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Firebrick Resistance-heated Energy Storage: Existing Technology Base

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INTRODUCTION

Increasing demand for electricity caused by a rapidly increasing global population, combined with concerns about climate change and the depletion of our finite fossil fuel reserves are expected to cause a global shift away from fossil fuels. Renewable energy sources, such as solar and wind, are being added to the grid. Notwithstanding the many advantages of renewables, they have a negative effect on the economics of power generation in areas in which they have been heavily used; during periods of high solar and wind output the price of electricity collapses nearly to zero, damaging the electricity market for wind, solar, and nuclear. [1] Large-scale, cheap electricity storage technology would help prevent electricity price collapse.

To meet this need, we are developing Firebrick Resistance-Heated Energy Storage (FIRES), a system that stores low-priced electricity as high-temperature heat in firebrick for later release when the electricity prices are high. FIRES is specifically being developed for use in the Fluoride-salt-cooled High-temperature Reactor (FHR) with Nuclear air-Brayton Combined Cycle (NACC) for peak electricity production and in industrial heat applications. The large-scale deployment of FIRES would reduce times of very low electricity prices during periods of high wind or solar production and thus improve the economics of existing and future base-load nuclear plants.

A literature search was undertaken to understand the use of similar firebrick heat-storage technology for at least the past fifty years at both small and large scales, from domestic to industrial applications. The FHR heat storage scale (100s MWh), power levels (100s MW) and peak temperatures (up to 1800°C) are, however, significantly larger than the historical application of this technology.

This paper provides a description of the FIRES system, its proposed industrial heat applications and use in the FHR, an explanation of the motivations for its development, and the history of the use of the technology that provides the starting point for development of FIRES for industrial and nuclear power applications.

DESCRIPTION OF FIRES [2]

FIRES consists of a configuration of high density, high heat capacity ceramic firebrick with air channels and a maximum operating temperature of approximately 1800°C. The firebrick is electrically heated during periods of low or negative electricity prices (where "low" means electricity prices are less than the heating value of competing fossil fuels). Electrically conductive firebrick is heated by direct application of electric current, acting as both the resistance heating element and storage medium. The storage medium is surrounded by insulating firebrick and conventional insulation that allows thermal expansion of the firebrick; the heat storage capacity is ~0.5 MWh/m^3. The heat can subsequently be recovered by blowing air through channels in the hot firebrick storage medium. The hot air may be used directly in industrial processes or be converted back into electricity to be used in increasing the output of a power plant such as the FHR.

APPLICATIONS [2]

A major application of FIRES is in natural-gas-fired industrial furnaces. It may be used in a wide range of industrial processes, providing hot air to replace the burning of natural gas. Cold air is heated in FIRES. If the hot exit air is hotter than the furnace requirements, it is mixed with cold air; if it is cooler than the furnace requirements, it is heated with natural gas. If FIRES is heated at the same time that it is providing heat for industrial processes, it acts as a direct electric heater.

The application of firebrick heat storage to nuclear reactors, and particularly to the FHR, requires a large-scale system. The FHR uses a NACC – a power cycle based on natural gas combined cycle power systems. Within NACC, air is compressed, heated by salt coolant from the FHR in an air-salt heat exchanger and sent through turbines producing electricity. The hot air is exhausted to a steam boiler with the steam used to produce added electricity and sent up the stack. Peak power can be produced by additional heating of the air after nuclear heating using either natural gas or FIRES stored high-temperature heat. This raises the inlet temperature to the turbine and produces more power. Because the added heat is a topping cycle above the nuclear heating, it is very efficient with a heat to electricity efficiency of 66% – higher than a stand-alone natural gas plant.

THE CASE FOR FIRES

The desire for a new kind of electricity storage technology has two main motivations. Firstly, the depletion of fossil fuels and concerns about the effect of fossil fuel emissions on global atmospheric temperature is beginning to cause a global shift away from them towards renewable power generation and nuclear power. The current advice of the International Panel on Climate Change is that average global temperatures should not rise beyond 2ºC above pre-industrialization levels to prevent the most serious consequences of global warming. Such a rise seems now virtually unavoidable. Moreover, British Petroleum (BP) estimates that remaining global oil reserves can last at current production for only approximately 50 years. When natural gas, shale gas, shale oil and other unconventional fossil fuels are added, estimates range between 100 and 200 years. In short, it has long been clear that the use of fossil fuels is unsustainable in the long-term. This has led to increasing adoption of alternative power sources – chief among them has been nuclear power, which has been joined more recently by renewable sources such as wind and solar power (as the cost of the technology has decreased and with the aid of government subsidies).

Renewables present two main challenges. First, their power output is necessarily dependent on the weather and fluctuates considerably through the day and year. The wind does not always blow and the sun does not always shine. Moreover, the periods of high solar and wind output tend not to coincide with periods of high electricity demand. For example, solar output peaks in the middle of the day but peak electricity demand is in the evening – as people return from work to cook, watch television and the like – when the sun has already set or is setting. This means that widespread application of renewable power will only come with the development of a cheap way of storing large amounts of electricity during periods of high supply and low demand, for release later during periods of low supply and high demand.

The second challenge that renewables present is their effect on the price of electricity. Since solar and wind generation do not require the purchase of fuel, they can always outcompete other electricity sources on price. Thus, in regions with high solar and wind generation capacity the price of electricity collapses almost to zero during periods of high output. Power plants with fuel costs – especially those using fossil fuels – are forced to shut down in decreasing order of the price of the electricity they produce. The base-load power stations, notably those that use coal and nuclear power, are difficult or uneconomical to shut down and restart as demand or solar and wind output fluctuate; this may require them to sell their electricity at negative price to induce buyers to take the power. [1] The low prices are equally damaging to wind and solar because it collapses their revenue stream and thus limits their adoption. [3]

Renewables, then, distort the market by creating a price that is impossible to match and generating electricity at times when it is not needed. A new energy storage technology would allow the storage of electricity produced both by renewables during periods of low demand and by nuclear power during periods of high renewable output. This improves the economics of power generation all-round, making a general shift away from fossil fuels more feasible.

FIRES has a number of advantages over other energy storage technologies. Unlike batteries, which are expensive and difficult to scale up, FIRES is comparatively very cheap to build and scalable (doubling the temperature difference of heating doubles stored energy; doubling the volume of the system with the same temperature difference doubles stored energy). While batteries are well suited only to relatively small storage applications (e.g., personal electronic devices and cars), FIRES works on both small and large scales. Pumped-storage systems, though well suited to storing large amounts of power relatively cheaply, require locations with the correct topographies and often require the destruction of ecosystems through flooding. FIRES can be deployed virtually anywhere.

HISTORY OF FIREBRICK HEAT STORAGE

Firebrick heat storage was popular in Britain in the 1960s. This was a period of increasing prosperity and demand for electricity. Base-load power generation was installed to meet demand during the day (this accounted for some 80% of total power production – 70% from coal and 10% from nuclear power), but demand inevitably slumped during the night. The continuous running of these power stations generated large quantities of excess electricity overnight, so utility companies strove to smooth demand through day and night by time-shifting some of the daytime demand to the night. [4] The smoothing of demand reduced electricity grid requirements. It also reduced air pollution within cities.

Night storage heaters were widely installed and the "Economy 7" tariff was introduced to incentivize their use. For 7 hours during the night (typically starting at 1:30am), those using the tariff were given a discount of around 50% from the daytime electricity price. Electricity would be used to heat the firebrick in the device overnight, and a system of vents and fans would circulate warm air to warm the house during the day. This benefited customers by reducing the total cost of their electricity use and the utility companies by smoothing daily demand. By 1973 there were 150,000 MWh of storage capacity in Britain and Germany. [5]

CURRENT FIREBRICK HEAT STORAGE TECHNOLOGY

Though the prevalence of these systems declined sharply in the 1980s because of the changing structure of electricity generation, a number of companies still manufacture night storage heaters. Dimplex in Canada, SKRECC in Kentucky and Sivelec in France are good examples.

The design and function of the machines produced by the various companies are similar to each other and the technology is largely unchanged from that used in the 1960s and 1970s. A series of heating elements (typically nichrome) wind through various levels of stacked firebricks either horizontally or vertically and resistance heat the firebricks with off-peak electricity. The various levels of heating elements can be differentially controlled to give more efficient even heating of the firebricks. The SKRECC system uses high-density iron oxide bricks, with a maximum core temperature of 800°C; in a test, the core temperature was found to be 120°C three days after being switched off from peak temperature. Iron oxide was probably chosen because of its low cost compared to other common firebricks. In 2013 VCharge installed 15 MWh of firebrick heat storage capacity across 200 homes in eastern Pennsylvania at a cost of around \$15/kWh.

Firebrick heat storage has also been used extensively in industry, though typically not as electric heat storage. The main application has been in heat recuperators and regenerators to transfer heat between gases in various industrial processes, allowing the recovery and reuse of heat that would otherwise be lost in a range of different industrial processes. [6]

The historical large-scale application has been in open-hearth steel production where two recuperators alternate in storing heat and providing high-temperature air to the steel-making process. In that process pig iron with a high carbon content is converted to steel with a low carbon content. Hot air is blown over a molten bath of iron (~1600°C) to oxidize the carbon to carbon dioxide. The hot exhaust gas goes through a brick recuperator that is heated up while the exhaust gas is cooled down before being sent to the stack. When the recuperator firebrick is hot, the fans are reversed. Cold air enters the recuperator, is heated to high temperature by the firebrick, added fuel is burnt to further raise air temperatures, the air is sent over the pig iron to oxidize carbon, and the resulting exhaust gas is sent through the second recuperator before being sent up the stack. The air must be preheated to high temperatures to avoid freezing the pig iron that is being converted to steel. The recuperators save large quantities of energy that otherwise would have to be used to heat incoming air.

The use of high-temperature brick recuperators is common in high-temperature processes to recover heat and improve energy efficiency. [7] Many of these systems operate with over 1000°C between cold and hot conditions.

CHOICE OF FIREBRICK

Considerations of heat capacity, conductivity, melting temperature, cost and abundance of primary material determine the firebrick composition chosen. The most common materials are iron oxide, magnesia, alumina and olivine. In the SKRECC system, iron oxide was chosen for its low cost. Olivine was used extensively in the 1960s and 1970s because of its great abundance (it is reckoned to be the most abundant mineral in the shallow parts of the Earth's crust). Magnesia has a very high specific heat capacity and melting temperature (940 J kg^{-1} K^{-1} and 2850°C respectively, compared to 650 J kg^{-1} K^{-1} and 1560°C for iron(III) oxide, and 880 J kg^{-1} K^{-1} and 2070°C for alumina). Alumina has interesting conductive properties and would be particularly useful for the conductive firebrick storage medium in FIRES.

CONCLUSIONS

FIRES is being developed for converting low-price electricity into high-temperature heat for industrial applications or peak electricity production. Its deployment would avoid electricity price collapse at times of high wind or solar inputs. That improves the economics of wind, solar, and nuclear while productively using that electricity. For these applications FIRES builds upon several existing technologies from home heat storage systems to industrial recuperators.

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