it economic to operate these systems at part-load to provide economic variable electricity, mechanical work, and heat to the customer.

Nuclear, wind, and solar have high capital costs and low operating costs. Unlike fossil fuel systems, operating these energy production technologies at half their nominal full capacity approximately doubles the cost of energy. The nominal base load capacity depends upon the technology (EIA 2020). In the United States, the capacity factor is more than 90% for nuclear, 34% for wind, and about 25% for PV. Nuclear plants are shut down for refueling and maintenance. Wind capacity depends upon wind speed with time. PV capacity factors are lower because there is no sun at night and cloud cover. The fuel costs of nuclear plants are low so if operate at 45% capacity the cost of energy almost doubles. Wind and solar have low operating costs; thus, operating them at half nominal capacity doubles energy costs. Energy storage systems, coupled with low-carbon generation, offer the potential to minimize the cost of energy in a low-carbon world by enabling these technologies to operate each at near their nominal full capacity while providing variable energy as needed to the customer. Storage can also support systems with mixtures of fossil, nuclear, wind, and solar.

There are three classes of large-scale energy storage technologies: (1) work (electricity) storage: batteries, hydro pumped storage, and so on; (2) heat storage; and (3) chemical storage (hydrogen, and so on). Electricity storage couples best to the electricity grid and electricity-generating technologies, such as wind and PV. Heat storage technologies couple to heat generating technologies such as nuclear, concentrated solar power (CSP), fossil fuels with carbon capture and sequestration, and geothermal. Hydrogen storage couples to different hydrogen production technologies that may be driven by electrical and thermal energy input and has the capability for seasonal energy storage.

MIT, INL, and Exelon have conducted recent workshops (Forsberg 2018; Forsberg, Sabharwall, and Gougar 2019) that examined proposed heat storage systems coupled to nuclear reactors with storage capacities from a few hundred MWh to 100 GWh. Heat storage is less expensive than electricity storage because low-cost materials (crushed rock, liquid salts, and so on) are used. If very low-cost heat storage coupled to nuclear reactors can be developed and deployed, it would benefit nuclear, wind, and solar by allowing these technologies to be operated in their most economic mode at full capacity. Large scale heat storage was originally developed for CSP systems to enable these systems to provide electricity to the grid after the sun sets. Current CSP systems have heat storage capacities of up to several GWh of heat. This chapter describes heat storage systems, heat storage technologies, and integrated heat/hydrogen storage systems.

1.1 Heat Storage Systems

The nuclear heat storage system is shown in Figure 1. The same system design can be used for any heat generating technology. To minimize the cost of energy, the reactor operates at full capacity. When electricity demand is high, resulting in high prices, reactor heat is sent to the turbine to produce electricity. When demand is low, resulting in low electricity prices, a majority of the heat is diverted to heat storage. When peak demand exceeds the base load reactor electricity output, combined heat from the reactor and heat storage is sent to the turbine-generator for electricity production, supported by either oversizing the turbine generator or building a separate peaking turbine-generator for peak power output. At times of very low (or negative) electricity prices, grid electricity can be converted into stored heat using resistance heaters coupled to the heat storage system. Hence, the power plant system can both sell and buy electricity. If stored heat is insufficient to meet peak demand, combustion of natural gas or low-carbon biofuels and hydrogen can provide heat to support peak electricity production.

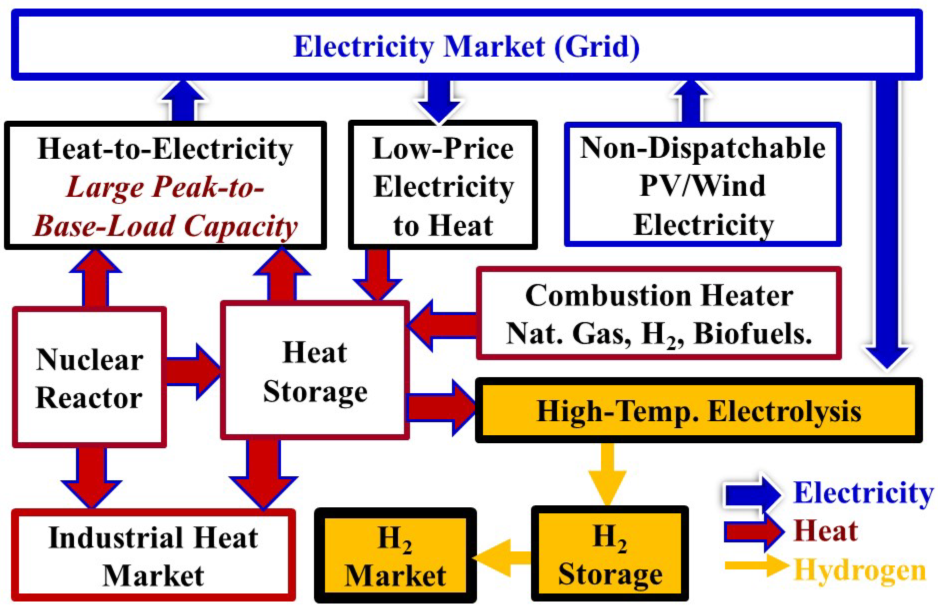

Figure 1. Base load nuclear, wind, and solar with heat storage to provide variable heat, electricity, and hydrogen

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The system design enables economic, larger-scale use of wind and PV. First, large amounts of wind and PV collapse the price of electricity at times of high output and, thus, revenue. There is excess electricity production. This system can absorb excess electricity by converting it to stored heat and setting a minimum price for electricity to support solar and wind. Second, the system provides assured generating capacity at times of low wind and solar output at a lower cost than using electricity storage backed up with gas turbines when that storage is depleted.

The system supports cogeneration of electricity and heat for industry. Cogeneration has major implications for the electricity grid because it directly links the industrial heat market to electricity markets. Some industrial processes can operate flexibly or vary heat demand, freeing up heat for electricity production when needed and consuming added heat at times of low electricity demand.

Coupling the industrial sector with the electricity sector via storage adds an additional dimension to balancing energy production with demand.

Energy can also be stored in the form of hydrogen. Hydrogen can be stored underground in the same facilities used for seasonal natural gas storage; thus, hydrogen enables seasonal storage of energy. The leading candidate for nuclear hydrogen production is high-temperature (steam) electrolysis of water a process that requires heat and electricity. Hydrogen production facilities are capital intensive, not just due to the production process but also the compressors, pipelines, and associated facilities—all with large economies of scale. Hence, it is uneconomic to operate such facilities at low capacity factors. This may require that plants producing hydrogen operate more than 80% of the time (Boardman et al. 2019). The high-temperature electrolysis plant is embedded into a system that includes nuclear and renewable generators and heat storage. At times of low electricity prices, electricity from the grid, or electricity produced by the nuclear reactor, can be used for electrolysis while heat from the nuclear plant is directed to storage and the high-temperature electrolysis plant for hydrogen production. At times of high electricity prices, heat from the reactor and heat storage produce peak electricity with no hydrogen production.

This nuclear heat-storage hydrogen system has three characteristics. First, large-scale hydrogen storage, supporting flexibility on an hourly to seasonal basis, is inexpensive when using the same underground storage facilities used for natural gas. Hence, stopping hydrogen production due to increased electricity demand does not disrupt the hydrogen supply to the customer. Second, the system design allows excess low-price wind and solar electricity, when available, to produce higher-value hydrogen while excess heat from the nuclear plant is directed to storage for later use. Third, it enables the nuclear plant to operate at full capacity as a peaking unit for electricity production while producing hydrogen for as much as 80% of the time. This enables the nuclear plant to provide electricity to address seasonal peaks in electricity demand.

1.2 Heat Storage Technologies

There is no single optimum or best heat storage technology. Different types of nuclear plants deliver heat at different temperatures and use different coolants. The heat storage technology must match the reactor type. In addition, different markets may require different heat storage technologies. If heat storage is use on a daily basis, as might happen in a system with a large PV capacity, the storage technology will be used several hundred times per year that creates a large economic incentive for efficient storage. If heat storage is used to store excess energy from the weekend at times of low demand for use during the weekdays at times of high demand, the storage system will be used, at most, 52 times per year. There are fewer storage cycles per year to pay for the capital cost of the storage system. In such an application, the economics will prefer a storage system with very low capital costs even if it is somewhat less efficient.

1.2.1 Liquid Salts

The primary heat storage materials used in high-temperature CSP systems are nitrate salts where the most common salt is solar salt with a composition of 60 wt% $NaNO_3$- 40 wt% KNO_3. In these systems, there are cold and hot nitrate salt storage tanks. Cold salt is sent through the CSP system, is heated, and is sent to the hot salt storage tank. Sensible heat of storage is obtained by varying salt temperatures from 290° C to 565 °C. Hot salt is sent to a steam generator to produce steam that is used to produce electricity with the resultant cold salt returned to the cold salt storage tank.

The largest CSP nitrate-salt storage system sizes are measured in gigawatt-hours of heat. Nitrate salts can be used to move heat to industrial customers.

Similar nitrate-salt storage system designs are proposed for SFRs, fluoride-salt-cooled high-temperature reactors with solid fuel and liquid salt coolants, molten salt reactors (MSRs) with fuel dissolved in the salt and fusion machines with liquid salt blankets. In each of these cases the nitrate salt replaces the intermediate heat transfer loop that separates the low-pressure reactor from the high-pressure power cycle. Because the nitrate salt replaces other fluids in the intermediate loop with hot salt, there is no efficiency loss by adding storage to these reactors—salt after being heated goes directly to storage, just like in a CSP system.

1.2.2 Heat Transfer Oils

Lower-temperature CSP systems use heat transfer oils, such as Therminol-66. These systems have operating temperatures below 400°C—the upper limit for these oils. These heat storage systems are compatible with existing LWRs with peak temperatures of ~300° C.

1.2.3 Crushed Rock and Cement

The costs of liquid salt and heat-transfer oil heat-storage systems can be reduced with the use of a lower-cost filler material in the tank partly replacing salt or oil for heat storage. Both crushed rock and special high-temperature cements are being considered as fill materials. Cements can be formed into specific shapes, such as parallel plates with narrow channels in the storage tanks to minimize the inventory of heat transfer fluid. Crushed rock is the lowest-cost fill material but has a higher void volume.

Westinghouse is examining a system for LWRs where steam is used to heat oil that, in turn, transfers its heat to concrete in prefabricated boxes filled with closely packed cement plates with small cooling channels between the plates. This minimizes the inventory of the more expensive heat transfer oil. At times of high electricity demand, the oil transfers heat back to the steam cycle.

Korean researchers (Amuda and Field 2019) are examining a similar system for LWRs that uses crushed rock as the heat storage material. There would be multiple tanks of crushed rock with heat-transfer oil only in tanks where heat is being transferred from the steam cycle to the crushed rock or from the crushed rock back to the steam cycle. This reduces the inventory of expensive heat-transfer oil. Roundtrip efficiencies can approach 80%; that is, if a MWh is generated without storage, 0.8 megawatt hours of electricity is generated from the stored heat. The Korean design proposes that the storage system be built as a large barge (60 m by 450 m) with multiple tanks with a heat storage capacity of 20 GWh of electricity. The barge, the size of a supertanker, would be delivered to coastal nuclear power sites where it would be floated into a dry dock at the reactor site. Hot-oil heat transfer also allows easily coupling to industrial heat customers.

Germany (Odenthal, Klasing, and Bauer 2018) is examining nitrate salt heat storage in single tanks filled with crushed rock with lower-density hot salt on top of cold salt. The single tank reduces costs relative to the use of separate hot and cold salt tanks. The crushed rock is a heat storage medium and helps prevent mixing of hot and cold nitrate salt.

Third-generation systems, where only limited work has been done (Forsberg 2020), store heat in crushed rock in insulated and covered trenches up to 60 meters wide, 20 meters high, and 1 kilometer long. For systems coupled to LWRs using oil as a heat transfer medium, every 10 meters of crushed rock provides about a GWh of heat storage, assuming a 200° C hot-to-cold temperature swing. When excess energy is available, some of the steam from the reactor heats oil rather than being sent to the turbine-generator to produce electricity. The hot oil is sprayed over sections of crushed rock to heat the rock as it flows down to the oil pan under the crushed rock. The oil is collected and cycled back to the reactor to be reheated. At times of high electricity demand, cold oil is sprayed on the hot rock, flows through the rock, is collected by the oil pan, and is used to convert water into steam. The steam is sent to a peaking steam turbine-generator to produce electricity. There is a parallel system for nitrate salts that operates at higher temperatures. Costs are minimized by three features. Crushed rock is the cheapest heat storage material. Flowing the salt or oil over the rock rather that filling all the rock void spaces minimizes the inventory of heat transfer fluid. The large storage system size minimizes the surface-to-volume ratio and, thus, the cost of insulation and liners.

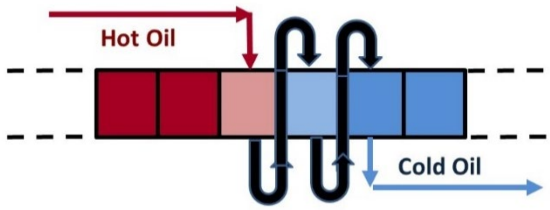

Figure 2. Sequential heating of crushed rock bed with hot oil

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There is other ongoing work using crushed rock for GWh heat storage systems because of its low cost. Siemens (Kosowatz 2019) is developing a hot rock heat storage system where air is heated by electric resistance heaters at times of low electricity prices and blown through the crushed rock to heat it to 650° C. At times of high electricity prices, cold air is blown through the hot rock to produce hot air for a steam boiler.

1.2.4 Cast Iron With Cladding

Sensible heat can be stored in solid tightly packed hexagonal assemblies 10–20 meters high made of cast iron with a stainless-steel cladding chosen for chemical compatibility to match the coolant—sodium, salt, lead, or helium. Coolant flows between the solid assemblies. This option places an upper limit on the cost of heat storage associated with any coolant—water, salt, sodium, and helium. It is compatible with any reactor coolant with the appropriate choice of clad. It may be particularly attractive for SFRs with its low-pressure secondary loop by enabling storage in the secondary sodium loop. This system minimizes flammable sodium in the storage system, and the cast iron is cheaper than sodium.

The DOE goal for the capital cost of heat storage systems is \$15/kWh of heat. The commercial nitrate salt storage system costs are near \$20/kWh. The projected costs for second-generation nitrate-salt crushed-rock heat storage systems are near \$10/kWh, whereas predicted capital costs for some of the third-generation systems are only a few dollars per kWh in sizes to 100 GWh to enable weekend/weekday storage. Today, commercial heat storage system costs per unit of electricity are a factor of three to four less than electricity storage technologies. Advanced heat storage technologies have the potential to be an order of magnitude lower in cost than electric storage technologies reflecting lower cost materials of construction (i.e., crushed rock and thermal salts versus lithium, cobalt, carbon, or steel) and higher operating efficiency

1.2.5 Hydrogen

The synergistic combination of two energy storage technologies (heat and hydrogen) would enable nuclear plants to address subhourly, hourly, and seasonal mismatches between demand and energy production. This includes integration of nuclear and renewable systems to enable high capacity factors for all low carbon-generating technologies to minimize total energy costs. The central question is whether the future size of hydrogen markets is sufficiently large to achieve this goal.

Hydrogen generation provides an approach to store energy in a chemical form, offering different benefits relative to heat or electricity storage. Massive quantities of hydrogen are used in fertilizer and liquid fuels production. In a low-carbon world, hydrogen may replace coal as a chemical reducing agent in the production of steel (Millner et al. 2017) and be used to produce biofuels. In these roles, hydrogen is used because of its chemical properties—not primarily as an energy source. Hydrogen may also be used as a fuel for transport vehicles, peaking gas turbines, and to produce very high temperature heat for industrial processes.

Recent assessments (Miller et al. 2020) indicate hydrogen may become 10% to 30% of total energy demand in a low-carbon economy. Equally important is that this scale of operations is not dependent upon a single hydrogen market or technology. It is credible that the combination of heat and hydrogen storage can address subhourly to seasonal storage requirements at the required scale.

1.3 References

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