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100-Gigawatt-Hour Crushed-Rock Heat Storage for CSP and Nuclear

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Abstract. We are developing 100-GWh heat-storage systems for use with Concentrated Solar Power (CSP) and nuclear reactor systems. Crushed rock fills a trench (20 m by 60 m by up to 1000 m long) with insulated floor, walls and roof structures. Heat is transferred from the heat source to the crushed rock and then to the power cycle using (1) heat transfer oils for lower-temperature power systems to 400°C or (2) nitrate salts for higher-temperature power systems to 600°C. In charging mode, hot heat transfer fluid is sprayed over crushed rock and drains through the rock to the collection pan at the bottom to be reheated. Sections of rock are heated sequentially. In discharge mode cold heat transfer fluid is sprayed over crushed rock and drains through the rock to the collection pan below to deliver hot fluid to the power cycle. This design minimizes the inventory and thus the cost of heat transfer oil or liquid nitrate salt. The large trench size minimizes the surface to volume ratio and thus insulation and structural costs. Crushed rock is the lowest-cost storage material. The goal is to drive storage capital costs down to several dollars per KWh of heat.

INTRODUCTION

Today gas turbines burning natural gas match electricity production with demand. The goal of a low-carbon world requires a replacement for the variable output of the gas turbine. There are limited options to replace gas turbines. Batteries are expensive with limited duration, pumped hydro is limited by location and hydrogen is an expensive fuel relative to natural gas for use in gas turbines. High-capital-cost low-operating-cost heat-producing technologies (CSP, nuclear reactors, etc.) can couple to heat storage technologies that enable these technologies to operate at full capacity while providing dispatchable electricity to the grid and heat to industry—a potential replacement for the gas turbine.

We describe herein (1) the energy system that includes the nuclear or CSP plant with heat storage and electricity-generating power block, (2) the crushed-rock heat-storage system, (3) design considerations associated with storage and (4) alternative heat transfer fluids that couple heat generation to heat storage and heat storage to the power block. Energy system design includes the basis for the proposed size: ~100 GWh. Two variants of the crushed rock system are described based on the peak temperature of delivered heat to storage. For lower-temperature light water reactors (LWRs) and CSP systems, the heat-transfer fluid is a heat-transfer oil. For higher-temperature reactors and CSP systems the heat-transfer fluid is a liquid nitrate salt.

HEAT STORAGE GOALS AND SYSTEM DESIGN

Figure 1 shows a heat storage system [1-2] to enable heat generating technologies to match the output characteristics of the gas turbine. To minimize the cost of energy, the heat generating systems (CSP, nuclear, etc.) operate at maximum capacity at all times. When electricity prices are high, all heat is sent to the turbine to produce electricity. When electricity prices are low, heat is diverted to heat storage with the fraction diverted depending upon plant design and operational requirements. If electricity is not needed for some time, the turbine may be shut down and all heat goes to storage. If it is required that the turbine respond quickly to changing demand, the turbine-generators will be operated at minimum load with the rest of the heat going to storage. At times of peak electricity prices, heat from the CSP or reactor and heat from storage is sent to the turbine(s) for peak electricity production that can be several times base-load electricity output. Peak electricity production can be achieved by (1) oversizing the main 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-generator operating at minimum load is converted into stored heat with resistance heaters coupled to the heat storage system. Alternatively, excess electricity can be converted to stored heat using a heat pump (Carnot battery)—an electricity-to-heat technology that is more efficient but has higher capital costs. The likely low-temperature heat source would be the warm cooling water from the plant. 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.

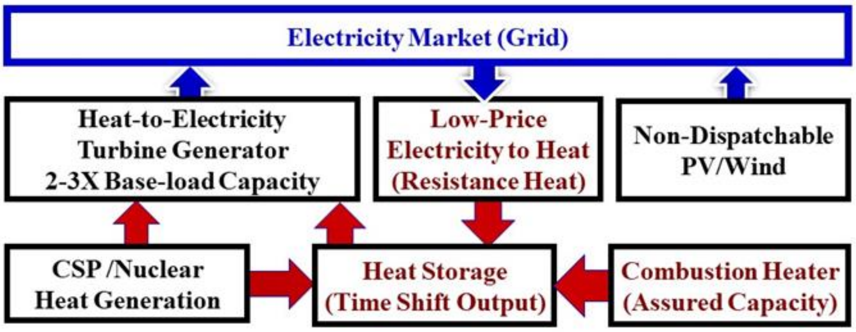

FIGURE 1. Power system with heat storage

The capital cost of this system is less than an equivalent PV/wind system with electricity storage. The cost of batteries or other technologies is much higher than the cost of heat storage because crushed rock is very cheap relative to the materials of any other energy storage system. If on buys a kW of PV or wind, a kW of storage capacity is needed to provide electricity at times of low wind or solar conditions. If the storage capacity is a battery, an added kW of gas turbine capacity is required to back-up the battery for assured generating capacity if multiday cloudy weather or low-wind days. In Figure 1, every kW of generating capacity is available by providing a low-cost combustion heater to provide backup heat if storage is depleted of heat.

This system design with very-low-cost heat storage results in significant changes in the capital cost structure of CSP and nuclear plants [3]. In a traditional nuclear plant, the power conversion block (turbine-generator) is sized to match the nuclear reactor output. Recent studies [3] indicate that if add heat storage, in many markets the optimum size of the power conversion block will be two or three times the capacity of the reactor. A much larger fraction of the capital cost is associated with the conventional power block that is designed for peak power production. Total plant costs are less sensitive to the capital cost of the heat-generating components of the nuclear or CSP plant.

One other feature of this system design is that it enables larger-scale non-subsidized economic deployment of wind and solar. 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. In these markets, large-scale heat storage systems can buy cheap electricity and convert it to heat for later use in electricity production. Because the incremental cost of electric resistance heaters and any incremental addition to the storage capacity is much less than any other electricity to stored-energy system, this system can set a minimum wholesale price for electricity above zero. The heat generating capability provides assured electricity.

System capabilities are dependent upon the cost of heat storage. If heat-storage capital costs can be driven down to several dollars per KWh of heat, heat storage systems can provide variable electricity on an hourly to weekly basis. On the demand side, there is a daily cycle, the multi-day cycle due to changing weather and the weekday/weekend cycle for electricity. On the production side, solar has a daily cycle while wind has a multiday cycle. In a low-carbon system, there will be massive excess production on weekends creating additional incentives for large-scale storage.

As described herein, we are developing a third-generation heat-storage system capable of storing excess energy produced on weekends for use during the weekday with a capital cost goal of several dollars per KWh of heat storage. If one has a 1000 MWe reactor with a thermal output of 3000 MW, a 100-GW heat storage system is capable of storing 30+ hours of heat that addresses the weekday to weekend variations in energy demand. The 100 GW heat storage capacity is close to the maximum heat storage capacity for any CSP system. The maximum size of a CSP system is limited by pumping distances for hot and cold fluids to central storage of heat and the power block.

The above analysis is a local market perspective. There is also a macro-economic perspective. The U.S. energy system, depending upon the time of year, has somewhere between 45 and 90 days of energy storage—primarily in the form of stored fossil fuels such as oil in tanks, piles of coal and natural gas in underground storage facilities. This addresses seasonal swings in energy demand in addition to expected events such as hurricanes and winter blasts that disrupt energy supplies. The annual U.S. energy consumption is about 25,000 Terrawatts. One month's energy storage is about 2 million gigawatt hours. Based on this experience, the storage requirements for a low-carbon society will be measured in millions of gigawatt hours. One can debate whether it's a half million gigawatt hours or four million gigawatt hours—but not the scale of the storage challenge.

If the capital cost of the storage system is $1/kWh, a million gigawatt-hours of storage will have a capital cost of a trillion dollars. One can afford capital costs of a few dollars per kWh of storage. However, one can't afford large-scale deployment of $100/kWh storage systems. That would imply a hundred trillion dollars of capital cost—many times the annual gross national product of the United States. In this context, a 100 GWh heat storage system implies about 10,000 units to meet storage requirements—a reasonable number given the requirements.

CRUSHED-ROCK HEAT STORAGE WITH LIQUID HEAT-TRANSFER OIL OR NITRATE SALT

Today commercial large-scale heat storage systems associated with CSP facilities use heat transfer oils or nitrate salts with hot and cold oil or salt stored in large tanks. Second generation heat storage systems add low-cost crushed rock for heat storage to reduce capital costs. Work is underway [4] to develop single-tank storage systems using crushed rock and nitrate salt. The tank is filled with crushed rock with hot lower-density salt on top of cold higher-density salt. The single tank design lowers tank costs and the crushed rock reduces the inventories of nitrate salts. In parallel, work is underway [5] to develop heat storage systems using crushed rock and heat transfer oils. In these systems there are tanks of crushed rock where heat transfer oils fill the void spaces between the crushed rock in tanks only when heat is being moved into or out of storage to minimize inventories and costs of the heat transfer oil.

This paper describes a third-generation heat-storage system as shown in Fig. 2. The heat storage material is crushed rock—the lowest cost heat storage medium. The container is a large trench (20 m by 60 m and up to 1000 m long) to minimize the container surface-to-volume ratio and thus minimize cost of insulation and the cost of the liner per unit of crushed rock. Lower-temperature CSP systems and light-water reactors would use heat transfer oil to move heat to the crushed rock and from the crushed rock to the power cycle. Higher-temperature CSP and reactor systems would use nitrate salts for heat transfer.

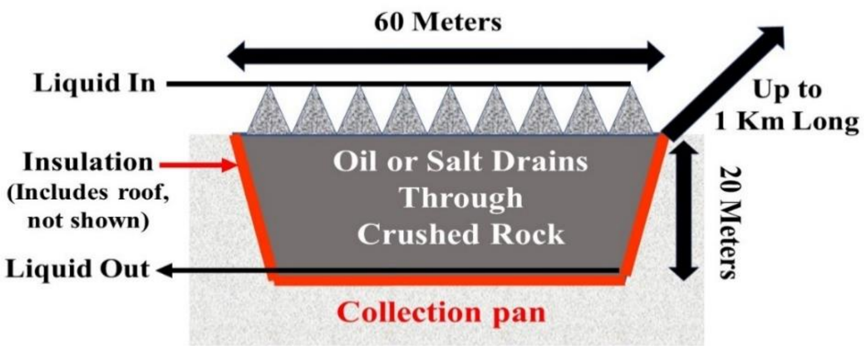

FIGURE 2. Cross-section or crushed-rock heat-storage system

Heat is added to the crushed rock by spraying the hot heat-transfer fluid over the crushed rock section by section as shown in Fig. 3. The cold heat transfer fluid is collected by the bottom collection pan to be reheated. Inert gas fills the void space between rocks. If the nitrate salt or heat transfer oil is not fully cooled by the time it reaches the collection pan, the warm fluid is pumped onto the top of the next section of crushed rock to preheat the crushed rock. A wave of hot oil or hot salt heats the crushed rock from left to right down the trench length.

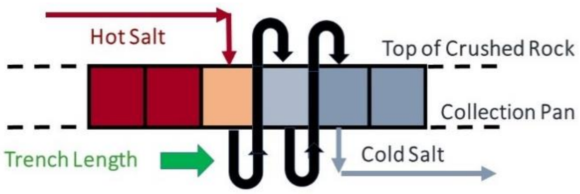

FIGURE 3. Side view of sequential heating of crushed rock with hot liquid spray and gravity flow of liquid through the crushed rock

Heat is recovered by spraying cold heat-transfer fluid over hot crushed rock and collecting the hot oil or nitrate salt at the bottom. Over the length of the trench, there is a rock heating wave followed by a second wave to recover heat as shown in Fig. 4. When either wave reaches the end of the trench, it starts over at the other end of the trench. The design minimizes the inventory of the heat transfer fluid that is expensive relative to the crushed rock.

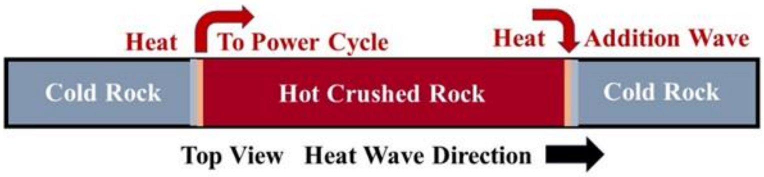

FIGURE 4. Top view of sequential heating and cooling of crushed rock

This system has another safety, environmental and cost advantage relative to first and second generation heat-storage systems. With liquids stored in tanks, there is always a concern about leaks. The liquid imposes a hydrostatic pressure on the tank wall that provides the driving force for leaks. In this system the oil or nitrate salt drains down to the collection pans. There is at the bottom at most a few centimeters of liquid oil or nitrate salt on top of the sloped floor heading toward the drains. There is no large hydrostatic pressure to push liquids out of the structure if there is a leak.

Heat storage systems have several auxiliary systems. The cover gas is chosen to minimize coolant degradation. If oil is the heat transfer coolant, the cover gas will be nitrogen. The system has many square kilometers of crushed rock surface area. There is the potential for the heat transfer oil to slowly degrade by reactions with oxygen in the air aided by any chemical catalytic activity associated with the rock surface. A nitrogen cover gas can eliminate many mechanisms of oil degradation with time. Like large oil tanks, the system will have filtered vents to minimize loss of volatile compounds to the atmosphere with changes in atmospheric pressure. For the nitrate salt coolant, the cover gas will likely contain oxygen. There is also a liquid coolant cleanup system. The thermal expansion and contraction of the rock will generate fines; thus, there will be a coolant filter system to remove those rock fines. There may also be a secondary coolant cleanup system to address longer-term degradation of the coolant.

There is another class of hot rock storage. Siemens is developing a gigawatt-hour hot-rock system [6] where at times of low electricity prices air is heated and blown through the crushed rock to heat it. At times of high electricity prices, cold air is blown through the hot rock and the resultant hot air is sent to a steam boiler to produce electricity. The peak crushed-rock temperature is about 650°C. There is an operating pilot plant. Such systems will provide useful information about the generation of fines by thermal cycling of the crushed rock.

Crushed Rock Storage Design Considerations

From the design perspective, there are three major design decisions: (1) choice of crushed rock, (2) crushed rock size and size distribution and (3) bed height. When not transferring heat to and from the crushed rock bed, the expectation is that the bed will be 70 to 80% crushed rock and 20 to 30% cover gas in the void spaces. The distribution of rock sizes determines the fraction of the bed that is rock. Small pieces of rock can fit between larger pieces of rock. The more tightly packed the bed, the more heat storage capacity per cubic meter but more resistance to liquid gravity flow through the crushed rock bed. Models are being built to enable system optimization. We describe herein the major physical constraints to the design.

There is an optimum crushed rock size determined by a tradeoff between fluid flow and heat transfer. If we had a crushed rock bed where each piece of crushed rock was a meter in size and a hot liquid was poured on top of the bed, the liquid would flow downward to the catch pan within a few seconds. Heating of the rock would be slow because heat transfer would be limited by conduction of heat from the surface of the one-meter-diameter boulders to the center of each rock. The hot fluid would be only partly cooled by the time it reached the collection pan because there was not enough time or surface area to transfer heat to the rock.

As we reduce the rock size, several things happen. First, it takes more time for the liquid to reach the collection pans. The fluid has to flow around more pieces of rock. Gravity wants to accelerate the fluid in the downward direction but smaller crushed rock sizes implies a longer flow path with resistance to liquid flow to the collection pan. This is a water slide problem. If we have a water slide that is short and steep, water flows quickly from top to bottom. Gravity wants to accelerate water flow but the bottom surface of the slide offers resistance to downward flow of liquid. If we have a longer water slide with a shallow slope, water takes more time to flow from top to bottom. The longer surface of the water slide slows the water. The same is happening here as the rock size is reduced.

In terms of heat transfer, as we go to smaller-diameter crushed rock, the heat conduction distance from the surface to the center of each rock decreases. This accelerates heat transfer. At the same time heat transfer from fluid to rock improves because there is much more surface area.

There are other constraints. There is an upper limit to the gravity flow rate of liquid through the rock pile. As the rock sizes get smaller, the path length for liquid flow increases. The cover gas gets pushed down by the downward flow and becomes a source of liquid flow resistance. As the rock size becomes very small, surface tension holds the liquid between pieces of rock. If the crushed rock is the size of sand particles, flow time from the top of the pile to the bottom may be measured in hours or days versus minutes. The flooding limit decreases; that is, the maximum flow rate of liquid that will flow through a square meter cross section of the crushed rock pile decreases.

Based on experience, the nominal crushed rock diameter will be measured in centimeters with the optimum diameter partly dependent upon bed height, desired fluid temperature drop and rock properties. Important rock properties include thermal conductivity, volumetric heat capacity, surface properties and geometric shapes. High-thermal conductivity implies larger rock sizes because of more rapid movement of heat from the surface to the pebble interior. High volumetric heat capacity implies smaller rock sizes because more heat is stored per unit volume of rock and more heat must be transferred from the liquid to the rock. Surface properties (smooth, rough) change liquid flow velocities around each piece of crushed rock. Rocks when crushed that produce relatively round rocks will pack differently than rocks with greater length-to-width ratios. Analysis will allow general design; but, experiments are required to validate performance.

Partly decoupled from thermal hydraulic considerations is the long-term holdup of oil or nitrate salt in the crushed rock. Residual fluid holdup is to be minimized because of the cost of the fluid versus the crushed rock. Surface tension will result in holdup of fluid at points where rocks touch each other. Smooth rock surfaces result in less residual liquid on surfaces. Fluid holdup considerations may eliminate some types of rock as fill material and create incentives for larger pebble sizes with smaller total surface area.

There is relevant experience from other industries. There has been significant work on crushed rock heated by hot air. In the mining industry, heap pile leaching is used. Low-grade ores are crushed and placed in large piles. Solutions are sprinkled on top of the pile and flow through the pile leaching the valuable copper or other elements into the liquid. There are a variety of trickle filters with similar geometry. Last, cooling towers with the fans turned off operate in a similar manner. None of these exactly match the conditions herein but inform design.

Heat Transfer Fluid Choices

There are two heat transfer fluids: heat transfer oils and nitrate salts. Both are used in CSP systems. Heat transfer oils have been used in the chemical industry for over a century. Nitrate salts have been used in metal heat treatment systems for similar time periods. Both fluids are well understood in clean storage systems.

Heat-Transfer Oils

Synthetic heat transfer oils are used to transport heat in lower-temperature CSP systems and to store heat as oil in hot and cold tanks. These oils are stable to about 400°C and have low vapor pressures, thus minimizing the risk of fire. Heat transfer oils are the primary fluid in most CSP plants [7]. KINGS, a Korean research university, is examining a heat storage system for light-water reactors (LWRs) using heat transfer oils [8] where the heat storage material is crushed rock. Most nuclear power reactors are LWRs. There would be multiple tanks of crushed rock with heat-transfer oil only in tanks where heat is being transferred to the crushed rock or from the crushed rock to the turbine generator. When heat is transferred, the tank is full of oil—unlike our proposed system. Hot oil displaces cold oil to heat the crushed rock. This system has multiple tanks so oil is only in tanks where heat transfer is occurring to minimize oil inventory and costs.

Therminol 66 and Therminol VP-1 from Eastman Company as well as Dowtherm A from The Dow Company are available synthetic heat transfer oils that are used for several industries including in CSP systems [9]. Therminol-66 maintains a liquid phase for the operation temperature range because of its high boiling point

(359°C) and its low freezing point (-3°C) [10]. Peak temperatures in an LWR are near 300°C, thus, the peak oil temperatures are significantly below the oil boiling point. The low freezing point is important to avoid viscous oil at lower temperatures and avoid risk of freezing in pipes when the system is shut down.

The use of oil in CSP systems provides much of the required technology for oil-based heat storage—from hot oil exiting storage through the steam plant and electricity production. Data collected in 2017 [11] show that there are 133 CSP plants in operation. Parabolic Trough Collector (PTC) is the most used technology accounting for 65% of the operational CSP units. Thermal oil accounts for 85% of the HTF used in PTC plants. Thermal oil, typically, enters the absorber tube at 293°C and exits at 393°C [7]. Therminol VP-1 by Eastman and Dowtherm A by Dow are the most commonly used synthetic oils in CSP plants. They are both composed of eutectic mixture of diphenyl-oxide (DPO)/biphenyl. They are characterized by low viscosities as well as good heat transfer properties in both liquid and vapor phases. They can be used up to 400°C. The freezing temperature of Therminol VP-1 and Dowtherm A is 12°C while the boiling point is 257°C [12]. Therminol-66 maintains a liquid phase for the operation temperature range because of its high boiling point (359°C) and its low freezing point (-3°C) [9/5]. This is the leading candidate for the proposed crushed rock system because the crushed rock is operated at atmospheric pressure whereas CSP plants have the choice to operate the oil at higher pressures to maintain a liquid state.

PTC plants consist of solar fields and a power block that uses a Rankine steam cycle. Data collected [11] on operational CSP units show that the capacity of oil-based PTC units ranges from 5MW to 280MW with most units rated around 50MW. The hot oil outlet temperature ranges from 348°C to 395°C with most units operating at 393°C. The efficiency of PTC units vary depending on the components of the power cycle and weather the unit is coupled to a natural gas burner. For example, the steam cycle efficiency of Shams 1 in Abu Dhabi increased from 33% to 39% by superheating the steam using gas burners [13].

Heat-Transfer Nitrate Salts

Higher-temperature CSP systems use nitrate salts with peak temperatures approaching 600°C. Multiple advanced higher-temperature reactors propose to use nitrate salts in their intermediate heat transfer loop and as part of a heat storage system. This includes sodium-cooled [14] and salt-cooled [15] reactors.

The base-line CSP salt is solar salt (60 wt% $NaNO_3$ - 40 wt% KNO_3). Higher-temperature CSP systems use molten salts with peak temperatures that can vary from 550 to 650°C. A review paper by Nunes, et al., [16] discusses pure molten alkali nitrate salts as well as their commercially relevant mixtures. Solar salt and Hitec salt (7 wt% $NaNO_3$ - 53 wt% KNO_3 - 40 wt% $NaNO_2$) were shown to have greater ranges of operational temperatures than the pure alkali salts and could thus be more economic and efficient heat transfer and storage fluid options. Recent papers [17] have summarized the status of various nitrate-salt CSP systems.

Beginning in 2000, several studies were initiated on the option of adding naturally-occurring crushed rock to nitrate salt tanks to reduce costs. Pacheco, et al. [18] screened 17 minerals: anhydrite, barite, bauxite, carborundum, cassiterite, corundum, fluorapatite, hydroxyapatite, ilmenite, limestone, limestone, magnesite, marble, quartzite, scheelite, taconite, and witherite. These were immersed in Hitec—limestone, marble, quartzite, and taconite were also immersed in solar salt in a separate trial. Out of the substances tested, taconite, marble, limestone, and quartzite had comparatively less reactivity with the molten salt and were also more cost-effective; thus, they were further examined during the latter part of the experimental program. This consisted of conducting thermal cycling trials (with a cold salt temperature of 290°C and a hot salt temperature of 400°C) and assembling a small-scale thermocline (with the same cold salt temperature and a hot salt temperature of 361°C) to observe the mechanical and chemical degradation of the molten nitrate salt and the rock samples. They concluded that quartzite and silica sand were the most effective filler materials due to their lower costs and their stability with molten nitrate salts.

Based on the results of this study, a second set of testing was initiated to understand the interactions of quartzite and silica sand with nitrate salts over the long term. Here, Brosseau, et al. [19] tested how these substances interacted with a ternary salt similar in composition to HitecXL salt (44 w% $CaNO_3$, 12 w% $NaNO_3$, and 44 w% KNO_3) over a year, with a cold salt temperature of 285°C and a maximum temperature of either 450°C or 500°C for both the rock and the sand. In addition to this isothermal test, researchers also conducted a thermal cycling test, in which both rock and sand underwent 10,000 cycles to model the 30-year-project life of a commercial storage system (which would undergo around 10,000 cycles during that time). They discovered that the quartzite rock and silica sand were both able to withstand the molten salt over extended durations of time as well—minimal deterioration affecting the heat storage system was observed—indicating that these were both viable options for heat storage systems.

In 2013, Calvet, et al. [20] tested a post-industrial ceramic compound named Cofalit® with molten solar salt as well as Hitec salt for 500 hours at 500°C. Cofalit was selected as it was thought to: a) be more cost-effective than mining naturally occurring crushed rock, as it is produced by vitrification of hazardous waste and is thereby a recycled material and could promote the conservation of natural resources, b) be easily crushed into small fragments to increase the surface area for heat transfer in the storage system and thus counter the low thermal conductivity of ceramic, and c) have a high heat capacity (up to 1100°C). Experimentation revealed that the Cofalit formed a corrosion layer of calcium silicate when submerged in the molten Hitec, yet this did not occur with the solar salt, indicating that molten solar salt and Cofalit could potentially be used in tandem for a thermocline heat storage system.

The most recent study of the interactions of crushed rock and nitrate salts occurred in 2017 [21], where Bonk, et al. tested how four different types of rock fillers—quartzite (mostly composed of Al_2O_3 and SiO_2), diabase, Hühnerberg basalt, and Rossdorf basalt—interacted with solar salt at 500 and 560°C over 500, 1000, 2000, and 5000-hour durations. They found that while the thermal capabilities of the salt were slightly affected due to the crushed rock, there was still leaching from the fillers into the salt over time in all cases. The diabase was seriously degraded, produced small particle fragments and leached carbonates into the solar salt. It was concluded that it was not viable as a crushed rock for heat storage systems, whereas basalt and quartzite were viable options due to their relative stability with the salt over extended durations of immersion. The laboratory experience emphasizes the need with higher-temperature nitrate salt systems for testing in the laboratory of rock / salt choices under realistic conditions.

CONCLUSIONS

A low-carbon energy future requires massive quantities of energy storage to replace the storage functions of fossil fuels. For the United States or Europe the size of the storage requirements will be on the order of a million gigawatt-hours. That requires very low-cost storage. We are developing a system with capital cost goals of several dollars per kWh of heat. The low cost is enabled by three features: (1) crushed rock heat storage, (2) 100 GWh scale to minimize the surface to volume ratio of the heat storage system and thus the costs of the container structure with insulation system and (3) using oil or nitrate salt as the heat transfer fluid but not for heat storage. Such heat storage systems may enable high-capital-cost low-operating-cost heat-generating technologies (nuclear and CSP) to become economic replacements of the gas turbine for dispatchable electricity to the grid.

The system described herein is a third-generation heat-storage system. The first generation systems are commercial systems with clean oil or salt in tanks. The second generation systems have crushed rock in tanks of oil or nitrate salt to reduce the capital cost of heat storage. These systems are in the laboratory and pilot plant stages of development. The technical development risks are less for the oil-based systems because of the much lower risk of chemical reactions between oil and rock versus higher-temperature nitrate salts and rock. The third generation systems, as discussed herein, are in the research stage building upon the experience of first and second generation systems.

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