Abstract and Executive Summary

ADVANCED NUCLEAR POWER PROGRAM

Heat Storage Coupled to Generation IV Reactors for Variable Electricity from Base-load Reactors: Changing Markets, Technology, Nuclear-Renewables Integration and Synergisms with Solar Thermal Power Systems

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Abstract

Heat Storage Coupled to Generation IV Reactors for Variable Electricity from Base-load Reactors: Workshop Proceedings: Changing Markets, Technology, Nuclear-Renewables Integration and Synergisms with Solar Thermal Power Systems

Electricity markets are changing because of (1) the addition of wind and solar that creates volatile electricity prices including times of zero-priced electricity and (2) the goal of a low-carbon world that requires replacing fossil fuels that provide (a) energy, (b) stored energy and (c) dispatchable energy. Wind and solar provide energy but not the other two other energy functions that are provided fossil fuels. Nuclear energy with heat storage can provide all three functions and thus replace fossil fuels.

To address the challenges and opportunities for nuclear energy in this changing market the Massachusetts Institute of Technology (MIT), Idaho National Laboratory (INL) and Exelon conducted a workshop on July 23-24, 2019 in Idaho Falls on *Heat Storage Coupled to Generation IV Reactors for Variable Electricity from Base-load Reactors*: *Changing Markets, Technology, Nuclear-Renewables Integration and Synergisms with Solar Thermal Power Systems.* The results from this workshop are described herein. The workshop included participation of the concentrated solar power (CSP) community because nuclear energy and CSP produce heat and thus face many of the same technological and institutional challenges. Some CSP plants today have several gigawatt-hours of heat storage to better match market needs.

The changing market requires a different nuclear plant design that incorporates heat storage. The base-load reactor sends variable heat to (1) the turbines to provide variable electricity to the grid and (2) storage. At times of high electricity prices, all the heat from the reactor and heat from storage is used to produce peak electricity output significantly greater than the base-load capacity of the reactor. At times of low or negative electricity prices, (1) minimum steam is sent to the turbine and (2) there is the option that electricity from the turbine operating at minimum output and electricity from the grid is converted into heat that is sent to storage. The nuclear plant has the capability to buy and sell electricity to increase revenue in these markets relative to a base-load nuclear power plant. Heat storage (salt, rock, concrete, etc.) is much less expensive than electricity storage (batteries, etc.) because of the low cost of the materials used in heat storage systems relative to materials used in electricity storage systems.

Generation IV reactors deliver heat at higher temperatures to the power cycles compared to water-cooled reactors. This lowers the cost of heat storage by two mechanisms. First, if the hot-to-cold temperature swing in a sensible heat storage system is doubled, the cost of heat storage is reduced by a factor of two assuming all other factors are equal. Second, the higher heat-to-electricity efficiency reduces the storage requirements per unit of electricity storage. This may become the primary economic incentive to develop Generation IV reactor technology

Twelve heat storage technologies applicable at the gigawatt-hour storage scale were discussed that can be deployed between the reactor and the power cycle. Several of these technologies are deployed at CSP facilities. Nitrate salt heat storage is used at the gigawatt-hour scale in CSP systems and is proposed for salt and sodium-cooled nuclear plants.

Two storage technologies were examined that are incorporated into advanced Brayton power cycles. One proposes to use cold water to boost power when needed. The other uses a thermodynamic peaking cycle with incremental heat-to-electricity efficiencies of 70 to 75% when coupled to high-temperature reactors providing heat to the lower-temperature bottoming cycle. The heat for the topping cycle can be provided by natural gas, hydrogen or stored heat produced by converting low-price electricity into high-temperature stored heat.

A nuclear plant capable of producing, selling and buying electricity is different than any existing plant. There are large incentives to demonstrate heat storage in existing LWRs to improve LWR economics and address many of the operational, grid, and regulatory challenges that are common to all heat storage systems coupled to nuclear plants. There are large incentives for joint nuclear/CSP heat storage development and demonstration programs because the same technologies are being used.

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Executive Summary

Heat Storage for Gen IV Reactors for Variable Electricity from Base-load Reactors
Changing Markets, Technology, Nuclear-Renewables Integration and
Synergisms with Solar Thermal Power Systems

Charles Forsberg, Piyush Sabharwall and Hans D. Gougar

INTRODUCTION

The electricity market is changing because of (1) the goal of a low-carbon electricity grid and (2) the addition of wind and solar. The large-scale addition of wind and solar results in highly volatile prices with times of low or negative prices and other times of high prices—depending upon wind or solar conditions. The goal of a low-carbon grid requires new energy systems that can economically provide the three services of fossil fuels: (1) energy production, (2) energy storage and (3) dispatchable electricity.

Adding heat storage to nuclear power plants enables nuclear power plants to (1) boost revenue in markets with large-scale wind and solar and (2) replace fossil fuels in providing dispatchable electricity including assured peak generating capacity while operating the reactor at base load. These systems are applicable to all heat generating technologies: fission, concentrated solar power (CSP), fossil, geothermal and fusion. Heat storage also has potentially major implications for nuclear power plant design including (1) a nuclear island with all vital areas and (2) a separate zone with storage and the power block outside the security zone.

These challenges and opportunities were addressed at the Massachusetts Institute of Technology (MIT) / Idaho National Laboratory (INL) / Exelon Corporation workshop [1] that was held in Idaho Falls on July 23-24, 2019 to examine heat storage coupled to Generation-IV reactors (helium, sodium/lead and salt coolants). This is the second heat-storage workshop. The first workshop addressed heat storage coupled to light water reactors with saturated steam cycles [2]. This workshop included experts in concentrated solar power (CSP) systems [3] that use heat storage to enable providing electricity after sunset. The largest CSP heat storage systems have over four gigawatt-hours heat storage capacity. Most heat storage technologies are applicable to nuclear reactors, CSP, fossil and fusion systems; thus, there are large incentives for joint research, development and demonstration programs.

SYSTEM DESIGN

Figure ES.1 shows the system design for heat storage coupled to a nuclear reactor. The analogous system design would be applicable to any other heat generating technology including CSP, geothermal, fossil and future fusion machines. The choice of storage technology is dependent upon (1) the exit and return temperatures of the reactor coolant that must match 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. In most parts of the United States and in many other countries there is also a large difference in the electrical demand between weekdays and weekends.

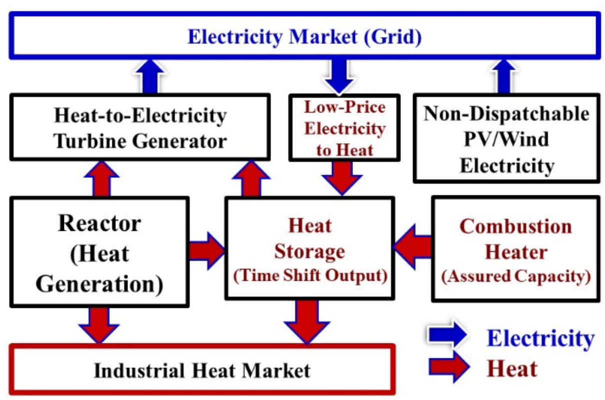

Fig. ES.1. System Design for Heat Storage Coupled to a Nuclear Reactor

To minimize the cost of electricity, capital intensive generating assets (nuclear, wind, solar and fusion (future)) should operate near their maximum capacity. Using the system depicted in Fig. ES.1, when electricity prices are high, all reactor heat is sent to the turbine to produce electricity. When electricity prices are low, most heat 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 or gas 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 becomes not only sellers but also a buyer of 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.

Heat storage may change reactor power-plant system design with the reactor facility inside a security zone that includes all vital areas for reactor safety and the storage and power blocks outside this security zone. Fig. ES.2 shows the plant layout for a CSP or nuclear plant using salt storage with this configuration. In CSP systems, heat storage simplifies operation. On partly-cloudy days the power output of a CSP system varies depending on whether the clouds are blocking the sun. With storage, the power block does not see such transients and thus storage simplifies operations.

The same design can be used for a nuclear power plant as proposed by TerraPower for sodium and salt reactors. There are several factors that create incentives for such designs. Current reactors put the power block (turbine generator) next to the reactor—a design that followed the design of earlier coal-fired power stations and that was developed before tight security requirements for nuclear power plants. The separation of the reactor and vital areas from the power block creates a clear division between areas with (1) requirements for nuclear security, maintenance, licensing, safety and construction versus (2) normal industrial requirements. This has the potential to reduce costs. Second, gigawatt-hour heat storage systems may become the largest set of structures on site. They will be in the protected area that has industrial safety and security requirements but in some case may need to be some distance (100 meters) from reactor vital areas. Some heat storage systems (concrete heat storage) could be next to the reactor but other heat storage systems such as hot salt storage tanks may need to be some distance away because their failure would create a thermally hot area that could damage buildings and equipment next to such tanks. Last, storage isolates the reactor from the electricity grid and reduces transients from the grid-to-reactor and reactor-to-grid. The reactor becomes a heat generation system.

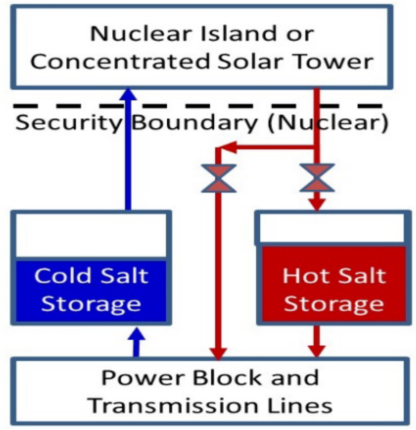

Fig. ES.2. System Design for CSP and Nuclear With Storage

The round-trip efficiency of many heat storage systems exceeds lithium ion batteries. In the system with heat storage, heat is generated, heat goes to storage and then stored heat is converted to peak electricity generation. The equivalent lithium battery system is heat generation, heat conversion to electricity, electricity to stored energy in the battery and conversion of the stored energy in the battery back to electricity. In systems where the intermediate loop of a reactor system is the storage medium, the inefficiency costs of storage may be near zero. Collapsing electricity prices at times of high wind and solar inputs has also resulted in work to develop stand-alone storage systems where electricity is converted into stored heat and then converted back to electricity. These systems have much lower efficiencies but are economic in certain markets.

Storage economics are based on several considerations. First, heat storage is cheap relative to storing electricity. The U.S. Department of Energy (DOE) heat-storage capital-cost goal is \$15/kWh(t) versus \$150/kWh(e) for batteries. Nitrate heat storage systems coupled to CSP systems today have a capital cost of ~\$20/kWh(t) that translates into a capital cost of about \$50/kWh(e). The cost of the electronics associated with the batteries approximately doubles the cost of installed systems. This cost difference between electricity and heat storage technologies reflects the cost of the raw materials to build the different storage systems. A recent DOE report [4] summarizes cost and performance parameters of electricity (work) storage technologies including six battery energy storage technologies (lithium-ion batteries, lead-acid batteries, redox flow batteries, sodium-sulfur batteries, sodium metal halide batteries, and zinc-hybrid cathode batteries), pumped storage hydropower, flywheels, compressed air energy storage, and ultra capacitors—as well as for combustion turbines. Heat storage technologies were not included but current estimates are that heat storage today is a third to a fourth the cost lithium ion batteries per kWh(e).

Second, the incremental cost of storing an additional kWh of heat storage is extremely low relative to batteries and other storage technologies—storage for more than a few hours is economic. Last, the capital cost of the backup furnace or boiler (natural gas, biofuels, hydrogen, etc.) to provide assured heat for assured peak generating capability is low. This provides a low-cost system for assured generating capacity and added income from capacity payments for assured peak generating capacity for the nuclear plant. Heat storage will usually cover the peak demand—particularly given the low incremental cost of heat storage. Thus, the backup system main function is to provide assured capacity to meet grid reliability goals. The assured backup generating capacity for electricity storage systems is a gas turbine (combustor, turbine and electrical generator) that costs two or three times the cost of a boiler or furnace per unit of assured peak electricity delivered to the grid.

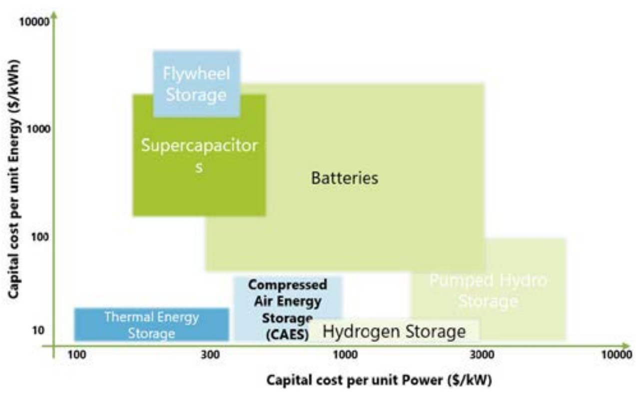

Fig. ES.3. Capital Cost per Unit of Storage versus Capital Cost per Unit of Power

A recent assessment examined the cost structure of different large-scale electricity-grid energy storage technologies in terms of cost per unit of storage and cost per unit of generating capacity. For large-scale systems, thermal storage is the low-cost technology (Fig. ES.3) by a large margin—partly reflecting the low cost of heat storage materials relative to other technologies.

HEAT STORAGE TECHNOLOGIES

The workshop examined multiple heat storage technologies for multiple reactor types. Different reactors operate at different temperatures and thus not all storage technologies are applicable to any reactor type. Table ES.1 shows nominal delivered heat temperatures for different reactors. Table ES.2 summarizes storage technologies and the upper temperature limits of these technologies. This is a list of the leading candidates for heat storage at the gigawatt-hour scale where heat storage cost is the most important criteria and the size and weight of the system is not a constraint.

Table ES.1. Temperatures of Delivered Heat from Different Reactors

Power System	**Coolant**	**Inlet Temp. (°C)**	**Exit Temp. (°C)**
Nuclear	Water	270	290
Nuclear	Sodium	450	550
Nuclear	Helium	350	750
Nuclear	Salt	600	700

Table ES.2. Sensible Heat Storage Materials and Maximum Temperature Limits

Storage Technology	Temp. Limit (°C)		Storage Technology	Temp. Limit (°C)
Nitrate Salt	<650		Hot Sand	>1000
Chloride Salt	<1000		Crushed Rock	800
Cast Iron	<900		Geothermal	<300
Pressurized Water	<300		Liquid Air	<1600
Concrete	>600		Sodium	<700
Hot Oil	<400		Cold Water	~0
Graphite	>1400		Alumina	>1000

Liquid Salts

The primary heat storage materials used today in CSP systems are nitrate salts with solar salt (solar salt: 60 wt% $NaNO_3$- 40 wt% KNO_3) the most common salt. These salts are chemically stable in air and water. Sensible heat of storage is obtained by typically varying temperatures from 290 to 565°C. CSP salts need reasonable margins from decomposition temperatures to avoid hot spots in solar collectors that can degrade the salt. With control of gas compositions over the salt storage tanks and salt chemistry, salt storage temperatures in the 600 to 650°C range may be possible. Heat storage system capital costs in CSP systems are near $20/kWh(t). The largest storage system sizes are measured in gigawatt-hours of capacity. Nitrate salts can be used to move heat to industrial customers.

Nitrate salt storage systems are proposed for Sodium Fast Reactors (SFRs: TerraPower), Fluoride-salt-cooled High-temperature Reactors (FHRs: Kairos Power) with solid fuel and clean salt coolants, thermal-spectrum Molten Salt Reactors (MSRs) with fuel dissolved in the salt and fusion machines. In addition to providing heat storage, in all of these systems the low-pressure nitrate salt intermediate loop would provide isolation of the reactor from the high pressures in the power cycle. In SFRs it avoids the risk of generating hydrogen from a sodium-steam interaction. For FHRs, MSRs and fusion the salt serves two purposes: (1) heat storage and (2) tritium trapping. These reactor systems generate tritium in the coolant that may diffuse through heat exchangers. If tritium enters a nitrate salt, it is converted into steam that can be collected in the tank off-gas system. Hot nitrate storage acts as a backup tritium removal system. Nitrate salt systems could be used with High-Temperature Gas-cooled Reactors (HTGRs).

Work is underway to develop second generation salt systems that would allow CSP systems to operate at peak temperatures of ~750°C with higher-temperature stored heat. The goal is to have a pilot plant within 5 years. The proposed salt is a sodium, potassium, magnesium chloride eutectic with a melting point near 400°C. This salt was chosen because of its extremely low cost combined with reasonable physical properties. Allowable peak salt operating temperatures could exceed 1000°C. This salt requires careful control of chemistry to avoid corrosion. The major economic challenge is development of low-cost heat storage tanks. With nitrate salt tanks the insulation is on the outside of the tank. At these higher temperatures, the cost of a metal tank with insulation on the outside exceeds the cost of the salt. Tanks are being developed with insulation on the inside of the tank so carbon steel tanks can be used. These salts are similar to the salts that are used to produce magnesium in electrochemical cells; thus, there is overlap in technology with the magnesium industry.

The chloride storage salts are proposed to be used with molten chloride fast reactors (TerraPower) with reactor peak temperatures near 750°C. The chloride storage salts would couple to higher-temperature HTGRs.

Concrete

Low-cost specially-formulated concrete is being developed for heat storage at different temperatures. The Westinghouse system consists of thin concrete slabs designed to couple with light-water reactors (LWRs) and lead-cooled reactors. Heat is transferred from the reactor coolant to the heat storage system using high-temperature heat transfer oils at atmospheric pressure that can operate up to 400°C—the same heat transfer fluids used in many chemical plants and lower-temperature CSP systems. In LWRs, the oil would be heated by steam from the reactor system and then used to heat the concrete at times of low electricity prices. For peak power production, the hot oil would be used for preheating of feed water. Using stored heat for feed-preheating enables peak electricity production 20 to 25% higher than base-load. The heat transfer oils are not used for heat storage because of their high cost relative to the low cost of concrete.

Bright Energy is developing a concrete heat storage system that consists of helical tubes in special concretes capable of temperatures in excess of 600°C. The base-line design has steam in the tubes but other fluids could be used. When steam is added, it heats long concrete modular units from one end to the other while the steam is converted to water. To recover the heat, water is sent in the reverse direction to produce high-temperature steam. This system will couple to any steam power cycle. The initial market is for retrofit to existing coal plants with multiple boilers into peak electricity production systems. If the plant had three boilers, two can be shut down. Heat storage enables one boiler to operate to produce electricity and charge the heat storage system. At times of peak electricity demand, heat from storage is used to provide steam to operate the steam turbines of the other two units. Prototype systems are to be tested in cooperation with EPRI.

Sand and Crushed Rock

CSP systems using sand storage are being developed by Sandia National Laboratory as well as by organizations in Europe and the Middle East. Small CSP systems at the one megawatt scale have been tested at Sandia. Falling sand is heated by concentrated light in the solar power tower and flows into a hot-sand storage tank. Hot sand from the tank flows through a heat exchanger to the power cycle fluid. The primary technology and cost challenge are the sand heat exchangers where two types of heat exchangers are being developed: flow-through and fluidized bed. For the CSP system, special sands are used to maximize light adsorption. For heat storage with any nuclear system, regular quartz or other sands could be used. The major advantage is the extremely low cost of sand. Such storage systems would couple with HTGRs and other high-temperature reactors.

Siemens is developing a crushed-rock heat-storage system. Low-price electricity heats air that is blown into crushed volcanic rock to raise its temperature to 750°C. At times of high electricity prices, cold air is blown through the crushed rock to provide hot air for boilers that produce steam for electricity production. The near-term market is retrofitting shutdown coal plants to become energy storage systems. A 130 MWh pilot plant is operating in Germany with the expectation that the commercially deployed system would be several gigawatt hours. Some work has been done on using crushed rock to store heat from different types of nuclear reactors.

Cast Iron with Cladding

Sensible heat can be stored in solid tightly-packed hexagonal assemblies 10 to 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. In a SFR it would enable sodium heat storage in an intermediate loop where most of the heat capacity is in the iron and thus minimize the inventory of hot sodium and risk of sodium fires. Cast iron costs less than $500/ton—less than sodium and some other coolants per unit of heat storage capacity. This option is applicable to all reactor technologies and thus places an upper limit on the cost of heat storage associated with any coolant—water, salt, sodium and helium. Only limited analytical studies have been conducted.

Saturated Steam Cycle Heat Storage

This workshop did not cover heat storage coupled to saturated steam systems; but, it was covered in the first heat storage workshop [2]. Any Generation IV plant with a steam cycle will have saturated steam at lower temperatures in the power cycle. As a consequence, the heat storage systems for LWRs are applicable to most Gen IV reactor systems. Two of those systems are discussed herein.

Heat storage coupled to steam accumulators is used at several CSP plants and is applicable to all steam cycles. At times of low electricity prices, steam is diverted to a steam accumulator—a pressure vessel filled with cold water. The hot steam heats the cold water to the saturation pressure. At times of higher prices, valves are opened and the hot pressurized water partly flashes to steam that is sent to the power cycle while the remaining water is cooled.

Saturated steam can also be coupled to geothermal heat storage that can be used for hourly to seasonal heat storage. At times of low prices, saturated steam is used to create hot water that is injected 500 to 1000 meters underground to create a hot rock zone. At times of high prices, the hot rock zone produces high-pressure hot water that is used to produce steam for the power cycle. The system is a man-made geothermal heat storage system. These systems have two limits. First, peak temperatures are limited to about 300°C. At higher temperatures various chemical reactions with rock result in dissolution and precipitation of components of the rock that will plug flow channels. Second, the minimum size of such systems is near a gigawatt-month of heat storage. One can’t insulate rock deep underground so there are conduction heat losses from hot rock to cold rock. Those losses are a function of the surface to volume ratio of the rock that is being heated. In small systems these heat losses become excessive.

Thermochemical

There are several classes of thermochemical systems where heat is stored in chemical bonds. These are at a much earlier stage of development than most of the above heat storage technologies. In hydride systems heat is used to decompose a hydride producing hydrogen. When the reaction is reversed the formation of hydride releases heat. In carbonate systems the chemical reaction is conversion of a carbonate such as calcium carbonate into calcium oxide and carbon dioxide. Last, there are a set of chemical reactions that involve forming hydrates where steam is release when the hydrate is heated and heat is generated in the reverse direction. The major advantages of such systems are (1) no heat losses during storage because one is not storing high-temperature heat and (2) the smaller size per unit of heat storage. In most of these systems there is the question of whether they can be cycled 10,000 times as would be required in a utility-scale system. It is not clear if any of these systems can meet the cost goals required for a utility system.

POWER SYSTEMS WITH THERMODYNAMIC TOPPING CYCLE

Gas turbine combined cycle (GTCC) power plants burning natural gas have become the preferred technology to produce dispatchable electricity to the grid. These systems have a Brayton power cycle and a bottoming steam cycle. The technical advances in gas turbines enable Nuclear Air-Brayton Combined Cycle (NACC) plants with thermodynamic topping cycles and integrated heat storage (Fig. ES.4). NACC would couple to sodium, salt, helium or other higher temperature reactor. The power cycle is similar to a GTCC plant. Research on NACC power cycles is just beginning and dependent upon the development and deployment of higher-temperature reactors. These cycles are not viable for lower-temperature LWRs.

The reactor would operate at base load. Within NACC filtered air is compressed, heated in heat exchanger 1 (HX1), goes through turbine 1, is reheated in HX2, goes through turbine 2, is reheated in HX3, goes through turbine 3 and exits to the steam cycle. The system can have two or three reheat cycles. The warm air from the Brayton cycle goes through the heat recovery steam generator (HRSG) and up the stack. Steam produced in the HRSG can be used to produce electricity or sent to industry. In base-load operation, this system is very similar to a GTCC.

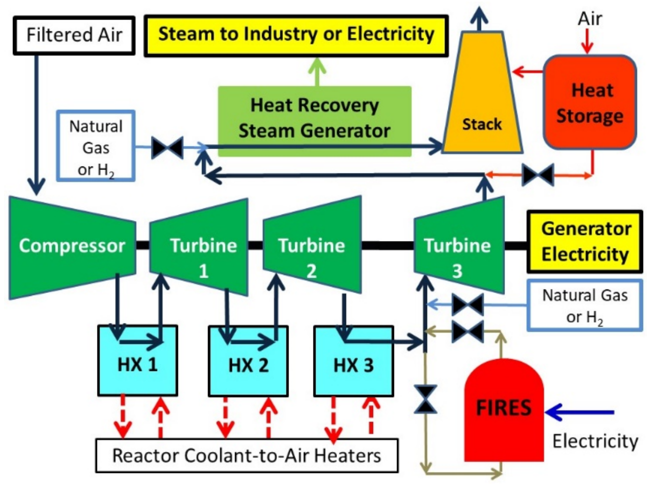

Fig. 4. Nuclear Air Brayton Cycle with Thermodynamic Topping Cycle and Heat Storage

For peak electricity production, the hot air exiting HX3 can be further heated by natural gas, biofuels, hydrogen or high-temperature stored heat in a Firebrick Resistance Heated Energy Storage (FIRES) system before entering Turbine 3 to produce peak power—a thermodynamic peaking cycle. The peak temperature limits of modern turbines are far beyond the temperature limits of the heat exchangers between the reactor and the power cycle. Table ES.3 shows the projected nominal performance of this system for different reactor heat input temperatures (sodium and salt reactors) and different peak temperatures assuming existing gas turbine technology.

Table ES.3 Performance of Different NACC Cycles

Turbine 1&2 Exit Temp	Turbine 3 Nominal Exit Temp	Turbine 3 Boosted Inlet Temp	Base Efficiency	Fraction Base from Steam	Hydrogen Burn Efficiency	Combined Efficiency	Brayton Gain	Overall Gain
Sodium Near-Term System (Nominal Inlet Temperature 773 K (500°C)								
680.5 K	640.5 K	1100 K	32.8%	18%	**71.1%**	48.4%	**1.464**	**2.522**
680.5 K	640.5 K	1700 K	32.8%	18%	**74.2%**	60.4%	**2.347**	**5.744**
Molten Salt Advanced System (Nominal Inlet Temperature 973 K (700°C)								
792.5 K	722.5 K	1100 K	45.5%	24%	**74.5%**	51.1%	**1.168**	**1.403**
792.5 K	722.5 K	1700 K	45.5%	24%	**75.0%**	61.6%	**1.834**	**3.070**

In this specific example it is assumed that hydrogen is used to provide peak electricity with incremental heat-to-electricity efficiencies above 70%, far above the natural gas-to-electricity efficiency of existing GTCC systems and a higher incremental heat-to-electricity efficiency than any other heat engine. The four cases that are shown in Table ES.3 include two cases for sodium-cooled reactors and two cases for salt-cooled reactors. Two peak turbine temperatures are shown for each reactor type. The first is for uncooled turbine blades. The second is for cooled turbine blades used in high-performance GTCC systems. The overall NACC efficiencies when producing peak power with internally-cooled turbine blades are near 60% and similar to current GTCCs except low-cost uranium fuel provides the heat when operating as a base-load power plant at lower efficiency while a higher-cost fuel (natural gas, hydrogen, biofuels, stored heat) provides the heat for the thermodynamic topping cycle. The topping cycle increases the NACC output. For the first case in Table ES.3, if the power output is 1 megawatt, operating the peaking cycle increases the Brayton cycle output by 46.4% (relative factor of 1.464) and the total plant output increases by 152.2%. Other designs allow much higher peak-to-base power outputs.

NACC can incorporate heat storage in several locations. Peak power can be produced using the Firebrick Resistance Heated Energy Storage System (FIRES) where low-price electricity is used to electrically heat firebrick to very high temperatures. For peak electricity production, compressed air is diverted after HX3 into FIRES, directly heated by the firebrick and then sent to turbine 3. FIRES is inside a pressure vessel. Only firebrick is capable of withstanding the high temperatures required to match combustion temperatures.

Heat exhausted from the gas Turbine 3 at times of low electricity demand can be diverted from the HRSG to a heat storage recuperator (red) using firebrick, concrete, crushed rock or other storage medium as described earlier. At times of high electricity demand, cold air can be blown through the recuperator in the reverse direction to provide hot air to the HRSG in addition to the hot air from Turbine 3. The cost of this heat storage system is low because these heat storage systems operate at low pressure and lower temperatures. Assured peak generating capacity can be provided with a combustible fuel to provide heat to the boiler if the heat recuperator storage system is depleted. This system is separate from the thermodynamic peaking cycle and thus is an option whether or not a high-temperature peaking cycle is included with NACC.

Such heat storage systems for HRSGs are being developed for GTCCs to enable the gas turbine to operate at full power and maximum efficiency with variable power from the HRSG. GTCCs are very efficient (~60%) but cost more than simple gas turbines with 40% efficiency. A heat storage recuperator may enable highly-efficient GTCCs to partly replace simple gas turbines for peak power with variable steam from the HRSG—a heat storage option directly applicable to a NACC with the reactor operating at base load.

HYDROGEN

The United States consumes 10 million tons of hydrogen per year for fertilizer production, oil refining and production of various chemicals. In a low-carbon world hydrogen will likely replace coal as a chemical reduction agent for the production of iron and other metals from their ores. Hydrogen may be used directly as a fuel for vehicles or in the production of biofuels. One can almost double the yield of high-quality fuel per ton of biomass with hydrogen addition. Last, it may be used for heating and peak electricity production including in NACC systems. However, hydrogen is a higher-cost source of heat. It takes several units of heat to produce one unit of electricity for electrolytic production of hydrogen; thus, the cost of heat to industry would be half to a third from a nuclear reactor than heat from combustion of hydrogen. One could have a future where 10 to 20% of all primary energy is used for hydrogen production. Unlike electricity, hydrogen has been stored at low-cost for decades in underground geologies, like natural gas. This enables hydrogen to be stored on an hourly to seasonal basis.

The workshop addressed the question of the roles of hydrogen in the electricity grid relative to heat storage. Hydrogen can be made by room temperature electrolysis and high temperature electrolysis that requires steam and electricity that can be provided by a nuclear plant. High-temperature electrolysis is more efficient. In addition, there are large incentives for centralized hydrogen production because of the economics of scale associated with hydrogen handling, including compressors, pipelines and storage.

However, the capital costs of hydrogen production (Fig. ES.3) are much higher than for heat storage. Economics requires that a hydrogen production plant operate many more hours per year. Recent studies for coupling hydrogen production to existing LWRs are beginning to provide a strategy for nuclear hydrogen production when coupled to the electricity grid as shown in Fig. ES.4. The figure shows the price of electricity over a year. The hydrogen plant operates at times of lower electricity prices—in this case over 7000 hours per year. The number of hours the nuclear plant produces hydrogen versus electricity depends upon the price curves for hydrogen and electricity. The nuclear plant operates like a natural gas peaking turbine today in terms of sending electricity to the grid only when prices are high. What a fleet of such reactors would not provide is a large sink for very low price electricity or large amounts of peak assured generating capacity at times of low wind or solar input—services that can be provided by nuclear plants coupled to heat storage.

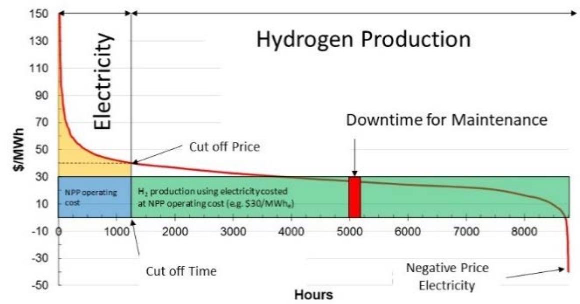

Fig. ES.4. LWR Operation for Electricity and High-Temperature Hydrogen Electrolysis

Nuclear heat storage and hydrogen production meet the demands of different segments of the energy market. If reasonably priced hydrogen does become available, it creates added incentives to deploy nuclear reactors with NACCs with their very high heat-to-electricity efficiency for peak electricity production. All of these future scenarios have large uncertainties because the market is evolving with a different market structure in a low-carbon electricity grid compared to today.

INSTITUTIONAL FACTORS

The institutional factors associated with heat storage were the subject of several presentations and two panel sessions. The regulatory rules as defined by the Federal Energy Regulatory Commission (FERC), state Public Service Commissions (PUCs), Independent System Operators (ISO) and other agencies have major impacts on the economics. FERC released recent guidance that encourages storage as a grid service. However, there are many questions how storage will operate. A 1000 MWe nuclear power plant could have a storage system with 500 MWe of peaking capacity. Using the same grid connections, such a plant could buy 1500 MWe for conversion of low-price electricity into stored heat. Because electric resistance heating can be turned off and on in a fraction of a second, the system could be used for frequency control and other purposes. No existing power station has such a set of capabilities and thus there are many market and operational questions that have not been answered.

CONCLUSIONS

The first large-scale heat storage systems for CSP are less than 10 years old. While heat storage is a very old technology, large-scale heat storage at the gigawatt-hour scale is a new development. Only nitrate salt heat storage has been built at scale. Five years ago the addition of heat storage for variable electricity output from a base-load nuclear reactor would have been uneconomic. Market changes now indicate heat storage is economic at a few reactor locations depending upon the variations of wholesale electricity prices with time and grid capacity payments for assured generating capacity. Westinghouse and several startup companies (Kairos Power, TerraPower, etc.) include heat storage systems for their advanced reactors.

Different storage technologies are in different states of development from commercially available to early in the research and development process. It is unlikely there will be a single winning technology because of the different temperatures of delivered heat from different reactors and different markets that imply different storage times and technologies. The workshop led to several recommendations.

- *Large-scale demonstrations*. There is a need for a joint government-utility demonstration program of coupling heat storage to light-water reactors to demonstrate alternative storage technologies at scale and address the institutional and regulatory challenges (FERC, PUCs, ISO and NRC) that are independent of the reactor or storage technology. A reactor that buys and sells electricity with large assured peaking capacity has very different capabilities than any technology now in service. A joint program can reduce the financial risks for the first utilities to deploy the technology. For the government the incentives in accelerating deployment of the technology are potentially lower-cost electricity while improving the economics of nuclear, wind and solar plants.
- *Market assessments*. There is a need for independent studies (EPRI, etc.) to better understand revenue and the size of the market for such heat storage systems.
- *Research, development and demonstration.* There are large incentives to accelerate research, development and demonstration of heat storage technologies because (1) heat storage coupled to nuclear reactors may be the low-cost enabling technology for dispatchable electricity in a low carbon grid and (2) increased nuclear plant revenue. In this context, there are large incentives for joint nuclear-CSP-fossil programs because the goals, scale of storage, and technologies in many cases are identical. The benefits of developing heat storage are much larger if one looks at the multiple applications for nuclear, fossil and solar rather than the benefits of heat storage for just a single energy source.
- *Alternative nuclear plant designs.* The addition of heat storage enables alternative nuclear plant designs (Fig. ES.2) that separate the reactor and its vital systems from heat storage and the power block. Isolation of the reactor to a heat production system has the potential for major reductions in cost. The implications of such designs are not well understood. However, the potential is sufficiently large that a major effort should be undertaken to determine the benefits and costs.

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Table of Contents

Abstract ... 1

Acknowledgements ... 3

CANES Publications ... 4

Executive Summary ... 6

Table of Contents ... 15

List of Figures ... 17

List of Tables ... 18

1. Introduction ... 19

2. Markets and System Design ... 21

2.1. Markets: The Challenge ... 21

2.2 System Design ... 24

3. Integrating Reactors and Storage Systems ... 26

4. Storage Technologies ... 30

4.1. Steam Accumulators (<300°C: Saturated Steam Cycles) ... 32

4.2. Heat Storage in Hot Oil or Hot Oil and Secondary Storage Media ... 35

4.3. Concrete ... 36

4.4. Nitrate Salts ... 41

4.5. Chloride Salts ... 43

4.6. Hot sand ... 45

4.7. Atmospheric-Pressure Crushed-Rock Heat Storage ... 47

4.8. Pressurized Counter-Current Condensing-Steam Solid Heat Storage ... 48

4.9. Cast Iron with Cladding ... 50

4.10. Nuclear Geothermal Heat Storage ... 52

4.11. Cold Water ... 55

4.12. Graphite 56

5. Power Cycles with Heat Storage and Thermodynamic Topping Cycles...................................58

5.1. Nuclear-Air Brayton Power Cycles with Thermodynamic Topping Cycles.............................58

6. Hydrogen 70

6.1. Using Hydrogen Production to Consume Low-Price Electricity 70

6.2. Electricity from Hydrogen Production with Brayton Cycles Coupled to Heat Storage..........71

6.3. Thermochemical Heat Storage Using Hydrogen...73

7. Discussions on Path Forward...75

8. Observations and Conclusions...78

9. References...80

Appendix A: Workshop Agenda 90

Appendix B: Workshop Participants 91

Appendix C: Presentations 92

Appendix D: Posters...93