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Multi-Gigawatt-Day Low-Cost Crushed-Rock Heat Storage Coupled to Nuclear Reactors for Variable Electricity and Heat

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INTRODUCTION

Energy markets worldwide are changing because of two factors: (1) addition of low-cost non-dispatchable wind and solar and (2) the goal of a low-carbon society. In electricity markets this results in times of high and low wholesale prices for electricity creating the potential for large increases in revenue for power systems that can provide dispatchable electricity to the grid with assured peak generating capacity. In the industrial markets, these changes create large incentives for nuclear cogeneration of heat and electricity.

We examine the use of crushed rock as a very-low-cost heat storage media using heat-transfer oils to move high-temperature heat from the steam cycle to storage and back to the power cycle. This is a Generation III heat storage system with the goal of capital costs of a few dollars per kilowatt hour of heat storage. Heat is transferred from hot oil to crushed rock by spraying the oil over the crushed rock. The inventory of heat-transfer oil is determined by the rate of heat movement to and from heat storage—not storage capacity. Low-cost crushed-rock heat storage may make possible economic multi-gigawatt-day heat storage. Heat transfer oils are chemically stable to about 400°C. With light-water reactors (LWRs), oil transfers heat from steam cycle to the crushed rock and back. With higher temperatures reactors, high-temperature steam is sent through the high-pressure turbine to produce electricity. When steam goes below 400°C, steam can be sent to the low-pressure turbines or used to heat oil that is then used to heat crushed rock. Heat-transfer oils are used to move heat in chemical plants; thus, the same oils can be used for heat transfer to industrial facilities.

CHANGING ELECTRICITY AND HEAT MARKETS

The large-scale addition of wind and solar has massive electricity-market impacts. Wind and solar in good locations provide low-cost electricity at times of high wind and solar output but can’t provide assured generating capacity. The large-scale addition of solar results in collapse of wholesale electricity prices in the middle of the day with higher prices before sunrise and as the sun goes down. Recent studies [1] of the impacts of wind and solar on California electric wholesale markets provide insights to the long-term market effects of wind and solar.

- Revenue to base-load power plants goes down with large-scale wind and solar additions.
- There are large economic incentives for dispatchable electricity with fast response to produce electricity at times of higher prices (low wind/solar output) and avoid selling electricity at times of low or negative prices (high wind/solar output).
- As more wind or solar is added, the revenue per installed kilowatt of capacity of wind and solar goes down [2].

The changing market creates incentives to couple heat storage to nuclear power plants to enable base-load nuclear plants to produce variable electricity and increase revenue by selling more electricity when prices are high.

Fossil fuels have reasonable costs, are easy to transport and have low storage costs. As a consequence, the cost of a shipload of coal, oil or liquefied natural gas (LNG) is about the same in New York Harbor as in Shanghai. The result is a relatively flat price of energy in much of the world. If carbon dioxide emissions must be eliminated, the use of fossil fuels requires large-scale carbon capture and sequestration (CCS) which requires the appropriate sequestration geology. Nuclear energy is the only technology not limited by location (TABLE I) and thus the only technology capable of preventing large geographical variations in energy prices. If it is to replace fossil fuels, the requirement is to provide economic variable electricity and heat.

TABLE I. Characteristics of Low-Carbon Energy Sources

Energy Source	Dispatchable	Geographically Limited
Solar	No	Yes
Wind	No	Yes
Hydro	Yes	Yes
Fossil with CCS	Yes	Yes
Nuclear	Yes	No

Last, economic low-cost heat is required for industry. The U.S. industrial heat demand is about twice the total electricity production and the cost of electricity is about six times the cost of natural gas as a heat source. The price difference between electricity and heat is a consequence of two factors. First, the laws of thermodynamics requires several units of heat to produce a unit of electricity; thus, the cost of electricity is a multiple of that of any heat source. Second, electricity requires an electrical grid to move from generator to user that doubles electricity costs. Technologies that directly produce electricity (wind and solar PV) have relatively low electricity production costs but produce expensive heat since one unit of electricity yields one unit of heat. Technologies that produce heat (natural gas, nuclear, concentrated solar power (CSP), etc.) produce lower-cost heat but make more expensive electricity because it takes several units of heat to produce a unit of electricity. The economic low-carbon industrial heat sources are (1) nuclear energy and (2) location-dependent fossil fuels with CCS.

NUCLEAR POWER PLANT DESIGN TO MEET CHANGING REQUIREMENTS

Figure 1 shows the system design for heat storage and assured peak energy production capacity coupled to a nuclear reactor [3, 4] to meet changing market requirements. To minimize the cost of energy, the nuclear reactor operates at base load. When electricity prices are high, all reactor steam is sent to the turbine to produce electricity. When electricity prices are low, most steam is diverted to heat storage. At times of peak electricity prices, heat from the reactor and heat storage is sent to the turbine for peak electricity production that is significantly above base-load reactor electricity output. Peak electricity production can be achieved by (1) oversizing the turbine generator or (2) building a separate peaking steam turbine for peak power output. At times of very low electricity prices, electricity from the grid and from the main turbine operating at minimum load is converted into stored heat with resistance heaters coupled to the heat storage system. The power plant sells and buys electricity. If heat storage is depleted, natural gas or low-carbon biofuels and hydrogen are used to enable assured peak electricity production by providing the extra heat that would have come from the heat storage system. The same system is used for cogeneration of electricity and heat for industry.

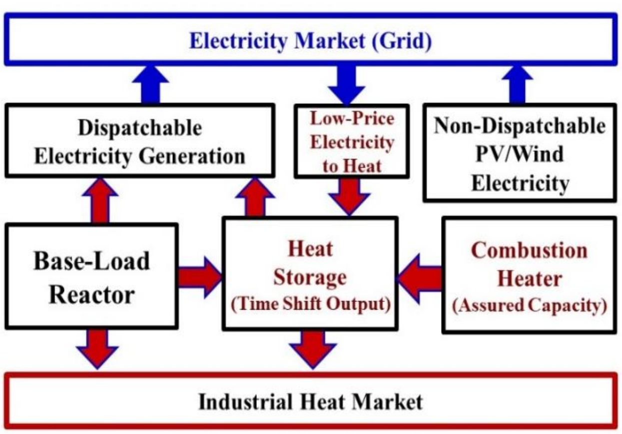

Fig. 1. System Design for Base-Load Nuclear Reactor to Provide Variable Heat to Industry and Electricity to Grid

The choice of storage technology is dependent upon (1) the exit and return temperatures of the reactor coolant that must match those of the storage media and (2) the specific market. A market with large quantities of solar will have large daily variations in electricity prices whereas a market with large quantities of wind will tend to have multiday variations in electricity prices. There are large differences in the electricity prices in some markets between weekdays and weekends that favor weekly energy storage.

Figure 2 shows hot-rock storage with oil for heat transfer coupled to a high-temperature reactor (HTR) or light-water reactor (LWR) with a steam cycle. HTRs include high-temperature gas-cooled reactors, salt-cooled reactors and sodium fast reactors. A generic system design is described that incudes high-temperature nitrate-salt heat storage and intermediate-temperature hot-rock heat storage. The high-temperature heat storage is applicable to HTRs where the intermediate-temperature heat storage matches LWR steam conditions or steam from a HTR steam cycle after exiting the high-temperature turbine.

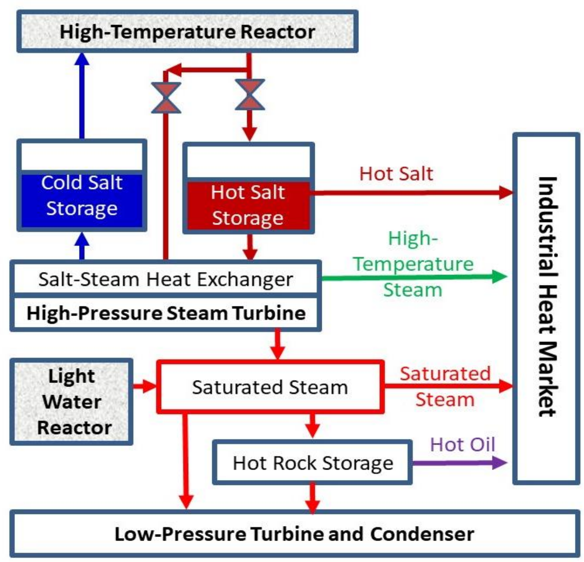

Fig. 2. Heat Storage Options for Rankine Cycles

Most salt-cooled and some sodium-cooled reactors under development include an intermediate nitrate salt loop between the reactor and power cycle. The intermediate loop provides (1) isolation between the low-pressure reactor system and high pressure power cycle, (2) the option for heat storage between the base-load reactor and customer whether it be the power cycle for electricity or industrial heat and (3) a way to deliver high-temperature heat to industrial customers. The preferred salt is the sodium-potassium nitrate salt used for heat storage in higher-temperature concentrated solar power (CSP) plants with steam cycles. It is a Category I heat storage system; that is, a commercial technology.

With heat storage one can produce peak electricity. As an example, the Moltex reactor being developed in the United Kingdom proposes that the peak electricity output using reactor heat and stored heat in nitrate salts be three times the base-load reactor capacity. Some commercial CSP plants with nitrate storage have backup fossil-fuel heaters to provide assured peak generating capacity if heat storage is depleted—the same option is applicable for nuclear systems with heat storage for assured peak power production.

High-temperature heat storage in salt has one unique feature—no significant efficiency loss with storage because the intermediate salt loop is required for other reasons. The only efficiency loses are conduction through tanks that is less than 1% per day in these large systems.

Work is underway on a second generation nitrate heat storage system that would be a single tank filled with crushed rock [5]. Hot salt would be on top of cold salt. The addition of crushed rock would replace much of the nitrate salt with much less expensive crushed rock. The crushed rock would also stabilize the thermocline between the hot salt/rock and cold salt/rock.

The heat is transferred from salt to a high-temperature steam cycle that allows sending high-temperature steam to industrial customers or sending the steam through a high pressure turbine producing electricity. Steam exiting the turbine is at similar conditions as steam direct from an LWR (~280°C). This saturated steam can be sent to (1) industrial customers, (2) a saturated steam cycle for electricity production or (3) a lower temperature heat storage system.

There are several heat storage technologies [3, 4] for heat provided by saturated steam using high-temperature heat-transfer oils to move heat to and from the steam cycle and the storage media. The leading heat storage options are concrete and crushed rock. The chemical industry has used heat-transfer oils for over 50 years that are stable to about 400°C. These oils have low vapor pressures; thus, minimizing the risk of fire. These same oils are used in some CSP systems. Earlier studies [6] examined the use of air to transfer heat to and from the steam cycle and hot rock storage. Using air for heat transfer allows higher temperatures but results in much larger pumping power requirements moving heat to and from the steam cycle.

The Koreans [7] are examining this Category II heat storage system for LWRs using heat transfer oils where the heat storage material is crushed rock. 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. Round-trip efficiencies can approach 80%; that is, if a megawatt hour 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 total 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.

The leading near-term oil option is Therminol-66, the most commonly used synthetic hot oil that operates between -3 to 343°C.

HOT-ROCK HEAT STORAGE WITH SINGLE TANK AND OIL SPRAY

The question is can one further reduce heat storage costs—a Category III heat storage system with capital costs of a few dollars per kilowatt-hour of stored heat. Two strategies are proposed herein to further reduce costs. First, it is proposed (Fig. 3) to store the crushed rock in an insulated trench that may be more than 60 meters wide and lengths that may exceed 1000 meters with no internal structures. The design minimizes structural components and insulation by minimizing the surface to volume ratio. The bottom and sides have three layers. Facing the crushed rock is the oil pan that collects oil. It is backed up by insulation with cooling tubes between the insulation and soil to prevent increases in soil temperature—a structure similar to the foundation structure for CSP nitrate-salt storage tanks. Above the crushed rock is a roof with insulation and oil spray equipment.

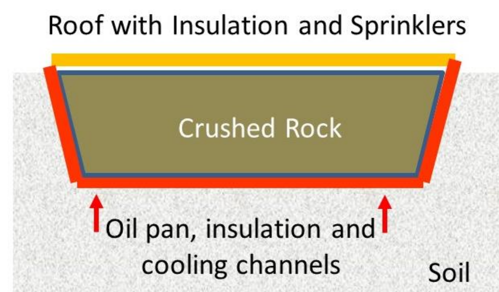

Fig. 3. Crushed Rock Storage System

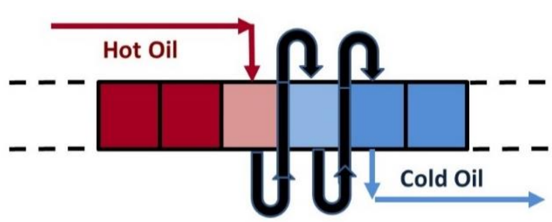

Fig. 4. Sequential Heating Crushed Rock Bed with Hot Oil.

Second, the hot rock is heated by spraying hot oil on top of the rock (Fig. 4) to minimize the inventory of expensive heat-transfer oil and minimize requirements on the rock and the confinement structure. The oil inventory is determined by the maximum rate of heat transfer to and from the crushed rock (MW), not by the heat storage capacity (MWh). Hot oil sprayed on a section of rock heats the rock while flowing through the rock to an oil pan at the bottom of the structure. If the oil is not fully cooled, it is collected and sprayed onto the next segment of crushed rock. The rock is heated sequentially from left to right. Heat transfer by convective movement of gases through the rock pile is small. To heat oil, a traveling wave of oil goes in the reverse direction.

Using properties of crushed granite (density = 2.69 gm/cm^3; heat capacity = 0.79 J/(gm K), void fraction = 0.33), the volumetric heat storage capacity is 39 kWh of heat per cubic meter per 100°C. Assuming a 200°C hot-to-cold temperature swing with 20 meters of rock in the vertical direction and 50 meters wide, a gigawatt-hour of heat can be stored in a structure 12.8 meters long.

There is a longer-term option to use the same system design for higher-temperature crushed-rock heat-storage systems with nitrate salts that would operate with peak temperatures near 600°C. These systems would couple to higher-temperature reactors.

There is ongoing work using crushed rock for other gigawatt-hour heat storage systems. Siemens [8] is developing a hot rock heat storage system where air is heated by electric resistance heaters at times of low electricity prices and the hot air is used to heat the crushed rock. At times of high electricity prices, cold air is blown through the hot rock to produce hot air for a steam boiler. Peak temperatures for this system are about 650°C.

CONCLUSIONS

Energy markets in the United States and worldwide are changing because of (1) addition of non-dispatchable wind and solar that creates highly volatile electricity prices and (2) the goal of a low-carbon energy system. Nuclear reactors produce heat with the potential for the cost of heat storage to be a factor of ten to a hundred less than the cost of storing electricity. This creates the option to operate nuclear reactors at base-load, store heat at times of low prices and sell electricity and industrial heat at times of higher prices. To maximize nuclear plant revenue, the goal is very low-cost heat storage measured in gigawatt-days of capacity to enable hourly to weekly heat storage.

Very low-cost heat storage requires low-cost materials. First-generation (existing) CSP heat-storage systems use hot oil or hot nitrate salts in tanks. Second-generation, in-the-laboratory, heat-storage systems add crushed rock to hot oil and hot nitrate storage tanks to lower heat storage costs. Crushed rock is the lowest-cost heat-storage material. We propose a third-generation crushed-rock heat storage in a trench to further reduce capital costs. The near-term option is to use heat-transfer oil to move heat from LWRs to storage and back to the power cycle. There are significant uncertainties: (1) the uniformity of heating of the crushed rock with oil spray flowing downward through the crushed-rock pile and (2) the support and oil pan structure behavior over time with thermal transients. The long-term option is to use nitrate salts for high-temperature reactor heat storage

ACKNOWLEDGEMENTS

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APPENDIX A: SEASONSAL ENERGY CHALLENGES, HEAT STORAGE AND HYDROGEN.

Any low-carbon energy future has to provide the three services of fossil fuels: (1) energy production, (2) energy storage and (3) dispatchable heat and electricity. The largest energy challenge may be the seasonal variation of energy demand and energy production if use solar, wind, and hydro. Figure A.1 shows the electricity demand of California over one year and electricity generation from wind and solar to match that demand in terms of total electricity produced. There is a massive seasonal mismatch.

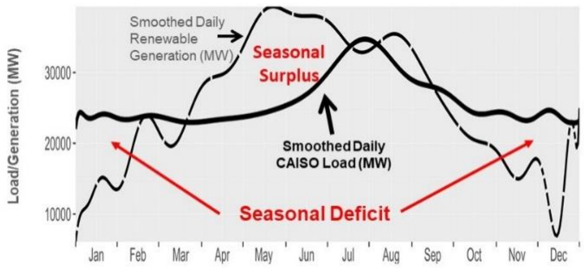

Fig. A.1. Smoothed Daily California Electricity Demand and Smoothed Daily Renewable Geneation with Total Annual Renewable Generation Equal to Total Annual Electric Demand (Courtsey of S. Brick, California Case Study, Clean Air Task Force)

Heat storage technologies such as hot-rock storage may be economic for periods of a week or more—but not seasonal heat storage. Nuclear geothermal heat storage enables seasonal heat storage. Hot water or steam is used to heat rock a 1000 meters underground that then becomes a manmade geothermal heat resource. The technology depends upon the appropriate geology and is in the early stages of development.

There is the option of combining base-load nuclear reactors with heat storage and hydrogen production to address this challenge. Hydrogen production could potentially be 10 to 30% of the total energy demand with three markets: (1) a chemical reagent in the production of fertilizer, metals and biofuels, (2) as a fuel used in fuel cells for vehicle transport and other purposes and (3) as a high-temperature heat source for industry and other markets.

There are four low-carbon hydrogen production options: (1) steam methane reforming (SMR) of fossil fuels with CCS, (2) electrolysis of water, (3) high-temperature electrolysis of steam and (4) thermochemical hydrogen production from water. Hydrogen production by SMR has a major advantage over all processes starting with water. Hydrogen is in a chemically reduced form in methane (CH_4) whereas with all the other processes hydrogen is in its oxidized form—water (H_2O). It takes less energy to get hydrogen from methane than water. It is the economic low-carbon production option in locations with low natural gas prices and good carbon sequestration sites. HTE has major economic advantages over low-temperature electrolysis because part of the energy input is in the form of steam that costs less than electricity. Hydrogen made from electricity is a higher-cost energy source relative to heat. Unlike electricity, hydrogen can be cheaply stored in the same underground storage facilities used for natural gas on an hourly to seasonal basis.

Hydrogen production facilities are capital intensive. It is uneconomic to operate such facilities at low capacity factors. This may require that nuclear plants producing hydrogen operate the hydrogen production facilities more than 80% of the time—the times at which electricity prices are low. Electricity is sold to the grid only at times of high prices. In effect, a nuclear electric hydrogen plant becomes, in terms of the electricity grid, a peaking plant as shown in Fig. A.2.

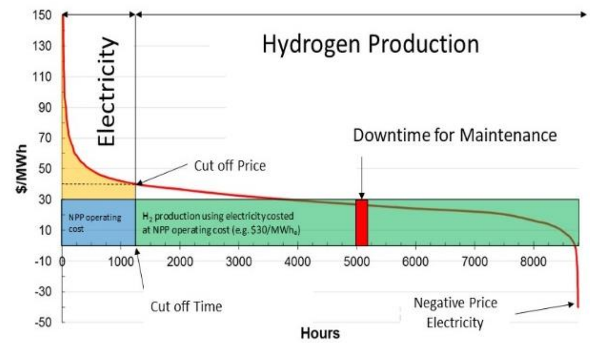

Fig. A.2. Hydrogen Electricity Production Strategy

The hydrogen plant is embedded into a system that includes heat storage (Fig. A.3) that is similar to the heat storage system shown in Fig. 1. At times of low electricity prices, electricity from the grid is used for electrolysis while heat from the nuclear plant goes into heat storage. At times of high electricity prices, heat from the reactor and heat storage produce peak electricity with no hydrogen production. This system configuration uses heat storage and hydrogen storage for a base-load nuclear plant with variable heat, electricity and hydrogen output.

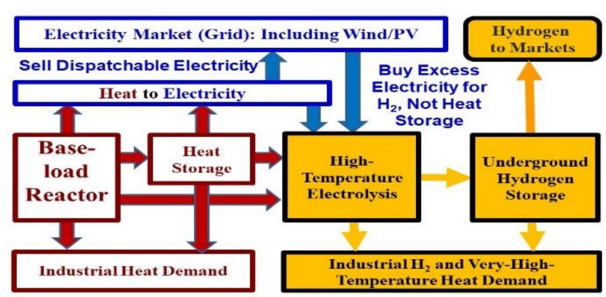

Fig. A.3. System Design with Base-Load Reactors, Heat Storage and Hydrogen Production

This system has the potential to efficiently address seasonal peak demands for electricity. It is a viable option because large-scale seasonal hydrogen storage is cheap and one can provide assured hydrogen to the customer.