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Separating Nuclear Reactors from the Power Block with Heat Storage: A New Power Plant Design Paradigm

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Changing the World's Energy Future

Charles Forsberg, Piyush Sabharwall, Andrew Sowder

Idaho National Laboratory

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Advanced Nuclear Power Program

Separating Nuclear Reactors from the Power Block with Heat Storage: A New Power Plant Design Paradigm

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Abstract

Separating Nuclear Reactors from the Power Block with Heat Storage: A New Power Plant Design Paradigm: Workshop Proceedings

The Massachusetts Institute of Technology (MIT), Idaho National Laboratory (INL) and the Electric Power Research Institute (EPRI) conducted a workshop on *Separating Nuclear Reactors from the Power Block with Heat Storage: A New Power Plant Design Paradigm*. The workshop was held as three webinars (July 29, August 12 and August 26, 2020). These proceedings include this abstract, an executive summary, the main report and presentations.

There are two reasons to consider a new design paradigm. First, the market is changing with (1) the addition of variable wind and solar that results in highly volatile electricity prices and (2) the goal of a low-carbon economy that requires (a) economic dispatchable electricity that is now provided by natural gas turbines in the United States and (b) heat for industry and commerce. Second, nuclear plant requirements have changed in the last 50 years suggesting that a lower-cost plant layout may be to separate the nuclear island from the power block with a clear separation of the nuclear island with nuclear requirements and the power block built to industrial standards.

Figure A.1 shows on the left the existing design of nuclear power plants. The new design paradigm is on the right. The intermediate loop of the reactor transfers heat to storage. The technology proposed today for sodium, lead and salt-cooled reactors is to use a nitrate salt intermediate loop—the same salt used for heat storage in concentrated solar power (CSP) systems. The reactor takes cold salt from a cold-salt storage tank, heats the salt, and sends hot salt to a hot-salt storage tank. The power cycle takes hot salt, produces steam for the turbine generator and returns cold salt to the cold storage tank. The hot-salt tank also provides heat to industrial and other customers. There are alternative intermediate loop coolants and heat storage technologies.

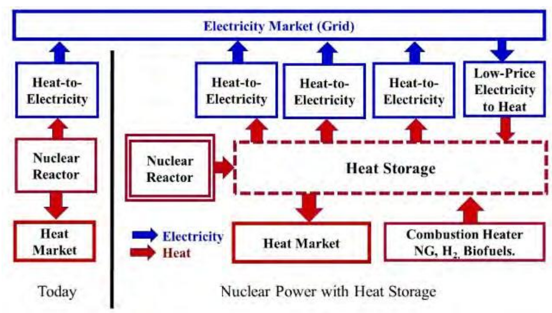

Fig. A. 1. Current (left) and alternative design (right) of nuclear power systems.

Nuclear reactors with heat storage become a low-carbon replacement for gas turbines. The reactor is designed for average required energy demand over a period from hours up to a week. The peak electricity output is sized to provide assured generating capacity for the grid and may be two or three times the "base-load" output of the reactor. Electricity is sold at times of high prices that maximizes revenue. At times of very low-priced electricity, it can be bought and converted into stored heat to produce electricity at times of high prices. A low-cost backup combustion heater can heat the salt if storage is depleted for assured peak generating capacity. The fuel could be natural gas or low-carbon hydrogen or low-carbon biofuels. Storage enables nuclear cogeneration of variable heat and electricity with the only requirement that demand equal production over a period of days.

The new design has the potential to lower the cost of nuclear power plants. Only the nuclear plant is built to nuclear standards. Security is only associated with the nuclear block—not the entire plant. Decoupling nuclear heat generation via storage from the electricity grid eliminates all of the requirements imposed on the nuclear reactor by the grid. The power block is built to normal industrial standards. Several advanced reactors are being designed using this system design—including the TerraPower sodium-cooled Natrium® and Moltex molten salt reactor.

There are many heat storage technologies. The largest CSP heat-storage systems use tanks of hot and cold nitrate salt with sensible heat storage measured in gigawatt hours (GWhs). This is a commercial technology that is deployable today for nuclear systems. At the same time technologies are being developed that may lower heat storage costs by an order of magnitude that would provide large additional economic benefits.

The power cycles are sized and designed for the specific market with capital costs significantly below that of gas turbines. Adding heat storage and associated peak power systems increases power system resilience by adding massive storage to the system.

There are several economic effects. First, added revenue from selling most electricity at times of higher prices significantly exceeds that of added capital costs in some markets today. Second, the system design can lower the capital cost of the nuclear block. Last, the importance of the capital cost of the nuclear component of the total plant decreases relative to the traditional design of a nuclear power plant. In a traditional nuclear power plant, the reactor output matches the turbine-generator output. In this alternative design the turbine-generator output may be three times the reactor output. A larger fraction of the plant is associated with the power block since its output is several times that of the reactor. The power block uses conventional industrial (non-nuclear) systems.

The economic incentives to couple heat storage to nuclear plants have existed for less than a decade; thus, these systems are relatively new with significant potential to reduce costs and associated uncertainties. For nuclear systems, heat storage creates the potential for a cost-competitive nuclear plant as a replacement for the gas turbine in providing a low-carbon variable heat and electricity power system -- what the energy system needs. Last, there are incentives for cooperative programs with CSP and fossil systems that are also developing heat storage and power block technologies.

Acknowledgement

The workshop was supported through the INL National Universities Consortium (NUC) Program under DOE Idaho Operations Contract DE-AC07-05ID14517. We would also like to thank the Electric Power Research Institute, Idaho National Laboratory, the Massachusetts Institute of Technology and all of the speakers for their contributions to the workshop and this report.

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Executive Summary

Separating Nuclear Reactors from the Power Block with Heat Storage: A New Power Plant Design Paradigm: Workshop Proceedings

Charles Forsberg, Piyush Sabharwall and Andrew Sowder

The Massachusetts Institute of Technology (MIT), Idaho National Laboratory (INL) and the Electric Power Research Institute (EPRI) conducted a workshop on *Separating Nuclear Reactors from the Power Block with Heat Storage: A New Power Plant Design Paradigm*. The workshop was held as a series of three webinars (July 29, August 12 and August 26, 2020). There were two earlier workshops specifically on heat storage technologies—one for light water reactors and the second for Generation IV reactors. These proceedings include this executive summary, the main report that integrates the results of the workshop including added information provided by participants and appendixes that include the presentations.

There are two reasons to consider a new design paradigm. First, the market is changing. The historic role of nuclear energy has been to provide base-load electricity. Because of the high capital cost and low operating cost of nuclear power plants, the economics favor base-load operation. Variable heat and electricity have been provided by fossil systems with low capital costs and high operating costs. The goals of a low-carbon energy system and the addition of non-dispatchable wind and solar create large variations in prices with time and thus large economic incentives to provide dispatchable variable heat and electricity. Figure ES.1 shows wholesale prices over one spring day in California with low prices in the middle of the day because of solar photovoltaics (PV). Prices quickly climb at sunset. Separate from this price cycle is the large weekday / weekend variation in electricity demand. Heat storage enables base-load nuclear plants to provide dispatchable heat and electricity at several times base-load capacity. The system can replace the role of gas turbines in the electricity system.

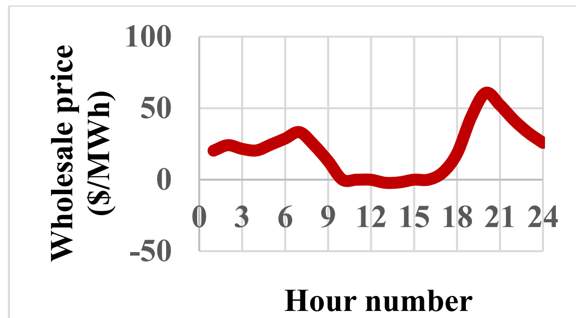

Fig. ES.1. Changes in California wholesale electricity prices over a spring day.

Second, nuclear plant requirements have changed in the last 50 years. The original nuclear plant designs followed those of coal plants—tight integration of the heat source with the turbine generators. Added safety and security requirements suggest that a lower-cost option may be to separate the nuclear island from the power block with a clear separation of the nuclear island with nuclear requirements and the power block built to normal industrial standards.

Figure ES.2 shows on the left the existing design of nuclear power plants. The new design paradigm is on the right. The intermediate loop of the reactor transfers heat to storage. The technology proposed today for sodium, lead and salt-cooled reactors is to use a nitrate salt intermediate loop—the same salt used for heat storage in concentrated solar power (CSP) systems. The reactor takes cold salt from a cold-salt storage tank, heats the salt and sends hot salt to a hot-salt storage tank. The power cycle takes hot salt, produces steam for the turbine generator and returns cold salt to the cold storage tank. The hot-salt tank also provides heat to industrial and other customers. There are alternative intermediate loop coolants and heat storage technologies.

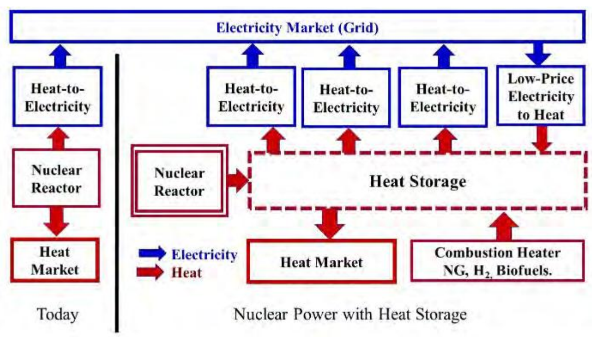

Fig. ES.2. Current and alternative design of nuclear power systems.

This design has several characteristics.

- *Decoupling reactor output from electricity or heat output.* The reactor is designed for average required energy demand over a period of several hours up to a week. The power block capacity (kW) is designed to meet market requirements. The peak electricity output may be two or three times the "base-load" output of the reactor. Nuclear reactors with heat storage become a low-carbon replacement of gas turbines. Electricity is sold at times of high prices that maximizes revenue.
- *Electricity storage*. The addition of wind and solar results in times of very low electricity prices. At times of very low prices (Fig. ES.1), electricity can be bought and converted into stored heat to produce electricity at times of high prices. The only additional cost is the cost of electric resistance heaters. Large-scale deployment would set a minimum price of electricity—improving the economics of wind, solar and nuclear.
- *Backup combustion heaters*. There is the option to add a backup combustion heater to heat the salt if storage is depleted. The fuel could be natural gas or low-carbon hydrogen or low-carbon biofuels. This feature provides assured peak electric generating capacity. The capital cost of such a backup combustion heater is very low.
- *Cogeneration*. Industrial heat demand in the United States is about twice total electricity production; that is, there is a massive heat demand. With traditional cogeneration of heat for industry and electricity, the industrial heat demand is first met with excess heat converted to electricity on a minute by minute basis. With heat storage the requirement is that reactor heat production equal industrial heat demand plus electricity produced over a period of several days. Heat storage enables meeting peak heat requirements and selling excess heat as electricity at times of the highest prices to maximize total revenue.

This system design applies to any heat-generating technology; thus, there is massive overlap in the heat storage and power block technologies for nuclear, solar thermal and fossil systems. This design is similar to that used today in some existing CSP plants. Storage in CSP systems is used for two purposes. First, on a partly cloudy day the CSP output will vary as clouds cover the mirrors. Storage enables constant power output with variable solar heat input. Second, storage enables electricity production after the sun sets. Lower-temperature CSP systems (<400°C) use oil to transfer heat and store heat as hot oil. Higher-temperature CSP systems (<600°C) use nitrate salt and store heat as hot salt.

Fossil plants are considering the same type of system design for two applications. Many old coal plants with multiple boilers and turbine-generators are now being used for peaking power. Adding heat storage allows one boiler to operate efficiently at steady state with heat to storage. That heat can then go to multiple steam-turbine generators for rapidly varying electricity to the gird. Second, low-carbon fossil plants are now being developed with carbon capture and sequestration (CCS). These plants have high capital costs. Storage enables the heat generation system to operate at base-load with variable electricity to the grid.

The new design has the potential to lower the cost of nuclear power plants. Only the nuclear plant is built to nuclear standards. The power block is built to normal industrial standards. There are no electricity grid requirements imposed on the nuclear plant. Nuclear security is only associated with the nuclear block with large reductions in the size of the secure areas of the plant.

There are many heat storage technologies. The largest CSP heat-storage systems use tanks of hot and cold nitrate salt with sensible heat storage measured in gigawatt hours (GWhs). This commercial salt storage technology is now proposed for several advanced sodium and salt-cooled reactors. At the same time, work is underway on advanced heat storage systems that may significantly lower costs providing much larger economic benefits for nuclear plants. The first generation that is commercially deployed has hot and cold nitrate salt in separate large insulated tanks—the two tank system. The second generation systems that are being developed in the laboratory add crushed rock or other lower-cost fill materials in single tank heat storage systems with hot salt (or oil) on top of cold salt (or oil). Crushed rock is much cheaper than nitrate salt as a sensible storage material. Single tank systems are less expensive than double tank systems where some fraction of the hot or cold tanks are empty much of the time. The third generation heat-storage systems, where work has just begun, propose crushed rock in large insulated structures. Heat is transferred from the reactor to the crushed rock as hot nitrate salt that is sprayed onto the rock and drains down to the salt pan below. The cold salt is returned to the reactor to be reheated. Heat is removed from the crush rock pile by spraying cold salt onto the hot rock, the salt being heating by the rock as it flows to the salt pan below and the hot salt sent to the power cycle. These systems may store over 100 GWHs of heat. Costs are minimized by (1) using crushed rock as the heat storage material, (2) minimizing the quantities of nitrate salt to what is required for heat transfer and (3) minimizing the surface to volume of the heat storage system to minimize container costs and heat losses. Similar systems exist and are proposed that use heat transfer oil that can couple to lower-temperature light-water reactors.

The U.S. Department of Energy capital cost goals for battery storage systems are $150/kWh of electricity. The DOE goals for CSP systems are $15/kWh of heat. Existing nitrate salt systems have capital costs near $25 per kWh of heat storage. The single tank cost goals are expected to reduce capital costs by a factor of two. The goals of the third generation heat-storage systems are to reduce capital costs to $2-4/kWh of heat. There is also work underway in the CSP community to develop lower cost salts to allow operating temperatures to 750°C that would be applicable to higher-temperature nuclear reactors. The much lower costs of heat storage relative to other storage technologies is because of the much lower cost of the raw materials—salt, crushed rock, etc.

There are several other heat storage technologies under development using materials such as concrete and cast iron. All of the leading candidates are sensible heat storage systems where heat is stored by varying the temperature of the heat storage material. Work is at an earlier stage of development for systems that use latent (phase change) heat storage or chemical reactions. Some of these systems preferentially couple to specific reactors or power cycles.

The power cycles are sized and designed for the specific market. If the system operates for only a few hours per day, the power cycle is designed for low-capital costs and rapid startup or shutdown. Steam cycles can be designed that have lower capital costs than natural-gas-fired gas turbines. Work is underway on advanced supercritical carbon dioxide cycles and gas turbine cycles that may have lower capital costs than steam cycles.

Limited studies indicate the potential for large capital and operating cost savings in a separate nuclear block and non-nuclear power-generating block. Many of these savings are independent of whether or not heat storage and peak electricity power blocks are included. This is driven by several decades of changing safety, regulatory, and security requirements for nuclear plants that are not required for the power block. To use a simple example, the addition of security requirements imposes special design features and operating costs on the power block if it is tightly coupled to the nuclear reactor. Those requirements do not exist for the power block if the power block is 50 meters away from the nuclear reactor and its associated safety systems.

Last, adding heat storage and associated peak power systems increases power system resilience. The reactor is no longer directly tied to the electricity grid. The reactor does not shut down if the grid fails for any reason. Similarly, the impacts of reactor shutdown on electricity to the grid do not occur for hours or days when heat storage is depleted—providing time for grid operators to decide what other units to bring on line to meet electricity demand. The power block can be designed for rapid response to electricity grid needs—faster than a turbine generator tied to a nuclear reactor because it is not constrained by reactor operating limits.

There are three economic effects of the new design paradigm. First, added revenue from adding heat storage and power conversion systems significantly exceeds added capital costs in some existing markets today. The economic advantage is expected to increase with (1) addition of wind and solar that changes how the price of electricity varies with time and (2) requirements for low-carbon energy system. Second, the system design can lower the capital cost of the nuclear block that is built to nuclear standards and the power block built to industrial standards. Last, the importance of the capital cost of the nuclear component of the total plant decreases relative to that of a conventional design of a nuclear power plant. In a traditional nuclear power plant, the reactor output matches the turbine-generator output. In this alternative design the turbine-generator output may be three times the reactor output—the capital cost per unit of assured generating capacity (kW) is much less. A much larger fraction of the plant is associated with the conventional power block since its output is several times of the reactor. The power block uses conventional industrial (non-nuclear) systems and construction that are cheaper and where the risk of cost overruns or schedule delays are much less. A much larger fraction of the total capital cost is non-nuclear with lower financial risks.

Several advanced reactors are being designed with heat storage including the TerraPower sodium-cooled Natrium® reactor and the Moltex molten-salt reactor. Other advanced reactors, such as the Kairos Power Fluoride-salt-cooled High-temperature Reactor, include salt intermediate loops that provide the option of coupling to heat storage.

There are several conclusions. The need to consider a new design paradigm is driven by two changes: (1) changes in the market that create volatile electricity prices with the incentives to provide variable heat and electricity and (2) changing safety, security and regulatory nuclear requirements that have evolved over several decades. The economic incentives to couple heat storage to nuclear, solar and fossil plants have existed for less than a decade; thus, these systems are relatively new with significant potential to reduce costs. For nuclear systems, heat storage creates the potential for a cost-competitive nuclear plant as a replacement for the gas turbine in providing a low-carbon variable heat and electricity power system -- what the electric power system needs. Last, there are large incentives for cooperative nuclear, solar thermal and fossil research-development-and-demonstration programs to develop advanced heat storage systems and the associated power cycles.

Acknowledgement

The workshop was supported through the INL National Universities Consortium (NUC) Program under DOE Idaho Operations Contract DE-AC07-05ID14517. We would also like to thank the Electric Power Research Institute, Idaho National Laboratory, the Massachusetts Institute of Technology and all of the speakers for their contributions to the workshop and this report.

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1. Introduction

The Massachusetts Institute of Technology (MIT), Idaho National Laboratory (INL) and the Electric Power Research Institute (EPRI) conducted a workshop on *Separating Nuclear Reactors from the Power Block with Heat Storage: A New Power Plant Design Paradigm*. The workshop was held as a series of three webinars (July 29, August 12 and August 26, 2020). There were two earlier workshops specifically on heat storage technologies—one for light water reactors [1, 2] and the second for Generation IV reactors [3]. These proceedings include a short abstract, an executive summary and this report which provides added details including references and a series of appendixes that includes the presentations. We include herein references from the literature and references to the presentations that are in Appendix D (Example - Appendix D: Parsons).

There are two reasons to consider a new design paradigm. First, the market is changing as discussed in Chapter 2. The historic role of nuclear energy has been to provide base-load electricity. Because of the high capital cost and low operating cost of nuclear power plants, the economics favored base-load reactor operation. Variable heat and electricity have been provided by fossil systems with low capital costs and high operating costs. The goals of a low-carbon energy system and the addition of non-dispatchable wind and solar create large variations in prices with time and thus large economic incentives to provide dispatchable variable heat and electricity. The system for integrating heat storage with a nuclear reactor operating at base-load to provide variable heat and electricity to match market needs is described in Chapter 3. The specific heat storage technologies and associated power cycles are discussed respectively in Chapter 4 and Chapter 5.

Second, nuclear plant requirements have evolved over the last 50 years. The original nuclear plant designs followed those of coal plants—tight integration of the heat source with the turbine generators. Changing licensing, safety and security requirements suggest that a lower-cost option may be to separate the nuclear island from the power block with a clear separation of the nuclear island with nuclear requirements and the power block built to normal industrial standards. Heat storage built to non-nuclear standards separates the reactor block from the power block. This is discussed in Chapter 6.

Such changes have major institutional and regulatory implications that are discussed in Chapter 7 with economics discussed in Chapter 8. The economics has two components—the changes in the market that impact revenue and changes in plant design that impact costs. Today two proposed advanced reactors include heat storage that separates the nuclear power block from the conventional power block. The TerraPower [4, 5] reactor is a sodium-cooled reactor whereas the Moltex reactor [6] uses molten salt as a coolant.

The workshop included participants from the concentrated solar power (CSP) and fossil communities. Many CSP systems incorporate storage for two different reasons. First, storage enables selling electricity after the sun sets. Second, on partly-cloudy days the solar input is highly variable. Heat storage is used to enable steady state electricity output rather than rapidly variable output from the CSP system. Heat storage is being considered in fossil plants for two different reasons [Appendix D: Hume, White]. First, many fossil plants are now being used as peaking plants for a limited number of hours per year. If a station has several units, there are economic incentives to shut down all but one of the steam boilers, add heat storage and use the steam turbine-generators from the multiple units. The one steam boiler operates near base-load with variable electricity output by using multiple existing steam turbine-generators. This minimizes the operational difficulties and costs associated with operating multiple boilers with variable output. The second application is for future fossil plants with carbon-capture and sequestration (CCS) systems. These plants have high capital cost and significant challenges in varying power output because of the CCS systems. There are incentives to add heat storage for variable output from a base-load fossil plant. There is massive technological overlap between heat storage and power block design for nuclear, CSP and fossil fuel plants as reflected in these workshop proceedings and as discussed in Chapter 9 on research and development.

2. Changing Markets

Electricity markets are changing because of the goals of a low-carbon energy system and the addition of non-dispatchable wind and solar that creates large variations in prices with time. Figure 1 shows wholesale prices over one spring day in California in 2012 and 2017. In 2012 the price of electricity was controlled by natural gas with peak wholesale electricity prices in the early evening at times of peak electricity demand. The large-scale addition of solar resulted in collapse of wholesale electricity prices in the middle of the day with higher prices before sunrise and as the sun goes down. Wholesale prices in the middle of the day can become negative as conventional power plants bid negative prices to remain online at minimum output so they are able to ramp up in the evening when electricity prices climb. The value of solar decreases as more solar is added [7, 8] as has been seen in multiple markets. This limits the large-scale economic deployment of wind and solar photovoltaic (PV).

Fig. 1. Wholesale California electricity prices over 24 hours on a spring day.

Historically the daily to seasonal variations in wholesale electricity prices have been small. Fossil fuel plants have low capital costs and high fuel costs. It is economic to operate fossil plants at variable load because the money is in the fuel. The development of nuclear power plants created an energy production system with high capital costs and low operating costs. The economics resulted in nuclear plants operating at base-load with fossil plants operating at variable load to meet variable electricity demand. Nuclear plants in some countries such as France have operated for decades with variable output. It is economics (not technology) that has resulted in nuclear plants operating as base-load power plants.

Recent studies [9] of the impacts of wind and solar on California electric wholesale markets provided insights to the long-term market effects of wind and solar. In the United States wholesale electricity prices have been decreasing. The primary cause on a national basis has been the reduction of natural gas prices from fracking. However, California has aggressively pushed wind and solar relative to most of the U.S. As a consequence, California provides a basis to understand the future impacts of wind and solar on wholesale electricity prices. Three conclusions follow from these studies.

- Revenue to base-load power plants goes down with large-scale wind and solar additions.
- There are large increases in the volatility of electricity prices. This creates 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). Today this favors gas turbines fueled with natural gas.
- As more wind or solar is added, the revenue per installed kilowatt of capacity of wind and solar goes down. This effect is larger for solar than wind. Revenue collapse limits the large-scale deployment of wind and solar unless there are large subsidies or markets are developed to absorb massive amounts of electricity to reduce times of very-low-electricity prices.

Historical studies [10] on electricity prices that cover multiple regions of the United States come to similar conclusions. We are going through a one-time transition by addition of non-dispatchable wind and solar with low levelized cost of electricity (LCOE) in those parts of the country with high-quality wind and solar resources. This change in the market creates incentives for electricity storage systems to buy electricity at times of low prices and sell at times of high prices to address hourly to daily price variations in electricity prices.

There are limits to such storage systems because of the seasonal variations in wind and solar. Figure 2 shows the smoothed electricity demand for California over a period of one year and the smoothed generating profile of wind and solar over the same time if sufficient wind and solar was built to meet the total electricity demand of California. That is, the total production of electricity from wind and solar matches total demand for electricity. There is a seasonal mismatch between production and demand with excess production in the spring and early summer. That mismatch will dramatically increase if significant movement of building heating loads to electricity.

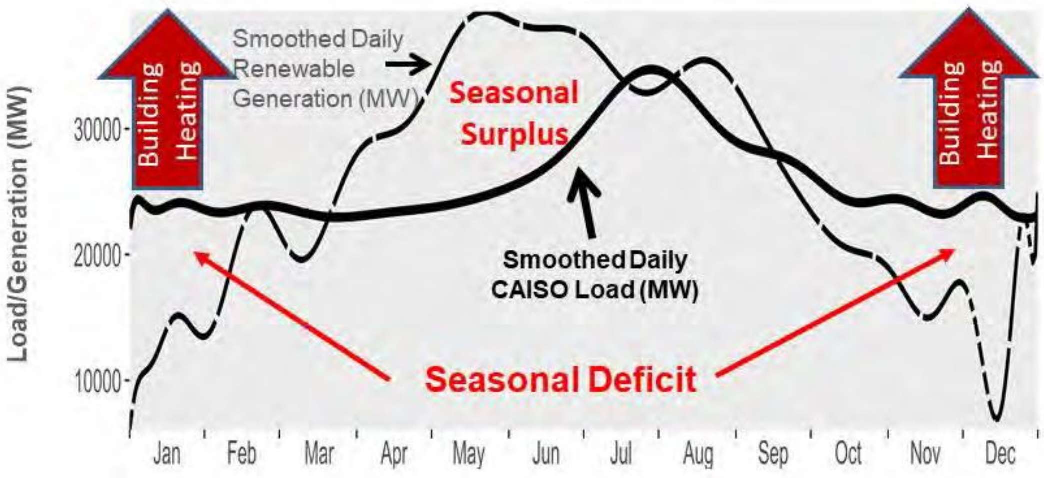

Fig. 2. Smoothed daily California electricity demand and smoothed daily renewable geneation with total annual renewable generation equal to total annual electric demand
(Courtesy of S. Brick, California Case Study, Clean Air Task Force).

The cost of electricity (kWh) from wind and solar is low. However, for every unit of generating capacity (kW), large amounts of energy storage and assured generating capacity is needed for times of low wind and solar output. The economics of large-scale wind and solar systems are determined by the economics of storage and assured generating capacity—not the cost of producing electricity from wind and solar systems. This is why electricity costs have gone up in Germany, Denmark, California and other locations that have attempted to create electricity systems based on wind and solar. Small amounts of wind and solar reduce electricity prices while large amounts increase the price of electricity to the consumer. Figure 2 is a snapshot in time where decarbonization will change the shape of the demand curve.

If a green-field electricity (start from scratch) system was built in the United States today with the goal to minimize costs [11] to the customer, the majority of electricity would be generated with natural gas with added wind and solar in locations with good wind or solar inputs. Wind and solar act in a fuel-saving mode. Most electricity would be generated by natural gas because wind and solar provide electricity to the grid less than half the time. The peak natural gas generating capacity would be close to the peak electricity demand for most of the United States. In northern climates peak loads occur in winter at times of minimum wind and solar output.

If there are limits on greenhouse gas emissions, replacements are required for the gas turbine that provides most of the electricity (kWh) and most of the assured generating capacity (kW). Studies [11] of such systems show that the minimum cost system contains a mixture of wind, solar, nuclear and storage. Nuclear energy provides both energy (kWh) and assured generating capacity (kW). The assured generating capacity to avoid blackouts is as important as the energy if there are tight restrictions on greenhouse gas emissions. These studies have considered existing storage technologies, but not large-scale heat storage coupled to nuclear power plants. What the electricity market needs for a low-carbon world with wind and solar is a low-carbon replacement for the gas turbine.

Separate from the electricity market is the heat market with different characteristics. Most heat is provided by fossil fuels (Fig. 3). In the United States electricity [12-14] provides slightly more than 17% of energy demand to customers. The industrial heat load alone is about twice the total the electricity output.

Much of this market is for steady state heat demand. In this market nuclear energy has a competitive advantage [13]. Because of thermodynamics (Carnot cycle), it takes several units of heat to produce a unit of electricity. Nuclear and fossil plants produce cheap heat and more expensive electricity. In contrast in most industrial applications one unit of electricity results in one unit of heat. This makes wind and solar photovoltaic that produce electricity expensive sources of heat separate and independent from the inability to deliver continuous energy to industrial processes.

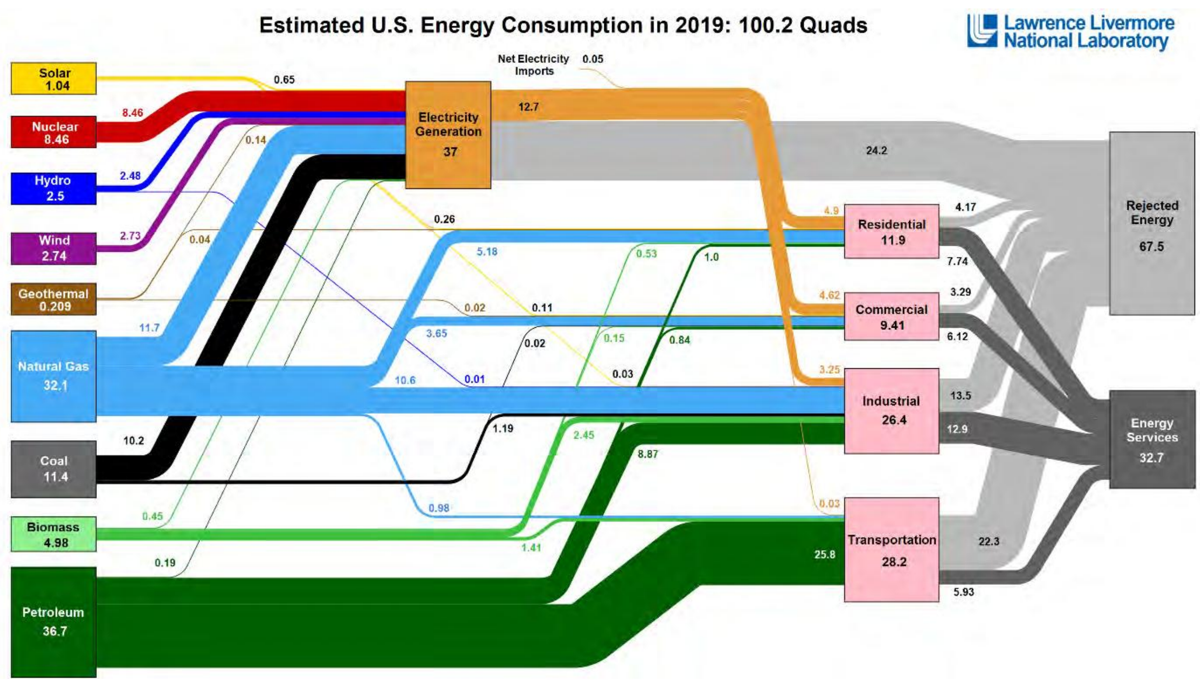

Fig. 3. Energy flow diagram of the United States for 2019 [12].

3. System Description

To address the changing markets requires rethinking the energy system for a world that has large quantities of non-dispatchable energy sources (wind, solar, run-of-the-river hydro) and limits on carbon dioxide emissions. Figure 4 shows on the left the existing design of nuclear power plants. The new design paradigm is on the right [13, 14, Appendix D, 1.1: Forsberg]. The intermediate loop of the reactor transfers heat to storage. The technology proposed today for sodium, lead and salt-cooled reactors is to use a nitrate salt intermediate loop. The system design is similar to that used in many concentrated solar power (CSP) systems with the same salts [15, 16]. The reactor takes cold salt from a cold-salt storage tank, heats the salt, and sends hot salt to a hot-salt storage tank. The power cycle takes hot salt, produces steam for the turbine generator and returns cold salt to the cold storage tank. The hot-salt tank also provides heat to industrial customers. For lower-temperature systems such as light-water reactors (LWRs), the heat transfer fluid would be a heat transfer oil. Lower-temperature (<400°C) CSP systems use heat transfer oils. There are alternative intermediate loop coolants and heat storage technologies.

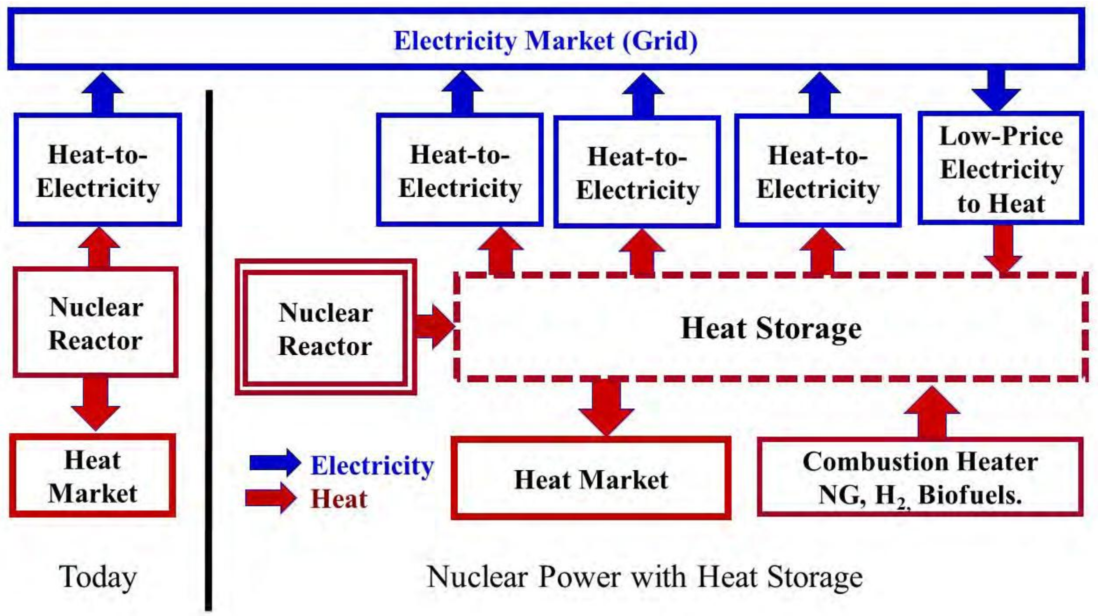

Fig. 4. Current and alternative design of nuclear power systems.

This system has several characteristics

Decoupling reactor output from electricity or heat output. The reactor is designed for average required energy demand over a period of hours up to a week. The power block is designed to meet market requirements. The peak electricity output may be two or three times the "base-load" output of the reactor. In this system nuclear reactors with heat storage becomes a low-carbon replacement of gas turbines. Electricity is sold at times of high prices that maximizes revenue.

Electricity storage. The addition of wind and solar results in times of very low electricity prices. At such times (Fig. 1) electricity can be bought and converted into stored heat to produce electricity for sale at times of high prices. The only additional cost is the cost of electric resistance heaters and an incrementally larger heat storage system. The grid connections, main heat storage system and power block already exist.

If there are many hours of low-price electricity, there is a second option—using heat pumps to convert low-temperature heat into high-temperature stored heat [17-21]. Whereas one unit of electricity yields one unit of heat with a resistance heater, heat pumps can convert one unit of electricity into several units of high-temperature heat. If a cooling lake is associated with the power plant, it can be the source of lower-temperature heat. Such systems are called Carnot batteries. Many of these heat pump systems can be operated in both directions; that is (1) electricity pumps heat from a lower-temperature reservoir to a higher temperature reservoir and (2) when operated in reverse convert heat into electricity. For large systems, there may be a combination of Carnot heat pumps and resistance heaters where the heat pumps first come on line as the price of electricity collapses and operate for many hours while the lower-cost electric resistance heaters are used only when there is a massive excess of electricity that is available for a limited number of hours. Heat pumps have higher capital costs than resistance heaters and thus economically would only be viable in systems with many hours of low-price electricity.

The ability to buy and sell electricity would have major impacts on electricity prices by setting a minimum price for electricity. That would improve the economics of wind and solar. As discussed later, heat storage capital costs are estimated to be one to two orders of magnitude less than batteries and other technologies that store electricity and thus would replace many other storage technologies.

Low-capital-cost generating capacity. The electricity generating capacity may be several times the base-load electricity generating capacity. It is sized to match market demand [Appendix D: Ingersoll, Scott]. This system is built (1) to industrial, not nuclear, standards and (2) to minimize capital costs. The power cycle will be operating only part of the time. The technical goal is a power cycle with ability to rapidly start and vary power levels to match demand. The economic goal is low capital costs per unit of capacity (kW)—substantially below conventional gas turbines or batteries and other electric storage systems. As the power cycle is used fewer hours per year, the capital costs become a larger fraction of the total cost of electricity and the cost of energy become a smaller fraction of the total cost of electricity. This economic relationship is shown in Fig. 5 for a simple gas turbine used to meet variable electricity demand but applies to all electricity generating technologies used to meet variable electricity demand [Appendix D: Conlon].

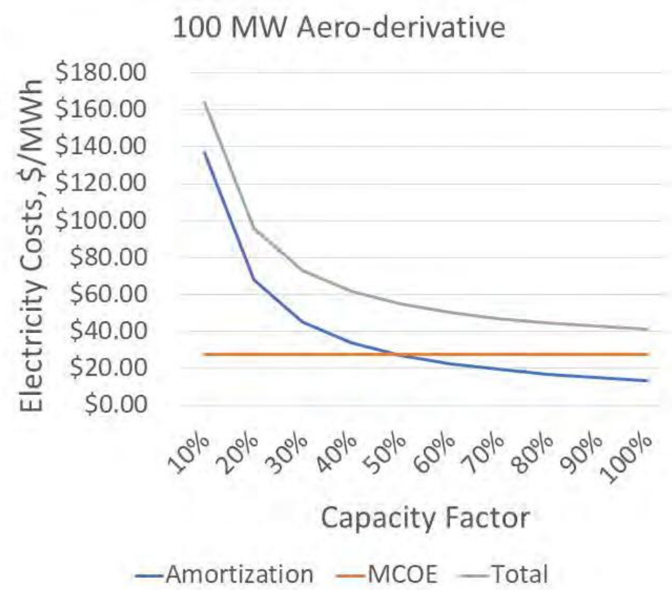

Fig. 5. Electricity costs versus capacity factor for natural gas peaking turbine
(Courtesy of Pin Tail Power LLC).

Backup combustion heaters. There is the option to add a backup combustion heater to heat the salt if storage is depleted. The fuel could be natural gas or low-carbon hydrogen [22, 23] or low-carbon biofuels [24]. This feature provides assured peak electric generating capacity. The capital cost of such a backup combustion heater is very low. Combined with the power block, this provides a massive competitive advantage to provide a low-carbon replacement for the assured generating capacity provided by the gas turbine.

- *Capital costs*. The capital cost of providing assured generating capacity is less than an equivalent PV/wind system with electricity storage. The cost of batteries or other technologies is higher than the cost of heat storage as discussed below. If one 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. One requires multiple kilowatts of generating capacity to back up the wind or solar—batteries and then gas turbines.

- *Combustible fuel consumption.* The low cost of heat storage versus electricity storage implies that the quantities of combustible fuel to provide assured generating capacity is lower—more storage is available.

Integration of industrial heat markets and electricity markets. About 80% of all energy used by the customer in the U.S. is in the form of heat [12] as shown in Fig. 3. Electricity is less than 20% of energy consumption in the United States as shown by the gold-colored flows in the figure. The total industrial heat demand in the U.S. is about twice the total electricity output. The future heat demand may be much larger. Many of the processes to convert biomass to liquid biofuels require massive quantities of heat and hydrogen [24]. The quantity of biofuels per unit of biomass can be almost doubled by addition of external heat and hydrogen.

Heat storage enables varying industrial production to provide more electricity at times of high electricity prices to (1) increase total revenue and (2) meet weekly to seasonal variations in electricity demand. Historically fossil and nuclear co-generation systems [25] that produced electricity and steam provided heat and electricity to industry and then sold any excess energy as electricity to the grid. The price of electricity was relatively constant (Fig. 1); thus, there were not large incentives on when to sell electricity to the grid. With the changes in the electricity market, electricity revenue is strongly dependent upon when electricity is sold. Industrial production requirements make it difficult to vary heat demand quickly on an hourly to daily basis to maximize revenue from electricity sales. However, many industrial processes can alter heat demand over a period of hours or days if there was a large economic incentive to do so. Large-scale heat storage eliminates the second-by-second requirement that industrial heat plus electricity output match reactor output. The requirement becomes that industrial heat and electricity output match reactor output over a period of hours to a week. This new degree of freedom in operations enables altering industrial production to provide more electricity to the grid at times of high demand and prices.

Changing functional requirements for the nuclear reactors. The system design changes the functional requirements for the nuclear reactor. There are no grid requirements on the reactor. The reactor produces heat on its own schedule. Transients are minimized.

Table 1 summarizes the characteristics of this system. The reactor is sized to meet average energy demands. The power block is sized to meet peak electricity demands with assured generating capacity. Heat storage, depending upon the market, is designed to meet daily to weekly variations in energy demand.

TABLE 1. System Characteristics

	Nuclear Reactor	Storage	Power Block
Function	Heat Production (kWh)	Minimize CO_2 Emissions	Assured Generating Capacity (kW)
Construction	Nuclear	Industrial	Industrial
Capacity Factor	~90%		20 to 60%
Sizing	Average Energy Demand	Match Production with Demand Up to a Week	Assured Capacity Requirements
Economic Driver	Low-Cost Heat	Low Capital Costs	Low-Cost Assured Capacity

4. Storage Technologies

4.1. Storage Capacity

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 with base-load operation of the reactor—with major savings to the electricity grid [26]. Electricity demand varies on (1) a daily cycle, (2) a multiday cycle tied to changing weather over several days, (3) holidays, (4) the weekday/weekend work cycle and (5) seasonal variations driven by weather. On the production side, solar has a daily cycle and in many locations a multiday cycle that drives cloud cover. Wind has a multiday cycle. Both wind and solar have large seasonal variations in output (Fig 2). Nuclear can operate at steady state. In a low-carbon system, there will be excess production capacity on weekends creating the incentive for large-scale heat storage at the weekly scale.

There is also a macro-economic perspective [Appendix D, 3.6: Forsberg]. 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 holidays, hurricanes, heat waves and winter blasts. The annual U.S. energy consumption is about 29,400 Terawatt hours. One month's energy storage is about 2 million gigawatt hours. Based on historical 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.

The market has created large economic incentives for hourly heat storage at the gigawatt-hour scale. At the same time it is creating large incentives to develop lower-cost heat storage technologies to access added heat storage markets. 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. This is similar in capabilities to a large hydro-pumped storage facility.

4.2. General Heat Storage Technologies

Most large-scale heat storage technologies were originally developed for CSP systems and are now being considered for nuclear systems. These systems can be defined by coolant and storage technology. There are three generations of such systems.

4.2.1 Heat Storage Using Clean Fluids

The first generation CSP systems store latent heat as clean fluids in tanks (Fig. 6). The oil and nitrate systems are commercially deployed in CSP systems today. These systems have one set of tanks to store hot fluid and a second set of tanks to store cold fluid.

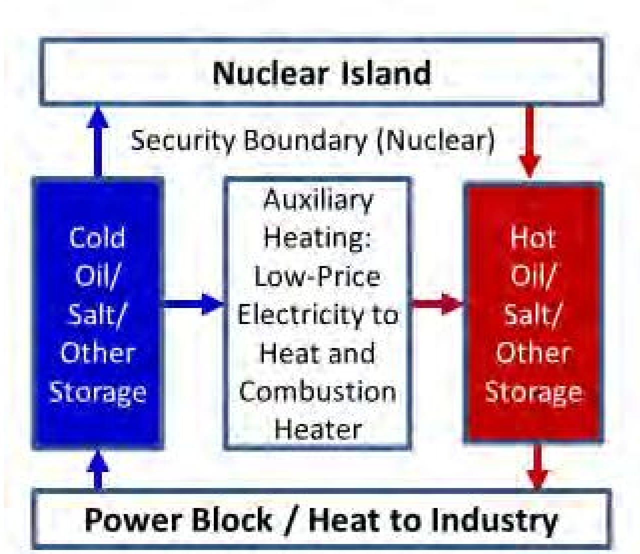

Fig. 6. Two-tank sensible heat storage system.

- *Synthetic heat transfer oils*. These 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 [27]. These heat transfer fluids are composed of eutectic mixture of diphenyl-oxide (DPO)/biphenyl. These oils would couple to water-cooled reactors with peak temperatures near 300°C.
- *Nitrate salts*. The primary heat storage materials used today in high-temperature CSP systems are nitrate salts with solar salt (solar salt (60 wt% $NaNO_3$- 40 wt% KNO_3) the most common salt. Sensible heat of storage is obtained by typically varying temperatures from 290 to 565 °C. These salts are stable in air at these temperatures. With control of gas compositions over the salt, salt storage temperatures of 600°C or more may be viable. Recent work indicates the possibility to raise

peak temperatures to 650°C [28, 29]. A review paper by Nunes, et al., [30] discusses pure molten alkali nitrate salts as well as their commercially relevant mixtures. CSP salts need reasonable large margins from decomposition temperatures to avoid degrading the salt at hot spots in solar collectors. Heat storage system capital costs in CSP systems are ~$20/kWh of heat. The largest storage system sizes are measured in gigawatt-hours of capacity. Nitrate salt storage is commercially deployed at multiple CSP sites with hot and cold liquid nitrate storage tanks. Nitrate salts can be used to move heat to industrial customers. Recent papers [30] have summarized the status of various nitrate-salt CSP systems

The same nitrate salt storage system designs are proposed for Sodium Fast Reactors (TerraPower) [4, 5], FHRs (Kairos Power) [31], thermal-spectrum MSRs, fast-spectrum molten-chloride fast reactors with fluoride-salt coolants [6] and fusion machines [32]. 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. It replaces the intermediate heat transfer loop in these systems. 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) secondary tritium trapping.

- *Chloride salts*. Work is underway [33, 34, 35, Appendix D: Turchi] to develop next-generation heat-storage 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 for heat storage is a sodium, potassium, magnesium chloride eutectic with a melting point of 383°C. This salt was chosen because of its low cost combined with reasonable physical properties. Allowable peak operating temperatures could exceed 1000°C. 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 also couple to higher-temperature HTGRs.

The sodium, potassium, magnesium chloride salt must be operated under highly chemically reducing conditions to minimize corrosion. There is also limited work [36] on chloride salts that could operate under chemically oxidizing conditions that may be more compatible with storage systems that include inert filler material as discussed below.

4.2.2 Heat Storage with Liquids and Low-Cost Filler Materials

Second-generation heat storage systems are being developed in laboratories and pilot plants using oil and nitrate salt coolants. In these systems a lower-cost filler partly replaces the oil or nitrate salt in tanks.

For light-water reactors, Westinghouse [Appendix D: Stansbury] proposes filling tanks with low-cost concrete slabs that partly replaces the more expensive oil. South Korea [37] is examining adding crushed rock to heat storage tanks filled with oil. 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. 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

Work is underway in Germany [38, Appendix D: Thess] using crushed rock to partly replace nitrate salts in heat storage tanks. This includes larger-scale pilot plant testing examining multiple types of rock and experimentally investigating multiple design options. The addition of crushed rock would replace much of the nitrate salt with much less-expensive crushed rock. This work includes examination of single-tank systems with hot salt above cold salt. In these systems the crushed rock would also stabilize the thermocline between the hot salt/rock and cold salt/rock. The use of a single tank versus double tank system would further reduce costs. The goal is to reduce the capital cost of storage to about $10/kWh of heat storage in CSP systems.

4.2.3 Crushed Rock Heat Storage and Liquid Heat Transfer

Some work has begun on third generation heat storage systems [39, Appendix D, 2.3: Forsberg] using either oil (lower temperatures) or nitrate salts (higher temperatures) to further lower capital costs to a few dollars per kWh of heat storage. There are three requirements for a low-cost heat storage system: (1) minimize cost of heat storage material, (2) minimize heat storage container per unit of heat capacity and (3) minimize heat transfer fluid inventory. The system is shown in Fig. 7.a through 7.c. The heat storage material is crushed rock—the lowest cost heat storage medium. The container (Fig. 7.a) configuration 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.

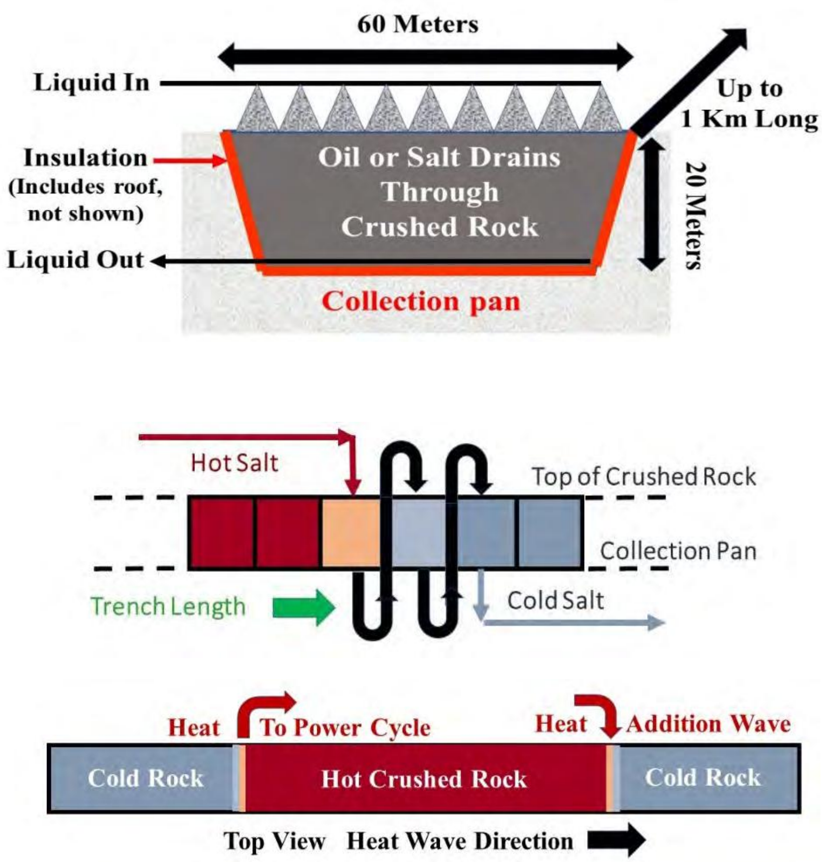

Fig. 7. Crushed Rock Heat Storage System: (a; Top) Cross section, (b: middle) Side view of sequential heating of crushed rock with hot liquid spray and gravity flow of liquid through the crushed rock and (c: bottom) Top view of sequential heating and cooling of crushed rock.

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. 7.a and Fig. 7.b. 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 nitrate salt heats the crushed rock from left to right down the trench length (Fig. 7.c).

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. 7.c. When either wave reaches the end of the trench, it starts over at the other end of the trench. The design minimizes the inventory and thus the cost of the heat transfer fluid that is expensive relative to the crushed rock.

The above description is a simplification. One could store about the same amount of heat in a crushed-rock bed in the form of square that is about 250 meters on a side. If we heat a 25 by 25 meter zone at a time, the storage system would be divided into 100 zones. The surface area (insulation) is minimized as the crushed rock depth increases and the facility geometry approaches a circle. The storage system can be built by excavating a hole or building the external walls. Various practical engineering considerations constrain the geometry.

This system has a safety and environmental 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 the leak.

4.3. Other Heat-Storage Technologies

It is unlikely that there will be a single preferred storage technology. Different reactors couple more or less efficiently with specific heat storage technologies. Markets will be different in Texas with low-cost wind and solar versus New England with (1) limited wind and solar and (2) a massive winter heating demand. We describe two other technologies to provide a broader perspective that may be preferred in some markets with some types of reactor systems. The first example is heat storage in cast iron for sodium-cooled reactors and CSP systems. It is an example where there are large incentives for cooperative nuclear/CSP joint development programs. The second example is geological heat storage that is constrained in terms of siting but the only heat storage system capable of gigawatt-year heat storage—the ultimate heat storage system in terms of capacity.

In the U.S., there is a renewed interest in sodium-cooled reactors [4, 5, 40]. At the same time sodium coolant is being proposed [41] for advanced Gen III-CSP facilities with operating temperatures to 750°C. Sodium is a preferred coolant because of its excellent heat transfer properties. Sodium coolants also couple efficiently to air-Brayton combined cycle plants [42] as discussed in the next section. Sodium-air heat exchangers for gas turbines are significantly smaller in size than most other liquid-air heat exchangers. This creates incentives for heat storage systems that use sodium as the coolant to avoid (1) heat exchangers between the sodium-cooled heat source (nuclear or CSP) and the heat storage systems and (2) between the heat storage systems and the power cycle. In this specific case it also creates large incentives for joint nuclear and CSP programs to develop the base storage technology. Sodium-cooled CSP systems were first examined in the 1970s; thus, there has been and continues to be work on storage systems using sodium [43, 44].

There are constraints. Sodium is a more expensive coolant and is highly flammable. That creates large incentives to minimize sodium in the storage system by adding a filler to the tank that occupies most of the volume and provides most of the heat capacity. Iron has been proposed as the filler. Early work proposed using iron balls [45]. More recent work [46, 47] proposes stainless-steel clad hexagonal ingots 10 to 20 meters tall (Fig. 8), with spacing between billets for coolant flow and to provide space for thermal expansion. The cast iron occupies more than 95% of the volume to (1) minimize cost, (2) minimize safety hazards from the sodium and (3) minimize heat transfer via the highly conductive sodium from hot to cold zone. Unlike most other storage materials, iron is chemically compatible with sodium. However, low-cost cast iron has impurities in it. The cast iron has stainless steel cladding to minimize slow corrosion of selected cast-iron components into sodium and thus assure high-purity sodium. High purity is required for both CSP and nuclear reactor applications because of the high heat fluxes in CSP solar receivers and in nuclear reactor cores. This geometry is the same geometry of fuel assemblies in sodium-cooled reactors. Those fuel assemblies have exterior hexagonal shrouds made of stainless steel. As a consequence, there is substantial understanding of hexagonal close-packed assemblies including thermal expansion effects.

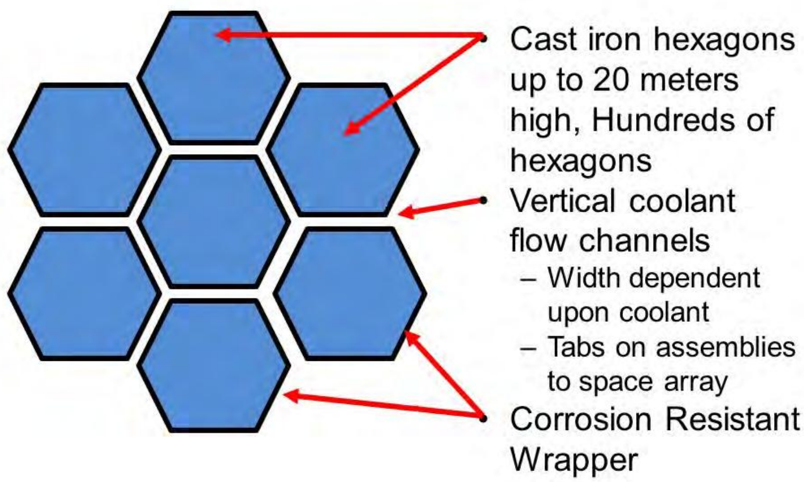

Fig. 8. Hexagonal cast iron heat storage with corrosion-resistant wrapper [Appendix D, 3.6: Forsberg].

The allowable temperature ranges from 100 to between 700 and 900°C depending upon the iron composition. Cast iron at higher temperatures undergoes a phase transition with a large change in volume that would likely cause major design challenges; thus, operating temperatures should be held below this transition temperature. The phase change temperature for cast iron (iron with carbon) is at 727°C. With pure iron the phase change occurs at 917°C.

If one uses a gigawatt hour as a measure of storage and assumes a 100 K hot-to-cold temperature swing, one requires 80,000 metric tons of iron per GWh (80 kg/kWh). Steel prices are typically near $500 per metric ton when ordered in quantity implying iron costs near $40/kWh of heat storage. If the temperature difference between hot and cold is increased to 300°C, heat-storage costs are reduced by a factor of three. Tripling the hot-cold temperature range in storage cuts storage costs by a factor of three or more, with the potential to meet the DOE cost goal for heat storage of $15/kWh, excluding other system costs. Such costs are viable for daily heat storage but not for weekly heat storage.

This design allows the use of other low-cost materials for heat storage to replace cast iron while retaining the stainless steel clad to assure pure sodium. Cast iron is the low-risk option—well understood with no major reactions between sodium and the cast iron if clad failure.

Figure 9 shows one possible arrangement of heat storage tanks between the reactor or CSP system and the power block. A series of heat storage tanks are used to minimize the hot-cold interface between hot and cold sodium. There is the option to choose a power cycle that results in very low temperatures of the sodium sent back to the reactor or CSP system. This minimizes the cost of heat storage by maximizing the hot-cold sodium temperature change. If the cold sodium temperature is below the allowable inlet sodium temperature for the reactor or CSP system, hot sodium can be mixed with cold sodium to match required sodium inlet temperature requirements.

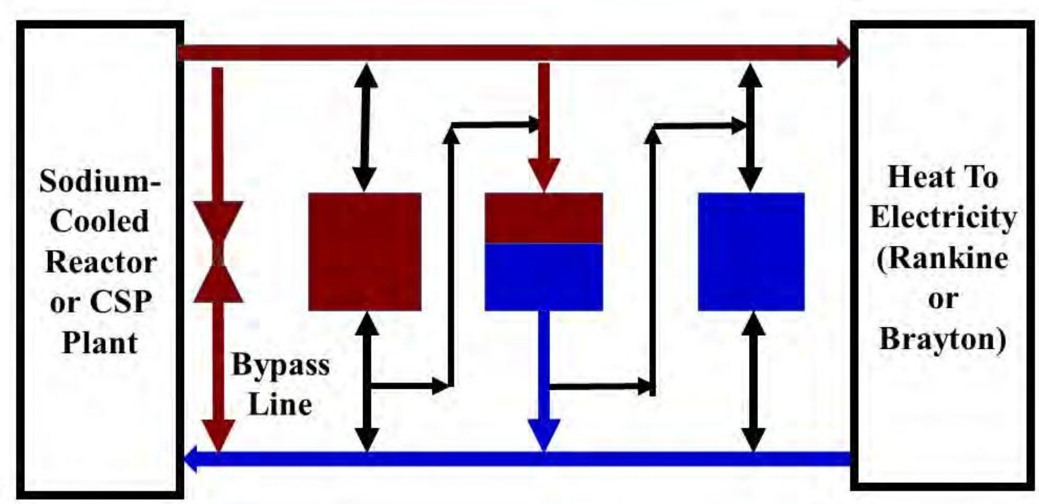

Fig. 9. Schematic tank system for sodium reactor or CSP system.

At the other extreme of heat storage systems are the geologic heat storage systems [1, 2, 48]. These proposed systems have the capability to store gigawatt-years of heat at low-costs to address seasonal variations in energy demand; but they are only viable in selected geologies. This is in contrast to other heat storage technologies that can be built anywhere. Geological heat storage combines the features of an enhanced geothermal energy facility with thermal energy storage. Thermal energy is stored underground by injecting hot pressurized water heated by the reactor into the rock reservoir; heat is primarily stored in the rock, and heat is recovered by water flowing through the rock back to the surface for electricity production in a conventional geothermal plant. Under certain circumstances, there may be the option to use carbon dioxide as the heat transfer fluid. This is the only heat storage option that is a candidate for hourly through seasonal energy storage because of the extremely low cost of the storage media—hot rock.

It is not possible to insulate rock 500 to 1000 meters underground. There is always the slow loss of heat by conduction into surrounding rock. However, heat losses are proportional to the surface area of the storage zone while heat storage capacity is proportional to the volume. Heat losses vary by the square of the storage reservoir size while heat storage varies by the cube of the storage reservoir size; thus, heat losses decrease as the system size increases. The minimum heat storage is a tenth of a gigawatt year—30 to 40 GWd of heat if heat losses are to be limited to a few percent of the heat being stored. As a consequence, this system would be designed for at least weekly (weekday/weekend) storage.

In most geologies, peak temperatures are limited to ~300°C because of rock-water interactions that dissolve rock components. Geothermal heat storage would couple to LWRs directly. For reactors with higher-temperature steam cycles, heat from those steam cycles could only be used after going through high-temperature turbines and reduction in temperature. The practical implications are that LWRs are near the peak allowable temperatures for water-based geothermal systems—higher temperatures create conditions where rock dissolution and precipitation may block pores and channels required for efficient hot water flow through the rock. The technology is at an early stage of development.

5. Power Cycles

The change in the market changes the requirements and design of the power cycle if nuclear power is to replace the gas turbine in providing low-cost dispatchable electricity. The power cycle may be operating only part of the time. Total generating capacity may be several times base-load nuclear plant output. The technical goal is a power cycle with ability to rapidly start and vary power levels to match demand. The economic goal is low capital costs—substantially below conventional gas turbines or batteries and other electric storage systems. As the power cycle is used fewer hours per year, the capital costs become a larger fraction of the total cost of electricity and the cost of energy become a smaller fraction of the total cost of electricity as shown earlier in Fig. 5.

There are multiple technical options. Each is based on a non-nuclear power block. We describe herein three options that are under development. EPRI [Appendix D: Charkas] is examining simplified steam cycles (Fig. 10) based on those used in gas-fired combined-cycle plants and CSP plants. Such designs using existing off-the-shelf commercial technologies are applicable to multiple Gen-IV reactors and use the common supply chain associated with fossil and solar systems to minimize front-end capital costs. The higher temperatures allow superheated steam with major steam-cycle simplifications and cost reductions in the power cycle.

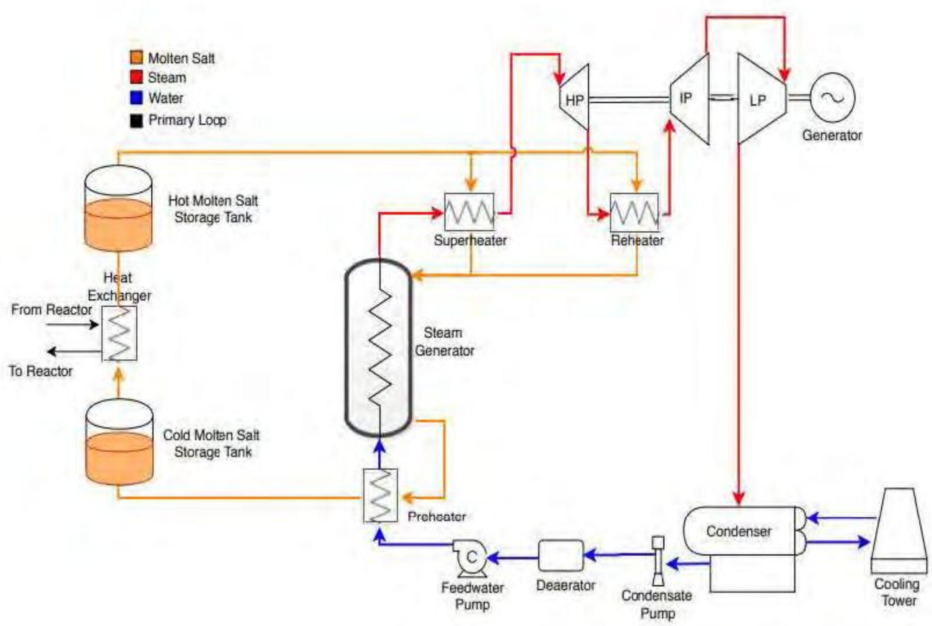

Fig. 10. EPRI simplified steam cycle for advanced Gen-IV plants [Appendix D: Charkas].

Pintail Power LLC [49, 50, 51, Appendix D: Conlon] is developing a very low-cost power cycle as shown in Figure 11 that includes nitrate-salt heat storage. This system was originally designed for markets with large quantities of low-price electricity. At times of low electricity prices, electricity is used to heat nitrate salt to high temperatures. At times of high prices, electricity is sold to the grid. The same power cycle couples to any nuclear system using nitrate storage.

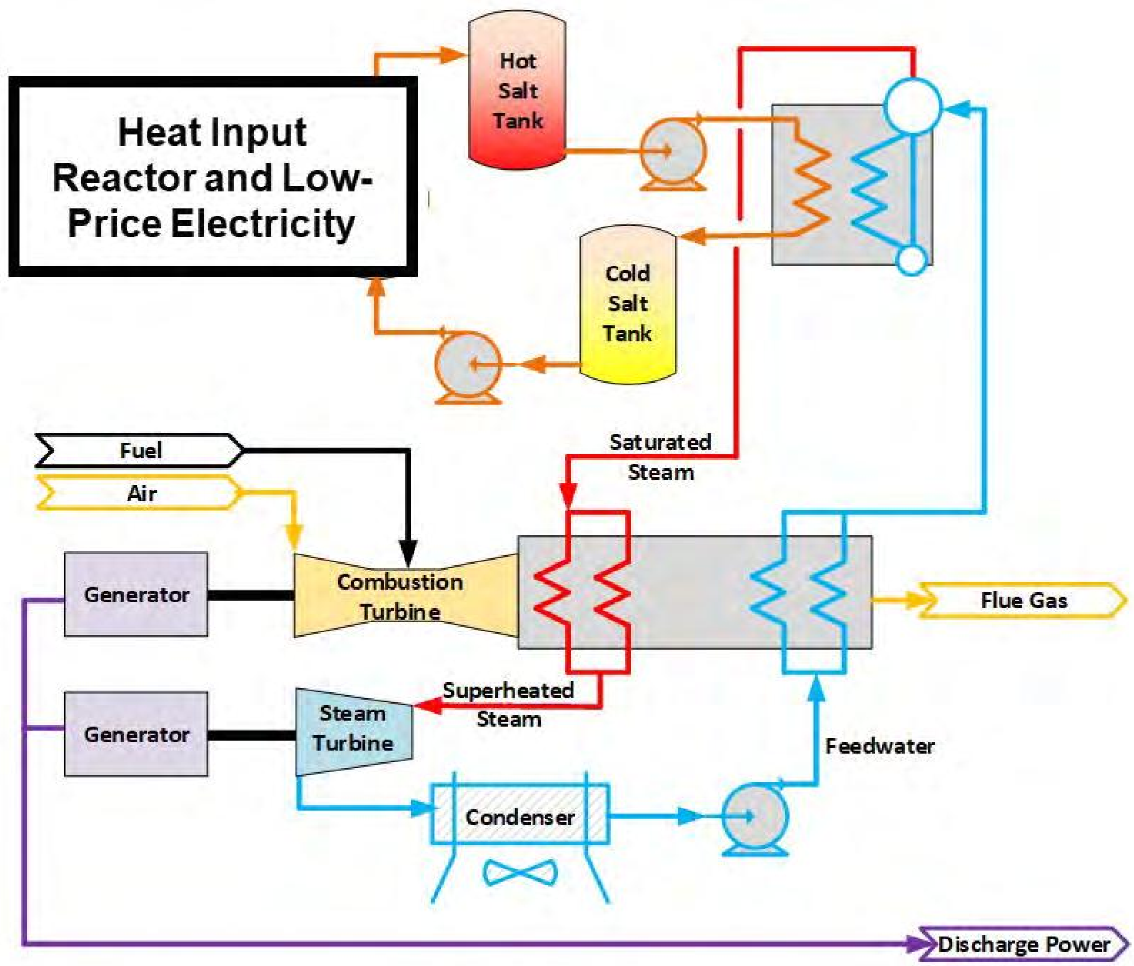

Fig. 11. Pintail Salt Liquid-Salt Combined Cycle™.

At first glance this power cycle looks similar to the traditional combined cycle plant—but its performance and cost structure is radically different—the steam cycle output is two to three times the output of the gas turbine. In a conventional combined cycle plant, two thirds of the electricity is produced by the gas turbine with a third from the steam cycle. In this system water is evaporated using energy stored in molten salt, while the gas turbine exhaust is used to preheat the water and then superheat the steam for a single pressure, non-reheat steam cycle. The high steam temperature is needed primarily for managing moisture content at the steam turbine exhaust.

The gas turbine is sized to enable superheating of the steam. The superheating of the saturated steam avoids complicated steam cycles and associated capital costs with multiple feed-water preheaters and steam separators. Much of the heat input is from liquid hot salt to boil water whereas in a conventional combined-cycle gas turbine warm atmospheric-pressure air from the turbine exhaust is used to boil the water. The heat transfer rate between hot salt and boiling water is extremely high resulting in small heat exchangers. In contrast, the heat transfer rate between warm air from the gas turbine and boiling water in a conventional combined cycle plant is low resulting in the large size of heat recovery steam generators (HRSGs). Those heat exchangers are the largest physical structure in a combined cycle plant. At the same time, the types of equipment remain the same and the existing supply chains can provide the new power block.

This system uses a combustible fuel with a remarkable heat rate. The combustible heat rate of a simple gas turbine, combined cycle turbine and this cycle are respectively 9300 KJ/KWh, 6000 KJ/kWh and under 4500 KJ/kWh. In a low-carbon world, the use of fossil fuels will be limited or there may be a carbon tax. The available combustible fuels may be low-carbon hydrogen or biofuels—with potentially higher costs. This creates large economic incentives for a more fuel efficient, lower-cost gas turbine cycle such as the Pintail Power cycle that includes heat input via salt storage.

A third class of power cycles are Nuclear Air Brayton Combined Cycles (NACC) where the heat from the reactor or heat storage system goes to the gas turbine [42, Appendix D, 3.6: Forsberg]. Figure 12 shows one NACC design using existing gas turbine technology. The technology is available but the system does not use existing off-the-shelf commercial equipment. The black lines show the airflow during normal operations. Air is filtered, 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 HRSG and up the stack. The steam produced in the HRSG can be sent to industry or used to produce electricity. In each heat exchanger, heat from a nuclear plant or heat storage system is transferred to the compressed air. The heat transfer fluid may be a liquid salt, sodium or other fluid.

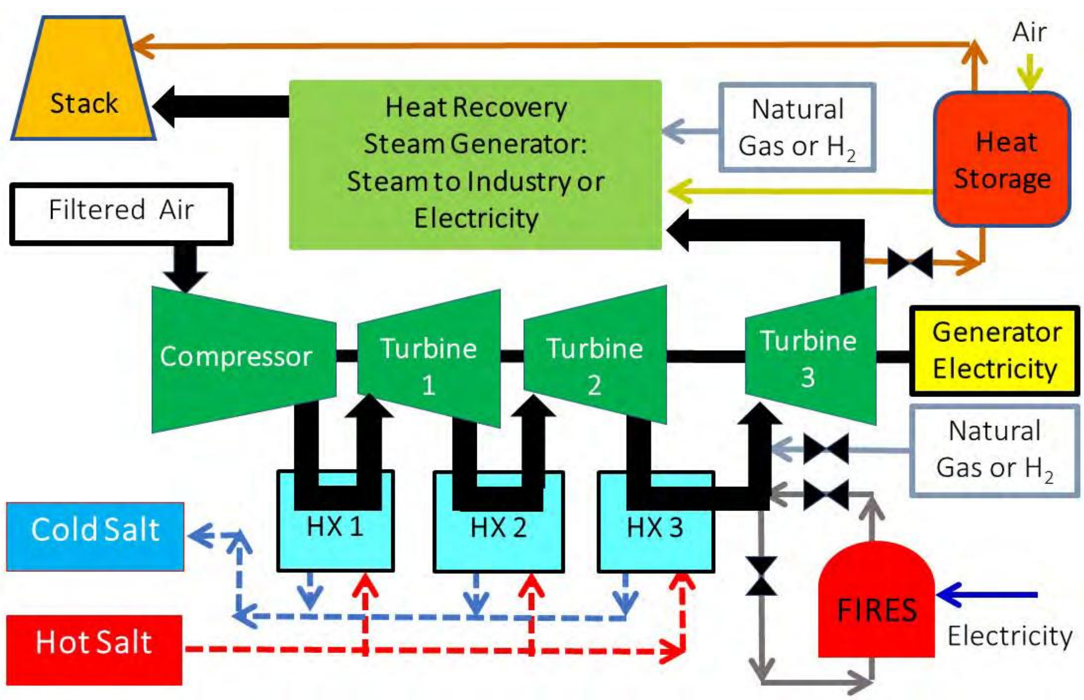

Fig. 12. Nuclear air Brayton cycle with thermodynamic topping cycle and heat storage.

For peak electricity production, the hot air exiting HX3 can be further heated by injecting natural gas, biofuels or hydrogen into the warm compressed air where fuel combustion raises its temperature to 1527°C, similar to the peak temperatures in a modern gas turbine with actively-cooled blades. The incremental heat-to-electricity efficiency in burning a combustible fuel in the thermodynamic topping cycle is 74 to 75%; that is, 100% times the added electricity from burning the combustible fuel divided by the added heat from burning the combustible fuel. The incremental heat-to-electricity efficiency is far above any other heat engine. In a low-carbon world the likely combustible fuels will be hydrogen or biofuels—premium fuels with premium prices and large incentives for their efficient conversion of heat to electricity. Lower-cost nuclear heat provides heat input at lower heat-to-electricity efficiency with the more expensive fuel converting heat-to-electricity at a much higher efficiency. The peak power output can be several times the base-load power output.

Several types of heat storage technologies are being developed today for GTCC plants that are also applicable to NACC. Groups are working on heat storage between the Brayton cycle and the HRSG. At times of low electricity prices, most of the hot air from the Brayton cycle is sent to a recuperator filled with firebrick, crushed rock or special concrete and then to the exhaust stack. The recuperator is heated by the exhaust gas from the gas turbine. At times of high electricity prices, cold air is blown through the hot recuperator, is heated and sent to the HRSG. At the same time added hot air comes from the Brayton cycle so the peak power output of the HRSG is increased. This increase in power input is separate and independent of any increase from operating the thermodynamic topping cycle. Several of these systems are at the pilot plant stage of development for natural-gas-fired GTCC systems.

The second storage technology that can be incorporated into NACC is Firebrick Resistance Heated Energy Storage (FIRES) where at times of low electricity prices firebrick is electrically-resistance heated to high temperatures. At times of high electricity prices, gas exiting from HX-3 is sent through FIRES before going to Turbine 3. Stored high-temperature heat replaces the use of a combustible fuel for the thermodynamic topping cycle.

All of the above cycles are built on existing power cycle technology. Work is underway to develop supercritical carbon dioxide cycles [Appendix D: Stansbury] that may have significantly lower capital costs. If these are commercialized, they create a new set of options.

There is also a second dimension that is relatively unexplored. The ramping rate (speed to change electricity output) of traditional nuclear, fossil and CSP power blocks is usually limited by the ramping rate of the heat source. If one has stored heat, the rate of heat delivery to the power cycle is controlled by the pump moving hot salt from storage into the power block. Pump speeds can be changed very rapidly. This creates the option for power blocks with much faster ramping speeds than traditional systems. Such fast ramping rates have the potential for these systems to replace pumped hydro, batteries and other technologies that are traditionally used to provide fast response. It also may dramatically reduce the need for spinning reserve in the traditional sense to pick up lost electrical load if a major power generator is shut down for any reason.

6. Rethinking Nuclear Islands

The original nuclear plant designs followed those of coal plants—tight integration of the heat source with the turbine generators. Events such as the Three Mile Island accident and the 911 terrorist attack added safety and security requirements. Regulations evolved over decades. These changes are resulting in a rethinking of nuclear power plant design where the nuclear island is separate from the non-nuclear balance of plant. The nuclear island follows nuclear standards and regulations with the balance of plant following standard industrial practice. There are several factors that are expected to lower costs [Appendix D: Charkas].

- *Reduced power system interface*. With existing nuclear power plants, reactor operations are directly coupled to the operation of the electrical gird. If the grid fails for any reason, it results in reactor shutdown. Varying demand result in varying reactor power output. If heat storage, the reactor interface is heating cold salt or another fluid and sending the salt or other fluid to a second tank. This is a radical simplification of the interface between the reactor and the outside world. This allows simplification of the reactor design, operations and safety—including nuclear regulatory concerns about grid impacts on reactor operations—there are none.
- *Security*. In current plants, much of the balance of plant is within the security boundary. This has major cost impacts. Physical security boundaries are much larger than the just the reactor and its safety systems. Security forces are larger to protect the larger footprint and address access by a much larger number of workers that enter the plant to work on non-nuclear systems in the security area. Nuclear security increases the cost of maintenance on non-nuclear systems because of access constraints.
- *Nuclear quality bleed over*. Nuclear quality standards bleed over into secondary systems because of the difficulty in defining the boundaries of different systems. If the boundary is a pipe of cold salt coming into the nuclear plant and a pipe of hot salt leaving the nuclear plant, the boundary is well defined.
- *Competitive bidding*. If one has a separate non-nuclear power block, the design and construction of that part of the plant can be done by any company or consortium that does non-nuclear industrial projects. The experience from other industrial projects is directly applicable. This also applies to spare parts and maintenance. This is a highly competitive industry with many suppliers that drives down costs versus the relatively small number of companies that build and maintain nuclear facilities. Separate from these considerations, many of the heat storage technologies and power block options may be identical for nuclear and CSP systems (See section 9) creating additional competitive forces to drive down costs.

Several advanced reactor designs [4-6] have adopted the separate nuclear island from the power block and reported large decreases in the quantities of concrete (TerraPower Natrium reactor) and other materials required for the nuclear plant. This is an area where change is occurring rapidly but little public information in the literature because of proprietary considerations and restrictions on release of data associated with security requirements.

7. Institutional and Regulatory Considerations

7.1. Resilience

Adding heat storage and associated peak power systems increases power system resilience. The reactor is no longer directly tied to the electricity grid. The reactor does not shut down if the grid fails for any reason. Similarly, the impacts of reactor shutdown on electricity to the grid do not occur for hours or days until heat storage is depleted—providing time for grid operators to decide what other units to bring online to meet electricity demand. The power block can be designed for rapid response to electricity grid needs—faster than a turbine generator tied to a nuclear reactor. Heat storage provides hours to a week of energy storage—a super battery.

System resilience has been defined by the Federal Electric Regulatory Commission [52] as "the ability to withstand and reduce the magnitude and duration of disruptive events, which includes the capability to anticipate, adsorb, adapt to, and/or recover from disruptive events." Work by Greene [53-56, Appendix D: Greene] has defined system resilience in terms of six defining functional capabilities.

- Robust real/reactive load-following and flexible operation capability
- Immunity to damage from external events (including grid anomalies)
- Ability to avoid plant shutdown (reactor scram) in response to grid anomalies
- Ability to operate in island mode (i.e., without connection to offsite transmission load and electric power supply)
- Unlimited independent safe shutdown cooling capacity (i.e. requiring no offsite or resupply of diesel fuel from offsite)
- Independent self-cranking black start capability (i.e., the ability to start with no offsite cranking power supply from the grid)

The proposed alternative design with heat storage and the decoupling of the reactor from the power block via heat storage improves five of those functional capabilities—only independent safe shutdown cooling is not changed. The reactor is fully isolated from the electricity grid. The power block is designed to meet grid requirements with no constraints or requirements imposed by the reactor. That is because a large fraction of the resilience challenge for the grid is at the interface of the grid and the power plant.

In this context, heat storage enables designs of power blocks not constrained by the ability to ramp up or down the heat source—be it nuclear, fossil fuels or CSP. Rates of changes in heat delivered to the power block are only limited by the pump moving hot salt or other fluid from storage into the power block. This creates the option for power blocks with much faster ramping speeds than the traditional power system. We are not aware of any studies that have evaluated the limits of ramping speeds for these technologies.

While the characteristics of resilience are understood, there are several unresolved questions including: (1) how to quantify resilience and (2) how to provide market incentives for resilient capabilities of power stations? Today there is not a clear financial incentive to build a more resilient system except the indirect political pressure associated with rotating blackouts and risks of lawsuits.

7.2. Licensing

The historical licensing structure in the U.S. has been prescriptive. The new licensing structure is risk based [57-59]. This change in licensing is a practical requirement if there are to be major changes in the basic design of nuclear power plants. The legal basis for such changes is in place—but there is limited experience in the new licensing basis for new plants.

Licensing will be reduced with the new plant design. A significant fraction of the off-normal events is associated with transients from the power cycle-either internally within the power cycle or transients that started from the electricity grid. Heat storage eliminates these transients that can impact the reactor operations. Similarly, the licensing associated with security is simplified—there is no power block in the security zone resulting in a much smaller security zone with far fewer people that require access.

8. Economics

The changing markets and the proposed redesign of nuclear power plants has major implications on plant capital costs, revenue and business structures [Appendix D: Charkas, Ingersoll, Sowder]. Some of these changes are reasonably well understood but many are not.

8.1. Plant Capital Cost Structure

The new nuclear plant design divides the plant into two components.

- *Energy production*. The nuclear reactor is bought to produce energy in the form of heat. It has high capital costs and sized to match average energy needs.
- *Assured electricity capacity*. Heat storage and the power block are designed to provide assured generating capacity. The assured power block output is several times the base-load capacity of the reactor. It is built to conventional industrial standards with lower and more predictable capital costs.

There are several implications. First [6, Appendix D: Scott] a much larger faction of the total plant cost (heat storage, turbine generators, etc.) is conventional industrial construction with its much more predictable cost and schedule. The cost, development and schedule project risks are reduced. Second, the heat-to-electricity conversion block may have very low capital costs per unit output because (1) it is designed to match market requirements and (2) designed, built and operated to industrial standards.

8.2. Assured Generating Capacity

Today assured generating capacity to the electricity grid is primarily provided in the United States by the gas turbine burning natural gas. Gas turbines are cheap (~$1000/kW capacity) and can rapidly vary their output. Their primary disadvantage is that the burning of natural gas releases carbon dioxide to the environment. The question is what replaces the role of the gas turbine burning natural gas?

The purpose of energy storage is to provide assured heat to industry and assured electric generating capacity. With the system design herein, the reactor provides heat input to storage. The power block provides several times the assured electric generating capacity with heat from storage with the primary source of heat being the reactor but a secondary heat source being a combustion heater burning natural gas or low-carbon hydrogen or biofuels. The system is capable of meeting variable demand on an hourly to seasonal basis.

If non-dispatchable low-cost wind or solar is available, it can be integrated into this system. Low-cost heat storage enables nuclear heat output to be sent to storage at times of large-scale wind or solar output. If there is excess wind or solar production, the electricity can be converted to heat for storage. The system adapts to whatever are the available energy sources. The relative inputs of nuclear, wind and solar depend upon the capital costs of the competing technologies, the quality of the local wind and solar resources and the cost of the heat storage system and power block with assured generating capacity.

The primary competing alternative to provide assured generating capacity is electricity storage that involves technologies such as hydro pumped storage and batteries. These technologies have an intrinsic cost disadvantage. To provide one kW of assured capacity, the battery must provide a kW of output. However, if the battery is depleted, a gas turbine backup is required to provide that assured kW of output. Table 2 shows the costs of batteries measured by two metrics. The first is the cost of the battery as measured in kW of capacity and the second is the cost if measured in storage capacity (kWh). Even if measured for batteries with very limited storage capacity (half hour), the cost is $500 to 1000//kW. To that one adds the cost of the backup gas turbine at about $1000/kW. Generating capacity is expensive with batteries because the cost of the electronics to convert AC electricity to DC electricity and back to AC electricity is expensive relative to a steam turbine generator. If need longer-term storage, battery systems become expensive.

TABLE 2. Electric Battery Energy Storage Costs for Systems Installed in FY2018 [60]

Technology	Rating (MW)	Duration (Hours)	Cost Range ($/kW)	Cost Range ($/kWh)
Lithium ion	50-100	4	1400 – 2300	350 – 575
Flow battery	50-100	4	2300 - 3700	575 - 925
Lithium ion	30-50	6	2000 - 3300	335 - 550
Lead acid	30-50	6	2700 - 4100	450 - 685
Flow battery	30-50	6	2800 - 4800	465 - 800
Sodium sulfur	30-50	6	2500 - 4100	415 - 685
Lithium ion	20	0.5	500 - 1000	1000 - 2000

These costs are separate from the cost of energy storage. The DOE storage cost goals for electricity batteries is $150/kWh versus $15/kWh for heat storage. The current heat storage systems have capital costs near $20/kWh with proposed systems that may drive those costs down to several dollars per kWh of heat. Heat storage is cheaper than electricity storage because the material costs are less—materials such as hot rock are much cheaper than lithium or steel. Technology advances can lower manufacturing costs but have had little impact on raw material costs that primarily depend upon the relative abundance of materials in the earth's crust. Recent studies have examined required cost goals for long-term storage [26] and evaluated technologies such as pumped hydro, compressed air storage and hydrogen with underground gas storage. The heat storage technologies have potentially better economics and do not require appropriate geology.

8.3. Business Models for Nuclear Cogeneration of Heat and Electricity

Today electricity is less than 18% of total energy consumption by the customer (residential, commercial, industrial, transport). The rest of the demand is for heat. The industrial heat demand is more than twice the total U.S. electricity production. As described earlier, there are large economic incentives for nuclear cogeneration with large-scale heat storage to enable variable electricity to the grid by varying heat demand. Heat storage is the enabling technology because it partly decouples in time heat demand with electricity demand. The requirement is that reactor output equal heat demand plus electricity demand when averaged over days to a week. Many heat customers can adjust their production schedule and thus heat demand over such a period of time.

While the economics are clear, what is the business model? If one has a large industrial facility with a massive demand for heat, the business model is simple. The industrial customer owns the reactors and internally optimizes heat for internal uses and external electricity sales to maximize net revenue [Appendix D: Hildebrandt]. Several studies evaluated high-temperature heat markets for nuclear cogeneration [61, 62]. In addition, there have been multiple business studies for specific applications [63-66] using this model.

The more complicated and less understood case is where one has a set of reactors selling electricity and heat to multiple customers [Appendix D: Parsons]. Developing the business case has been a major barrier to the deployment of conventional co-generation. The problem is how to align the business interests of multiple businesses. Industrial customers with large capital investments do not want to be hostage to the owner of the nuclear power plant raising the cost of heat to maximize short-term profits or sell electricity rather than heat if the price of electricity increases significantly. This is a contractual relationship that may extend over many decades. Over such a period of time, there can be massive changes in the business environment and the demand for heat or electricity. There have been many business studies of cogeneration [25, Appendix D: Parsons] where extra investment improves energy efficiency but economic efficiency is not assured by energy efficiency. There are difficulties in serving two customers. The features of the optimized system for a pair of products is very sensitive to economic variables. Industrial customers do not want to be captive to another business, the "hold-up" problem. Long-term contracts have limited value. For these and other reasons cogeneration scale has always fallen far short of engineering calculations of the value. There are in this case two differences that may reduce business barriers to cogeneration.

- *Heat storage*. Traditional nuclear or fossil cogeneration had a fixed maximum output that implied any increase in heat demand on a second-by-second basis implied less electricity to the grid. With storage, the requirement is to match production with industrial heat demand and electricity over a period of hours or days. Short term peak heat or electricity demands can be met. There is the option to schedule industrial production to maximize total revenue from heat and electricity. There is the additional degree of freedom in operations.
- *Goal of a low-carbon economy*. This goal takes away low-cost stored energy in the form of tanks of oil, natural gas and coal from multiple suppliers.

Historically most co-generation systems with many customers have been municipal systems where the city had the goals to provide economic electricity and heat to industrial customers as part of its industrial development strategy to increase taxable industrial property and support employment. The revenue benefits to the city are in the form of added industrial property on tax rolls and employment. This aligns the long-term economic interests of the city with the industrial and commercial customers. There are a variety of other business models from industrial coops to regulated utilities to totally private enterprises—but the full implications have not been explored.

9. Research, Development and Demonstration

There are large incentives for cooperative nuclear, solar thermal and fossil research-development-and-demonstration programs to develop heat storage and the associated power cycles. All of these technologies are heat generating technologies and have similar or identical heat storage and power cycle requirements.

In this context, the implications of low-cost large-scale heat storage with associated power cycles for CSP plants are as profound for CSP as for nuclear energy. This scale matches nuclear plants but if the technology is fully developed, it changes utility-scale CSP. Traditional designs of CSP systems have power outputs near 100 MWe. Power output in solar power towers is limited by the ability to focus mirrors over long distances to beam reflected light onto the collector. System size for parabolic and other ground-based solar collectors is limited by pumping costs through small pipes in these collectors. If very-low-cost storage is possible at larger scales (such as the crushed rock with hot fluid spray heat transfer), then the economics will favor multiple solar power towers or parabolic trough collector fields that pump hot oil or hot nitrate salt to central heat storage and a central power block with 500 to 1000 MWe output as shown in Fig. 13. There is considerable experience in pumping hot oil over distances of kilometers. Steam injection [67] is used to heat underground heavy oil and tar sands to raise temperatures and convert the oil into a hot liquid that can then be pumped to the surface and then to storage facilities. The storage and power-block economics of scale are greater than the additional costs of pumping hot fluid a few kilometers. The heat storage systems and power blocks become identical for nuclear, utility-scale CSP and many fossil systems. This commonality accelerates R&D but also implies common supply chains that drive down capital costs for everyone.

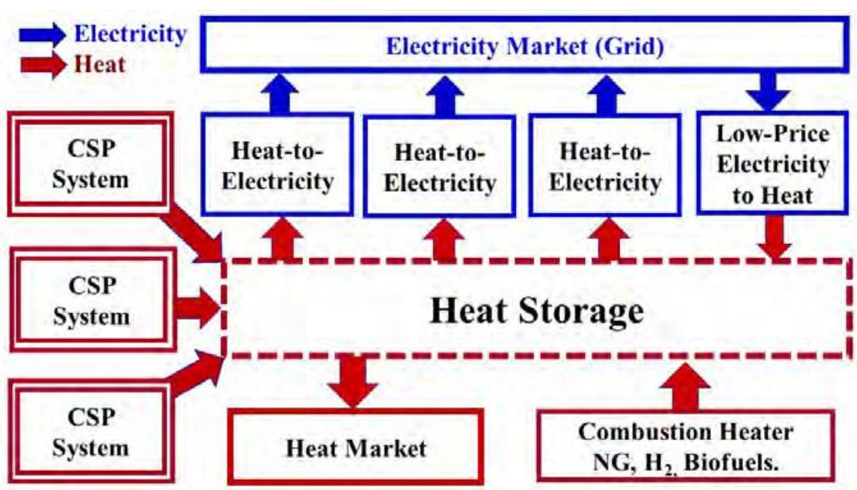

Fig. 13. CSP system coupled to large-scale heat storage.

While often not considered research and development, there is the need to develop business strategies that enables nuclear with heat storage to provide variable heat to multiple industrial customers, multiple commercial customers and the electricity grid. Most energy is used as heat as shown in Fig. 14. This is the primarily energy market—not the electricity market. The central question for a low-carbon world is how to provide that heat—not how to decarbonize the electricity grid. The business structures for large industrial heat demands is simple—the company that owns the industrial facility owns the reactor and economic optimization is done within a single organization. The question is what are viable business models if multiple smaller heat customers in a system with nuclear reactors? Today those heat demands are met by fossil fuels where there are multiple suppliers.

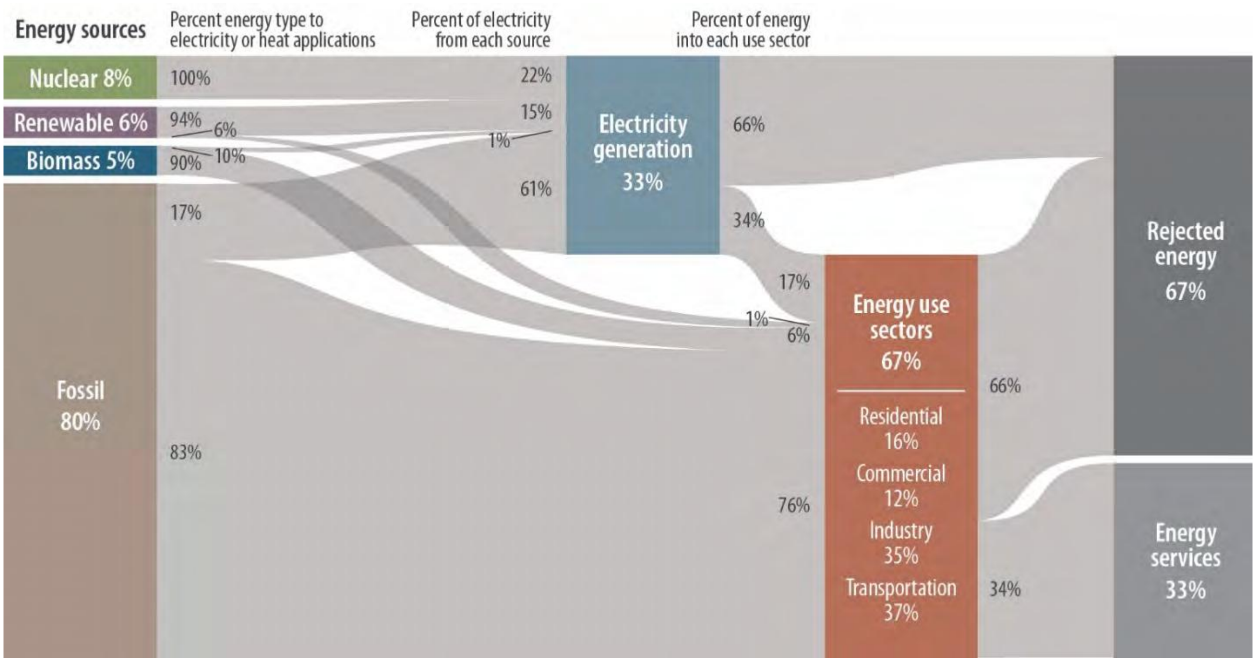

Fig. 14. Energy flow diagram of the United States [13].

10. Conclusions

The electricity market is rapidly changing with (1) the addition of variable wind and solar that results in volatile electricity prices and (2) the goal of a low-carbon economy. Those changes require a low-carbon replacement for (1) the gas turbine with its capability to provide economic variable electricity to the grid and (2) fossil fuel heat to industry. Second, nuclear plant safety and security requirements have changed in the last 50 years suggesting that a lower-cost plant layout may be to separate the nuclear island from the power block with a clear separation of the nuclear island with nuclear requirements and the power block designed and built to normal industrial standards.

These changes create the incentive to rethink nuclear power plant design with heat storage to: (1) increase plant revenue, (2) lower plant costs and (3) enable an economic low-carbon energy system. Nuclear power may become the required enabling technology because the low-cost energy storage technology replacing piles of coal, tanks of oil, and underground storage of natural gas is heat. The low-cost of heat storage reflects the fundamental thermodynamic difference between heat and work (electricity, hydrogen, etc.). The system design improves the economics of nuclear, wind and solar by addressing the storage challenge.

Large-scale heat storage is a commercial technology where there is the potential for major reductions in capital costs per unit of heat storage that may dramatically increase potential plant revenue. There has been only limited work on rethinking the nuclear island if not tightly coupled to the power block. There is the potential for major reductions in the capital cost of the power block while enabling much faster changes in power output. Last, most of the energy demand by the customer is in the form of heat where nuclear energy has a competitive advantage. However, the required business structures, particularly for cogeneration, are only partly developed if there are multiple customers for heat.

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Appendix A: Workshop Agenda

Web Workshop Agenda:
Separating Nuclear Reactors from the Power Block with Heat Storage:
A New Power Plant Design Paradigm

WEDNESDAY JULY 29, 2020: Session 1	
TOPIC	**PRESENTER**
1.1 Rethinking Nuclear Plant Design for a Low-Carbon World	Charles Forsberg (MIT)
1.2 Denuclearizing the Balance of Plant to Reduce the Future Nuclear Plant Steam Cycle Construction Costs	Hasan Charkas (EPRI)
1.3 Cogeneration Concepts -- Lessons from the NGNP Program	Philip C. Hildebrandt (INL)
1.4 Integration of Heat Storage with Fossil Energy Systems	Scott Hume (EPRI)
1.5 Energy Storage as an Enabler - Nuclear Power Plants and Electric Grids	Sherrell Greene (Advanced Technology Insights, LLC)
1.6 Discussion	All

WEDNESDAY AUGUST 12, 2020: Session 2	
TOPIC	**PRESENTER**
2.1 Combining Hot Rock and Nitrate Salts to Lower Heat Storage Costs	Andre Thess (DLR)
2.2. Advances in Chloride-salt Heat Storage	Craig Turchi (NREL)
2.3 Can we Get the Capital Costs of Heat Storage Down to $2/kWh? Hot Rock from Gigawatt-hours to Gigawatt-years	Charles Forsberg (MIT)
2.4 Keeping the 'Lotta Stuff' Simple and Dumb: A Practical Approach to Energy Storage	Cory Stansbury (Westinghouse)
2.5 Designing Power Systems for Peak Power Applications--What we have Learned	William Conlon (Pintail Power)
2.6 Discussion	

WEDNESDAY AUGUST 26, 2020: Session 3	
TOPIC	**PRESENTER**
3.1 Cost and Performance Requirements for Flexible Advanced Nuclear Plants with Heat Storage	Eric Ingersoll (Lucid Catalyst)
3.2 Business and finance models for nuclear cogeneration with heat storage	John E. Parsons (MIT)
3.3 Implications of Heat Storage Systems Design for fossil fuels with CCS	Briggs M. White (NETL)
3.4 Basis for Heat Storage to Enable Peak Electricity Production in the United Kingdom – Case Study	Ian Scott (Moltex)
3.5 Non-Technical Aspects of Integrating Thermal Energy Storage with Nuclear: Perspectives and Cautionary Lessons from History	Andrew Sowder (EPRI)
3.6 Observations and Conclusions	Charles Forsberg (MIT)
3.7 Discussion	

Massachusetts Institute of Technology | Idaho National Laboratory | EPRI ELECTRIC POWER RESEARCH INSTITUTE | American Nuclear Society Operations & Power Division

Web Workshop: Separating Nuclear Reactors from the Power Block with Heat Storage: A New Power Plant Design Paradigm

Session 1. Markets, Requirements and Systems Design

The energy market is changing because of (1) the goal of a low-carbon energy system and (2) the expansion of low-operating-cost wind and solar PV that collapse electricity prices at certain times. We examine the changes in markets and requirements and alternative nuclear system designs with large-scale heat storage to enable base-load nuclear plants to provide variable electricity to the grid and heat to industry. In the U.S., the industrial demand for heat is about twice the total electricity production; thus, there are two major markets for nuclear energy in the U.S. The addition of heat storage enables integration of electricity and heat markets because it partly decouples in time heat production versus heat and electricity to customers. Separate from these considerations, large-scale heat storage has massive implications for grid resilience because energy production is partly decoupled from the grid.

WEDNESDAY JULY 29, 2020

TIME	TOPIC	PRESENTER
10:00 am	Introduction and Logistics Schedule and Agenda	Andrew Sowder (EPRI) Piyush Sabharwall (INL)
10:10 am	1.1 Rethinking Nuclear Plant Design for a Low-Carbon World	Charles Forsberg (MIT)
10:35 am	1.2 Denuclearizing the Balance of Plant to Reduce the Future Nuclear Plant Steam Cycle Construction Costs	Hasan Charkas (EPRI)
11:00 am	1.3 Cogeneration Concepts -- Lessons from the NGNP Program	Philip C. Hildebrandt (INL)
11:25 am	Break	
11:50 am	1.4 Integration of Heat Storage with Fossil Energy Systems	Scott Hume (EPRI)
12:15 pm	1.5 Energy Storage as an Enabler - Nuclear Power Plants and Electric Grids	Sherrell Greene (Advanced Technology Insights, LLC)
12:40 pm	1.6 Discussion	All
1:00 pm	Webinar closes	

Together . . . Shaping the Future of Electricity

Web Workshop: Separating Nuclear Reactors from the Power Block with Heat Storage: A New Power Plant Design Paradigm

Session 2. Technologies for Heat Storage and Power Cycles

Work is underway in the nuclear and solar communities to develop heat storage systems from a few GWhs (hourly to daily storage) to 100 GWh (weekday/weekend storage) to match production with demand.[1] Research is ongoing for systems at different temperatures—suitable for LWRs or higher-temperature advanced reactors. Earlier workshops examined some of these systems. Much has happened since then as will be discussed in this session. The other half of the story are the power cycles that are now decoupled by storage from the reactor. There are the traditional cycles, but also advanced power cycles designed for peak electricity production that are directly coupled to grid dispatch for very fast response to market needs.

WEDNESDAY AUGUST 12, 2020		
TIME	**TOPIC**	**PRESENTER**
10:00 am	Introduction and Logistics Scheduling and Agenda	Andrew Sowder (EPRI) Piyush Sabharwall (INL)
10:05 am	2.1 Combining Hot Rock and Nitrate Salts to Lower Heat Storage Costs	Andre Thess (DLR)
10:30 am	2.2. Advances in Chloride-salt Heat Storage	Craig Turchi (NREL)
10:55 am	2.3 Can we Get the Capital Costs of Heat Storage Down to $2/kWh? Hot Rock from Gigawatt-hours to Gigawatt-years	Charles Forsberg (MIT)
11:20 am	Break	
11:45 am	2.4 Keeping the 'Lotta Stuff' Simple and Dumb: A Practical Approach to Energy Storage	Cory Stansbury (Westinghouse)
12:10 pm	2.5 Designing Power Systems for Peak Power Applications--What we have Learned	William Conlon (Pintail Power)
12:35 pm	2.6 Discussion	
1:00 pm	Webinar closes	

Web Workshop: Separating Nuclear Reactors from the Power Block with Heat Storage: A New Power Plant Design Paradigm

Session 3. Economics, Business Strategies and Demonstration Strategies

What are the economics? Is the base case nuclear with heat storage for variable electricity or is it nuclear co-generation with storage for variable electricity and industrial heat? What are the regulatory impacts of a system that has a 1000 MWe of base-load output that with heat storage a peak power of 2000 MWe and the ability to buy 1000 to 2000 MWe of electricity to convert to stored heat at times of low prices? What is the business model if industrial heat becomes a major product as well as electricity? What is the development and demonstration strategy? The same storage and power systems work with concentrated solar power (CSP) and fossil fuels with carbon capture and sequestration (CCS). Each of these communities has large incentives to develop similar storage/power systems to operate the heat generating technology at full capacity with variable electricity and heat to the market.

WEDNESDAY AUGUST 26, 2020

TIME	TOPIC	PRESENTER
10:00 am	Introduction and Logistics Schedule and Agenda	Andrew Sowder (EPRI) Piyush Sabharwall (INL)
10:05 am	3.1. Cost and Performance Requirements for Flexible Advanced Nuclear Plants with Heat Storage	Eric Ingersoll (Lucid Catalyst)
10:30 am	3.2. Business and finance models for nuclear cogeneration with heat storage	John E. Parsons (MIT)
10:55 am	3.3. Implications of Heat Storage Systems Design for fossil fuels with CCS	Briggs M. White (NETL)
11:20 am	Break	
11:45 am	3.4. Basis for Heat Storage to Enable Peak Electricity Production in the United Kingdom – Case Study	Ian Scott (Moltex)
12:10 pm	3.5. Non-Technical Aspects of Integrating Thermal Energy Storage with Nuclear: Perspectives and Cautionary Lessons from History	Andrew Sowder (EPRI)
12:20 pm	3.6 Observations and Conclusions	Charles Forsberg (MIT)
12:35 pm	3.7 Discussion	
1:00 pm	Webinar closes	

Appendix B: Workshop Participants

The workshop had over 400 registered participants from governments, national laboratories, industry, university and other organizations. Table B.1 shows the distribution of participants by organization. The wide participation reflects the growing interest in heat storage and changing markets. The workshop also included large participation by the solar and fossil community reflecting common interests and common challenges.

Table B.1 Participants by Organization

Organization	Percentage of Workshop Participants (%)
Government	6
National Laboratories	31
Industry	35
Universities	21
Other	7

Appendix C: Speaker Biographies

Hasan Charkas

Dr. Hasan Charkas is Principal Technical Leader in EPRI's Advanced Nuclear Technology program, where he leads the Engineering and Construction Innovation technical focus area. Previously, Hasan led structural reliability and integrity research activities in EPRI's Risk and Safety Management program. Before coming to EPRI, he was an Engineering Supervisor at Framatome (formerly AREVA) in the Reactor Internals & Aging Management Projects group. Hasan also spent a year on loan to the Institute of Nuclear Power Operations as a Senior Program Manager.

William (Bill) Conlon (Pintail Power LLC)

Bill Conlon is the founder and President of Pintail Power, which aims to bridge renewable and conventional electricity generation. Bill brings a broad perspective on power generation informed by his background as an engineer and executive with experience in nuclear, fossil, and solar engineering, construction, commissioning and operations. At his first startup, he co-invented a control system for a novel steam injected gas turbine power plant, and was responsible for new product development and licensing. Based in Silicon Valley, he has been a serial entrepreneur specializing in rapid innovation and commercialization. As a Senior Vice President of Engineering at AREVA, he was responsible for Engineering, Commissioning and Operations teams on three continents. Bill is a licensed Mechanical Engineer in California and an active life member of ASME.

Charles Forsberg

Dr. Charles Forsberg is a principal research scientist at MIT. His research areas include Fluoride-salt-cooled High-Temperature Reactors (FHRs) and utility-scale heat storage. He teaches the fuel cycle and nuclear chemical engineering classes. He was the director of the MIT Future of the Nuclear Fuel Cycle study. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory where he led programs on salt reactors. He is a Fellow of the American Nuclear Society (ANS), a Fellow of the American Association for the Advancement of Science, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers.

Sherrell Greene

Dr. Sherrell Greene is the President of Advanced Technology Insights, in Knoxville, TN. During the past several years, Sherrell has conducted pioneering studies of the relationship between nuclear power and electric Grid resilience, which formed the basis for his doctoral dissertation completed in 2018 at the University of Tennessee Knoxville (in an astonishing two years). Previously, many will know Sherrell from his 33 year career at Oak Ridge National Laboratory, which culminated in his role as Director of Nuclear Technology Programs.

Phil Hildebrandt

Mr. Phil Hildebrandt has over 52 years of experience in the nuclear energy and power generating industries – including engineering and management roles in the U.S. Naval Nuclear Propulsion Program and in commercial nuclear power. His is currently President of Engineering, Management and Technology, Inc. In this role, he consults for the Laboratory Director of the Idaho National Laboratory, providing assistance in the development of major projects, industry liaison and regulatory strategy. He is currently supporting development of a multi-decade strategy for the future of nuclear energy for rebuilding U.S. nuclear industrial infrastructure and maintaining U.S. industry leadership in the global nuclear energy marketplace.

Scott Hume

Scott Hume is a Principal Technical Leader at EPRI and has over 20 years of experience working in the power industry focusing on performance analysis of energy storage, power conversion systems, integration strategies and carbon capture technologies including pilot plant testing and validation. He holds a B.Eng. in Chemical Engineering and an M.Sc. in Energy Systems from the University of Strathclyde in the UK and is a chartered member of the IChemE.

Eric Ingersoll (LucidCatalyst)

Eric Ingersoll is Managing Director at LucidCatalyst. Eric is a strategic advisor and entrepreneur with deep experience in the commercialization of new energy technologies. He has extensive project and policy experience in renewables, energy storage, oil & gas, and nuclear, with a special emphasis on advanced nuclear technologies. Eric's focuses on commercialization and market entry strategies for advanced energy technologies such as advanced nuclear power generation, carbon capture, and zero-carbon liquid fuels. Eric was a principal author of ETI's Nuclear Cost Drivers Report. He leads multiple decarbonization modeling efforts, and advises governments and private sector on electricity and fuels applications of advanced nuclear and fusion energy systems. Before LucidCatalyst, Eric was an interim leader or paid strategic advisor to over 30 startups. He raised over $100 million of private equity for General Compression, of which he was a founder and the lead inventor of the technology.

John E. Parson (MIT)

John Parsons is a Senior Lecturer at MIT's Sloan School of Management. John's research is in the field of corporate finance, valuation and risk management applied to the energy industry. Most recently, John was a co-Director on MIT's study on the Future of Nuclear Energy in a Carbon Constrained World.

Piyush Sabbharwall

Dr. Piyush Sabharwall is a Senior Nuclear Staff Research Scientist working in the Nuclear System Design and Analysis Division at Idaho National Laboratory (INL). He has more than 14 years of research and development experience in nuclear/thermal engineering. He is currently the technical lead for the microreactor program and leading the development of gas cooled cartridge loop for the VTR. He is a member of the advanced (Gen IV) reactor technical advisory group for EPRI.

Ian Scott (Moltex)

Ian Scott is a Co-Founder and Chief Technology Officer of Moltex Energy. Ian went to Cambridge University to study nuclear physics, but was seduced during his first year by the excitement of the biological sciences and made his career in that field. He became Chief Scientist for Unilever plc before leaving to start an entrepreneurial drug discovery company. In 2012 he became bemused by how nuclear energy had gone from being "too cheap to meter" to too expensive to afford and determined to try to remedy that flaw. The result was his invention of the Stable Salt Reactor and the creation of Moltex Energy.

Andrew Sowder

Dr. Andrew Sowder is a Senior Technical Executive at the Electric Power Research Institute where he established and leads strategic RD&D on advanced nuclear energy systems. He previously led advanced nuclear fuel cycle assessment studies and managed EPRI's total system performance assessment for geologic disposal at Yucca Mountain. He is a Certified Health Physicist. Before joining EPRI, Andrew served as a physical scientist and foreign affairs officer at the U.S. State Department.

Cory Stansbury (Westinghouse)

Mr. Cory Stansbury is a Principal Engineer at Westinghouse Electric Company LLC. Since joining the company in 2008, he has been involved in a wide range of systems and equipment projects on legacy, current, and advanced reactor technologies, including balance of plant design for the Westinghouse Small Modular Reactor and AP1000 plant piping, systems, and valve design. Mr. Stansbury now serves as systems design lead for the Westinghouse Lead Fast Reactor (LFR) program, overseeing cost estimating, balance of plant, systems, power conversion design, and design of a new test loop, and other areas. Mr. Stansbury also serves as Westinghouse's technical lead for the evaluation and development of energy storage solutions; both in standalone applications and coupled to new plants.

André Thess (DLR)

Dr. André Thess is the Director of the Institute of Engineering Thermodynamics at the German Aerospace Center (DLR) and Professor of Mechanical Engineering at the University of Stuttgart. His research fields are high-temperature technologies, thermochemical energy storage, and electrochemical energy storage. His particular interests are simulation of energy storage systems from the microscale to the macroscale, the development of Carnot-Batteries and electric flight. Professor Thess is currently teaching "Thermodynamics of Energy Storage Systems" (in the winter term) and "Culinary Thermodynamics" (in the summer term). Culinary Thermodynamics is the first course at a German University that gives an evidence-based scientific proof of the superiority of home-made food over convenience food.

Craig Turchi (NREL)

Dr. Craig Turchi is a chemical engineer at the National Renewable Energy Laboratory, where he has been in the Thermal Energy Sciences group since 2008. He is Principal Investigator on a multi-national project designing a thermal transport system for Gen3 Concentrating Solar Power that uses a magnesium-chloride-based molten salt for thermal energy storage interfaced with a liquid-sodium heat transfer fluid.

Briggs M. White (NETL)

Dr. White serves as a Technology Manager at NETL where he manages three research and development programs related to fossil energy applications on behalf of the Department of Energy. These include: High Performance Materials, Water Management, and Energy Storage. These activities serve to accelerate R&D progress and develop concepts and technologies that enable improvements in fossil-based power generation, including its workforce and supply chain, and the electricity grid and markets with which generation assets must integrate. He holds degrees in Materials Science & Engineering from Alfred University (BS), the University of Florida (MS, PhD), and the Univ. of Rome (PhD) with an emphasis on solid-state high-temperature electrochemical devices.

Appendix D: Presentations

Table of Contents

Separating Nuclear Reactors from the Power Block with Heat Storage: A New Power Plant Design Paradigm

Charles Forsberg[1]
Piyush Sabharwall[2]
Andrew Sowder[3]

[1]*Massachusetts Institute of Technology Cambridge, MA 02139,*
Email: cforsber@mit.edu
[2]*Idaho National Laboratory, Idaho Falls ID 83415-3855*
Email: Piyush.Sabharwall@inl.gov
[3]*Electric Power Research Institute, Charlotte, NC 28262*
Email; asowder@epri.com

Separating Nuclear Reactors from the Power Block with Heat Storage:
A New Power Plant Design Paradigm
Session 1. Markets, Requirements and Systems Design
WebEx Workshop: July 29, 10:00 AM to 1:00 PM Eastern

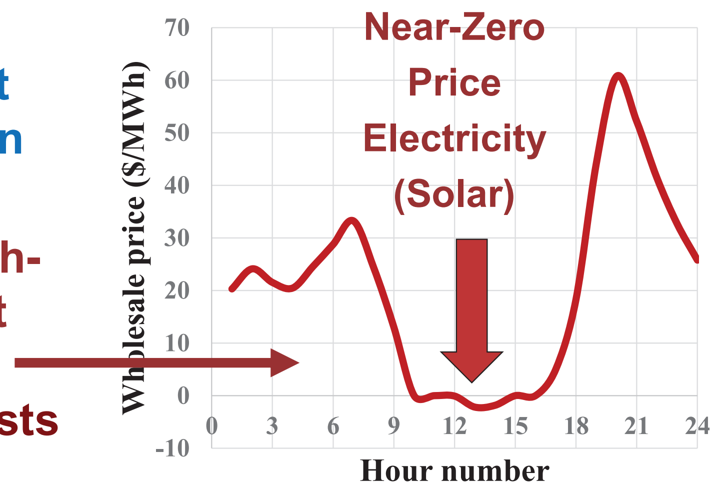
Two Categories of Low-Carbon Energy Sources

- Work (electricity)
  - Production technologies: Solar Photovoltaic (PV), Wind, Hydroelectricity
  - Storage technologies: Batteries, Hydro pumped storage, etc.
- Heat. Can be used directly or converted into electricity
  - Production technologies: Fission, Concentrated Solar Power (CSP), Fossil Fuels with Carbon Capture and Sequestration (CCS), Fusion (future), etc.
  - Storage technologies: Heat capacity, latent heat, etc.
- **All heat production technologies have much in common**; thus much of this fission workshop's discussion is equally applicable to CSP and fossil fuels with CCS

2

Electricity Markets are *Changing*

- **Electricity prices in fossil-fuel systems are relatively constant because most of the production cost is in the fuel.**
- **Volatile electricity prices in high-capital-cost low-operating-cost electricity systems (nuclear, wind, solar, etc.). Operating costs set minimum electricity prices**
- Large incentives to add storage to nuclear plants to sell electricity at times of high prices

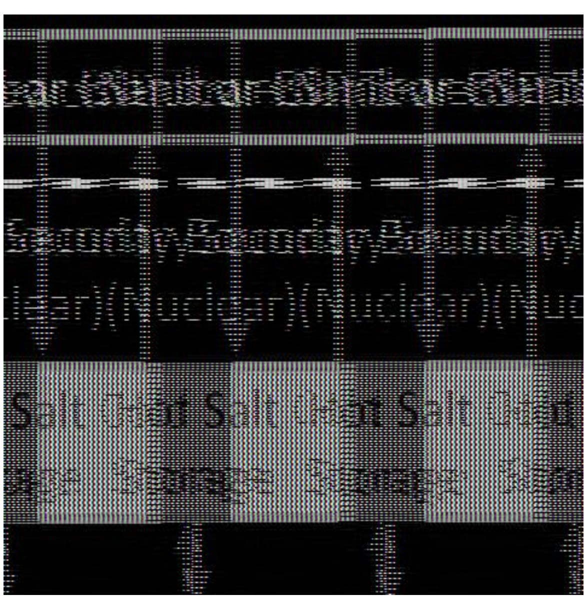


California Wholesale Electricity Prices With Midday Solar Price Collapse: 31 March 2019

3

New Nuclear Design For Changing Energy Markets

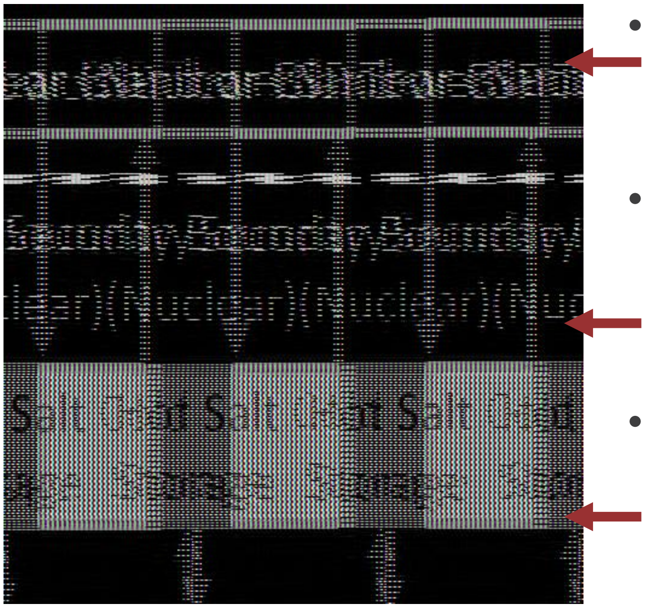
Design is Used in Concentrated Solar Power Plants



- Nuclear reactor island receives cold oil or salt from storage, heats fluid and sends fluid to hot storage
  - Storage fluid replaces intermediate heat transfer loop in salt reactors, high-temperature gas-cooled reactors and sodium fast reactors
  - Storage fluid heated by steam in light water reactors
- **Power block provides variable electricity to the grid depending upon market need**

4

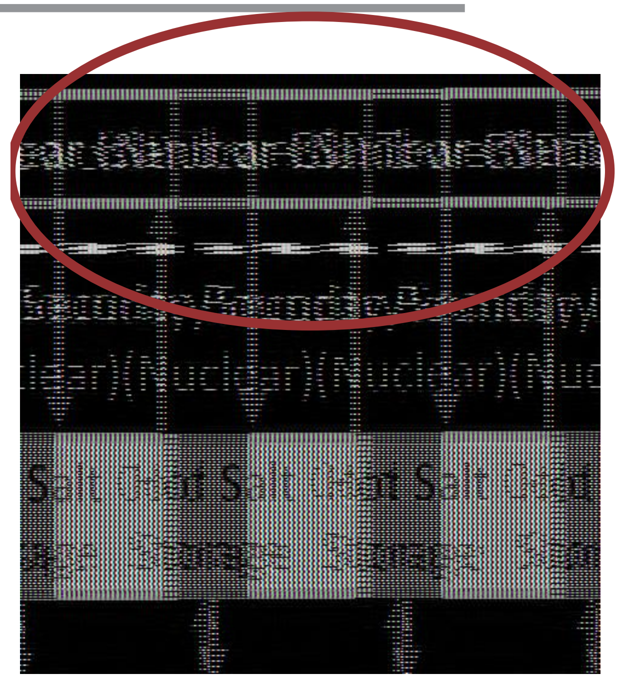
Implications of Alternative System Design



- Nuclear reactor island with nuclear design, construction, licensing, QA, security and operations
- Non-nuclear heat storage
  - 5 to 100 GWh of heat storage
  - Hourly to weekly (weekday/weekend) heat storage
- Non-nuclear power block
  - **Large peaking capacity to maximize sales at times of high prices**
  - Rapid response to changing grid demand

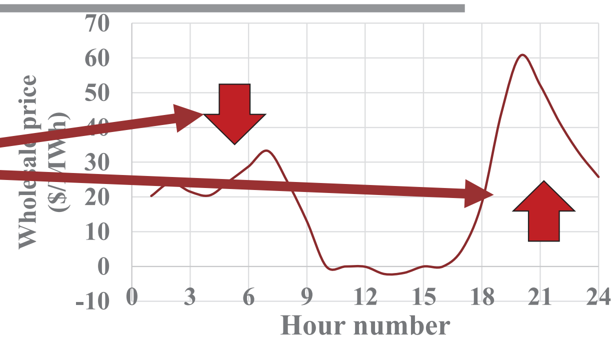
Implications for Reactor Island

- Much smaller security boundary and fewer people with plant access
- No grid/reactor interactions or safety implications
- Only reactor island designed, regulated and built to nuclear standards with option for separate balance of plant design and construction team
- Change in licensing

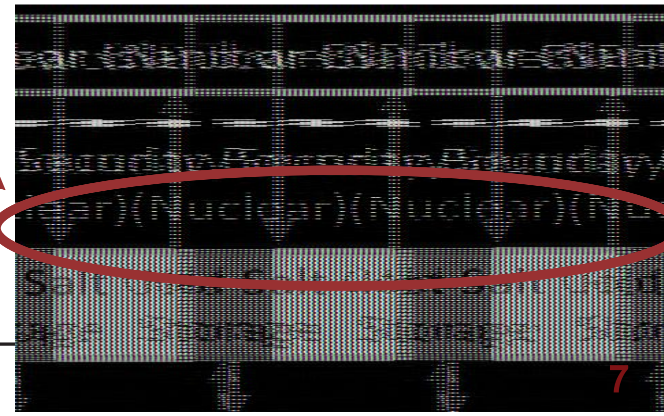


Implications of 5 to 100 GWh Heat Storage

- Increase in plant revenue by selling electricity when prices are high



- Cogeneration simpler—just another pipe from hot storage to industry and second pipe back to cold storage

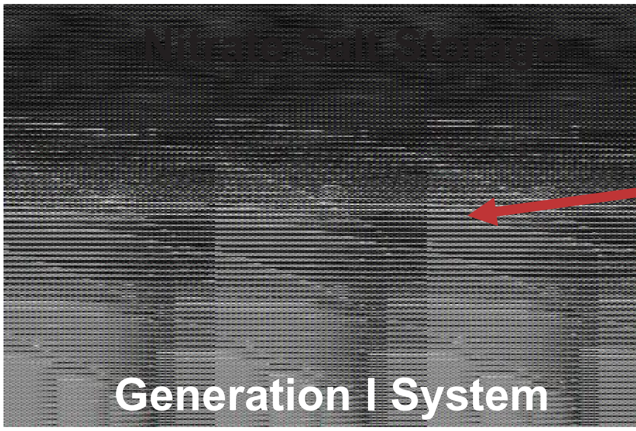


Massive Potential Demand for Energy Storage

- Energy storage today
  - Fossil: 1 to 3 months (including vehicle fuel tanks)
  - Nuclear: 9 months (average)
  - Hydro: seasonal
- Low-carbon world without fossil energy
  - Nuclear: 9 months
  - Hydro: variable
  - Wind and solar PV: zero
- **An all-electric world with battery storage is hours to days from total shutdown (light, transportation, heating/cooling) if electricity fails**

Nitrate-Salt Heat Storage is Done at the Gigawatt-hour Scale at Concentrated Solar Power Plants

Nitrate Salt Heat Storage Proposed for Sodium, Salt and Helium Cooled Reactors



Solana Generating Station (2013, U.S., ~4200 MWh(t))

- Three Generations oil and nitrate-salt storage systems
  - Generation 1: (Today) Heat storage using oil or salt and tanks
  - Generation 2: Crushed rock in oil or salt storage tanks
  - Generation 3: Crushed rock with oil or salt sprayed on crushed rock

[redacted]

Heat Storage Is Cheaper than Electricity Storage (Batteries, Pumped Hydro, etc.) with Many Technology Options

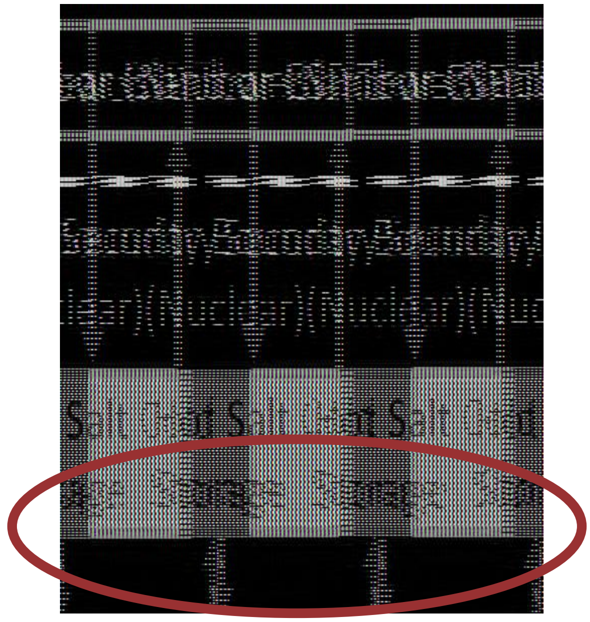
- DOE heat storage goal: \$15/kwh(t) but new technologies may be much cheaper (\$2-4/kWh)
- Battery goal \$150/kWh(e), double if include electronics
- **Cost difference is raw materials cost**

Storage Technologies (Partial List) *(Italic CSP Commercial)*
Pressurized Water
Geothermal
Concrete
Crushed Rock
Oil
Cast Iron
Nitrate Salt
Chloride Salt

[redacted]

Implications for Power Block

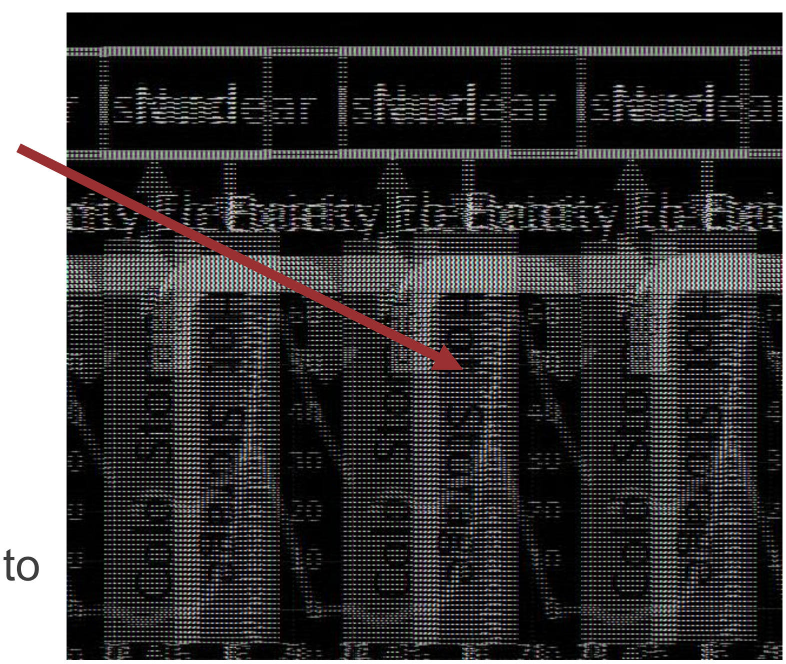
- Non-nuclear commercial design and construction
- **Peak power output based on markets.**
  - Moltex energy example: Peak power 3 times base load to maximize revenue at times of highest electricity prices
- Can use specialized power cycles designed for peaking power
- **Enable fast-response power block controlled by the grid operator—no nuclear system constraints**



11

Buy Low-Price Electricity & Provide Assured Peak Electricity

- **Buy low-price electricity and convert it into stored heat to produce electricity at times of higher prices**
- Low incremental cost to buy electricity: Own heat storage, transmission and power block
- If storage depleted, combustion heater with low-carbon fuels (biofuels, H_2, etc.) provides heat to assure peak generating capacity



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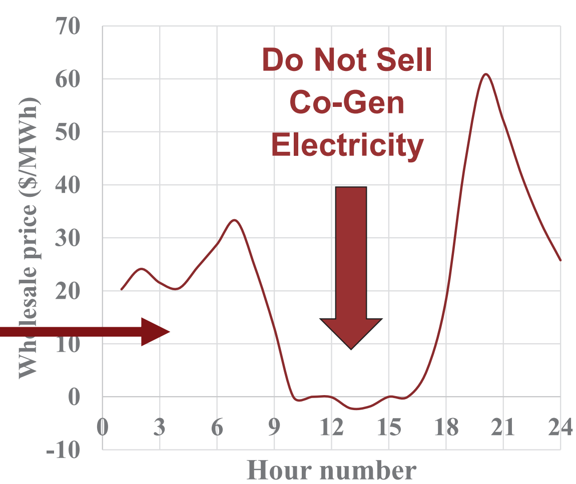
Nuclear Cogeneration May Be The Big Long-Term Market

- Industrial heat demand is twice total electricity output
- **Electricity six times more expensive than heat, electrification of industry may make industry non-competitive**
- Only two affordable low-carbon heat sources
  - Nuclear
  - Fossil with CCS

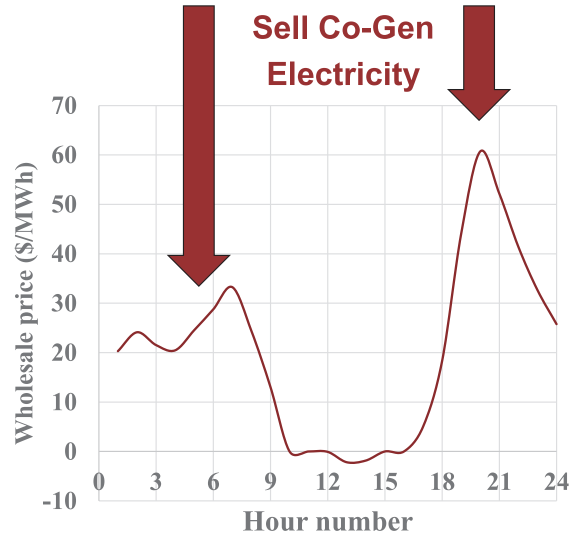
Nuclear Cogeneration Benefits from Heat Storage

- Traditional nuclear cogeneration
  - Base-load reactor operation
  - Meet industrial heat demand
  - **Convert extra heat when available to electricity and sell as electricity**
  - Economics based on fossil grid with approximately constant wholesale prices
- Low-carbon-world cogeneration
  - Massive variations in electricity prices
  - Dumping electricity onto market at wrong time limits revenue
  - Require heat storage to maximize value



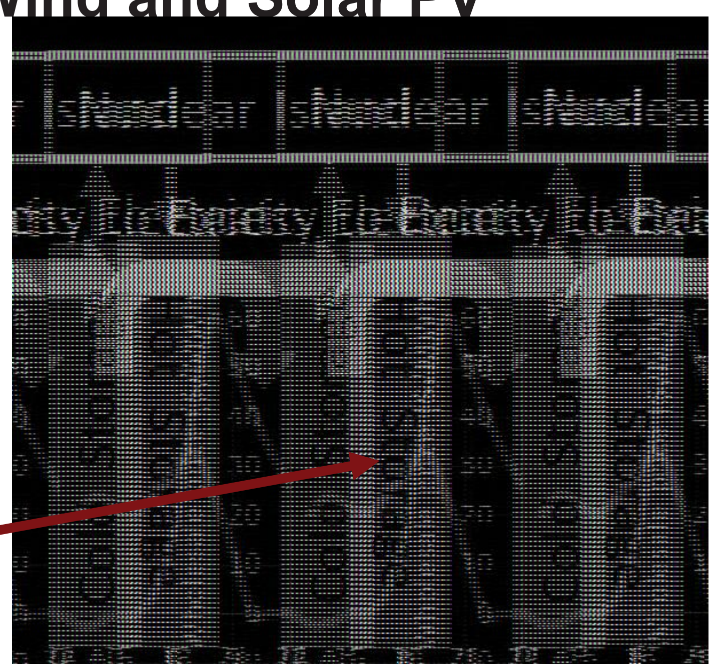
Heat Storage Changes Nuclear Cogeneration

- Cogeneration with heat storage
  - No requirement to adjust industry heat demand on an hour-to-hour basis to maximize electricity revenue
  - **Requirement is to match heat production with demand (industrial heat and electricity) over days to maximize revenue**
- Requires new business model between reactor and industrial customers to maximize revenue from electricity and industrial products



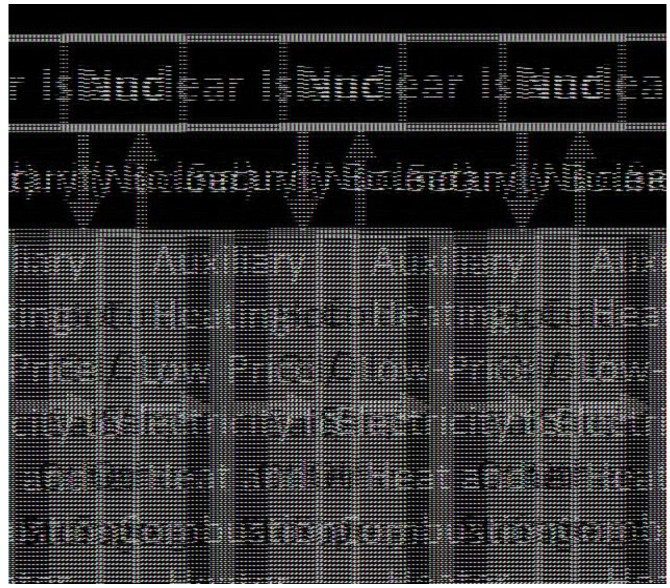
Heat Storage Adds Grid Resiliency and Enables Large-Scale Wind and Solar PV

- High resilience for the electricity grid with stored heat and combustion heating backup capability if reactor is down
- Enables economic larger-scale use of wind and solar PV
  - Lowest cost storage system
  - **Buying electricity at low prices sets a minimum price for electricity at times of high wind and solar PV output**



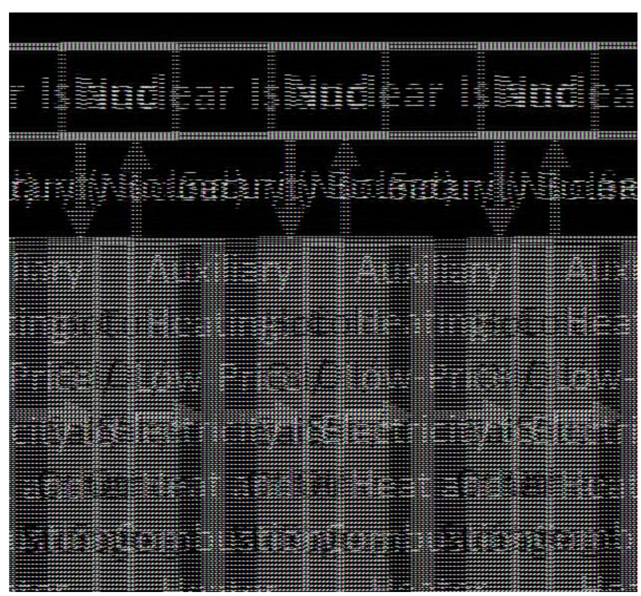
Storage Is Valuable for All Heat Generating Technologies

- Same system design applicable to all heat-generating technologies
  - Fission
  - Concentrated Solar Power
  - Fossil fuels with carbon capture and sequestration (CCS)
  - Fusion (future)
- **Incentives for joint research, development and demonstration programs**

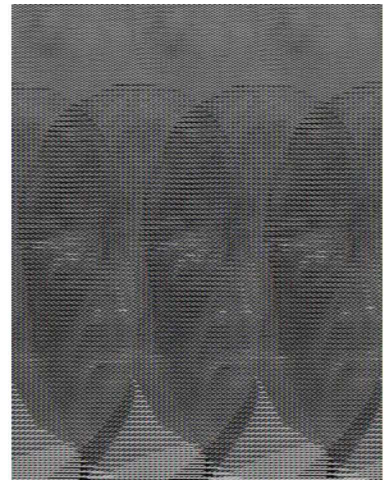


Conclusions and Webinar Path Forward

- Energy markets are changing with more volatile prices
- Economic incentives to sell dispatchable electricity with base-load reactors
- **Heat storage is less expensive than storing electricity (batteries, etc.)**
- Massive overlap with other low-carbon heat generating technologies



Biography: Charles Forsberg



Dr. Charles Forsberg is a principal research scientist at MIT. His research areas include Fluoride-salt-cooled High-Temperature Reactors (FHRs) and utility-scale heat storage including Firebrick Resistance-Heated Energy Storage (FIRES) and 100 GWh heat storage systems. He teaches the fuel cycle and nuclear chemical engineering classes. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory.

He is a Fellow of the American Nuclear Society (ANS), a Fellow of the American Association for the Advancement of Science, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in waste management, hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design and is a Director of the ANS. Dr. Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. He has been awarded 12 patents and published over 300 papers.

http://web.mit.edu/nse/people/research/forsberg.html

Added Information

Low-Carbon System Design for Nuclear Power with Heat Storage

Economics Require High-Capital-Cost Low-Operating-Cost Energy Systems Operate at High Capacity Factors

- High-capital-cost systems include nuclear, wind, solar, and hydrogen production systems. Operate at part load dramatically increases cost per unit of output
- **Need cheap energy storage to match production with demand**
  - Electricity demand varies hourly, weekday / weekend and seasonal
  - Electricity output if fully utilize generating assets
    - Nuclear: Constant output
    - Solar: Variable depending upon time of day, cloud cover and season
    - Wind: Variable depending upon daily, multiday and seasonal variations

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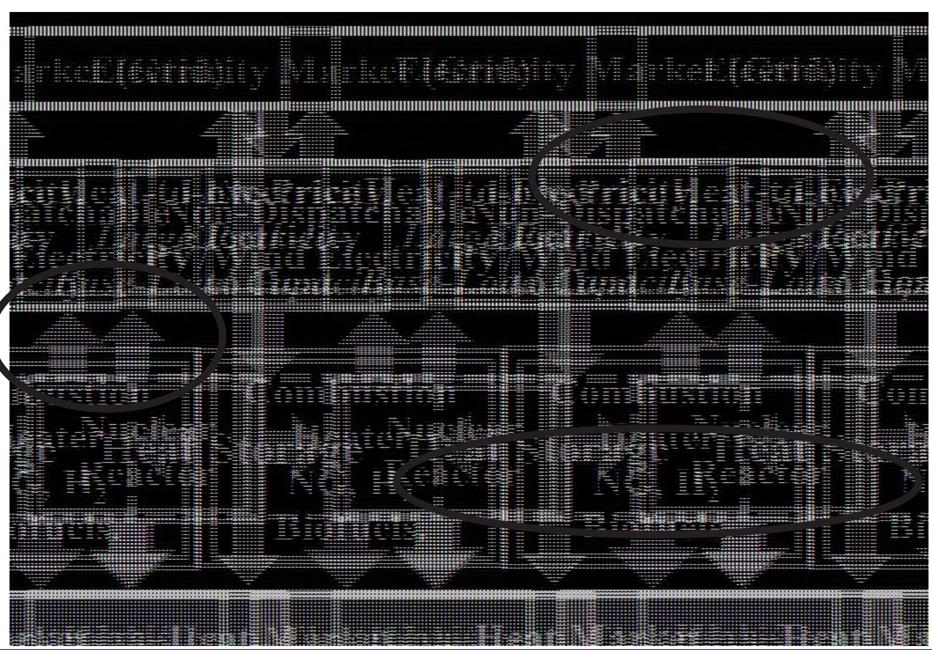
System Design to Enable High-Capacity Factors for High-Capital-Cost Components to Minimize Total Costs

- **High-capital-cost components**
  - **Nuclear plant**
  - **Wind / Solar**
  - **Hydrogen plant**
- Enabled by low-cost storage (Dashed boxes)
  - Heat
  - Hydrogen



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System Meets Daily to Seasonal Energy Demands

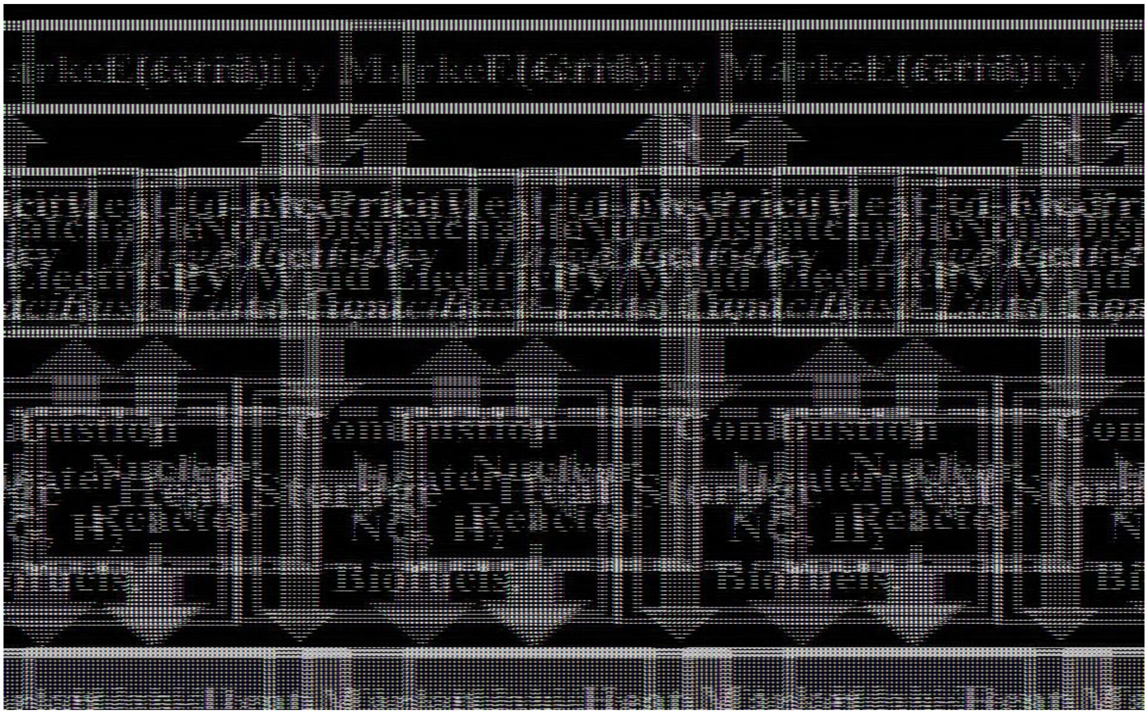
Electricity Markets

Electricity Conversions

Heat Systems

Heat Markets

Hydrogen



The Heat Storage System Design Is Applicable to Multiple Heat-Generating Technologies

- Nuclear
- Solar thermal
- Fossil fuels with carbon capture and sequestration (CCS)
  - Carbon dioxide removal from stack
  - Modified Allam cycle
- Fusion (future)

Heat Storage Is Cheaper than Electricity Storage (Batteries, Pumped Hydro, etc.) with Many Technology Options

- DOE heat storage goal: $15/kwh(t) but new technologies may be much cheaper ($2-4/kWh)
- Battery goal $150/kWh(e), double if include electronics
- **Difference is raw materials cost**
- **EPRI: Today batteries are 3 to 4 times more expensive per kWh(e)**

Storage Technologies (*Italic CSP Commercial*)	LWR Option	Sodium, Salt, Helium Options
Pressurized Water	X	Limited
Geothermal	X	Limited
Counter Current Sat Steam	X	Limited
Cryogenic Air	X	X
Concrete	X	X
Crushed Rock	X	X
Sand		X
Oil	X	Limited
Cast Iron		X
Nitrate Salt		*X*
Chloride Salt		X
Graphite (Helium and Salt)		X

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Separating Nuclear Reactors from the Power Block with Heat Storage

www.epri.com

Date: Add submission date and/or revision date & #

MOTIVATIONS

- Next-generation nuclear reactors, are currently under development, and are expected to be implemented on a broad scale over the next several decades.
- The high capital costs for nuclear plants result from regulatory requirements, quality assurance measures, safety systems and unique fuel and waste handling systems that are not required in other plant types.

SCOPE

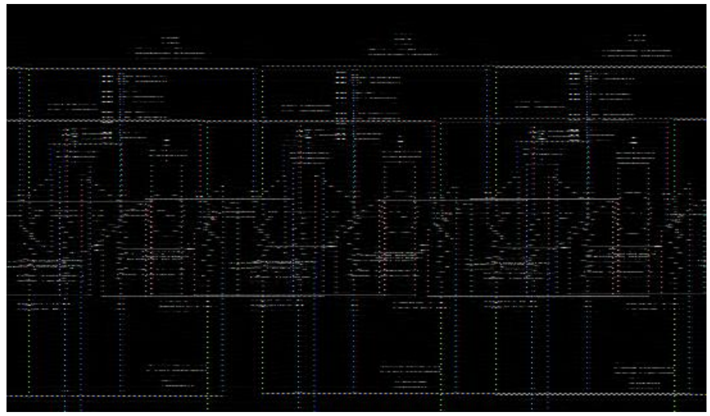
- Review of typical steam cycle designs for existing nuclear power plants, Combined Cycle Gas Turbine (CCGT) and Concentrated Solar Panel (CSP) power plants
- Comparison of the capital costs associated with the power cycle of each generating technology
- Collect insights on design and construction parameters that affect new power plant costs
- Identify approaches to reduce costs in the steam cycle for GenIV plants

Typical Light Water PWRs

- Reactor Primary System produces saturated steam in Steam Generators
- Large steam turbines specific to nuclear industry
- Large Moisture Separator Reheaters to increase steam quality to LP Turbine
- Feedwater heaters using extraction steam

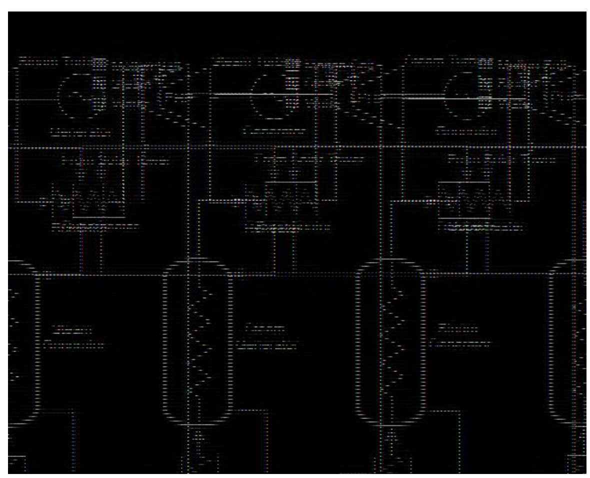
Typical CCGT

- Gas turbine exhaust produces superheated steam in heat recovery steam generators (HRSG)
- Compact turbine, “off-the-shelf”
- Reheat occurs in HRSG
- Feedwater heating occurs in HRSG
- CCGT compared to current nuclear:
  - Smaller, more commercial turbines
  - No moisture separator reheaters
  - No feedwater heaters / drains system



Typical CSP

- Heat transfer fluid (e.g., molten salt) produces superheated steam in steam generating heat exchangers
  - Preheater
  - evaporator
  - Superheater/Reheater
- Compact turbine, “off-the-shelf”
- Reheat in steam generator reheater stage
- Feedwater heating in steam generator preheater stage
- CSP compared to current nuclear:
  - Smaller, more commercial turbines
  - No moisture separator reheaters
  - No feedwater heaters / drains system

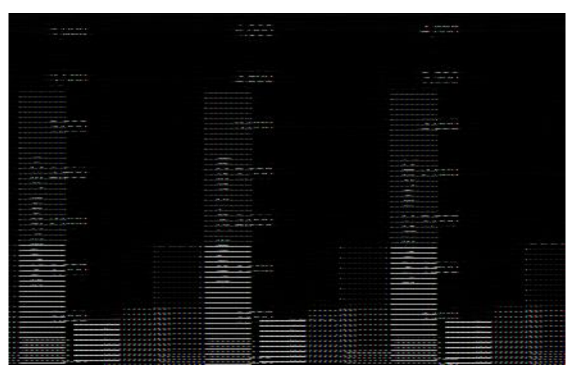


Comparison of Generating Technologies

Plant Type	PWR-12	CCGT	CSP
Steam Generator Primary Inlet Temperature (°F)	625	1100	1022-1202
Steam Generator Primary Outlet Temperature (°F)	553	200	550
Main Steam Conditions	Saturated Steam 532 °F / 900 psia	Superheated Steam 1050 °F / 2400 psia	Superheated Steam 1004 °F / 2321 psia
Steam Turbine-Generator	~1150 MWe Specific to nuclear	~350 MWe Standard Designs, Compact	~130 MWe Standard Designs, Compact
Feedwater Heating	Five to eight stages heated by turbine extraction steam	Within HRSG	Within one stage of steam generating heat exchangers
Reheat	Moisture Separator Reheaters	Within HRSG	Within one stage of steam generating heat exchangers

Historical Cost Assessments

- Energy Economic Data Base (EEDB) data is filtered to only include items directly associated with the steam cycle
- Cost estimates for CCGT and CSP plants are filtered to exclude costs associated with the primary heat generation source
- All costs are compared on a per KWe installed basis
- Adjusted to 2019 U.S. dollars
- Compares the direct costs and direct plus indirect costs for the different plants
- Indirect costs are a significant driver

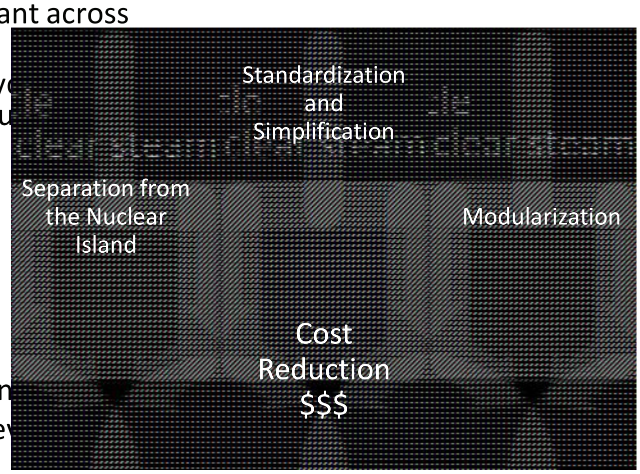


Key Cost Drivers Impacting Nuclear Steam Cycles

- **Construction Duration**
  - Average construction time for nuclear power plant is more than 7.25 years
  - CSP construction time is 3 years and CCGT takes about 2 years
- **Quality bleed-over**
  - Nuclear plants (Higher Quality on Steam Cycle components)
  - Proximity to safety related SSCs also lead to higher quality
  - Storage of materials for safety related structures adds the cost
  - Security and access protocols.
- **Secondary Operating conditions**
  - CSP and CCGT plants have significantly higher primary side temperatures
  - Superheated steam results in lower feedwater and steam flow rates
- **Construction experience**
  - Lack of recent nuclear construction experience will significantl increase costs of new nuclear construction
  - CCGT and CSP are much simpler to build.

Cost Reduction Strategies

- Standardization and Simplification
  - BOP designs should stay relatively constant across reactors
  - CCGT an CSP designs offer a degree of cy simplification over currently-deployed nu cycle designs
- Separation from the Nuclear Island
  - Intermediate loop
  - Lowered construction costs
  - Lowered licensing and regulatory risks
- Modularization
  - Importance of addressing modularization
  - Simplified BOP design offers increased le modularization

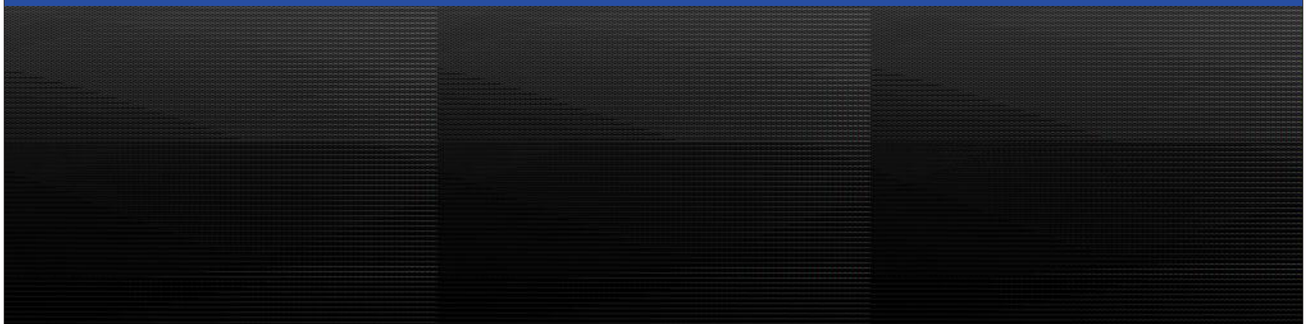


Proposed Standardized Power Cycle Design

- A steam cycle design based on that for CCGT and CSP plants appears to be implementable for future plants
- Intermediate loop
  - Allows standardization of design between GenIV types
  - Provides more physical separation of the steam cycle SSCs from safety-related SSCs
  - Permits easier integration of renewables and multiple thermal energy customers
- Primary side thermal conditions allow plants to produce superheated steam and reheat steam to boost the steam cycle efficiency and simplify steam cycle design.

Conclusions

- Primary side operating conditions for GenIV reactors closely aligned with those present in CCGT and CSP permitting the use of superheated steam in the turbine-generator
- Standardization and physical separation of steam cycle from the nuclear island have been identified as impactful cost reduction strategies.
- Construction timelines should be evaluated to see when the BOP construction activities can be performed to ensure reasonable separation and optimal duration.



Together...Shaping the Future of Electricity

Cogeneration Concepts – Lessons from the NGNP Program

Phil Hildebrandt

MIT/INL/EPRI Workshop
Separating Nuclear Reactors from the Power Block with Heat Storage:
A New Power Plant Design Paradigm
July 29, 2020

Topics

- **Brief background -- the Next Generation Nuclear Plant (NGNP) program**
- **Overview of cogeneration market opportunities**
- **Collaborations to evaluate potential cogeneration applications and notional energy production, conversion and transport concepts**
- **Results for an example collaboration to provide perspective for the challenges and lessons learned discussion**
- **The important challenges for the cogeneration nuclear energy business model**

2

NGNP Program

- Authorized by Energy Policy Act of 2005
- Formed a Consortium of technology developers, designers, nuclear owner-operators, major industrial energy end-users and national laboratories led by the Idaho National Laboratory
- Tasked to complete development, design, construct and demonstrate a high temperature gas-cooled reactor (HTGR) project for production of electricity and hydrogen via one or more public-private partnerships

****

The Consortium focused the program on interests of energy producers and end-users:

- What are the business interests for deploying HTGRs?
- Evaluated the potential North American market for cogeneration of electric power and high temperature process heat
- Assessed the technical feasibility, economic viability and possible market penetration for the cogeneration market

3

Potential Cogeneration Markets

Three useful evaluations have been performed, the first two for the NGNP Program and the third as part of a study in the MIT "*Future of*" series.

- *High Temperature Gas-Cooled Reactor Projected Markets and Preliminary Economics* INL/EXT-10-19037 Rev. 1, August 2011
- *Survey of HTGR Process Energy Applications*, MPR Associates, Inc, 2008
- *The Future of Nuclear Energy in a Carbon-Constrained World*, An Interdisciplinary MIT Study, September 2018

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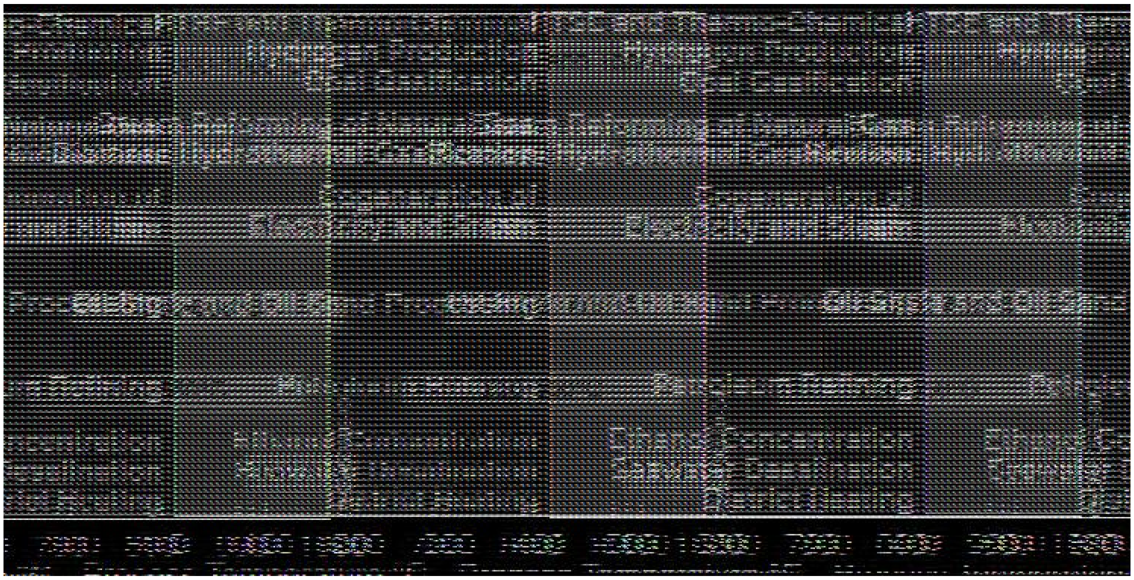
Potential Cogeneration Markets (continued)

(From: *High Temperature Gas-Cooled Reactor Projected Markets and Preliminary Economics*, INL/EXT-10-19037 Rev. 1, August 2011)



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Potential Cogeneration Markets (continued)

Takeaways from the evaluations

- Cogeneration opportunities exist in many industries, such as:
  - Process energy for industrial energy end-users (e.g., petrochemical, fertilizer and refinery operations)
  - Hydrogen production
  - Extraction of bitumen from oil sands
  - Carbon conversion for synthetic fuels
- The process industry interest in nuclear energy to replace natural gas, oil and coal for producing process heat is generally driven by goals of reducing carbon emissions, conserving feedstock, and economic advantage
- The industrial process heat market varies greatly regarding energy requirements (e.g., thermodynamic properties; heat load) and energy transport medium
- Depending on the postulated penetration into the various process heat markets, hundreds of reactors could be required to provide the required energy
- Expanding into the hydrogen market whether for industrial purposes or transportation needs could considerably increase the required number of reactors

6

Cogeneration Business Model Evaluations – Four Examples

- ***Integration of High Temperature Gas-Cooled Reactors into Industrial Process Applications***, INL/EXT-09-16942, Revision 3, September 2011
  - Summary of technical and economic feasibility for multiple industrial processes
- ***Next Generation Nuclear Plant Project Evaluation of Siting an HTGR Co-generation Plant on an Operating Commercial Nuclear Plant Site***, INL/EXT-11-23282, October 2011
  - Collaboration with Entergy to evaluate providing cogenerated power and process heat to two petrochemical plants in Taft, LA utilizing multi-module HTGR plant located on Waterford site. Includes collocated hazards analysis and selected licensing evaluations.
- ***Integration of High Temperature Gas-cooled Reactor Technology with Oil Sands Processes***, INL/EXT-11-23239, October 2011
  - Collaboration with Petroleum Technology Alliance Canada to evaluate cogeneration using multi-module HTGR plants for oil sands processes
- ***Overview of Energy Development Opportunities for Wyoming***, INL/EXT-12-27626, November 2012
  - Collaboration with State of Wyoming and University of Wyoming to evaluate developing a carbon conversion industry using cogenerated energy from HTGRs

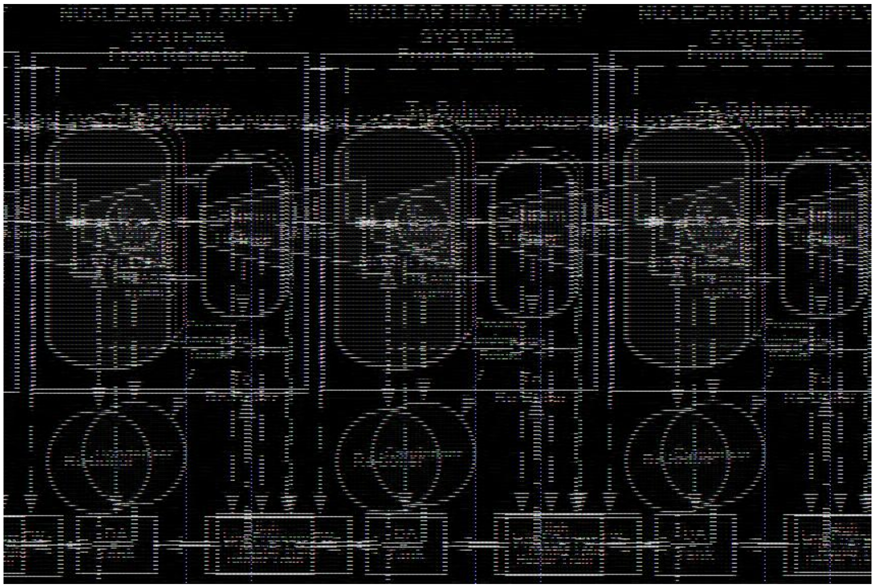
Example: Cogeneration for Petrochemical Plants

Taken from: ***Next Generation Nuclear Plant Project Evaluation of Siting an HTGR Co-generation Plant on an Operating Commercial Nuclear Plant Site****, INL/EXT-11-23282, October 2011*

The Dow Chemical Company (260 MWe power/1.8 million lb/hr steam) and Occidental Petroleum Corporation (220 MWe power/ 0.7 million lb/hr steam) petrochemical facilities are located within 2 miles of the Waterford Site.

Example: Cogeneration for Petrochemical Plants (continued)

Taken from: *Next Generation Nuclear Plant Project Evaluation of Siting an HTGR Co-generation Plant on an Operating Commercial Nuclear Plant Site, INL/EXT-11-23282, October 2011*



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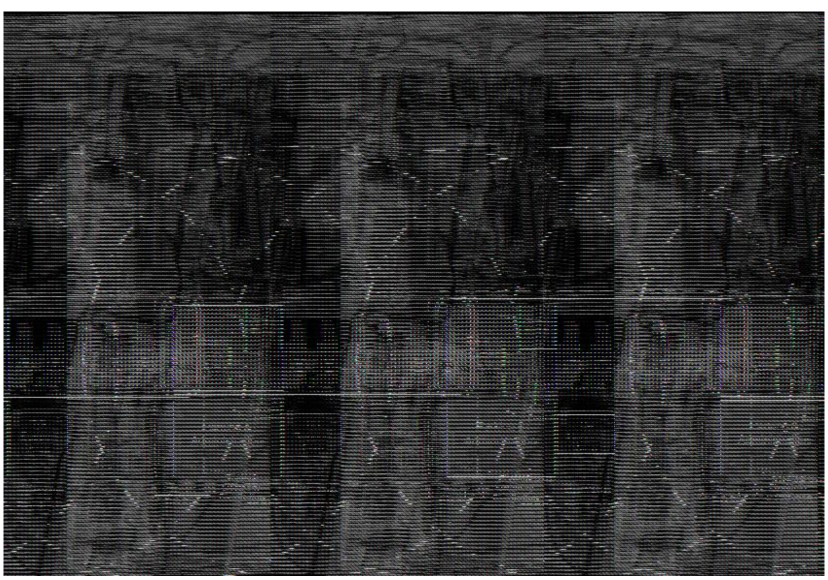
Example: Cogeneration for Petrochemical Plants (continued)



Reference HTGR six-module plant (3,600 MWt)

Power: 480 MWe to processes
750 MWe to grid

Steam: 2.9 million lb/hr (1060 MWt)

- Allowance for extended nuclear module outage
- Anticipated growth in petrochemical facilities
- Wholesale power sales to grid

Taken from: *Next Generation Nuclear Plant Project Evaluation of Siting an HTGR Co-generation Plant on an Operating Commercial Nuclear Plant Site, INL/EXT-11-23282, October 2011*

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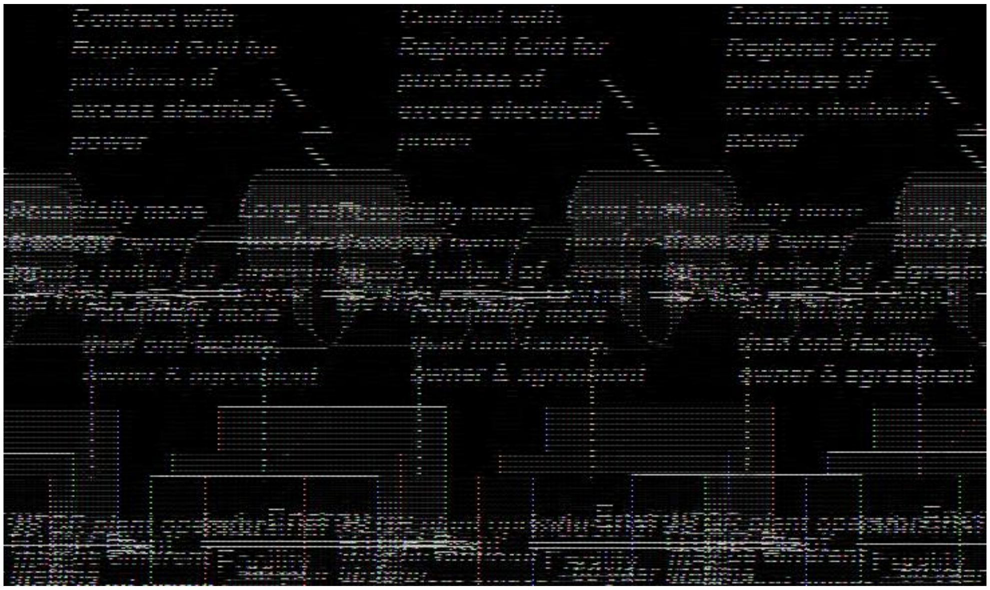
Example: Cogeneration for Petrochemical Plants (continued)



Taken from: *Next Generation Nuclear Plant Project Evaluation of Siting an HTGR Co-generation Plant on an Operating Commercial Nuclear Plant Site*, *INL/EXT-11-23282, October 2011*

Example: Cogeneration for Petrochemical Plants (continued)

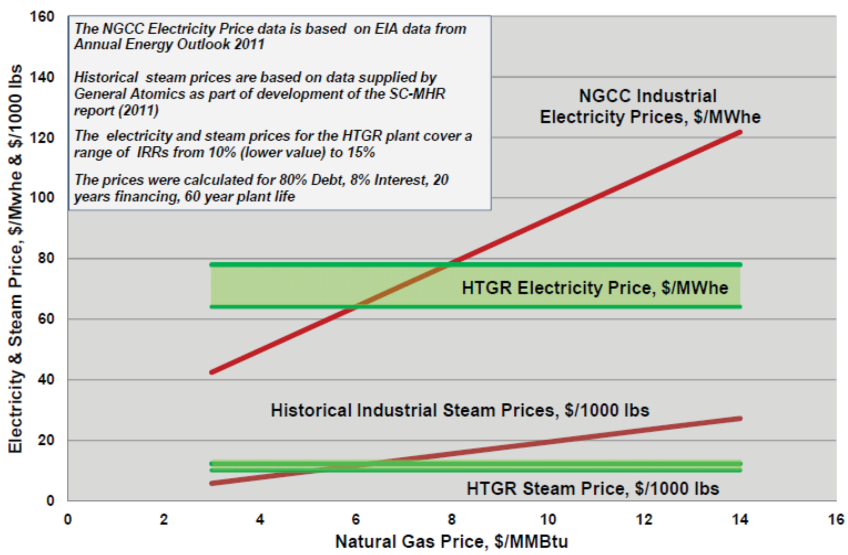


Figure 19. Comparison of HTGR Prices with natural gas plant *[Excel file Economics 6-600 MW(t) IRR Variation 10-26-10]*.

Taken from: *Next Generation Nuclear Plant Project Evaluation of Siting an HTGR Co-generation Plant on an Operating Commercial Nuclear Plant Site*, *INL/EXT-11-23282, October 2011*

Challenges – Lessons from NGNP Program Evaluations

Perspective – Cogeneration is anticipated to involve a symbiotic business relationship between a nuclear energy supplier and a large process plant(s) that is expected to endure for decades – and must be mutually beneficial.

- Acceptance by major industrial energy end-users of nuclear energy for process heat
- Anticipated availability of the nuclear plant compared to process plant operations is expected to require more modules than needed solely for peak power and process heat demands
- Postulated nuclear accidents
  - Effect of radiological releases on process plant investment
  - Overlap/integration with process plant emergency planning
- Authorities having jurisdiction – plant licensing, security, emergency planning
- Collocated hazards
- Business risk of locating nuclear facility on “others” property
- Flexibility for changes in process plant utilization and energy markets
- Ownership of nuclear facility
- Contractual arrangement that maximizes return for all investors/owners

13

ELECTRIC POWER RESEARCH INSTITUTE

Integration of Heat Storage with Fossil Energy Systems

Delivering essential flexibility to balance intermittent renewable energy sources

Scott Hume
Principal Technical Leader

Separating Nuclear Reactors from the Power Block with Heat Storage: A New Power Plant Design Paradigm

29th July 2020

A Growing Need for Energy Storage

Today: 2020

As variable renewable energy (VRE) grows, dispatchable resources are being shut down or operated flexibly

- Primarily batteries provide storage
- Other storage technologies being developed

100s MWh for 0–4 hours

Tomorrow: 2030

Conventional dispatchable resources further replaced with VRE, diurnal and multi-day energy storage needed

- Higher VRE penetration
- Retrofit stranded assets with thermal energy storage (TES)
- Other non-battery types

10s GWh for 4–48 hours

Target: 2050

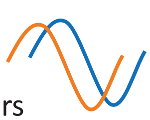
> 80% low-carbon generation, primary energy sources stored in sufficient quantities for year-round power resilience

- Bulk energy storage, e.g., large-scale TES (immediate use)
- Chemical fuel storage (hydrogen, ammonia) for seasonal energy shifting

100s TWh Stable and Dispatchable

Wind, solar, and batteries are inverter-based energy supplies – inertia limiting

Gas, nuclear, coal, and solar thermal plants provide system inertia by synchronizing generators

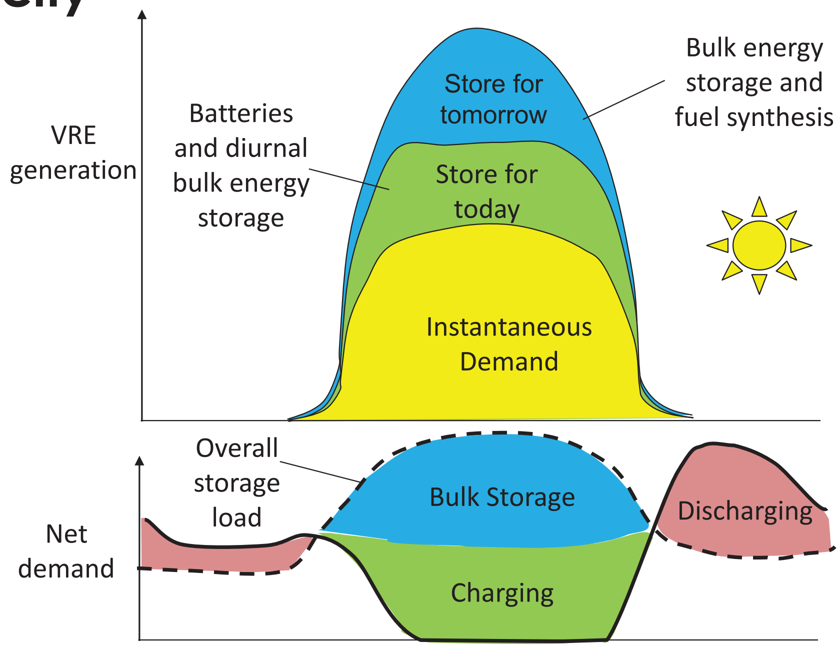


Low-cost bulk energy storage, coupled with power cycles, provides synchronous power and system inertia

Beyond Current Capacity

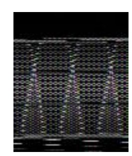
- Tomorrow
  - Summer VRE excessively exceed demand
  - Beyond diurnal needs

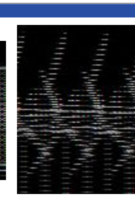
- Multi-day duration storage needed to cover high- / low-resource availability



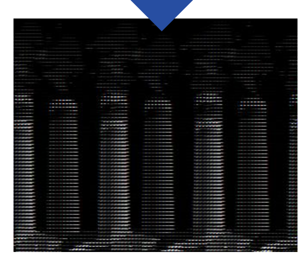
Longer duration in the future is essential

VRE and Energy Storage





- Growth in VRE is driving:
  - Potential grid instability and lack of "real" system inertia
  - Wasteful curtailment
  - Damage to thermal power plants providing grid support from cycling
- Current energy storage:
  - Batteries storage cost is high at **$1300–2100/kW** for a 4-hour system ($325–525/kWh)*; footprint and safety are also issues
  - Longer duration (8+ hours) is an even greater economic challenge
  - New pumped hydro opportunities are limited



Inertia, frequency response, ramping, spinning and non-spinning reserve, two-shift operation, standby

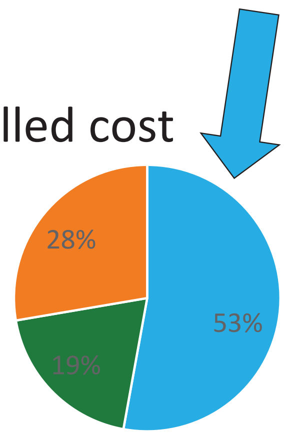
**Energy Storage Technology and Cost Assessment. EPRI, Palo Alto, CA: 2018. 3002013957*

Large-scale, bulk energy storage is a key enabler for VRE

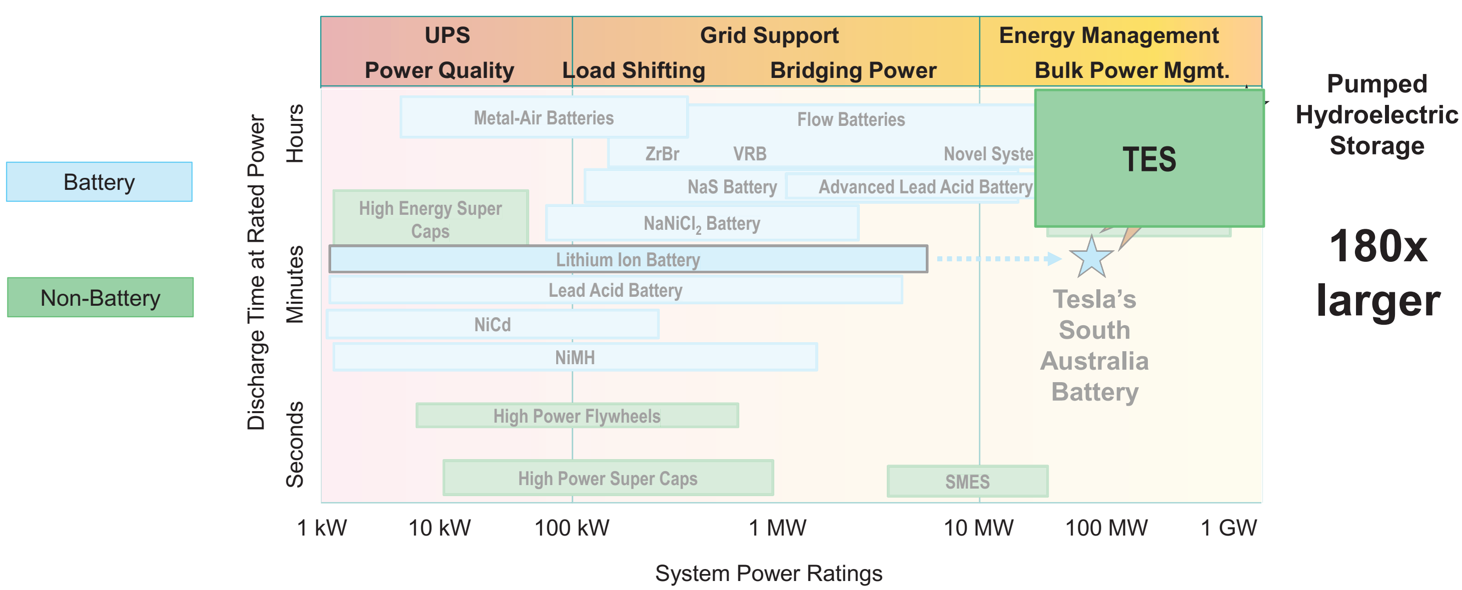
Why TES and Not Batteries?

- Lots of talk of batteries being ‘substantially cheaper’ in the future
- On a cell or module level, this is true due to:
  - Economies-of-scale thanks to electric vehicle manufacture
  - Reduced use of sensitive materials
  - Improving lithium ion chemistries
- Importantly, the module level is only half of the installed cost
- For a 4-hour system:
  - Battery/PCS/BOP/Control – $280/kWh
  - Engineering, Procurement, and Construction – $110/kWh
  - Taxes/Fees/Contingency – $150/kWh

Up to 50% lower in 10 years, but only 26% reduction of total installed costs

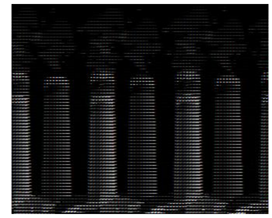


Also It’s a Question of Scale…

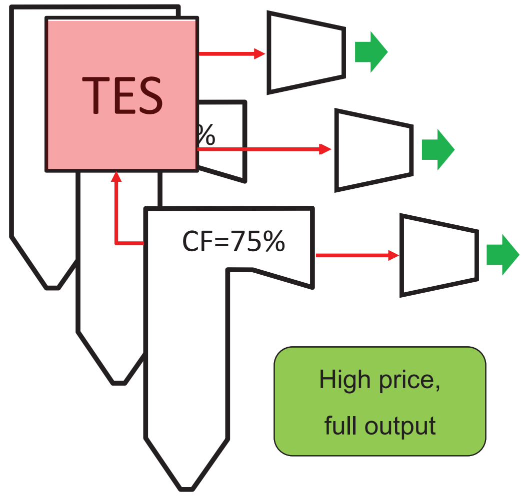


TES has potential for more power, longer duration, and lower cost

TES Deployment at Multi-Unit Fossil Plant

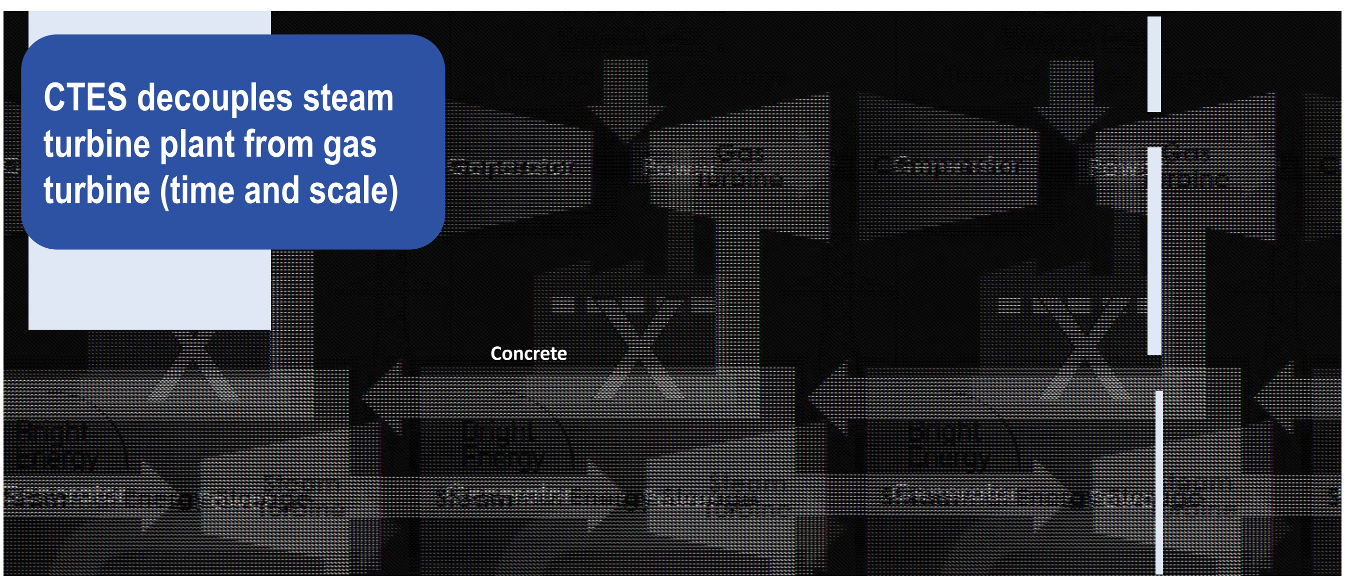


- By providing steam to TES during periods of low energy prices, the unit remains operational, avoiding shutdown and restart
- When energy prices increase, steam from the boiler can be diverted to the steam turbine AND the TES units can provide steam to the turbines of the units with retired boilers
- All three units generate power when needed



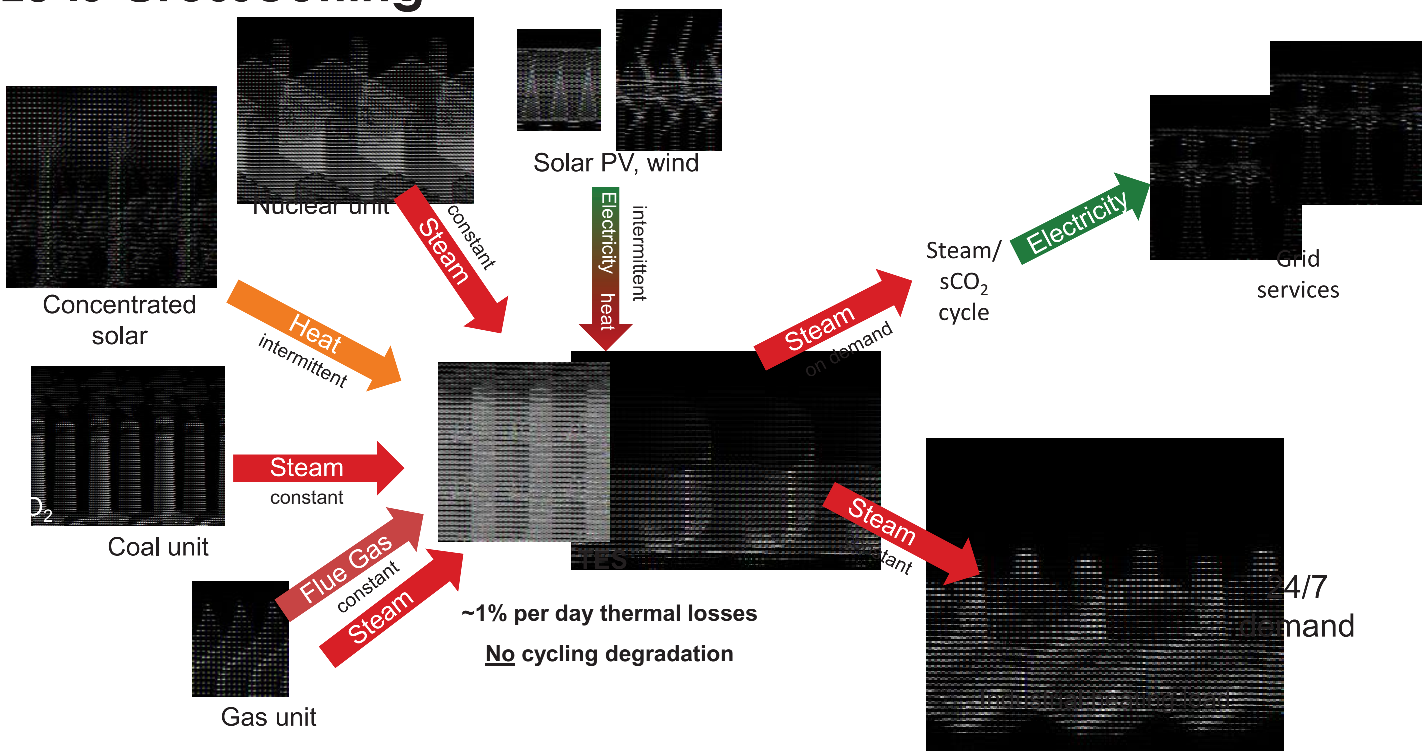
TES can be applied to any thermal plant (fossil, nuclear, etc.)

Example: Concrete TES (CTES) Integrated with Gas



CTES is flexible – delivering more peak power when needed

TES Is Crosscutting



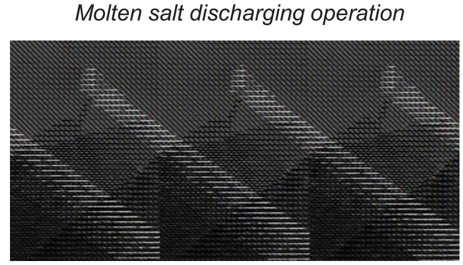
 www.epri.com

TES Materials: Molten Salt

- Developed for concentrating solar plants
- Used as a heat transfer medium between heat source and steam cycle
- Stored in a two-tank system operating between 290–565°C; temperature limited
- Round-trip efficiency up to 92%; losses ~1% per day
- Commercial salt, a blend of sodium and potassium nitrate; 23 tonnes/MWhe required. Cost: **$950/tonne**.
- Higher cost for longer durations

Crescent Dunes CSP, Tonopah NV (SolarReserve)

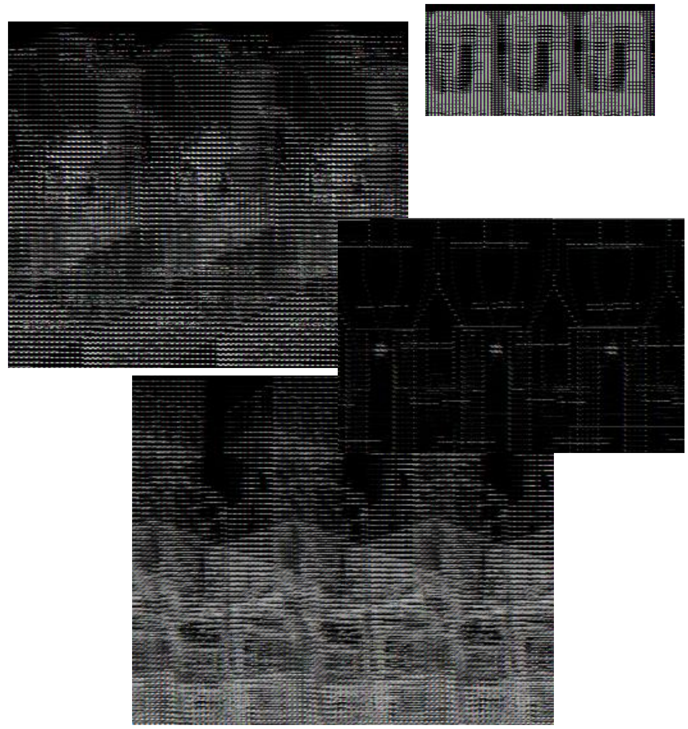
Molten salt discharging operation



 www.epri.com

TES Materials: Sand

- SandTES developed by Technical University of Vienna
- Ultra low-cost material with high availability: **$46/tonne**
- Heat transferred to and from sand in counter-current bubbling bed heat exchanger
- Sand stored at temperature in silos to provide large storage capacity and minimize heat losses
- Pilot plant operational (late 2017)

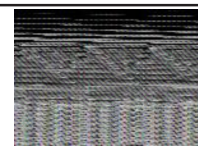


Courtesy of Technical University of Vienna

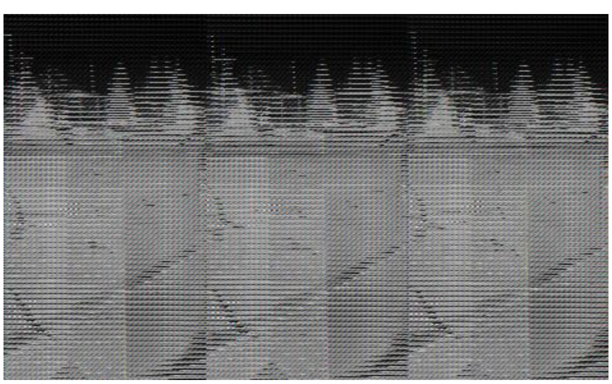
280-kWth pilot plant

TES Materials: Concrete

Very durable – see 2000-year old Pantheon in Rome, built of concrete!

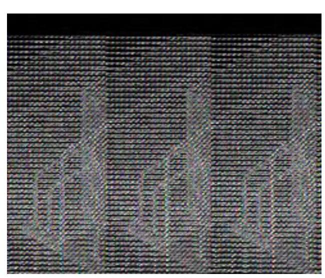


- Potential low-cost TES system
- Solid 'thermocline' structure used to store thermal energy
- Low-cost material **$68/tonne**
- Modular system (41' [12.5 m])

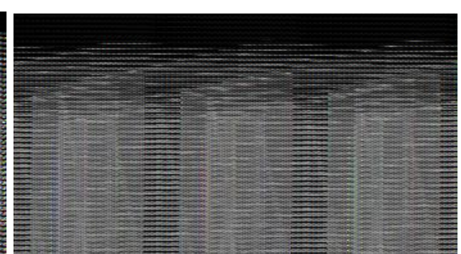


3-block, flue gas-heated testing modules

- Steam tubes embedded into concrete monoliths as coils – conductive heat transfer only
- No moving parts
- Road/rail transportable



Tube internal arrangement



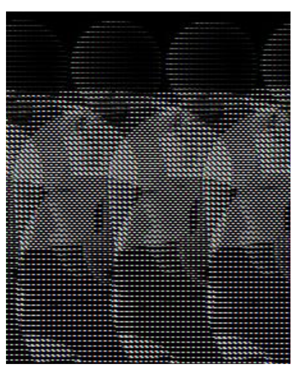
10 MWh-e scale unit

Images courtesy of Bright Generation Holdings

Summary

- Fossil and nuclear plants will need to be highly flexible in the future as VRE levels increase
- Extended durations will be critical (esp. in wind-dominated markets)
- Ultra low-cost materials essential at the scale needed
- System inertia will become a key grid service as direct current-coupled generation expands (solar, wind and batteries)
- Useful life extension for steam turbine assets coupled with retiring steam sources (emissions, safety case)
- In the long term, TES can be heated by the grid to become purely an energy storage system

Questions



Together…Shaping the Future of Electricity

Energy Storage As An Enabler of Resilient Nuclear Power Plants and Electric Grids

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Presented To
MIT / INL / EPRI Web Workshop

29 July 2020

From hindsight to foresight through insight.™

Presentation Overview

- Resilience defined
- resilient Nuclear Power Plants (**r**NPPs)
- **r**NPP Applications
- **r**NPP Attributes
- Energy Storage As Enabler of **r**NPPs and Grid resilience

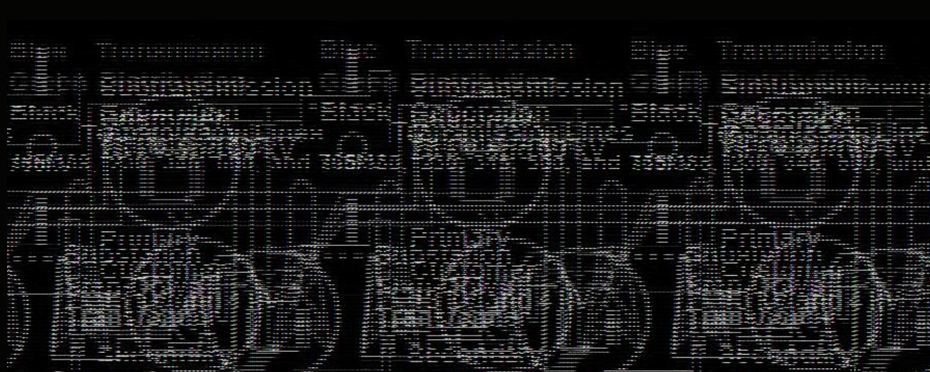
Details of concepts presented here are discussed in four publications

- Sherrell R. Greene (2018) "**Are Current U.S. Nuclear Power Plants Grid Resilience Assets?**" *Nuclear Technology*, 202:1, 1-14, DOI: 10.1080/00295450.2018.1432966
- Sherrell R. Greene (2016) "**Nuclear Power: Black Sky Liability or Black Sky Asset?**" *International Journal Of Nuclear Security*, Vol. 2: No.3, Article 3, http://dx.doi.org/10.7290/V78913SR
- Sherrell R. Greene (2018) "**The Key Attributes, Functional Requirements, and Design Features of Resilient Nuclear Power Plants (rNPPs)**," *Nuclear Technology,* 204:2, 131-146, DOI: 10.1080/00295450.2018.1480213
- Sherrell R. Greene (2018) "**Enhancing Electric Grid, Critical Infrastructure, and Societal Resilience With Resilient Nuclear Power Plants (rNPPs)**," *Nuclear Technology,* https://doi.org/10.1080/00295450.2018.1505357

The Grid is…

"*the integrated system of electricity generation, transmission, <u>and distribution</u> assets required to supply electricity* ***to the end-consumer***" (Greene)

"Fuel"



"Wall Socket"

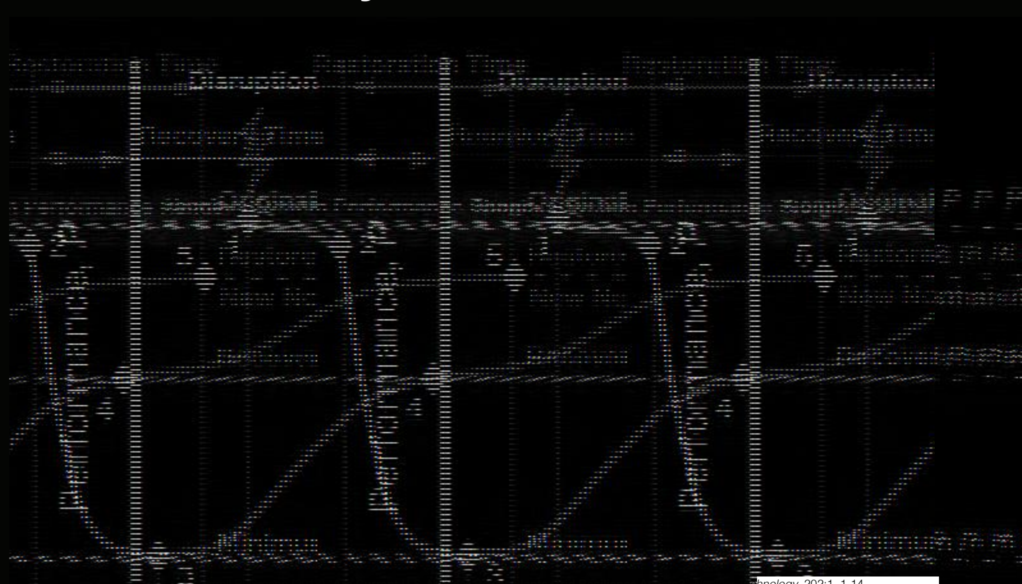
System Resilience is

"the ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to ***anticipate****,* ***absorb****,* ***adapt*** *to, and/or* ***recover*** *from" disruptive events"*

(FERC, 2017)

"System Resilience Curve" (SRC) illustrates key resilience attributes

Generic System Resilience Curve



Grid Resilience is

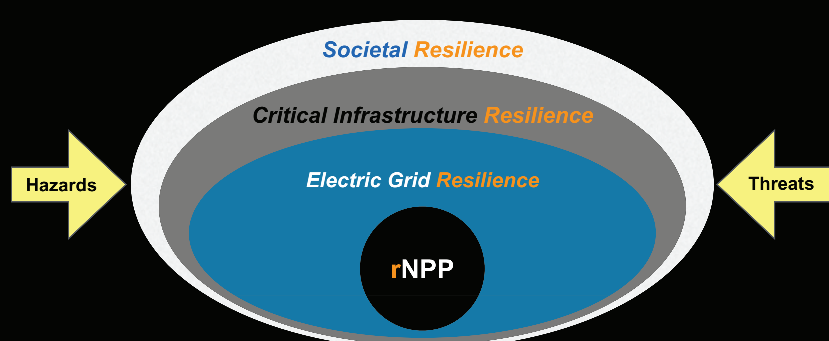
"a measure of the system's ability to minimize interruptions of electricity flow to customers, given a specific load prioritization hierarchy" *

*Sherrell R. Greene (2018) "**Are Current U.S. Nuclear Power Plants Grid Resilience Assets?**" *Nuclear Technology*, 202:1, 1-14. DOI: 10.1080/00295450.2018.1432966

rNPPs would be reverse-engineered from "outside-in"

A ***resilient*** **Nuclear Power Plant (rNPP) is** *a nuclear power plant whose performance attributes and functionalities enable and enhance electric Grid resilience.*

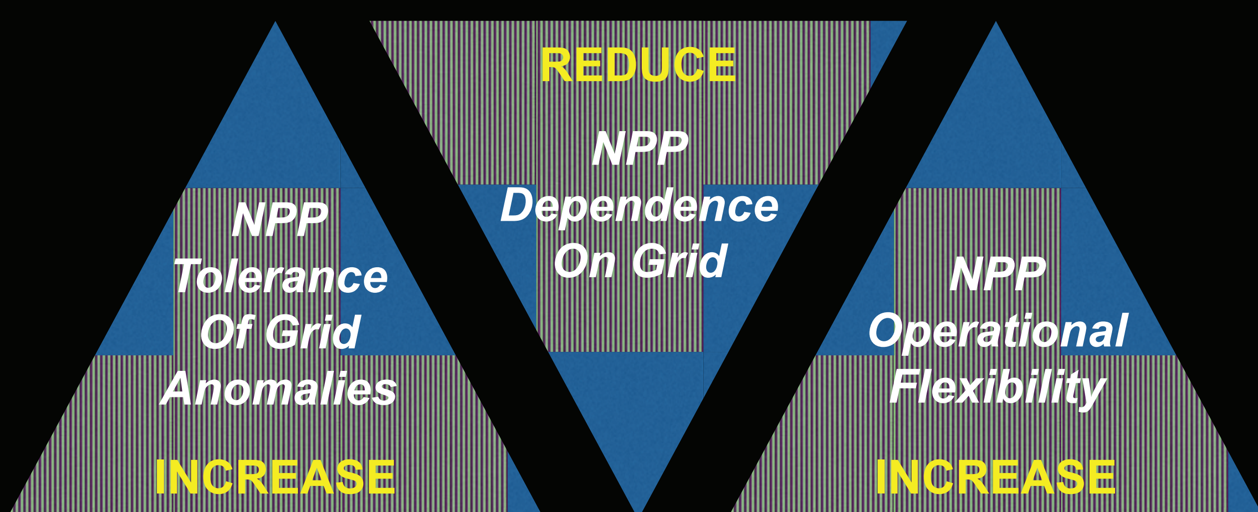
rNPPs *are nuclear power plants intentionally designed, sited, interfaced, and operated in a manner to enhance overall electric Grid and Critical Infrastructure resilience.*



Resilient power plants would exhibit two Key Attributes:

- **Key Attribute 1**: enable the electric Grid to **absorb** and **adapt** to a broad spectrum of Grid anomalies and disruptions.
- **Key Attribute 2**: enhance the Grid's ability to quickly **recover** from upsets, and to **restore** electric service in a manner consistent with the system operator's load prioritization hierarchy.

Enabling **r**NPP design features would…



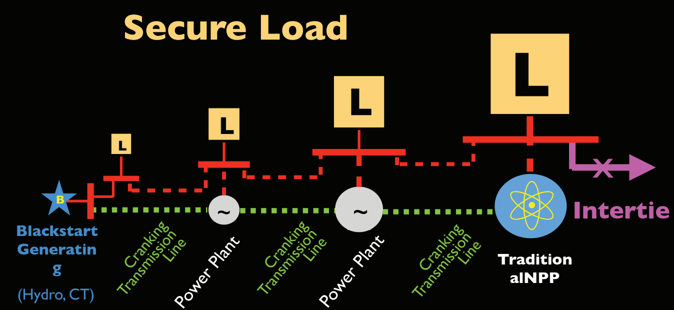
rNPPs would exhibit six defining functional capabilities

1. Robust real/reactive load-following and flexible operation capability
2. Immunity to damage from external events (including Grid anomalies)
3. Ability to avoid plant shutdown (reactor scram) in response to Grid anomalies
4. Ability to operate in Island Mode (i.e., without connection to offsite transmission load and electric power supply)
5. Unlimited independent safe shutdown cooling capability (i.e., requiring no offsite power or resupply of diesel fuel from offsite)
6. Independent self-cranking black start capability (i.e., the ability to start with no offsite cranking power supply from the Grid)

rNPP's enable four transformative nuclear power applications

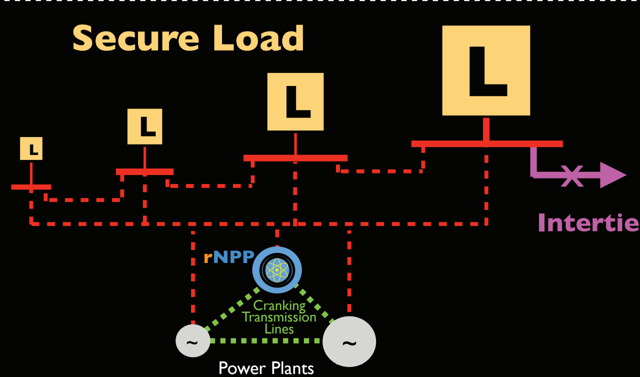
- Flexible power generation operations
- rNPP-anchored Hybrid Nuclear Energy Systems (HNES)
- **rNPP Black Start Resources**
- **rNPP-anchored resilient Critical Infrastructure Islands (rCIIs)**

rNPPs could transform Grid Black Start operations



Current Grid Black Start procedures…

- Rely on small hydro or (more commonly) combustion turbine Black Start Resources
- Require serial "daisy chain" startup of multiple power plants to recover and restore Grid

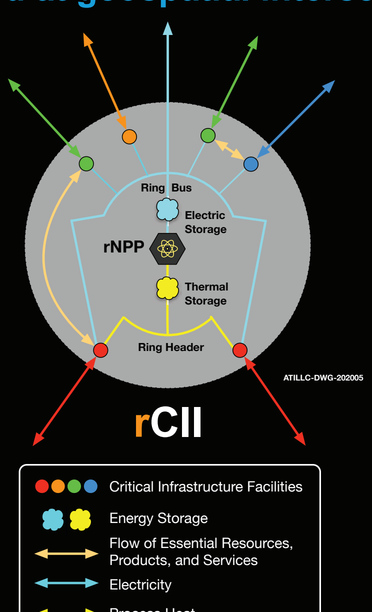


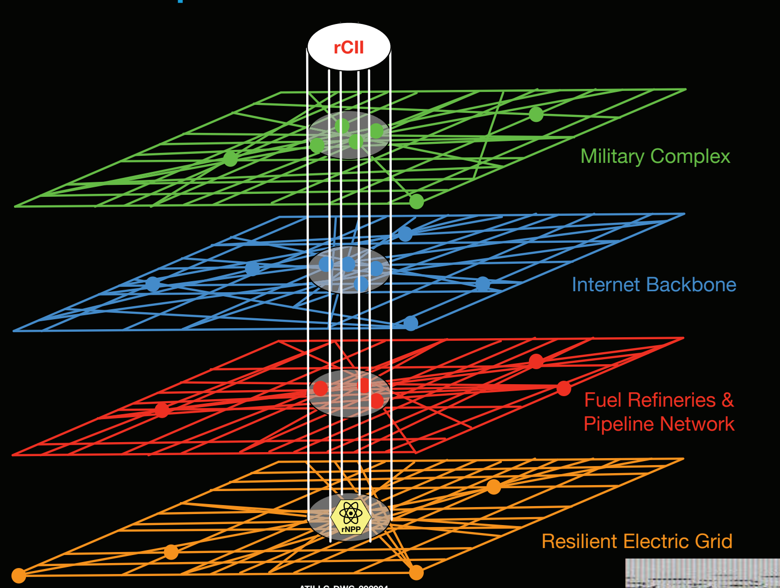
rNPP Black Start Units…

- Could operate in three Black Start Unit Ready States
- Would not be fuel-limited
- Would not be critical loads during Grid recovery operations
- Could enable Grid operators to depart from traditional serial Grid recovery and restoration process

rNPP-anchored rCIIs would be Strategic Resilience assets

rCIIs are networks of Critical Infrastructure, anchored by a rNPP, and sited at geospatial intersection of multiple Critical Infrastructure Sectors





Several design features could enable rNPPs

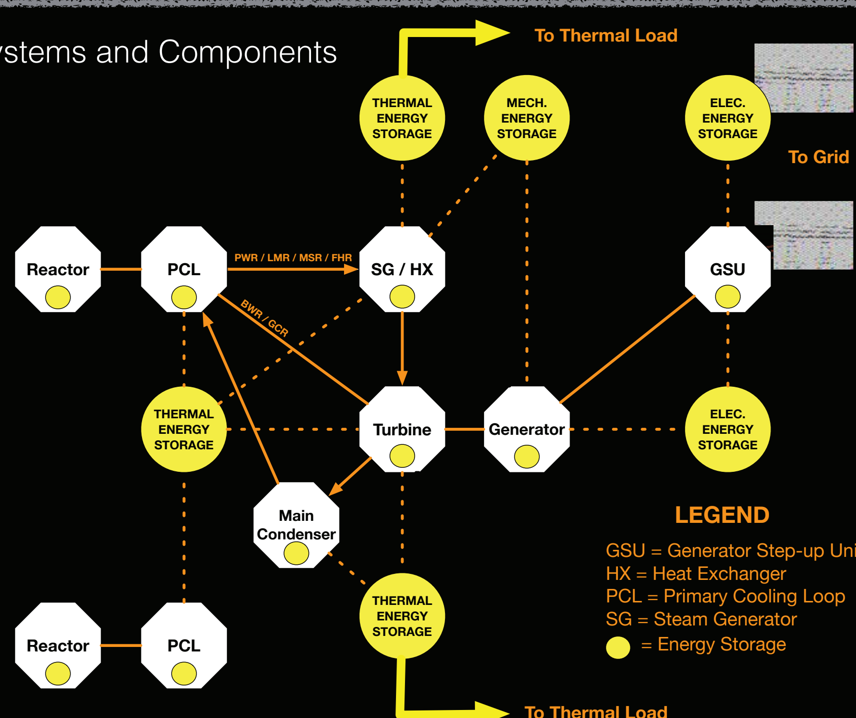
DC-DC or VFT NPP-Grid Interface	High Capacity Load Switching & Heat Rejection	Multiple Reactor Module NPP Architecture	Small Reactor Module Size	Adaptive Turbine–Generator Systems
Passive Shutdown Cooling	Passive and / or Active Energy Storage	Optimized Reactor Core (Physics)	Robust Nuclear Fuels	GMD/EMP* & Hack–Resistant IC&C* Systems

DC-DC = Direct Current – Direct Current
VFT = Variable Frequency Transformer
NPP = Nuclear Power Plant

GMD = Geomagnetic Disturbance
EMP = Electromagnetic Pulse
IC&C = Instrumentation, Control, and Computer

Many plant SSCs* and functions provide opportunity to embed storage

*Structures, Systems and Components



LEGEND

GSU = Generator Step-up Unit
HX = Heat Exchanger
PCL = Primary Cooling Loop
SG = Steam Generator
● = Energy Storage

Implementation of energy storage is complex trade

Plant-Level Functional Requirements

- Resilience
- Safety
- Op. Flexibility
- Reliability
- Capacity
- Availability
- Maintainability
- Economics

Implementation Options

- Storage Type
- Charge / Discharge Modes
- Storage Technology
- Storage / Conversion Efficiency
- Location
- Scale / Size
- System Complexity
- Cost
- Ownership

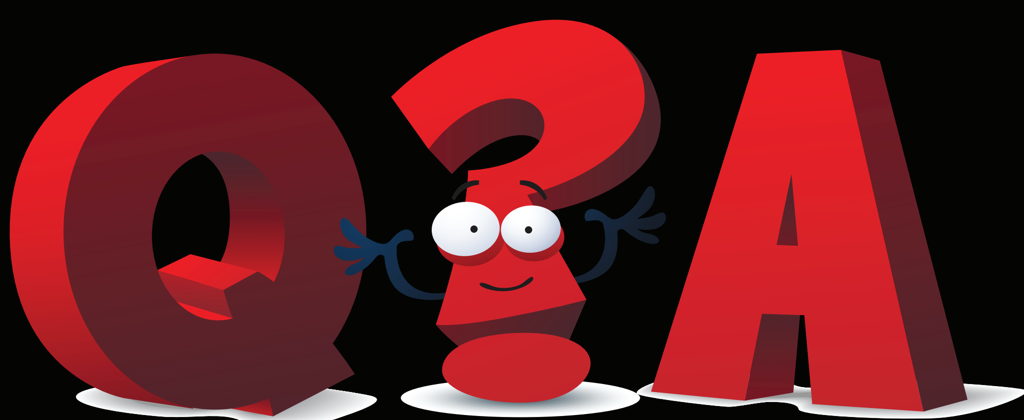
How can energy storage improve rNPP and Grid resilience behaviors?

- **Nominal Performance Range & Disruption Tolerance Time**
- **Shape of SRC**
- **Performance Levels**
  - Minimum
  - Restored
  - Recovered
- **Durations / Timing**
  - Shock & Response
  - Recovery
  - Restoration

Generic System Resilience Curve

Energy storage can enable more resilient NPPs and Electric Grids

- Grid and Critical Infrastructure resilience are key societal challenges
- NPPs can and should evolve to **r**NPPs - enabling Grid and Critical Infrastructure resilience
- Storage is one of several enabling **r**NPP design features
- Many options and trades for embedding storage in NPP design
- Need to focus on enabling key resilience behaviors



Thank You!

Presenter Bio:
Sherrell R. Greene, PhD

Dr. Sherrell R. Greene is the President of Advanced Technology Insights, LLC (ATI). Dr. Greene has 40 years experience in the nuclear energy arena, with specialized expertise in applied engineering research, advanced reactor concept development (for both terrestrial and space-based nuclear power systems), technology maturity assessment, systems analysis, nuclear systems licensing support, and U.S. nuclear technology export control compliance. He is an internationally recognized expert in the field of commercial nuclear power safety, in high-stakes technical and programmatic messaging and communications, and in the emerging field of electric Grid and Critical Infrastructure resilience assessment.

Dr. Greene founded Advanced Technology Insights, LLC in 2012, after a 33-yr career at Oak Ridge National Laboratory (ORNL). During his last seven years at ORNL, Dr. Greene served as Director of Nuclear Technology Programs and Director of Research Reactor Development Programs. In those roles, he was responsible for development and leadership of ~ $120M/yr of basic and applied nuclear technology and nuclear energy research for the U.S. Department of Energy (DOE), U.S. National Nuclear Security Administration (NNSA), the U.S. Nuclear Regulatory Commission (NRC), and the U.S. National Aeronautics and Space Administration (NASA) – as well as a host of international and domestic partnerships and collaborations in the governmental and private sectors.

Dr. Greene has worked with numerous scientific and technical organizations throughout North America, Europe, and Asia. His views and perspectives on complex technical issues have been sought by a variety of public media outlets, including National Public Radio, The Economist, Popular Science, Wired Magazine, and Japan's HNK television network.

Dr. Greene holds a B.S. and M.S. in Nuclear Engineering, and a PhD in Energy Science and Engineering from the University of Tennessee.

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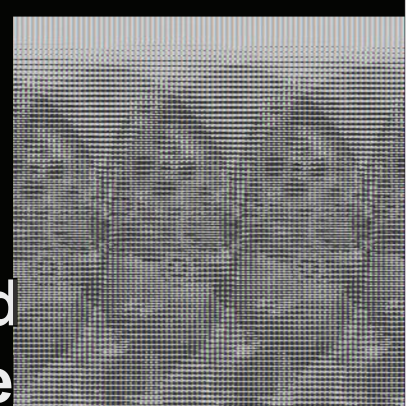
Backup

Integration of load prioritization into definition is necessary to capture reality…

- The societal impact / consequences of an outage depends not only on the magnitude, frequency, and duration of an outage at the BPS / BES level, but on **who** is denied service and **what** societal functions are impacted
- This reality is / should be embodied in the local distributor's **end-user** load prioritization hierarchy and **flow upstream** to all elements of the Grid architecture (**D** —> **T** —> **G**)

NPPs should evolve…
and so must our thinking

- ***From*** being simply
  - safe, reliable, and efficient sources of baseload electricity



- ***To*** being **rNPPs**
  - enablers of a **resilient Grid** and **Critical Infrastructure**

Grid resilience curve (GRC) illustrates application of generic SRC

Notional 3-Step Grid Resilience Curve (GRC)

Challenge is defining "Performance" and Resilience Metrics

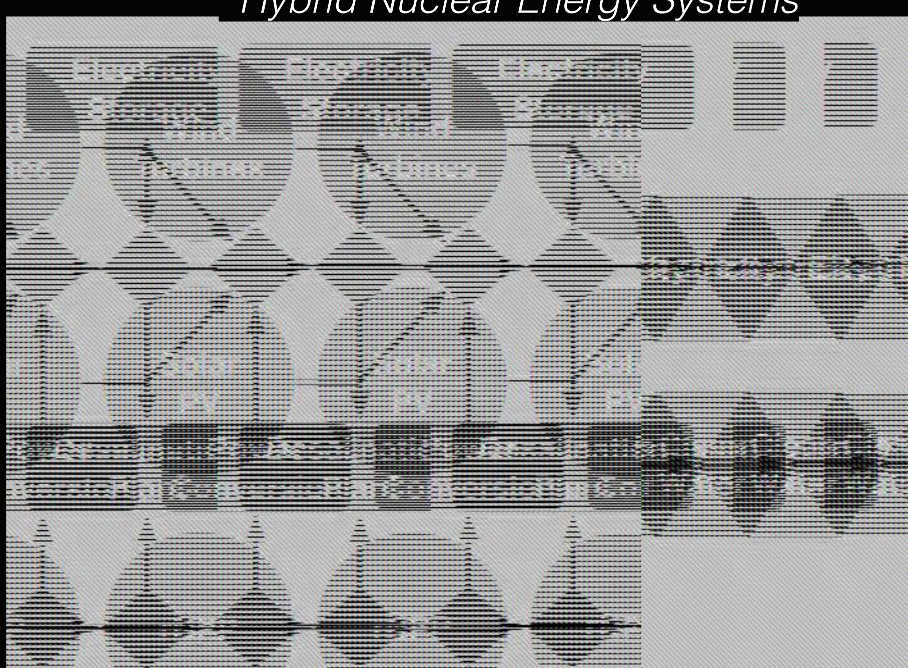
- SRC "Performance" is a multi-attribute function
- Need is for performance and resilience metrics
  - embody performance of integrated Grid (not simply BPS / BES)
  - capture impact of Grid architectures and operating modes
  - capture granularity of end-use disruption
  - useful both for predictive, forensic, and comparative analysis

rNPPs would have enhanced power generation flexibility

- Compared to current NPPs…
  - higher tolerance for off-normal load conditions
  - more frequent and rapid power ramping
  - deeper power cutbacks
  - extended low(er) power operations
- Enabling
  - operation as ancillary service providers
  - deeper penetration of renewable electricity generation sources
  - accelerated retirements of aged fossil units

rNPPs would be attractive anchors for HNES*

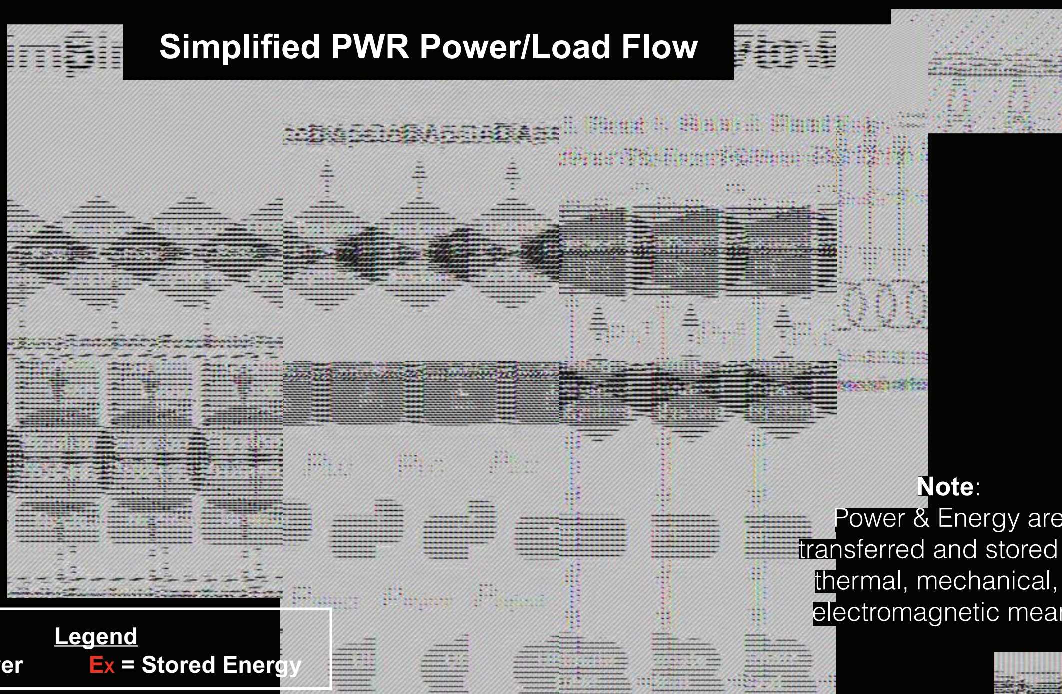
** Hybrid Nuclear Energy Systems*



Adapted from D. T. Ingersoll, "NuScale Power: Changing the Face of Nuclear Energy" (2018)

NPP's operational flexibility is power / load flow issue

Simplified PWR Power/Load Flow

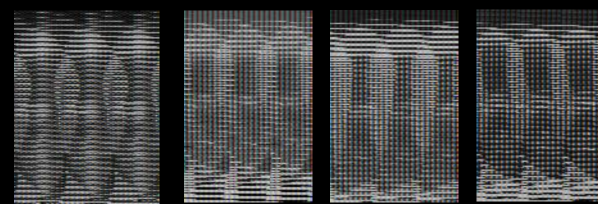


Legend
P_{xx} = Power E_x = Stored Energy

Note:
Power & Energy are transferred and stored via thermal, mechanical, & electromagnetic means

Combining Hot Rock and Nitrate Salts to Lower Heat Storage Costs

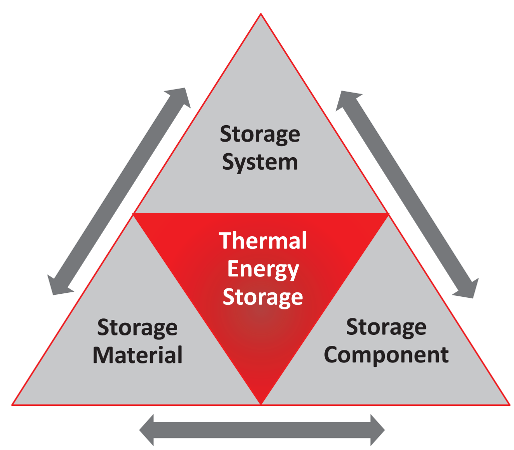
André Thess, Freerk Klasing, Christian Odenthal, Thomas Bauer
DLR German Aerospace Center
Institute of Engineering Thermodynamics



12 August 2020
Web Workshop – Session 2:
Separating Nuclear Reactors from the Power Block with Heat Storage:
A New Power Plant Design Paradigm

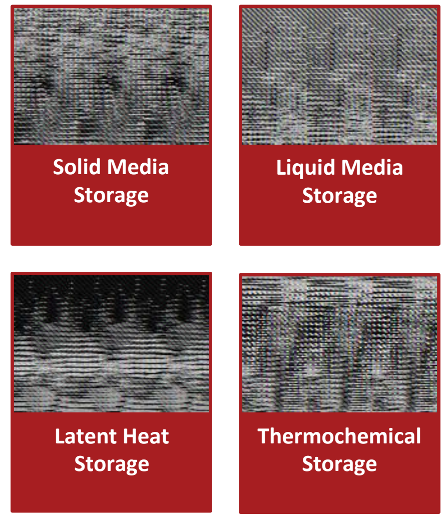
DLR Objectives of Thermal Energy Storage

- Increased level of flexibility and resilience to the energy system
- Development and experimental verification of cutting-edge thermal energy storage solutions
- Application-oriented research for the full spectrum of high-temperature TES technologies
- R&D on all TRLs, with international scientific collaborations and relevant industrial partners



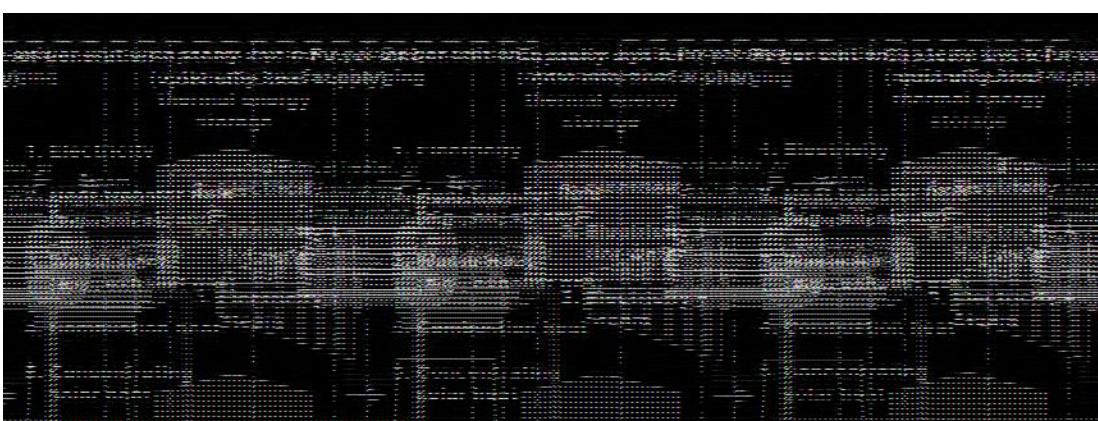
DLR Research Topics in Thermal Energy Storage

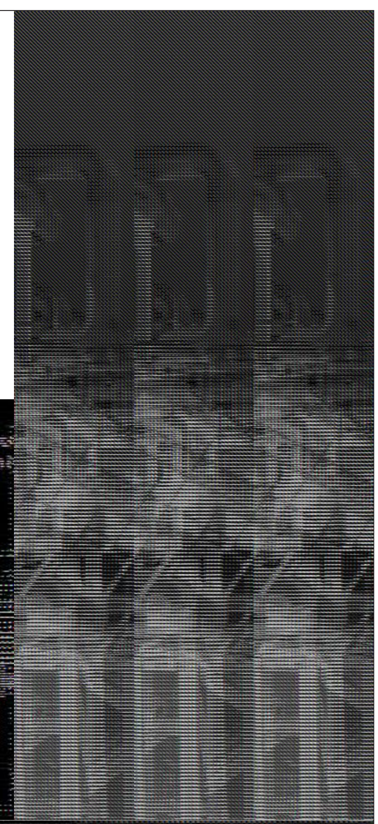
- Fundamental phenomena: Thermo-mechanics, reactions systems, salt chemistry, heat transfer
- Component development: Electrical heating, single-tank concept, heat exchanger design
- System Integration: Utility-scale electricity storage, industrial process heat, automotive applications
- Methodology: multi-scale modeling, coupled heat & mass transfer phenomena



Molten Salt Technology

1. Large-scale hourly storage for CSP Plants demonstrated (~3 GW_{el}, ~50 GWh_{th}, ~7 h average capacity in 2019)
2. Inexpensive, non-toxic, non-flammable, unpressurized medium
3. Separated heat exchanger for <u>constant</u> power and temperature
4. Potential to transfer technology from CSP to new applications

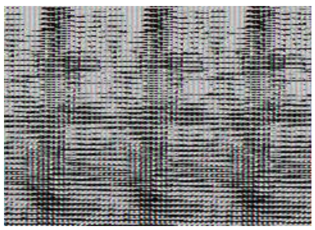




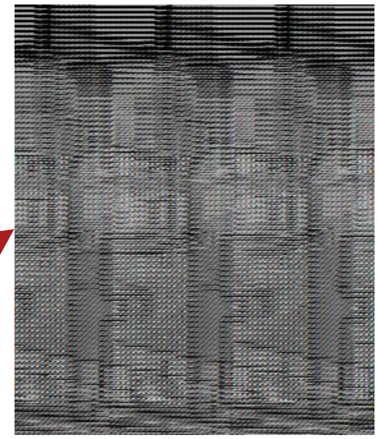
Nitrate salt systems for increased operation temperature

- Limitation today: Today's salt systems do not match the needs of modern power plant steam parameters
- Unique infrastructures for in-situ characterization with controlled gas atmosphere > 600°C


50 mg


100 g


100 kg

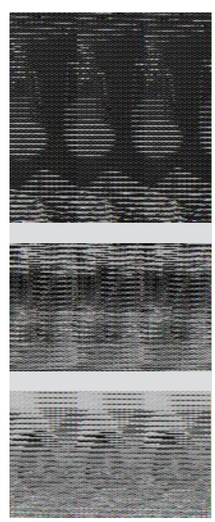

100 tons

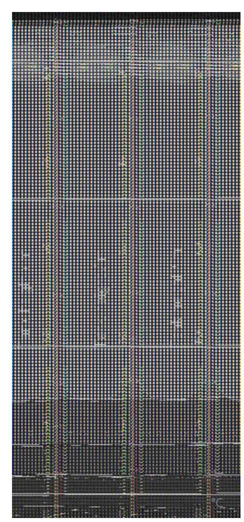
A. Bonk, S. Sau, N. Uranga, M. Hernaiz, T. Bauer, Progress in Energy & Combustion Science 67 (2018), 69-87

Single tank salt storage with filler materials

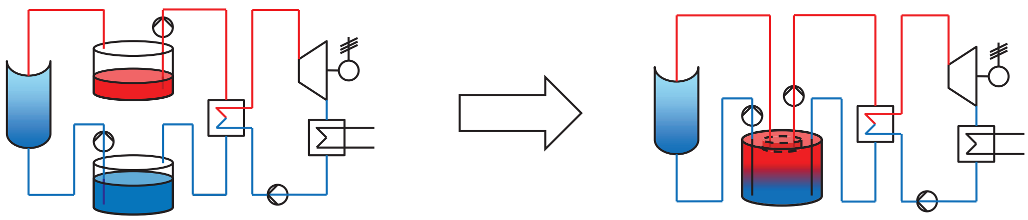
- Challenge: Further cost reduction (-40%) and higher volumetric energy density (+100%)
- World's largest high-temperature single-tank system with filler material
- Methodology developed for prediction of thermo-mechanical stress in the bulk material
- Further target is upscaling and system integration in power plants

C. Odenthal, F. Klasing, T. Bauer, Solar Energy 191 (2019), 410-419


20 t filler in 20 m^3 salt tank


measured temperature profile

Captial Cost of Thermocline filler vs. Two Tank



Two tank (2T) concept

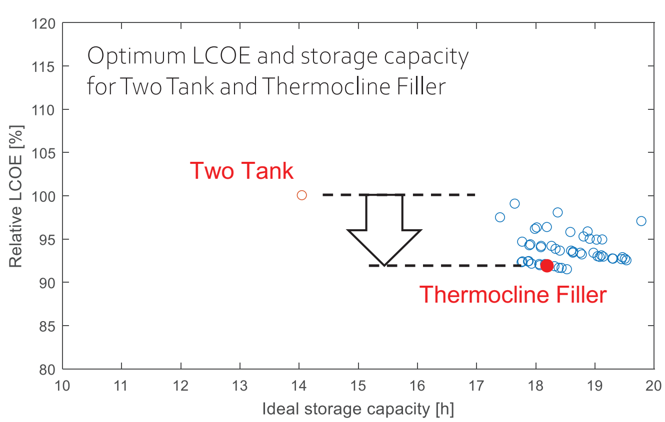
Thermocline filler (TCF) concept

TES-Costs = 100%

TES-Costs ~= 60%

F. Klasing, C. Odenthal, B. Trost, T. Hirsch, T. Bauer, AIP Conference Proceedings 2033, 090017 (2018)

Levelized electrictity costs of Thermocline filler vs. Two Tank



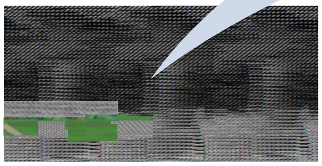
- LCOE: up to 8% lower levelized costs
- Storage capacity: Optimum shifts to higher capacities
- Thermodynamic inefficiencies have only little impact on levelized costs compared to capital cost savings for thermocline filler

F. Klasing,, T. Hirsch, C. Odenthal, T. Bauer, Journal of Solar Energy Engineering 142 (2020),

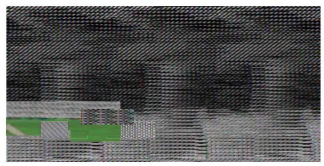
System integration for demand-oriented power generation

- Situation: limited experience beyond Concentrated Solar Power
- Utility-led concept development for flexible power plants successfully completed
- Hybrid power plants & Carnot Batteries (Reallabor) activities started

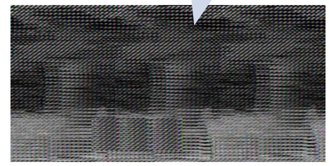
target



Today:
Power plant with lignite as fuel



Store-to-power:
Pilot plant as proof of technology for heat storage power plants

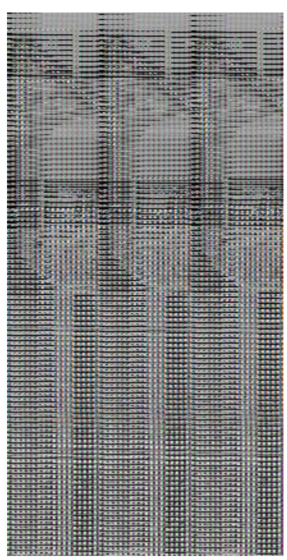


Post coal period:
Commercial sized power plants in pure storage mode using renewables

Research Infrastructure TESIS

Test facility for thermal energy storage in molten salts

- Part TESIS:store:
  world's largest research facility to investigate new single tank molten salt storage concepts
- Part TESIS:com:
  Testing and development of molten salt components for quality improvement and market introduction

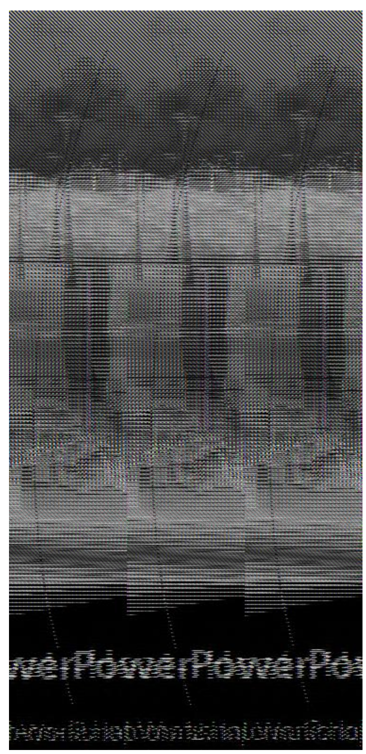


C. Odenthal, F. Klasing, T. Bauer, J. Energy Storage 17 (2018), 56-62

Summary

- High temperature TES = key technology for low carbon energy systems
- Molten salt TES at DLR: from materials to systems (TESIS infrastructure)
- Molten salt TES with filler material: significant potential for cost reductions
- Molten salt TES: potential application for decarbonization of coal plants

International Workshop on Carnot Batteries (Online)



For more information:

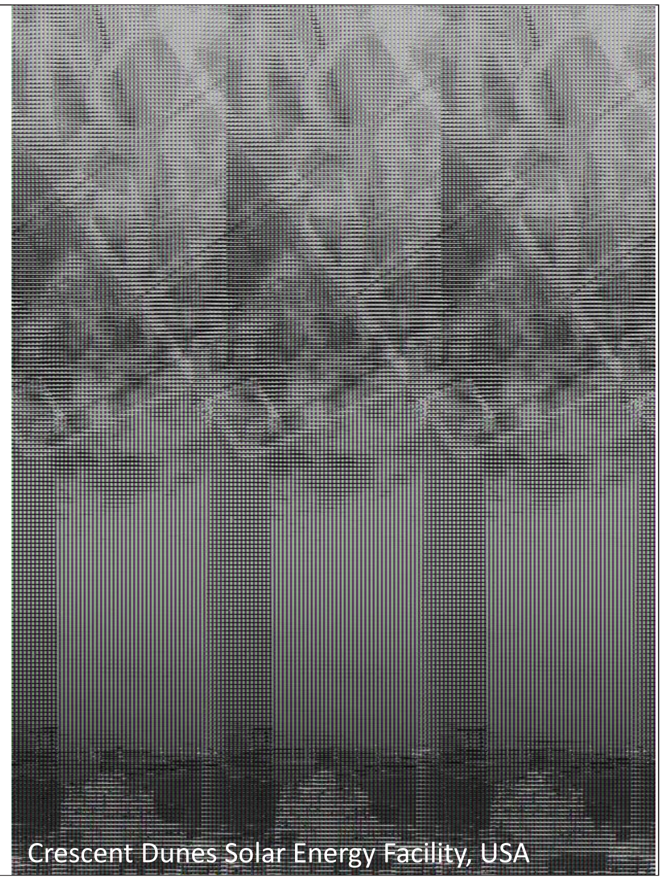
https://iwcb2020.besl-eventservice.de/

andre.thess@dlr.de

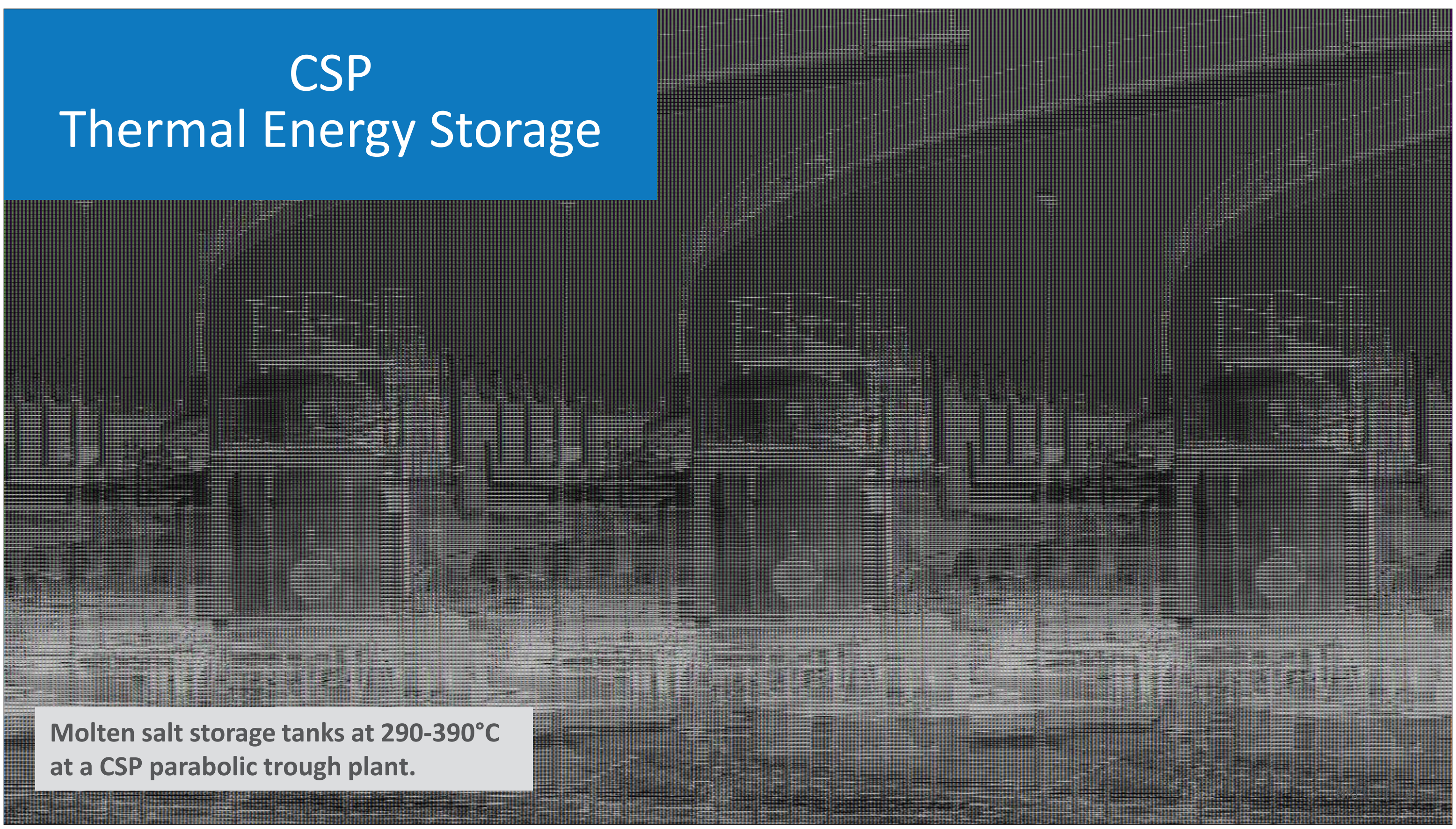
Advances in Chloride-salt Heat Storage

Workshop On Redesign of Nuclear with Heat Storage
August 12, 2020
Virtual Conference

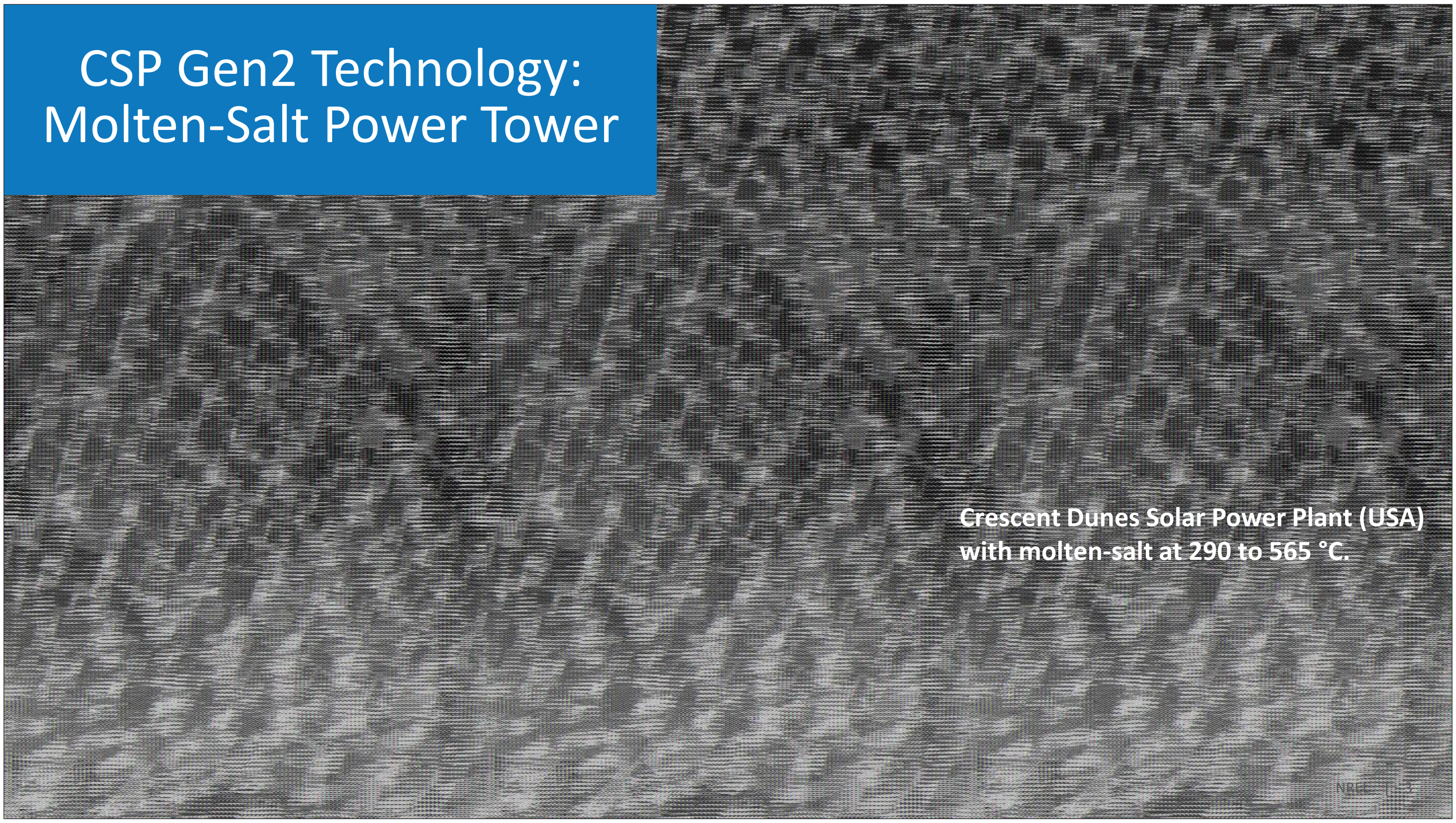
Craig Turchi, PhD
Thermal Energy Science & Technologies
National Renewable Energy Laboratory
craig.turchi@nrel.gov


Crescent Dunes Solar Energy Facility, USA

CSP Thermal Energy Storage


Molten salt storage tanks at 290-390°C at a CSP parabolic trough plant.

CSP Gen2 Technology: Molten-Salt Power Tower



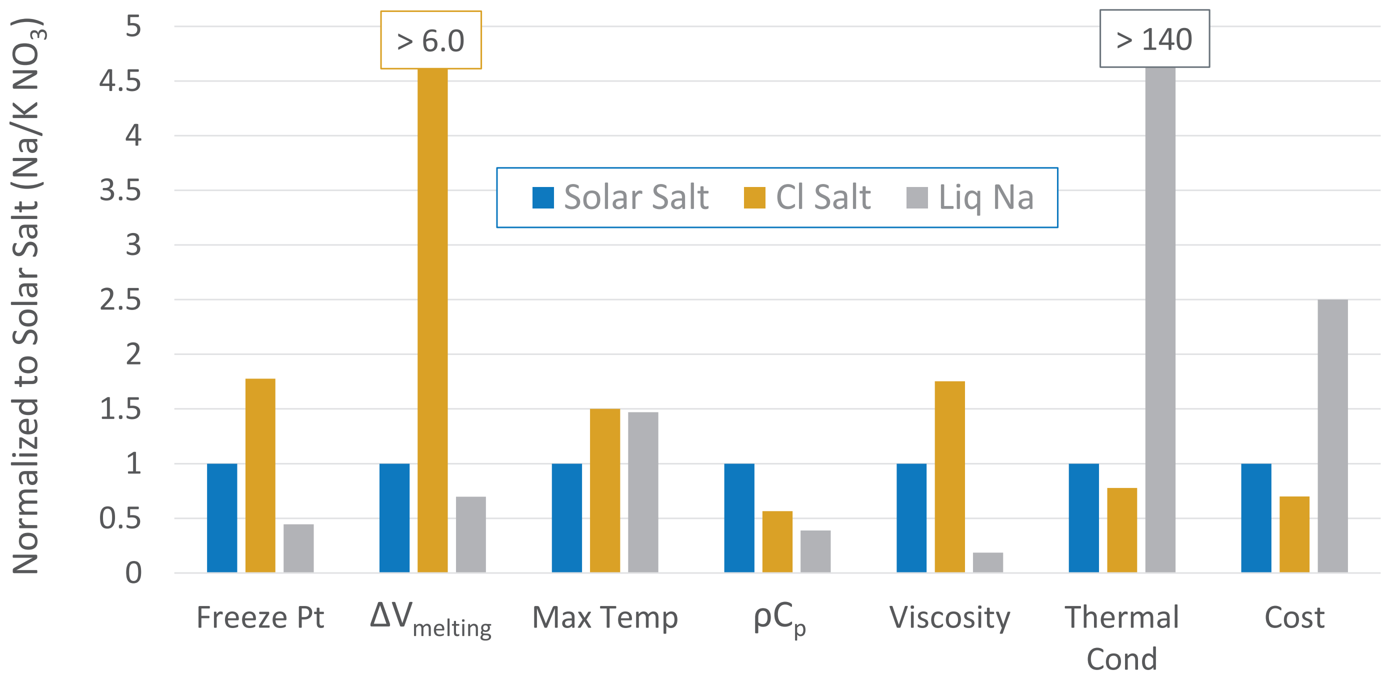
Crescent Dunes Solar Power Plant (USA) with molten-salt at 290 to 565 °C.

U.S. DOE's CSP Gen3 Program

In May 2018, the U.S. Department of Energy announced awards totaling $79 million for the CSP Gen3 program.

U.S. Department of Energy, https://www.energy.gov/eere/solar/generation-3-concentrating-solar-power-systems-gen3-csp

Gen3 Heat Transfer Fluids vs. Current Solar Salt



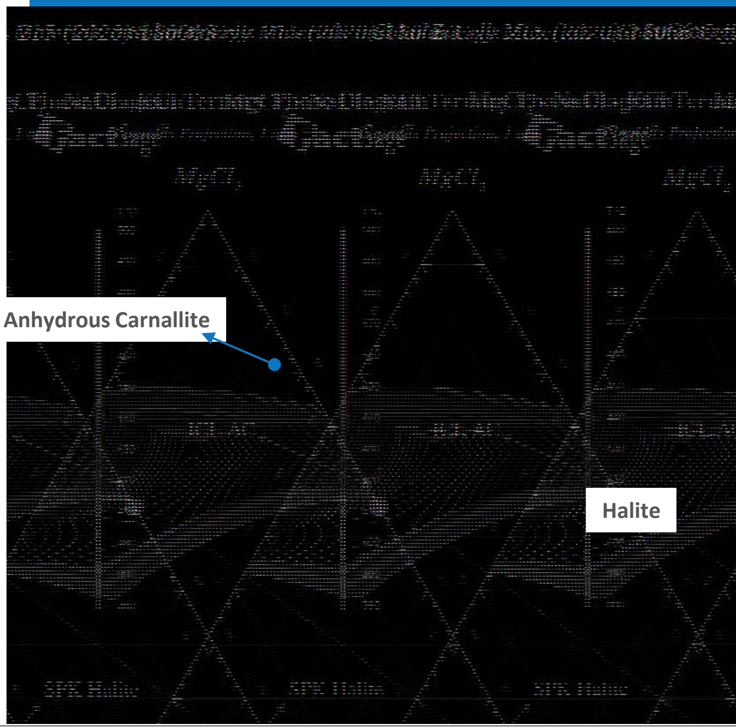
NREL | 5

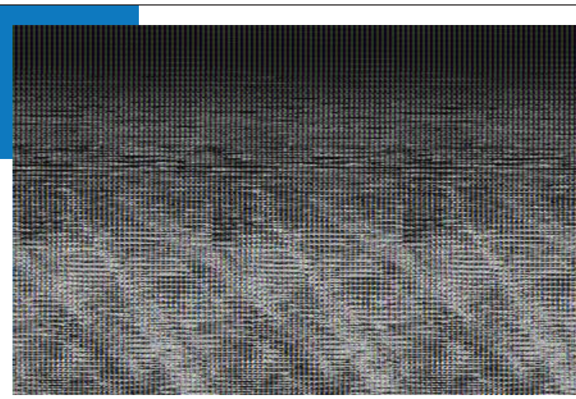
CSP Heat Transfer Fluids

Parameter	Solar Salt (Gen2)	Chloride Salt (Gen3)	Liquid Sodium (Gen3)
Composition	Binary $NaNO_3$-KNO_3	Ternary $MgCl_2$-KCl-NaCl	100% Na
Freezing Point (°C)	~238	~400	98
Volume change on melting	+3.3%	+20%	+2.6%
Stability Limit (°C)	~600	> 900	882 (bp)
Density (kg/m^3)	1770 @ 500°C	1560 @ 700°C	835 @ 700°C
Specific Heat (J/g-K)	1.53 @ 500°C	0.98 @ 700°C	1.26 @ 700°C
Viscosity (cP)	1.30 @ 500°C	2.28 @ 700°C	0.24 @ 700°C
Thermal Cond. (W/m-K)	0.54 @ 500°C	0.42 @ 700°C	64.2 @ 700°C
Major Concerns	NO_x formation Thermal stability	High freeze point Corrosion	Burns in air

NREL | 6

Chloride-Salt Formulation





Ternary Chloride Salt in Industry:

- 260,000 tons per year of carnallite is dehydrated, melted, and mixed with NaCl as feedstock for Mg production
- Target formulation is approx. (wt%):

  43% $MgCl_2$
  41% KCl
  16% NaCl

Salt Purification

Delivered Salt

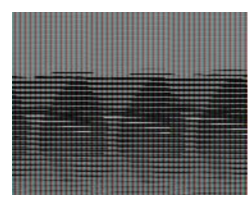
- Anhydrous carnallite: 49% $MgCl_2$, 38% KCl, 12% NaCl, < 1.5% H_2O by wt.
- Halite: NaCl

Dehydration and hydrolysis

117° to 400 °C
$MgCl_2 \cdot xH_2O \rightarrow MgOHCl + HCl(g)$

Thermal decomposition of MgOHCl

> 550 °C
$MgOHCl \rightarrow MgO(s) + HCl(g)$



Chemical purification

> 650 °C
$2\ MgOHCl + Mg \rightarrow 2\ MgO(s) + MgCl_2 + H_2\ (g)$

Settling of MgO and other impurities

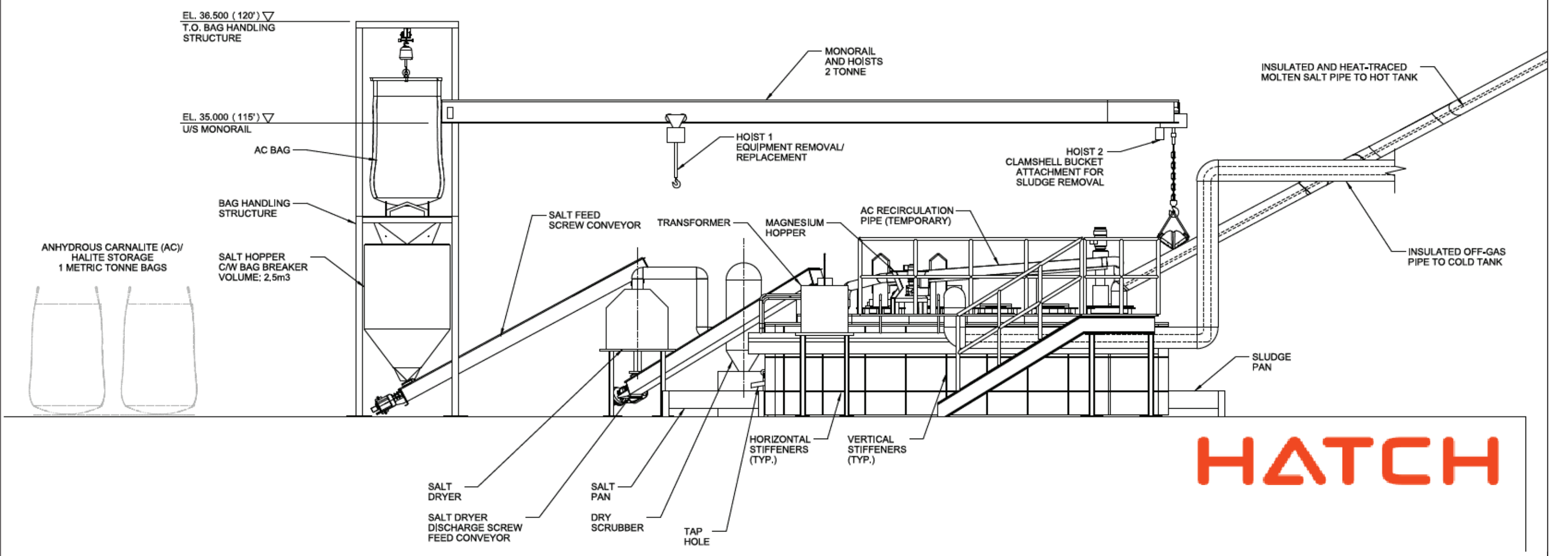
MgO, Fe, … ↓

MgOHCl is the primary concern:

- Its formation by hydrolysis produces HCl(g): corrosion
- Its thermal decomposition produces HCl(g): corrosion
- Its thermal decomposition produces MgO(s): erosion

➢ *Water must be kept out of the system*

Salt Melter: General Arrangement Drawing



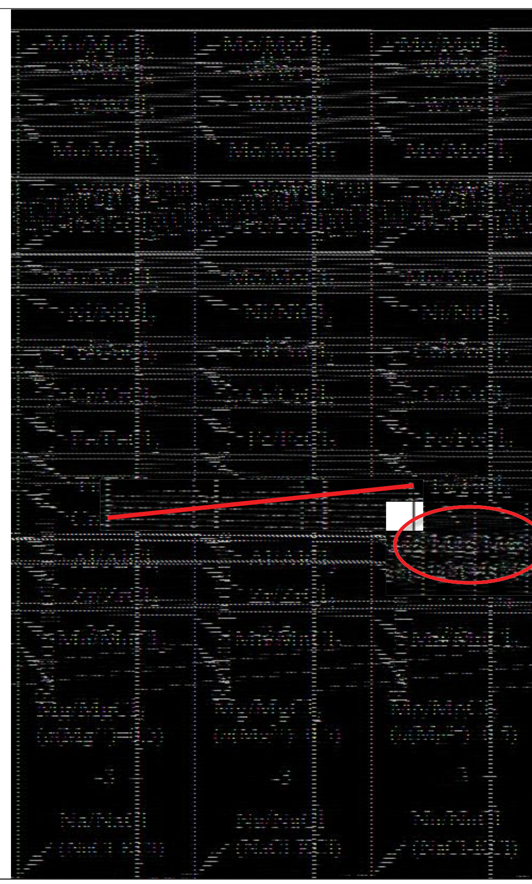
HATCH

Corrosion Protection

Mg^0 is used to protect other metals (e.g., Fe, Cr, Ni) within containment alloys against oxidation and extraction as mobile chlorides.

Left: Electrochemical sensor developed by Argonne National Laboratory

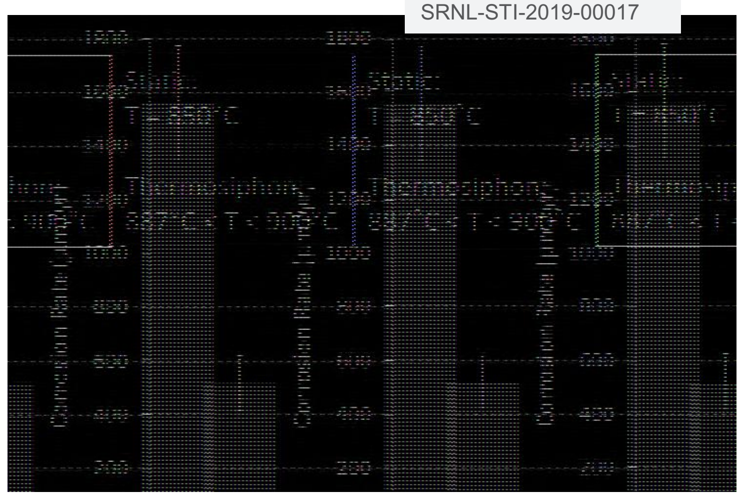
Right: Redox potentials as a function of temperature in chloride salts.
Guo et al., Progress in Materials Science, **97** (2018).



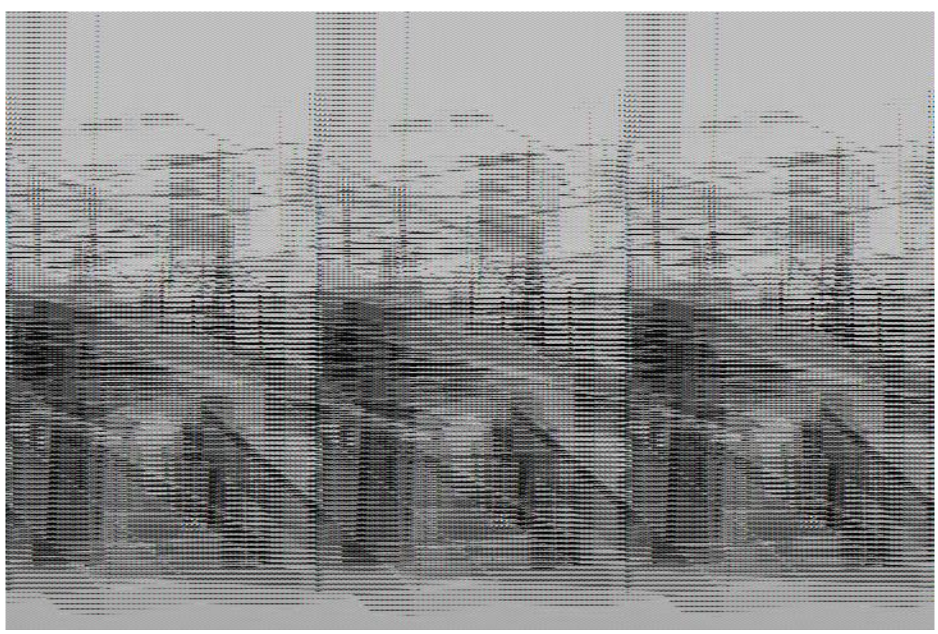
Corrosion Protection

- Above 650 °C Mg metal in the melt acts as an oxygen getter and redox control to protect against corrosion
- Extensive testing at Savannah River and Oak Ridge National Labs

Corrosion of Haynes 230
in chloride melt
SRNL-STI-2019-00017

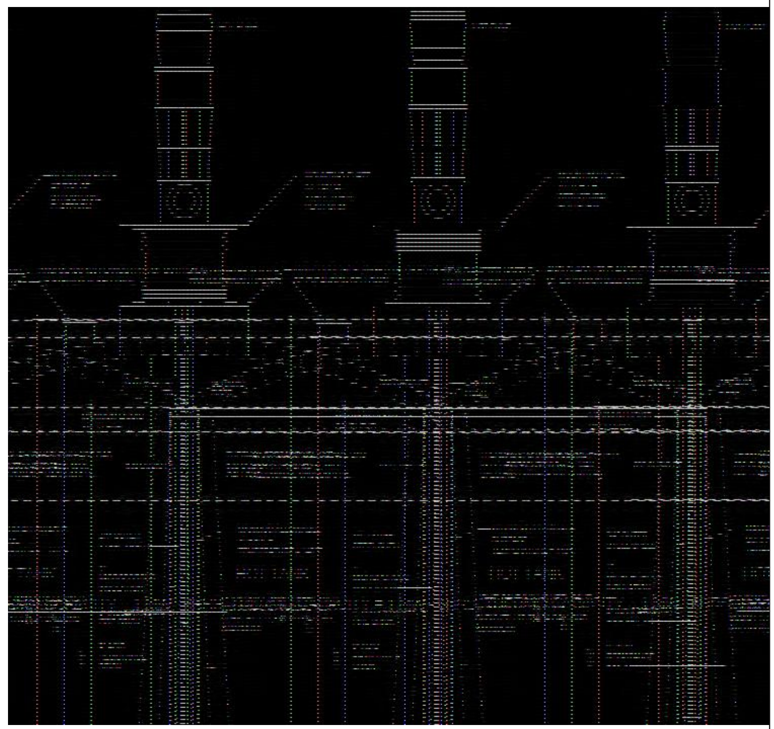


Molten Salt Storage Tanks

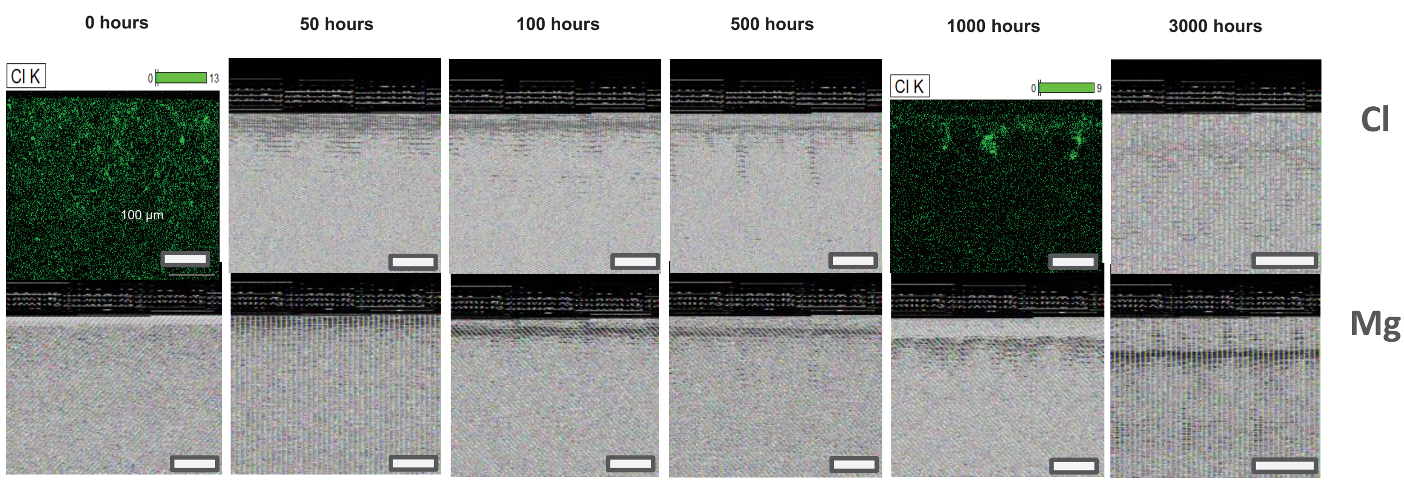


Pilot System Tanks

- Refractory-lined carbon steel tanks
  - Liner design patterned after Dead Sea Magnesium electrolysis vats
  - Tank wall design temperature is approximately 60 °C
  - Heat loss estimated at 123 W/m^2, equivalent to approx. 1% thermal losses per 24 hours (at full scale)
- Pilot-scale tanks will test liner and expansion joint design

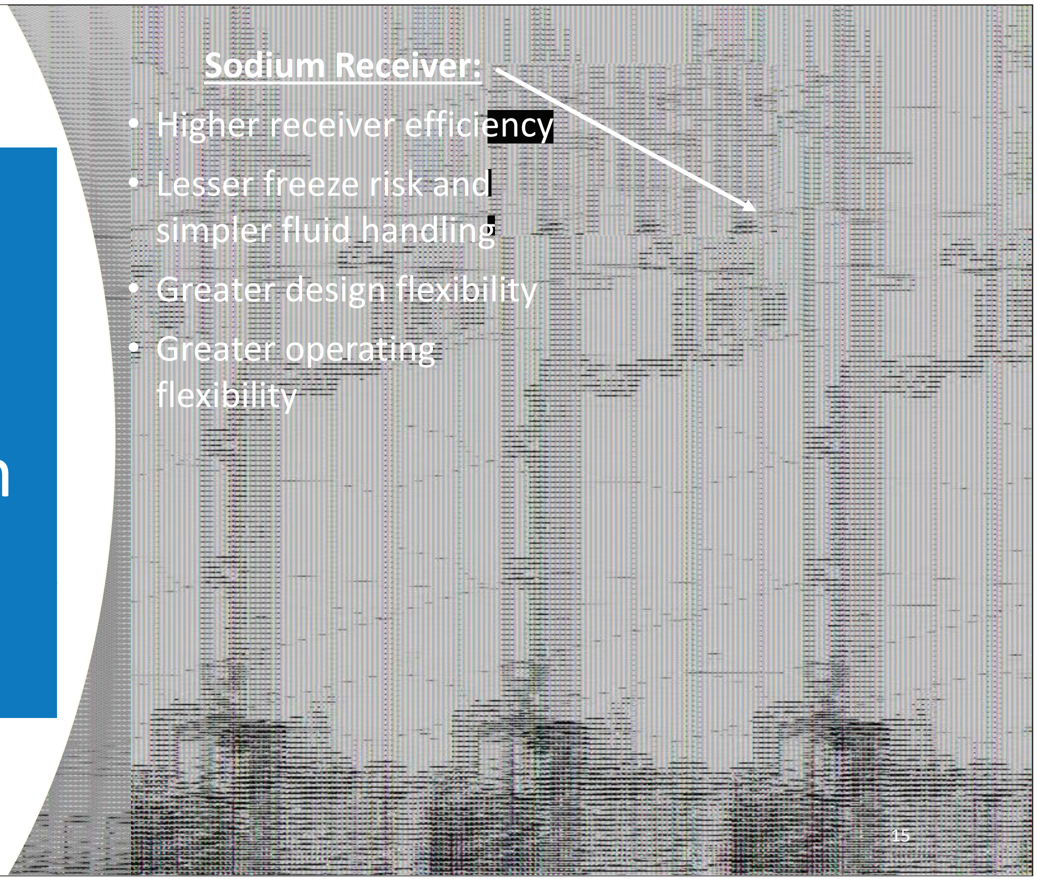


Tank Liner Materials: 3000-hr Salt Immersion Tests on Hot Face



Salt permeation into hot face brick as a function of time. EDS maps of cross-sectioned brick sample immersed in molten chloride salt up to 3000 hours. Estimated penetration depth < 0.2 mm per year.

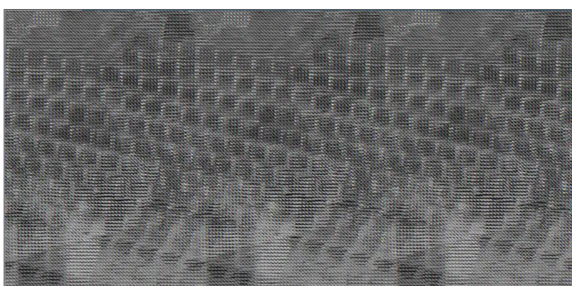
Integrated System Design

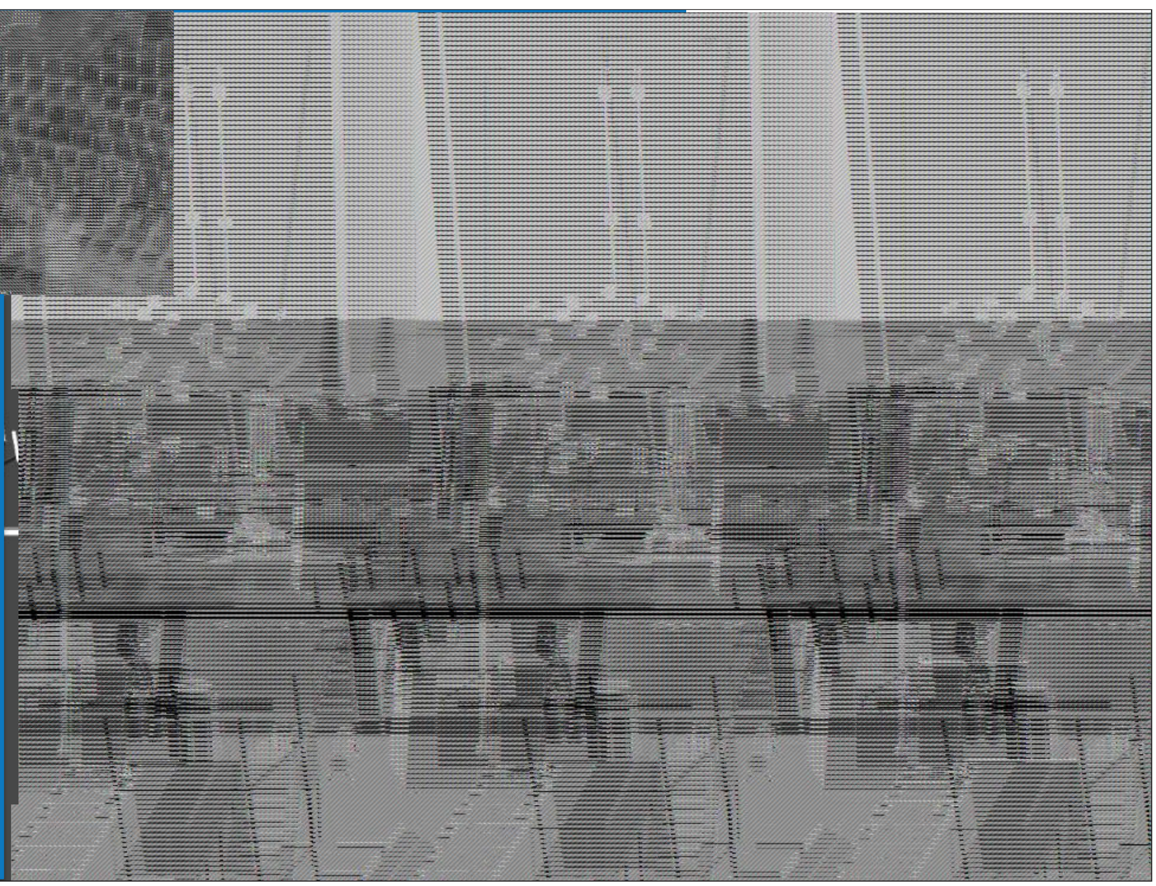


Sodium Receiver:

- Higher receiver efficiency
- Lesser freeze risk and simpler fluid handling
- Greater design flexibility
- Greater operating flexibility

15





Representation of the 1-MWt pilot scale system proposed for the National Solar Thermal Test Facility (inset)

Pilot Unit Summary Information

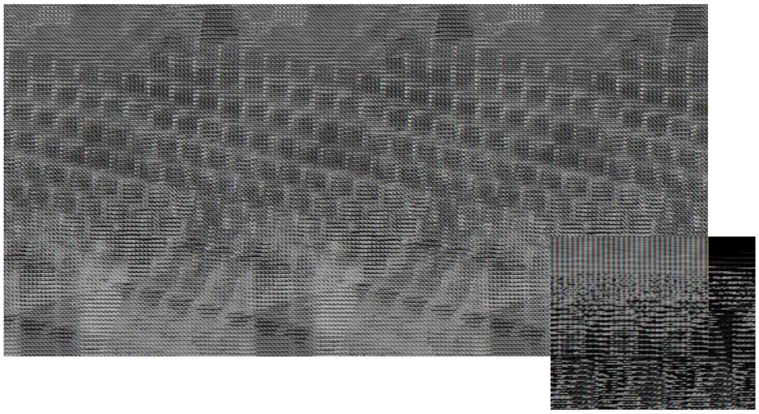
Component	General Specifications
Tanks (2)	Refractory-lined carbon steel, 6.4-m OD, 18 m^3 capacity
Cold side piping	500°C design, stainless 304H, all welded assembly
Hot side piping	720°C design, alloy H230, all welded assembly
Control valves	Globe valve, extended bonnet, bellows seal
Pumps	Long shaft, vertical turbine, Ni-alloy wetted parts with coating(s)
Salt quality control	Filtration and Mg contacting on cold side loop; electrochemical sensors
Cover gas	Dry nitrogen with purge gas scrubbing
Freeze protection	Heat tracing and ceramic fiber heaters, immersion heaters in tanks
Salt-to-sCO_2 Heat Exc.	Compact, diffusion-bonded design

Summary

- Ternary $MgCl_2$/KCl/NaCl molten salt for energy storage
  - Low cost, high operating temperature
  - Commercial source
  - Physical properties defined
  - Initial melting/purification process developed and mimics commercial practice of magnesium industry
  - Corrosion control requires careful redox monitoring and addition of Mg
- Salt tank design is major challenge – failsafe internal insulation is required
- Sodium to be used in the solar receiver to take advantage of its superior heat transfer properties and greater design and operating flexibility

Future: Integrated System Test

Phase 3 testing planned for Sandia's National Solar Thermal Test Facility



Key Objectives:

1. Demonstrate effective salt chemistry and corrosion control
2. Fabricate durable, cost-effective thermal storage tanks
3. Operate liquid-sodium receiver >720°C
   - Confirm temperature and heat transfer rates
   - Demo startup, shutdown, and power ramping
   - Define guidelines for receiver operations
4. Validate pumps, valves, and piping
5. Validate primary HX performance
6. Perform component and system modeling and simulate full-scale performance

Sandia National Laboratories

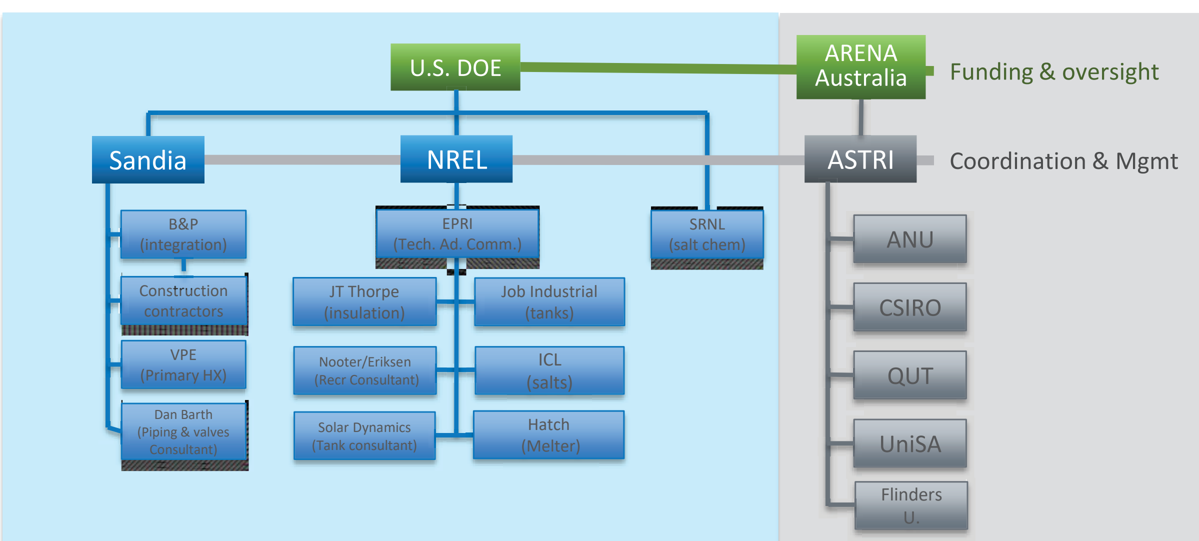
Thank you

www.nrel.gov

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Molten-Salt Tank Liner

Liquid Pathway Project Team



Can we Get the Capital Costs of Heat Storage Down to $2/kWh?

Hot Rock from Gigawatt Hours to Gigawatt Years

Charles Forsberg

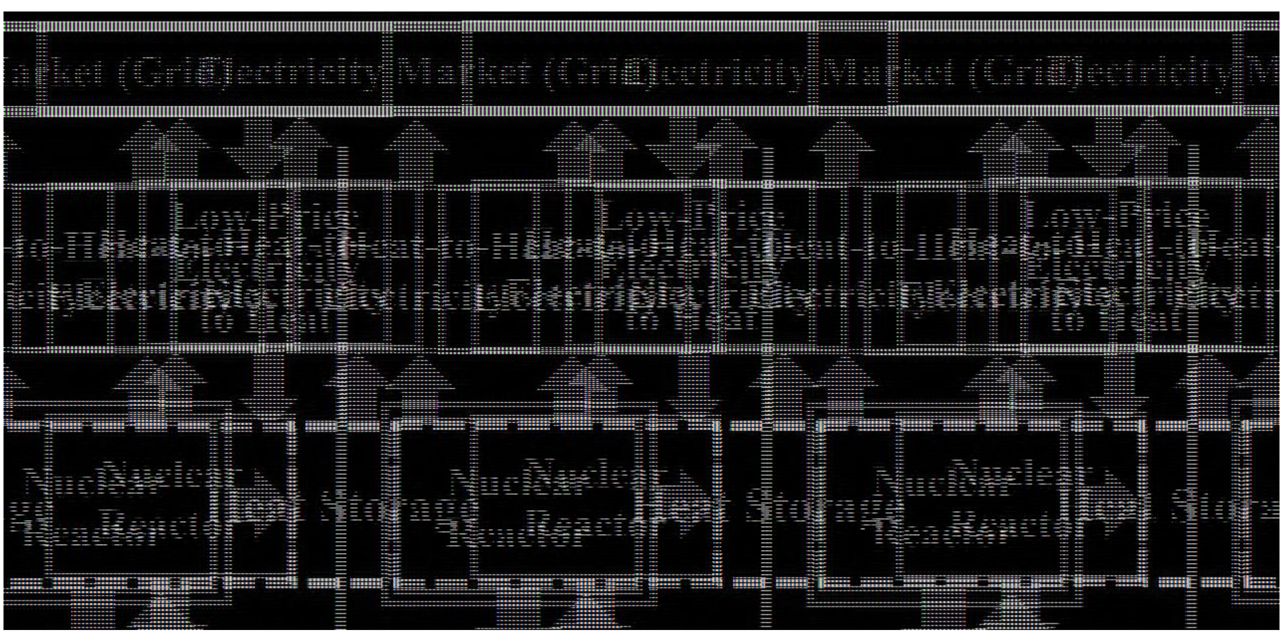
Massachusetts Institute of Technology Cambridge, MA 02139,
Email: cforsber@mit.edu

MIT / INL / EPRI Web Workshop: Separating Nuclear Reactors from the Power Block with Heat Storage: A New Power Plant Design Paradigm

August 12, 10:00 AM to 1:00 PM Eastern

1

Power System for Reactor with Heat Storage



Today | Nuclear Power with Heat Storage

2

Three Features of Low-Cost Heat Storage System

- Low-cost heat storage material: Rock
- Low-cost containment system (equivalent to tank)
- Minimize inventory of heat transfer fluid from power cycle to storage and from storage to power block
  - Heat transfer fluids cost more than hot rock

[redacted] 3

Hot Rock Heat-Storage Options

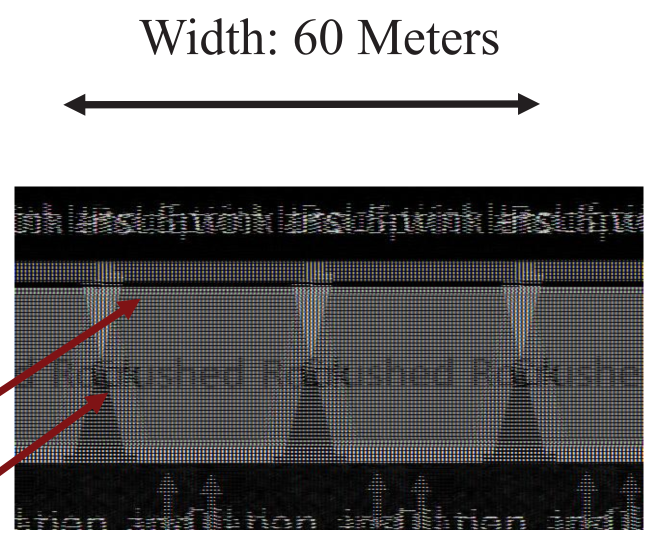
Heat Storage Material (Scale)	Containment	Heat-Transfer Coolant
Crushed Rock (1-100 GWh)	Insulated Trench with Insulated Roof and Drain Pan	Heat Transfer Oil (<400°C)
		Nitrate Salts (<600°C)
Underground Rock Enhanced Geothermal (0.1 to 10 GW-Years)	Variable Rock Permeability	Pressurized Water (<300°C)
		Super-Critical Carbon Dioxide (<600°C)

[redacted] 4

100 Gigawatt-Hour Low-Cost Crushed-Rock Heat Storage with Heat Transfer Using Oil or Nitrate Salt

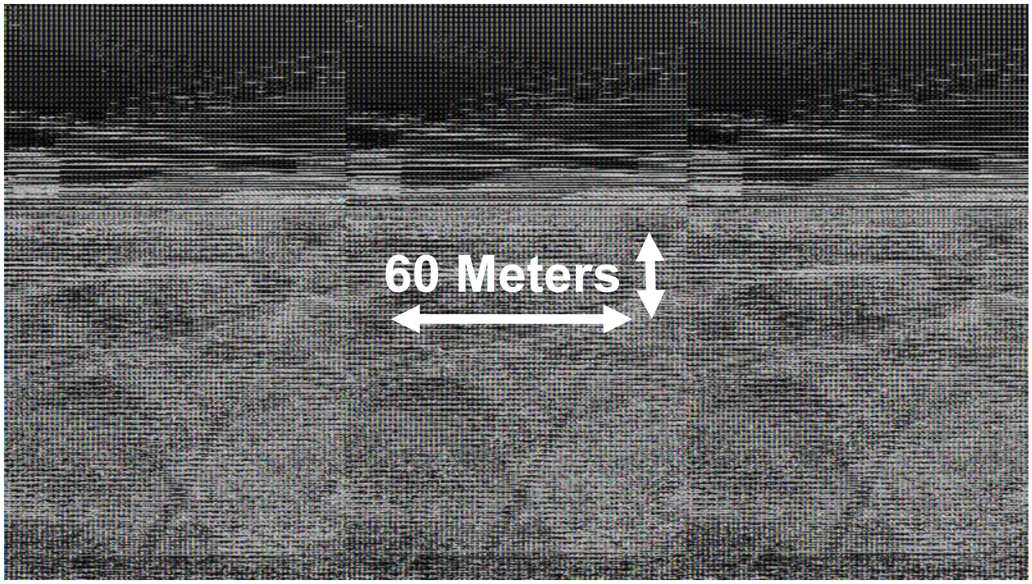
100-GWh Crushed-Rock Trench Heat Storage

- Single trench storage container
  - 60 m wide
  - 20+ meter high
  - 100 to 1000 meters long
- A gigawatt-hour of heat storage or more per 10 meters of trench length
- **Crushed rock: lowest-cost heat storage**
- **Minimize surface (steel and insulation) to volume ratio to minimize costs**



Neyland Stadium (U. of Tenn.) Vs Hot Rock Storage

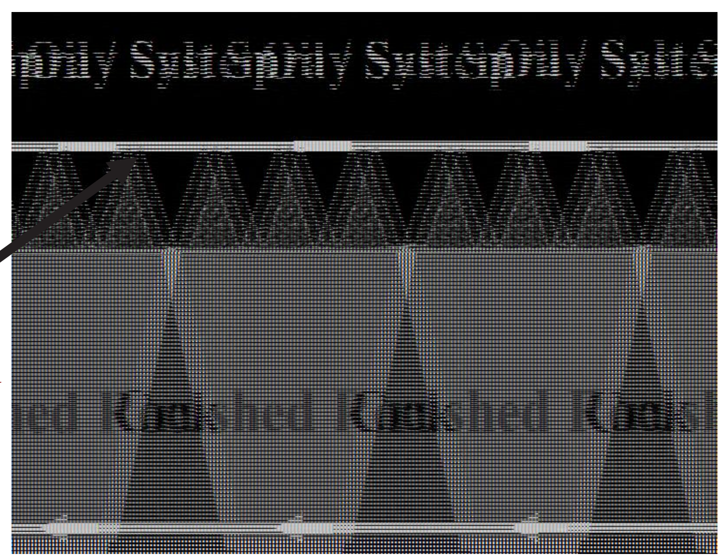
- American Football Field
  - 44.8 m Wide
  - 91.44 m Long



U.T. Sports

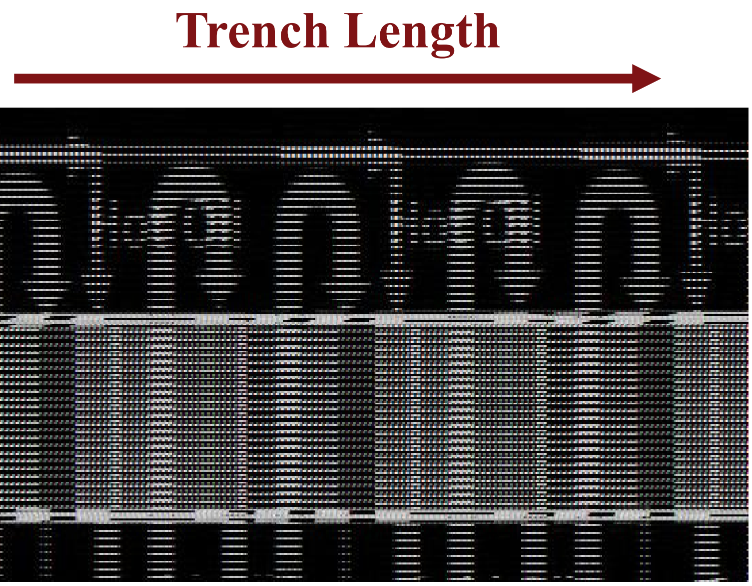
Transfer Heat from Reactor-to-Storage and Storage-to-Power-Cycle with Heat Transfer Oil or Liquid Salt

- Heat transfer fluid depends upon reactor type
  - Heat transfer oil for LWRs (<400°C)
  - Liquid nitrate salts for higher-temperature reactors (To 600°C)
- Spray hot or cold fluid over rock with gravity flow to salt or oil pan at bottom
- **Minimize heat transfer fluid inventory and cost—fluid moves heat, not used for heat storage**



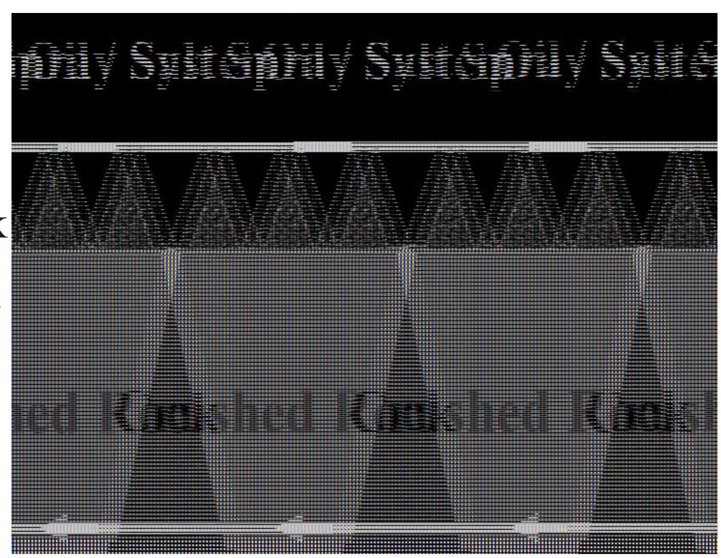
Sequential Heating or Cooling of Crushed Rock Section by Section

- Move left-to-right wave of hot fluid to heat rock
- Second left-to-right wave of cold fluid heated by crushed rock to power cycle



Minimizing Heat-Transfer Fluid Inventory Has Multiple Advantages

- Spray minimizes cost by minimizing oil or salt inventory
- Spray avoids hydrostatic pressure of tanks filled with liquid and crushed rock
  - If liner failure, near-zero hydrostatic pressure to leak fluid from system
  - Leakage limited to small inventory near leak—not stop operations



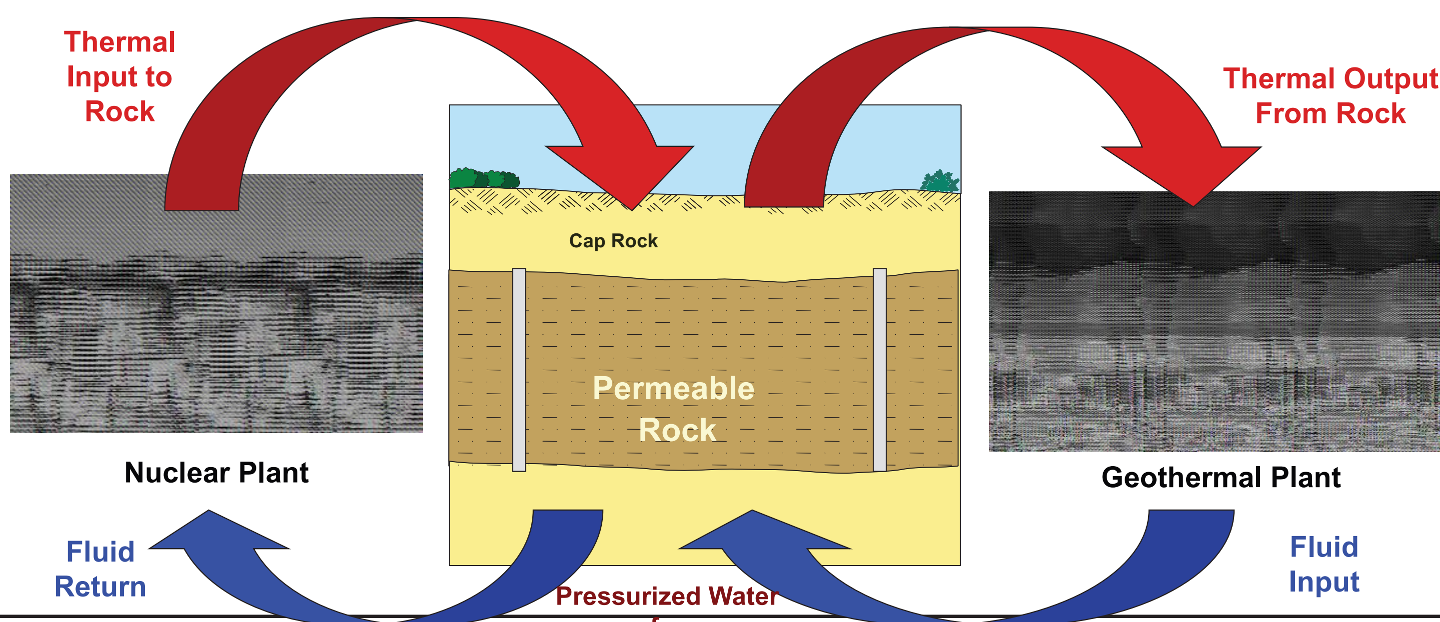
Nuclear Geothermal Heat Storage (0.1 to 10 GW-Year)

Hourly to Seasonal Storage

[redacted]

Geothermal Heat Storage System

Create Artificial Geothermal Heat Source



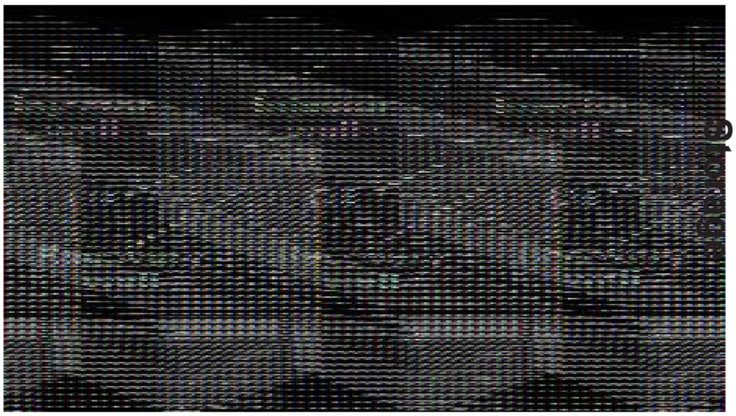
[redacted]

Nesjavellir Geothermal power plant; Iceland; 120MW(e); Wikimedia Commons (2010)

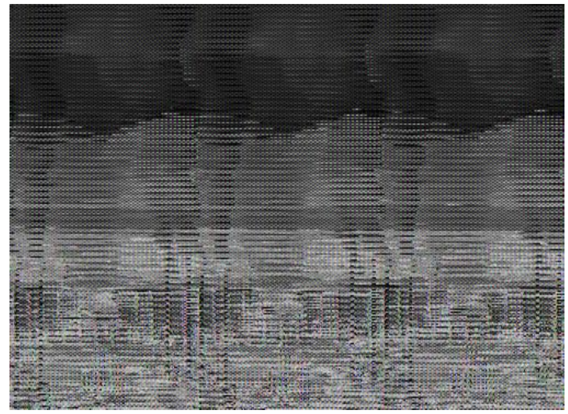
Nuclear-Geothermal Storage Is Based On Two Technologies

Recovery of Heavy Oil By Reservoir Heating

California and Canada

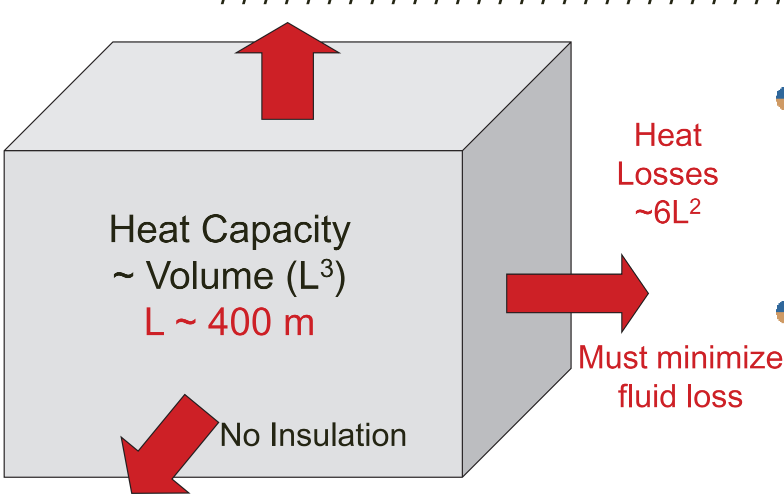


Geothermal Power Plant Heat Extraction



[redacted]ourtesy of Schlumberger; Nesjavellir Geothermal power plant, Iceland: 120MW(e); Wikimedia Commons (2010)

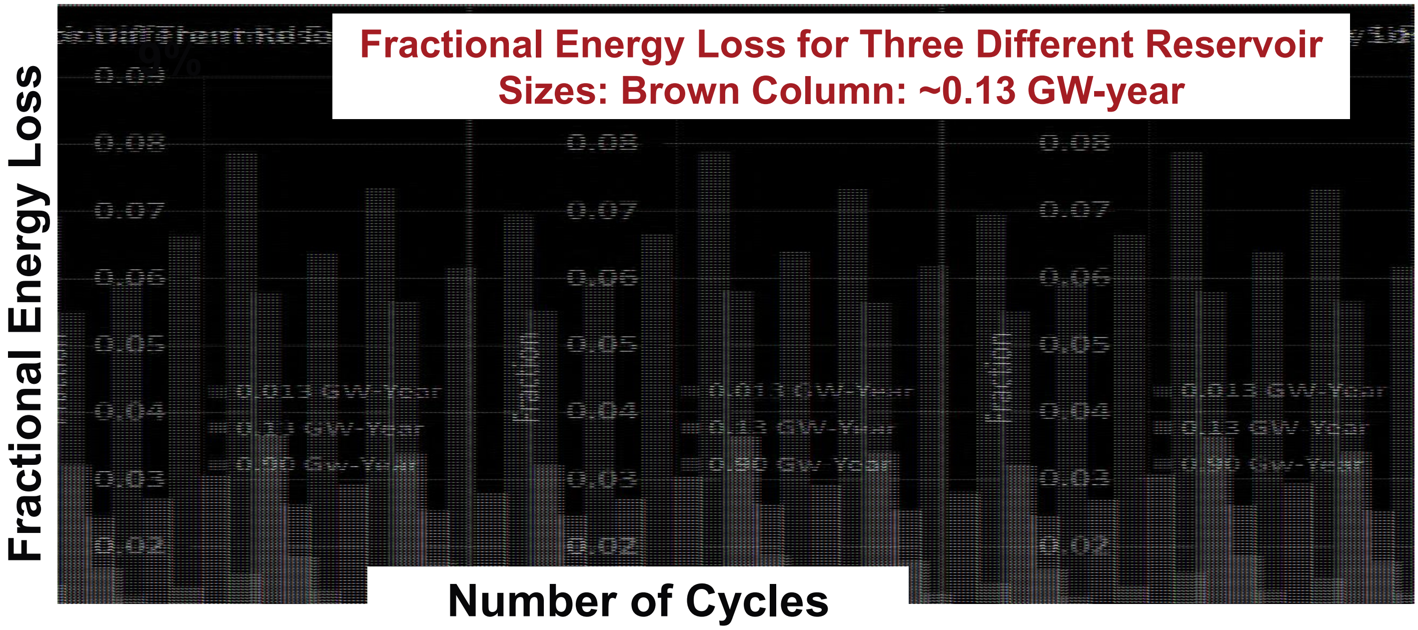
Heat Storage Must Be Large to Avoid Large Heat Losses: >0.1 GW-Year of Heat



- Can not insulate rock
  - Heat loses ~ surface area
  - Heat capacity ~ volume
- Large storage has smaller fractional heat loses

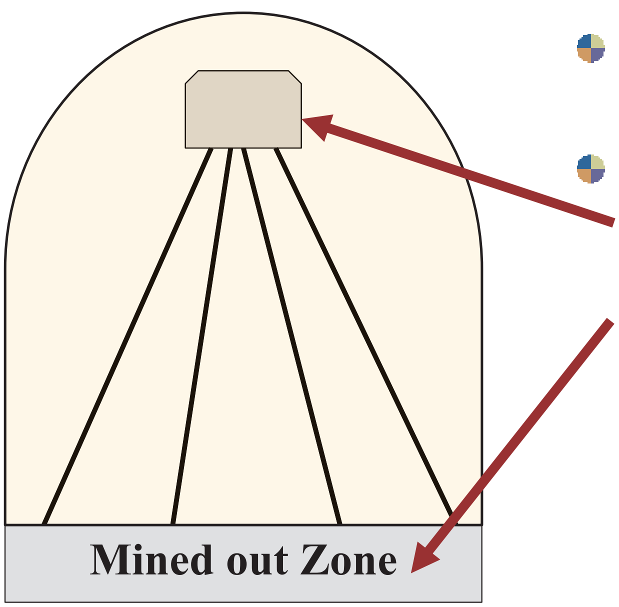
[redacted]

Seasonal Storage Energy Losses With Size



[redacted] Fixed Parameters Inlet Temp. 250^{o}C, Outlet Temp. 30^{o}C, Porosity 0.2, D/L = 0.331, Cycle Length = 6 months

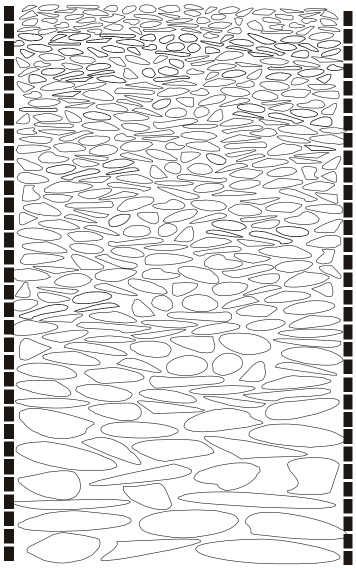
Create Highly Permeable Heat-Storage Rock Zone by Cave Block Mining: Option I



- **Standard mining technique used in copper and iron mining**
- **Mining technique**
  - Tunnel at top of future storage zone
  - Mine out zone at bottom
  - Controlled explosive detonation in boreholes create crushed rock zone
  - Crushed rock void volume matches voids of original mined rock zone

[redacted]

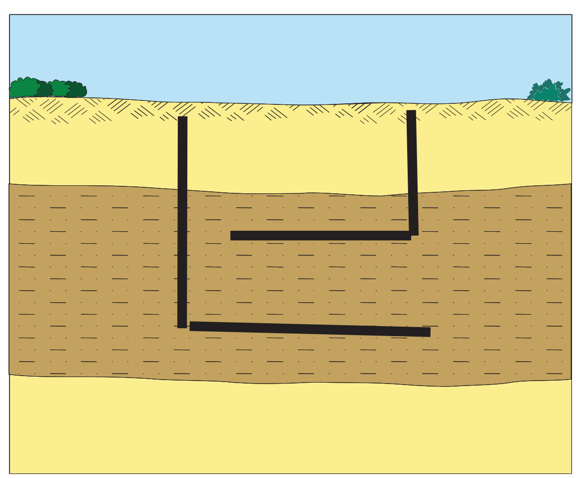
Create Permeable Heat-Storage Rock Zone by Selective Dissolution: Option II



- Many oil deposits (minus oil) have high permeability and void fractions
- Install nuclear geothermal heat storage system
  - Operates as washing machine with hot and cold cycles to extract oil
  - Remove oil at power plant
  - Oil as secondary product
- Initial operation for oil recovery and heat storage

Create Highly Permeable Heat-Storage Zone in Sandstone by Hydrofracture: Option III

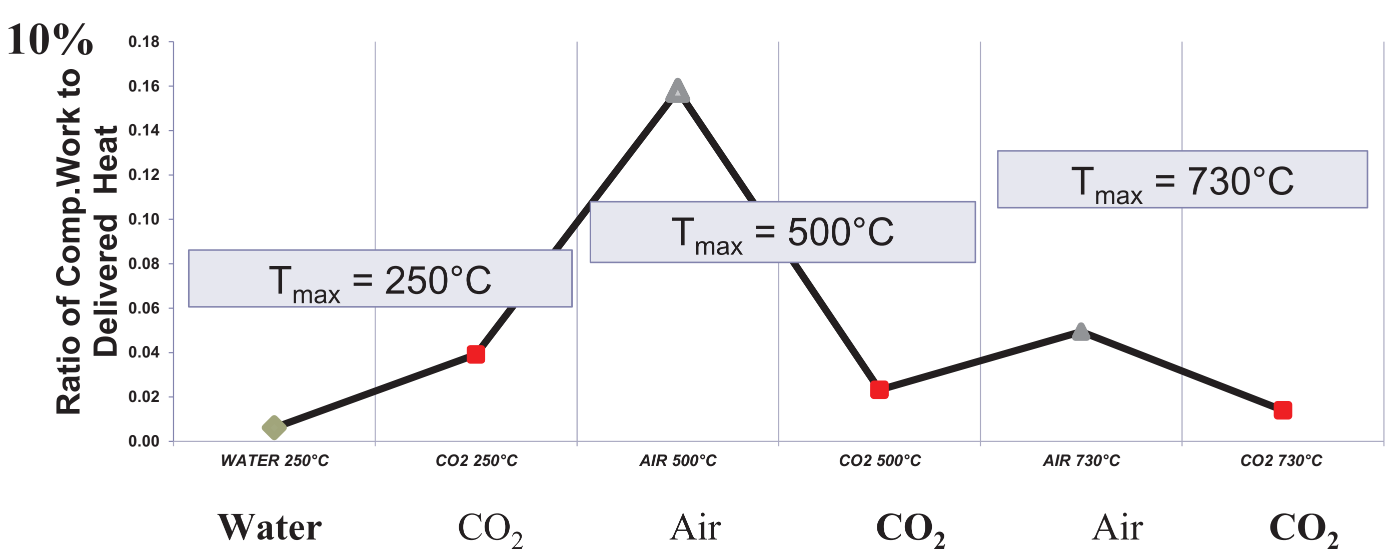
- Chose geology with reasonably high permeability
- Hydrofracture to increase permeability
  - Standard oil field technology
  - Inject water with sand to pry open fractures
  - Higher permeability



Choosing a Heat Transfer Fluid

- Requirements
  - **Compatible with geology over operating temperature range**
  - **Low pumping costs**
  - **Very low costs**
- Options
  - Air
  - Steam: Couples depth with condensation temperature
  - Pressurized water
  - Supercritical carbon dioxide

Pressurized Water (<300°C) and Super-Critical CO_2 (>300°C) Minimize Pumping Costs

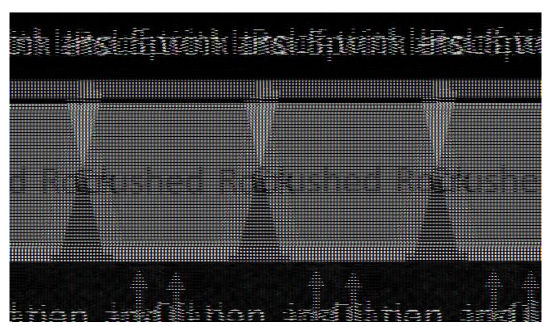


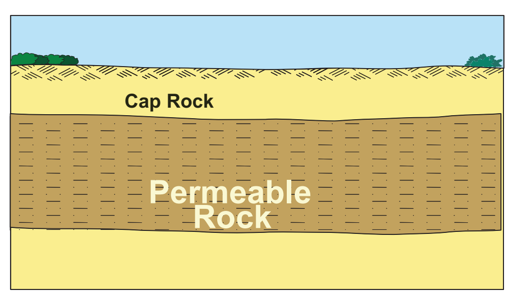
Status of Mega Hot-Rock Storage

Heat Storage Material (Scale)	Heat-Transfer Coolant	Status / Challenges
Crushed Rock In Trench (1-100 GWh)	Heat Transfer Oil: LWR (<400°C)	Near-Term Option Design/Pilot Plant
	Nitrate Salts (<600°C)	Rock/Salt Interactions
Underground Rock Enhanced Geothermal (0.1 to 10 GW-Years)	Pressurized Water: LWR (<300°C)	Develop Power Cycle, Geology
	Super-Critical Carbon Dioxide (<600°C)	Long-term Option

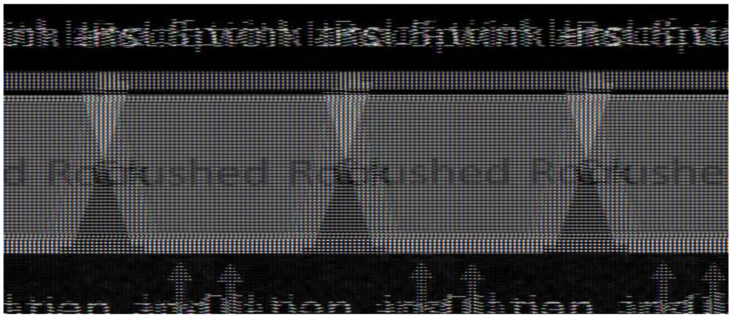
Conclusions

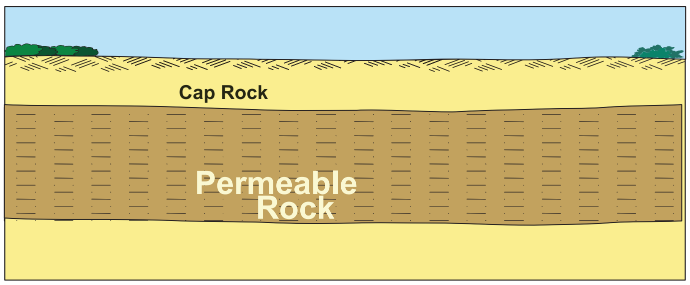
- Minimize storage cost with three features
  - Rock heat storage
  - Small container surface to volume ratio
  - Minimize heat transfer fluid inventory
- Two classes of options
  - Trench (build anywhere)
  - Geological
- Potential for $2/kWh capital cost





Questions





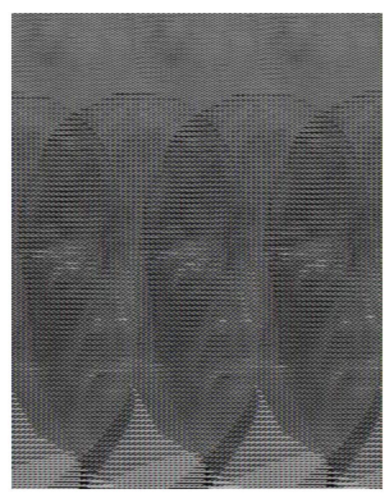
Acknowledgement Students

- You Ho Lee
- Rebecca Krentz-Wee
- Isaiah O. Oloyede
- Martin Kulhánek
- Ali S Aljefri
- Mriganka Mandal

Biography: Charles Forsberg

Dr. Charles Forsberg is a principal research scientist at MIT. His research areas include Fluoride-salt-cooled High-Temperature Reactors (FHRs) and utility-scale heat storage including Firebrick Resistance-Heated Energy Storage (FIRES) and 100 GWh heat storage systems. He teaches the fuel cycle and nuclear chemical engineering classes. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory.

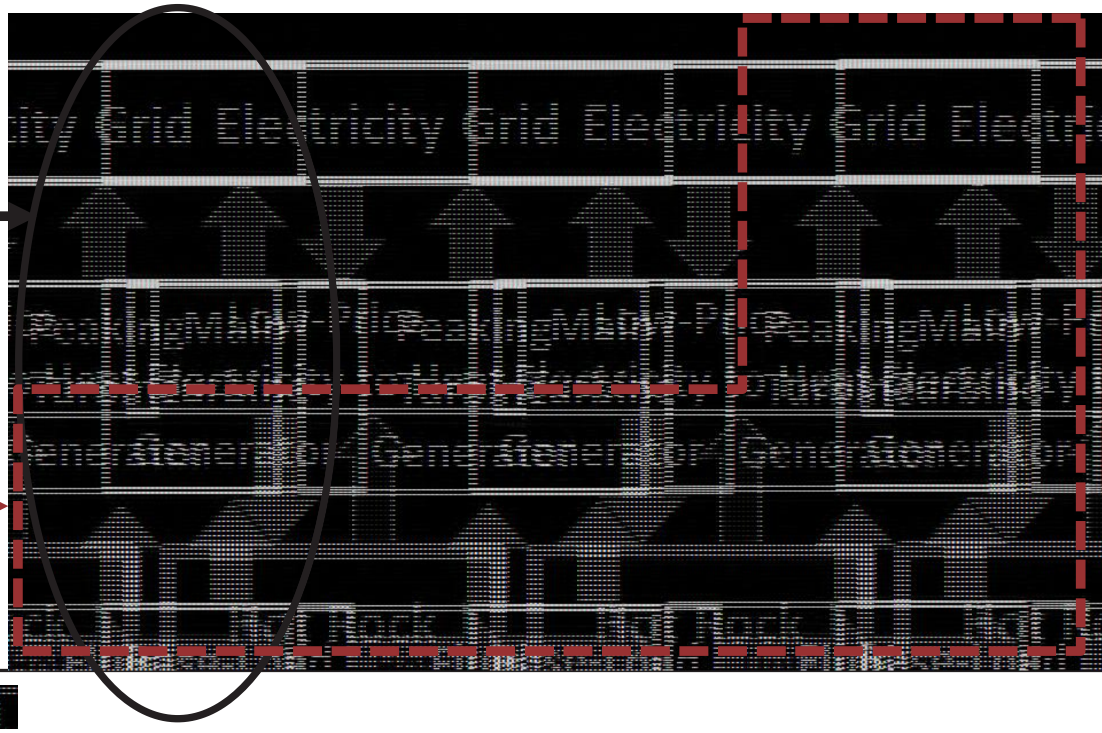
He is a Fellow of the American Nuclear Society (ANS), a Fellow of the American Association for the Advancement of Science, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in waste management, hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design and is a Director of the ANS. Dr. Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. He has been awarded 12 patents and published over 300 papers.



http://web.mit.edu/nse/people/research/forsberg.html

Power System for Reactor with Heat Storage

- Normal power cycle
- Heat Storage Cycle



Chose Heat-Transfer Oil or Nitrate Salt Depending Upon Reactor Peak Coolant Temperatures

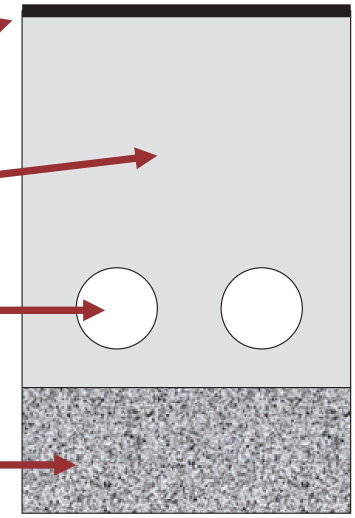
Both Coolants Used in CSP Heat Storage Tanks

- **Heat transfer oils <400°C for light water reactors**
  - Used in CSP and chemical plants for about a century
  - Inert relative to most types of rock
- **Nitrate salts <600°C, other salts for higher-temperature operation**
  - Used in CSP systems and some heat treatment facilities
  - Must carefully chose compatible rock types

Simple Container Structure to Minimize Cost

Similar to Solar-Nitrate Heat-Storage Tank Foundation

- Steel catch pan for heat-transfer oil or liquid nitrate salt—segmented sections with no requirement for continuous welded structure
- Insulation layer
- Air cooling channel to maintain cool foundation temperatures (natural circulation)
- Foundation



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Require Fluid Clean-Up System for Heat-Transfer Oil or Nitrate Salt

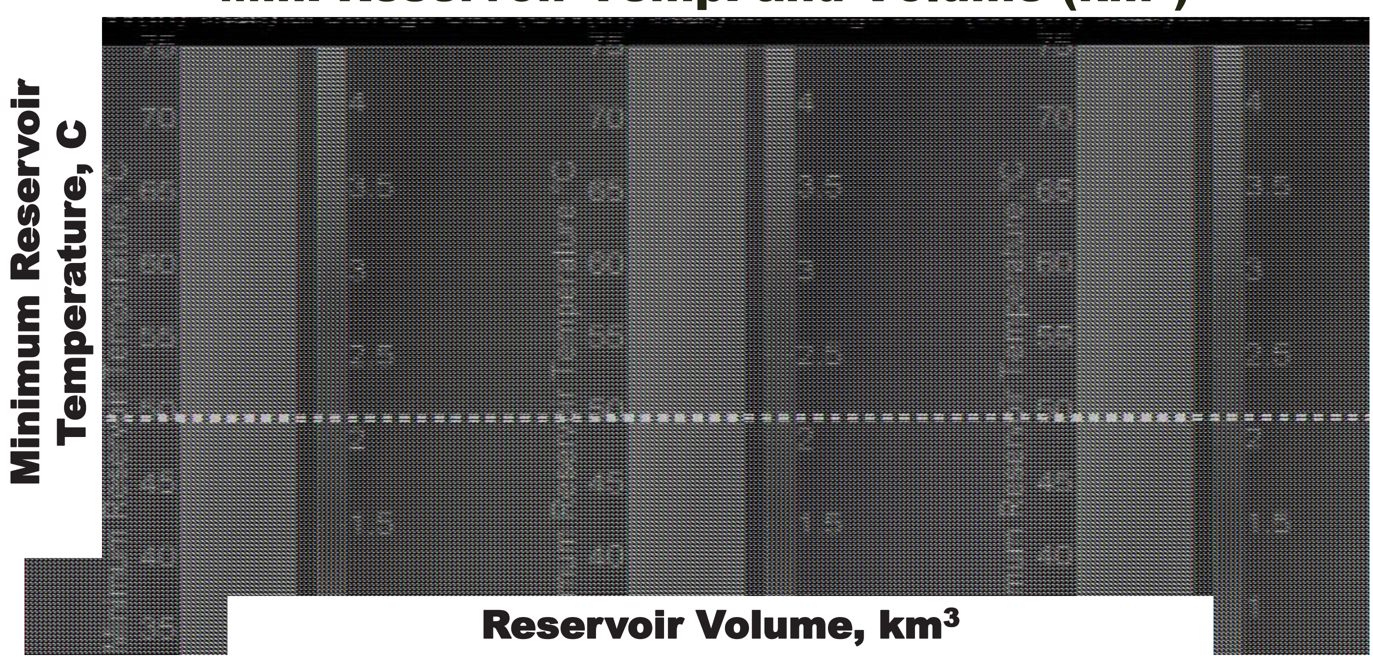
- Rock expansion and contraction will generate fine particulates
  - Particles may erode heat exchangers and clog pipes
  - Require on-line hot oil/salt filtering system
- Chemical control system may be needed to maintain long-term performance of heat-transfer oil or nitrate salts
  - Slow buildup of impurities from rock fluid interactions
  - Degradation of heat-transfer fluid

[redacted]

Permeable Rock Requirements

- Heat storage zone must have permeable rock to allow heat transfer fluid to heat and cool rock
  - Minimum permeability ~1 Darcy
  - Low permeable rock outside storage zone to avoid hot fluid loss (energy loss)
- Technologies to create permeable rock zone
  - Cave block mining
  - Selective rock dissolution
  - Hydrofracture in sandstone

Thermal Storage Size (GW(t)-Year: Color) vs Min. Reservoir Temp. and Volume (km^3)



1GW(th) Storage with Reservoir 0.05 km^3

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7. I. Oloyede, *Design and Evaluation of Seasonal Storage Hydrogen Peak Electricity Supply System*, MS Thesis, Massachusetts Institute of Technology, June 2011.
8. Y. H. Lee, *Conceptual Design of Nuclear-Geothermal Energy Storage System for Variable Electricity Production*, MS Thesis, Massachusetts Institute of Technology, June 2011.
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12. Y. H. Lee, C. W. Forsberg, M. Driscoll, and B. Sapiie, "Options for Nuclear-Geothermal Gigawatt-Year Peak Electricity Storage Systems," Paper 10212, *2010 International Congress on Advances in Nuclear Power Plants (ICAPP'10)*, San Diego, June 13-17, 2010.

Making the 'Lotta Stuff' Simple:
A Practical Approach to Energy Storage

Electro Thermal Energy Storage (ETES) Solution

MIT / INL / EPRI Workshop On Redesign of Nuclear with Heat Storage

August 12, 2020

Cory Stansbury – stansbca@Westinghouse.com, +1.412.374.4084

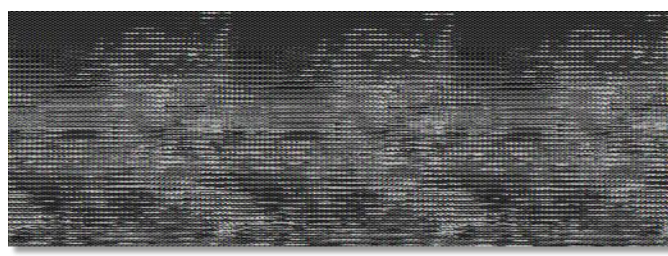
WAAP-11770

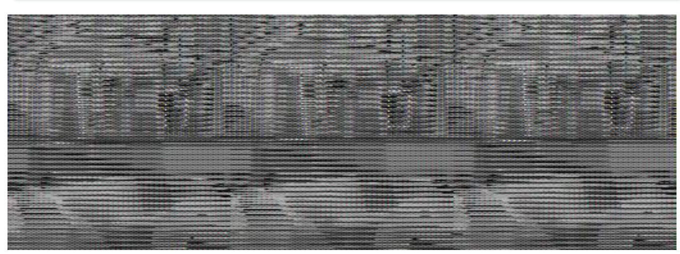
Brief History of Westinghouse / Stone & Webster Energy Storage Activities

- Project focused initially on assisting legacy plants and pure arbitrage
  - Challenges to cleanly and cost effectively tie into existing plant balance of plant (components did not have enough margin) and lack of utility interest shifted focus
- Refocused in two areas
  - Integration into new-build, targeting next generation plants
  - Standalone applications
- Participating in ARPA-E “DAYS” project in (2018-2020)
- Westinghouse is continuing to make very significant investments to develop technologies, access market dynamics, and execute testing programs

One Technology; Multiple Solutions

- Developed concrete / oil storage technology
- This heat storage module can serve three different implementations
  1. Integration with new-build light water reactors (LWR)
  2. Integration with Westinghouse’s lead-cooled fast reactor (LFR)
  3. Stand-alone applications
- The mid / long-duration grid-scale storage markets lack cost-effective solutions that are ready for deployment

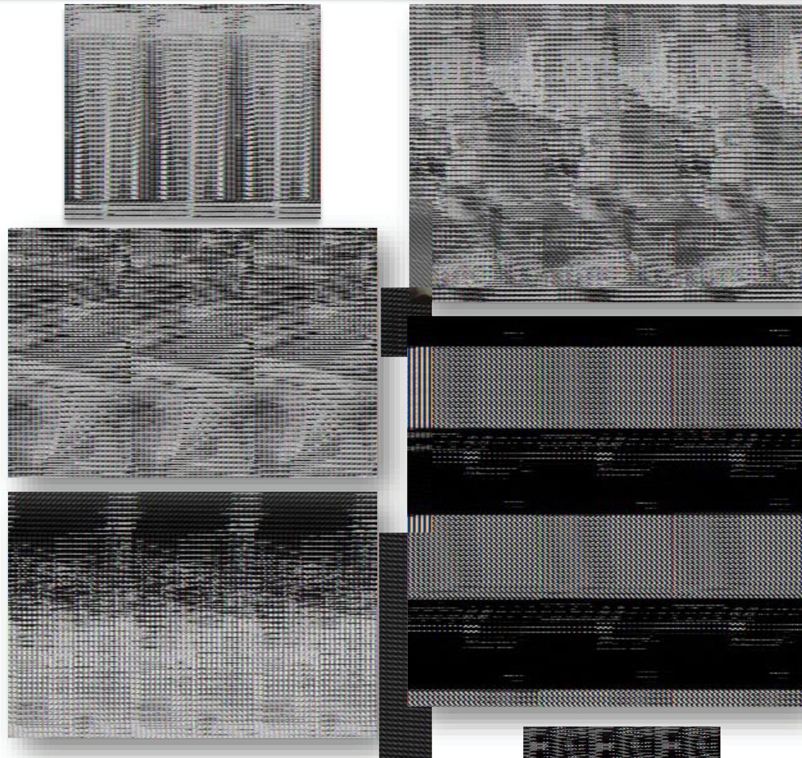




Thermal Storage is Flexible

Concrete Storage Technology

- No exotic materials
- No pressure vessels
- High degree of safety
- Single tank design
- Onsite, automated, modular construction
- Non-toxic, non-hazardous oil



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Keep the 'Lotta Stuff' Simple

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Technology Landscape for Mid / Long-Duration Storage

	ETES Solution	Li-ion	Flow Battery	Liquid Air Cryogenic	Competing Thermal	(New) Pumped Hydro
Economics (LCOS) $/MWh	[redacted]					
Scalability	[redacted]					
Technology Readiness						
Safety	[redacted]					
Supply Chain Risk	[redacted]					
Round Trip Efficiency						
Environmental Impact	[redacted]					

[redacted]

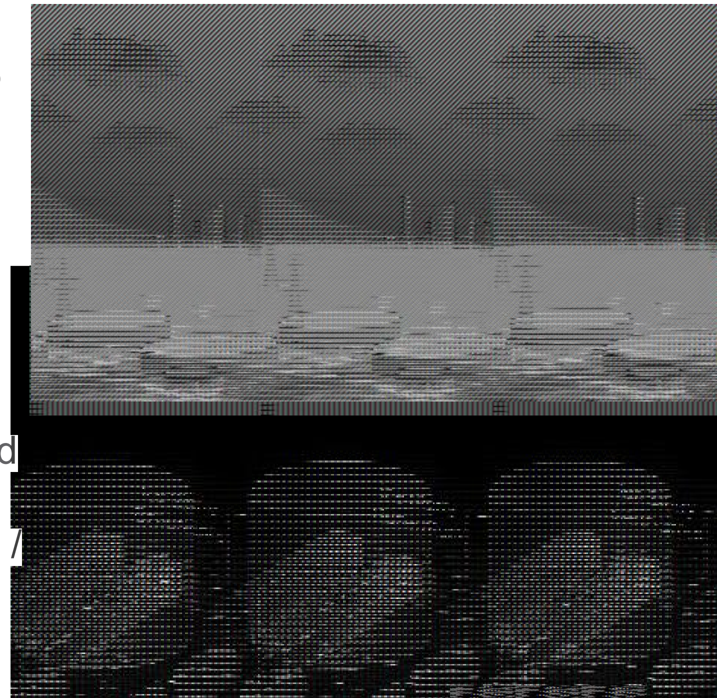
D-86

[redacted]

Standing Alone: The ETES Solution

Technical Differentiators

- Supercritical CO_2 heat pump cycle gives unprecedented performance at low temperatures
- Easily constructed and modular
- Long lifetime; decades of grid support, including reactive power (Target 20,000 cycles / >50 years operation)



1 GWh ETES Solution

Feed In 12 hours → **Storage** → **Generation** 10 hours

140 MW*
Electric

3,360 MWh
Thermal

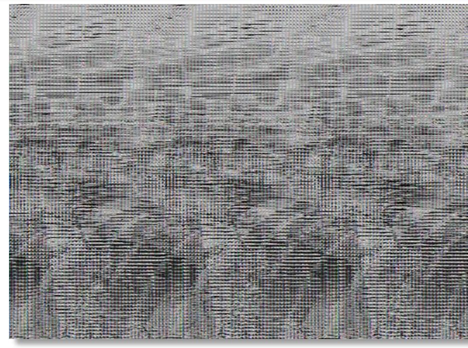
100 MW*
Electric

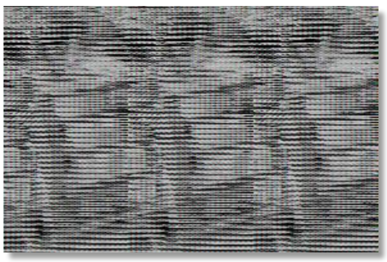
*Flexibility to size the system to charge and discharge at varying rates

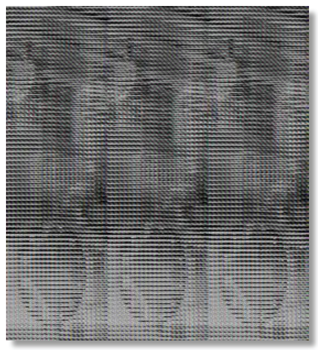
Round Trip Efficiency of ~ 60%

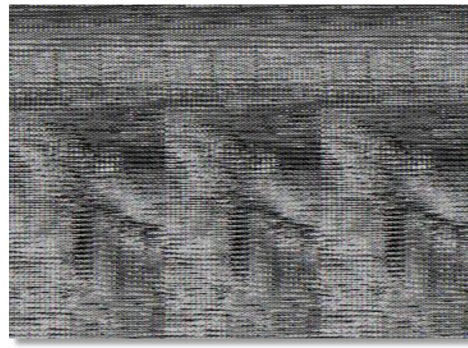
Rich History of Experience

- Over a century of experience in the design and construction of large power systems
- All power conversion hardware tested at scale
- Expertise in long-term reliability testing
- Leaders in supercritical CO2 cycles, control, and systems design









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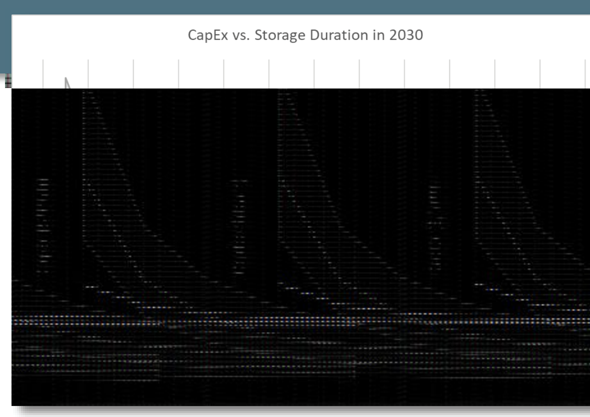
Levelized Cost of Storage

- CapEx, driven by low cost storage capacity, becomes largest driver of overall levelized costs
- Economics, even in a ***first*** application, ***favor ETES***
- Component lifetimes ***beyond 20 years*** minimize capital improvement costs

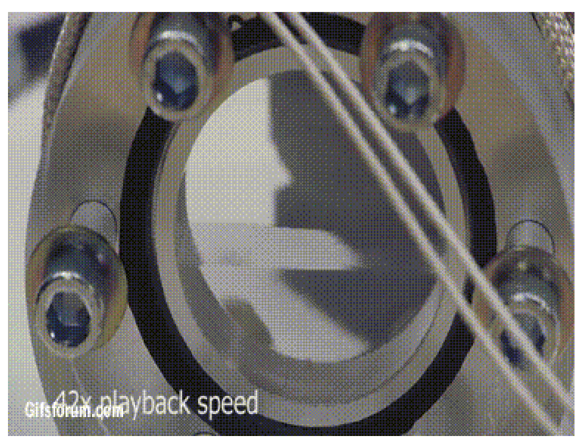


Questions?

[redacted] [redacted]

What is Supercritical CO_2 (sCO_2)?

- Supercritical state of matter exists above a material's "critical point"; a function of temperature and pressure
- In this state, the material has properties of both a gas and liquid → One might visualize it as a "squishy liquid" or "thick gas"
- Supercritical water is already used in many high-performance coal-fired plants around the world
- sCO_2 has properties which promise even greater performance than water in thermodynamic cycles
- sCO_2 is already in use as an industrial solvent; being used to decaffeinate coffee and in specialized drying applications, as well as an industrial, ozone-friendly refrigerant



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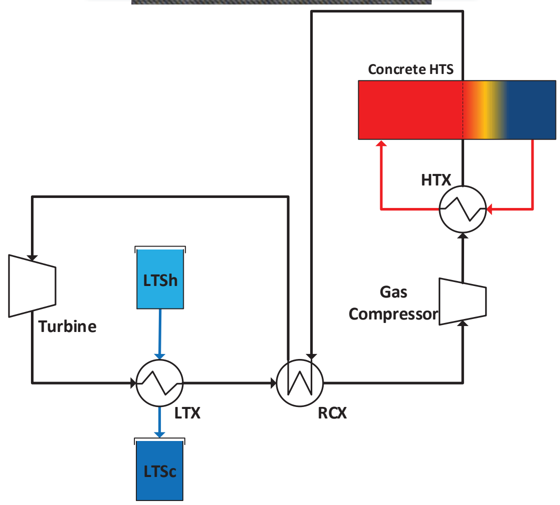
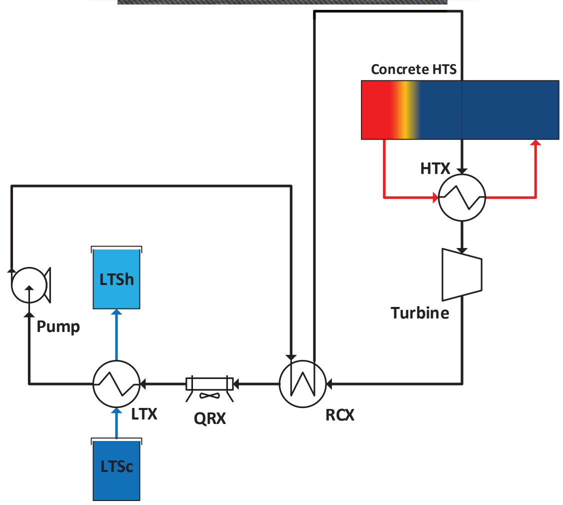
Source: Ben Krasnow, 2011, https://benkrasnow.blogspot.com/2011/09/close-look-at-supercritical-carbon.html

Simplified Process Flow Diagrams

Charging Cycle



Generating Cycle



HTS: High-Temperature Storage
LTS: Low-Temperature Storage
HTX: High-Temperature Heat Exchanger
LTX: Low-Temperature Heat Exchanger
RCX: Recuperator
QRX: Heat Removal Air-Cooled Condenser

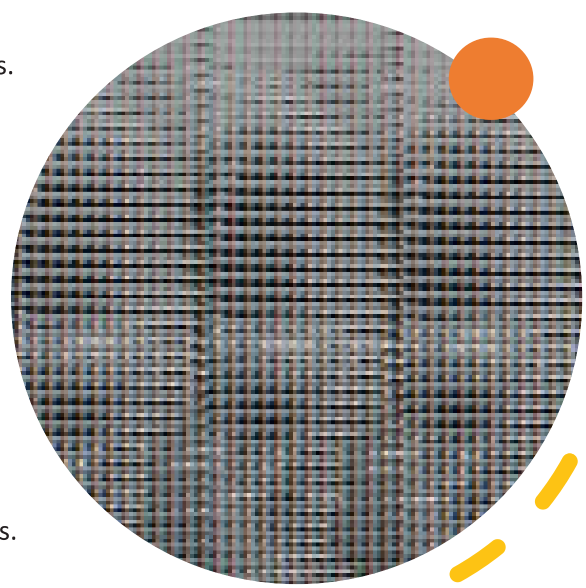
Designing Power Systems for Peak Power Applications

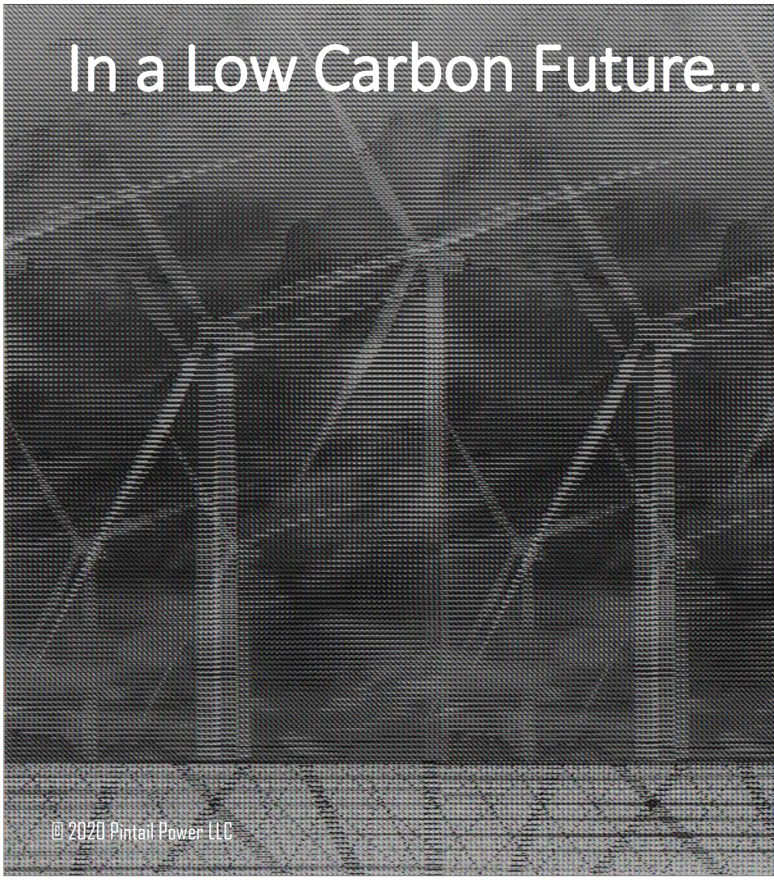
BILL CONLON, P.E. PH.D.

AUGUST 12, 2020

William Conlon, Ph.D., P.E

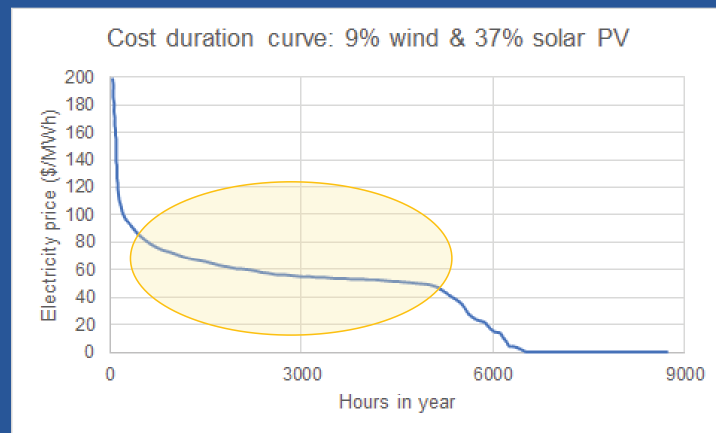
- Founder and President of Pintail Power LLC
- Engineer and executive with experience in nuclear, fossil, and solar engineering, construction, commissioning and operations.
- Engineer for PG&E
- At International Power Technology, Dr. Conlon co-invented the control system for the Cheng Cycle steam injected gas turbine power plant
- Dr. Conlon led technical turn-around of Ausra, taking CLFR technology to price-performance leadership of solar thermal
- Senior Vice President of Engineering at AREVA, responsible for Engineering, Commissioning and Operations teams
- Ph.D. in Nuclear Engineering and Science from Rensselaer Polytechnic Institute
- Licensed Mechanical Engineer in California, IEEE Life Senior Member, ASME life member, serves on the ASME PTC-53 Committee, Performance Test Code for Energy Storage Systems.





In a Low Carbon Future…

- Baseload is unprofitable
- Peaking is valuable but has low capacity factor
- Intermediate load earns the bulk of the revenue

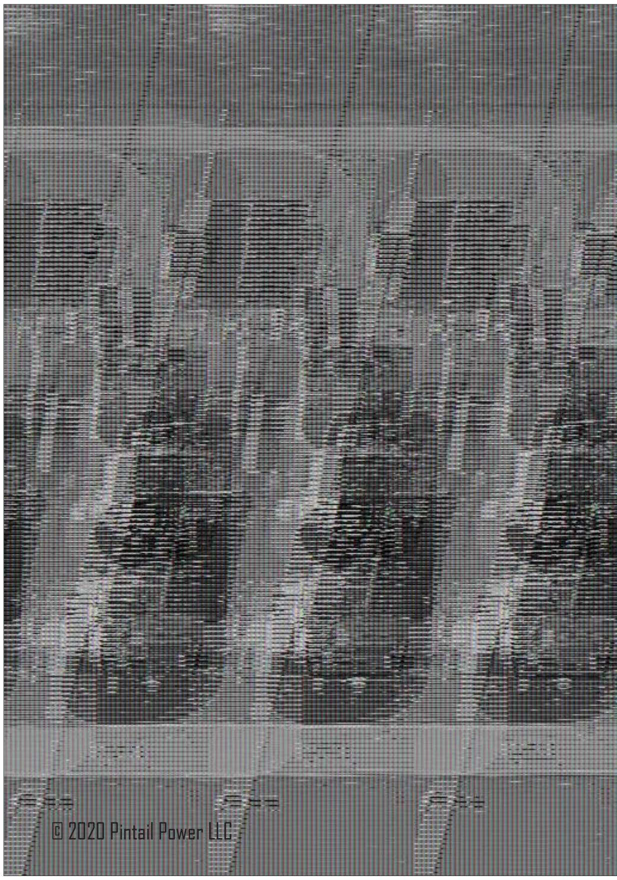


https://energycentral.com/c/ec/fuel-after-oil

Economics – Where Does the Money Go?

Overhead and Profit	Personnel, equipment, facilities, legal, debt service, dividends
Transmission and Distribution	The delivery network
Reliability	Reserves for contingency for 24 x 7
Ancillary Services	Voltage support to make T&D work
Generation	Equipment to make electricity to fill the T&D
Energy	Resources consumed by Generation

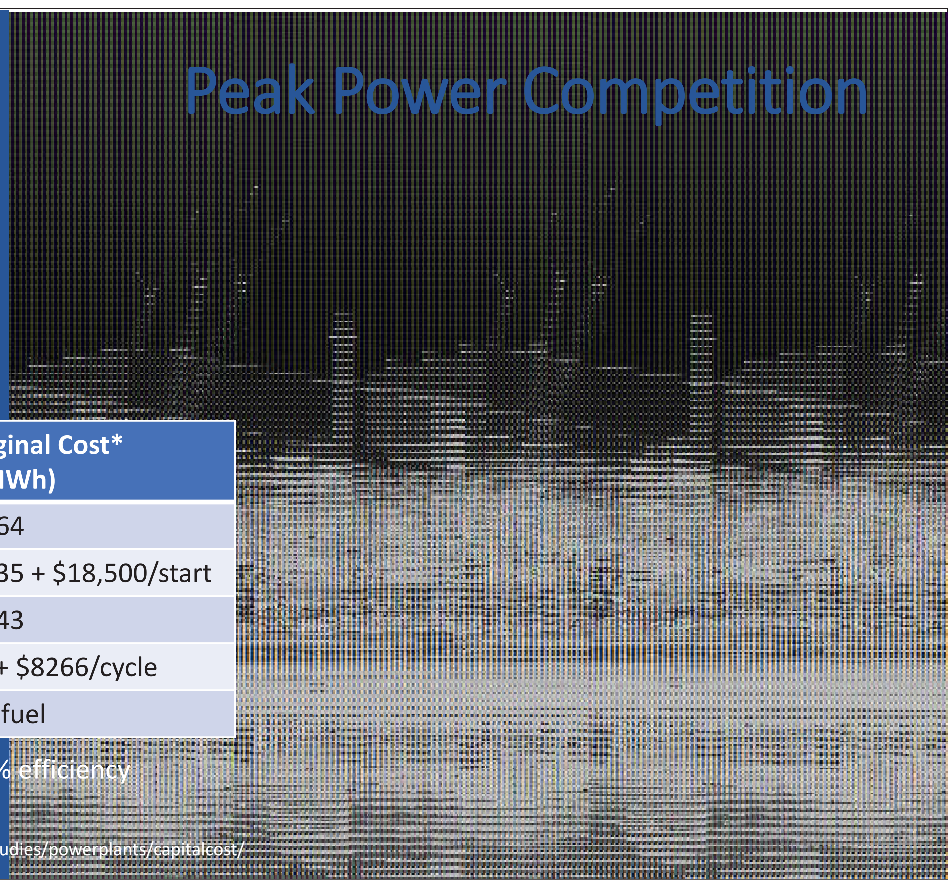
If energy is a marginal cost and everything else is capitalized, how does one sell new generating equipment, especially for peak power?



Generation Economics

- Problem 1: How to finance it
  - Rate based
  - Capacity or Resource Adequacy ($/kW-year)
  - Energy Sales Agreement
  - Merchant – not financeable
- Problem 2: How to pay for it
  - Need High Capacity Factor or
  - Need Capacity Payment
- Capital Cost of Energy CCOE ($/MWh) =
  - $$\frac{\text{Specific Cost (\$/kW)} * \text{1000 kW/MW} * \text{Amortization Factor}}{(8760 * \text{Capacity Factor})}$$
  - 10% is a convenient Factor (20 years @ 8%)

Peak Power Competition



Key figures of merit

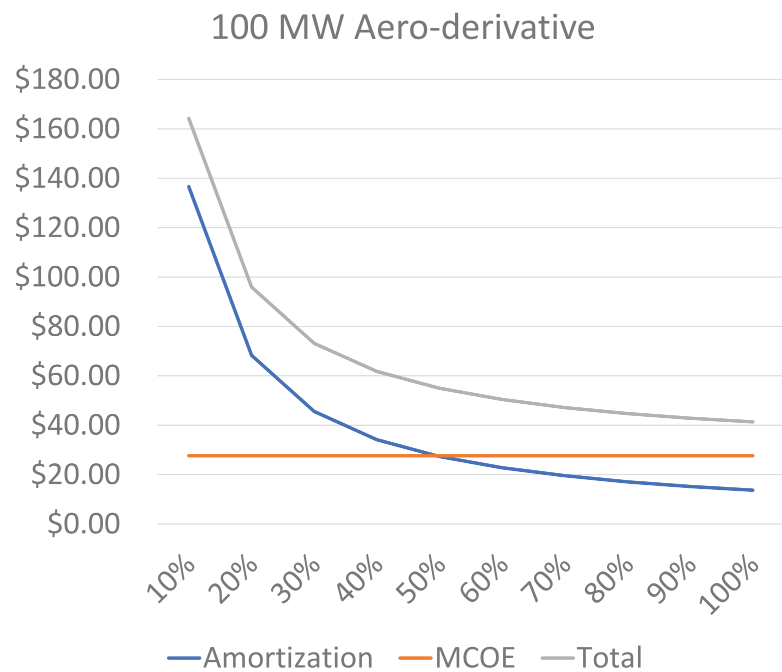
- Low CAPEX
- Flexibility (fast start, part load η)
- Maintenance (battery degradation, startup cost)
- Operations (unattended?)

Technology	Installed Cost	Marginal Cost* ($/MWh)
Aero-derivative	$1175/kW	$27.64
F-class	$713/kW	$25.35 + $18,500/start
RICE	$1810/kW	$26.43
50MW x 4-hr battery	$347/kWh	$25 + $8266/cycle
SMR	$6191/kW	$3 + fuel

* $2.50/MMBtu NG, $20/MWh charging @80% efficiency

Source: EIA 2020 Updated Cost Report https://www.eia.gov/analysis/studies/powerplants/capitalcost/

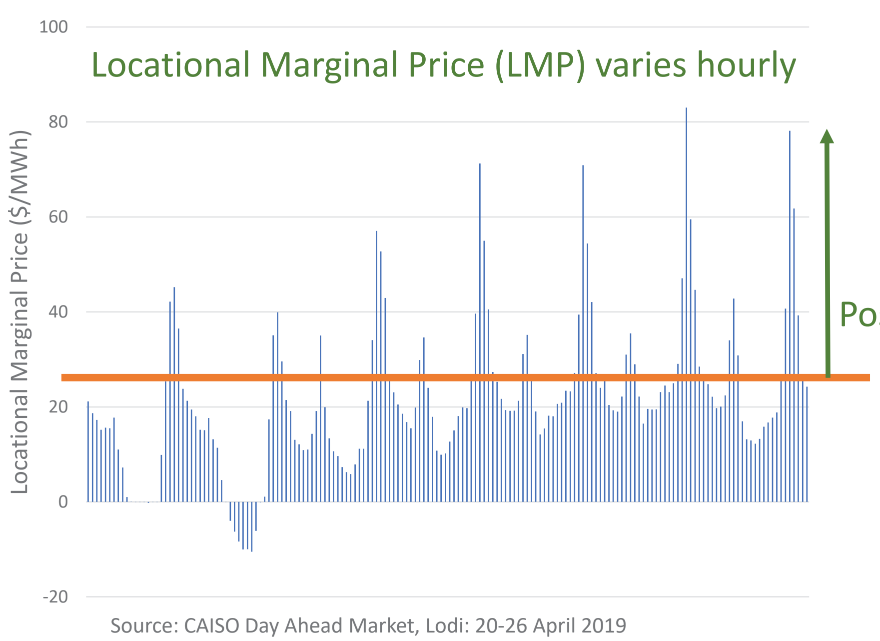
CAPEX dominates at low Capacity Factor



Low fuel cost will not overcome high CAPEX

Marginal Cost of Energy Drives Capacity Factor

MCOE ($/MWh) = Heat Rate (MMBtu/MWh) x Fuel Cost ($/MMBtu) + Variable O&M ($/MWh)



- Favorable spot in the dispatch stack
- Location, location, location

Positive Spark Spread

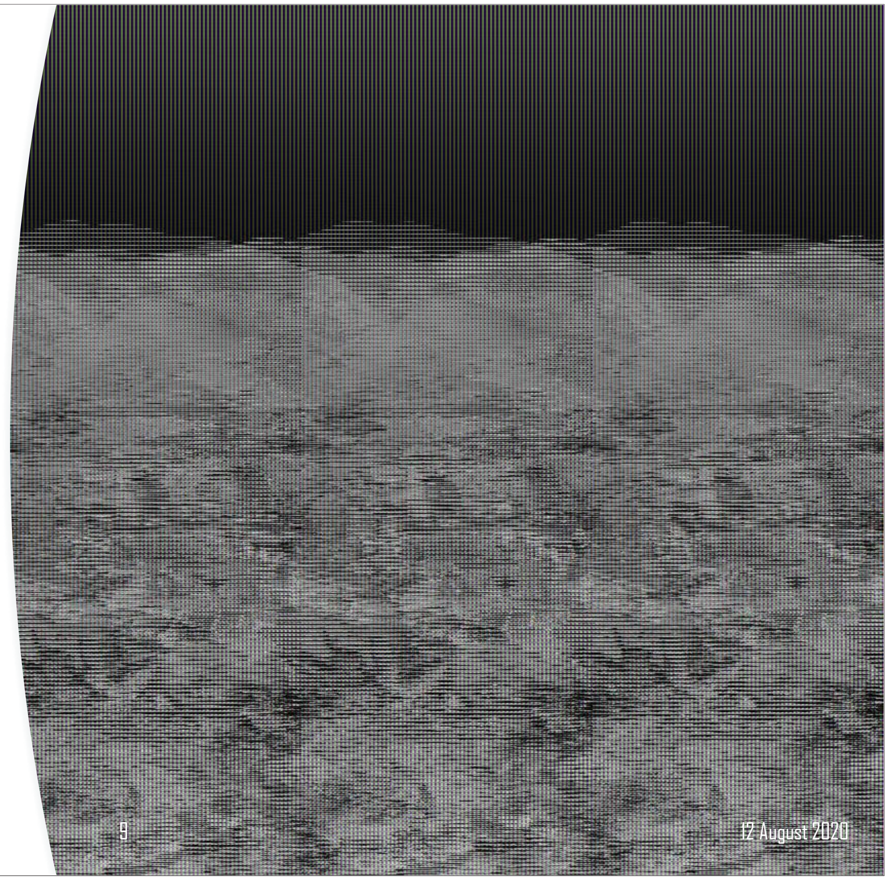
100MW Aero = 9.124 MMBtu/MWh x $2.50/MMBtu + $4.70/MWh

Can Nuclear Steam Be a Peaker Candidate?

Key issues

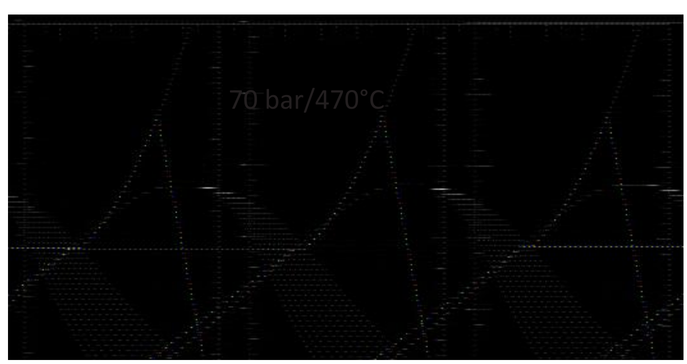
- Capital Cost
  - 50MW CFB is $1389/kW (excluding boiler)
  - Nuclear Boiler costs?
- Flexibility (startup time)
- O&M expense
- Competitive MCOE

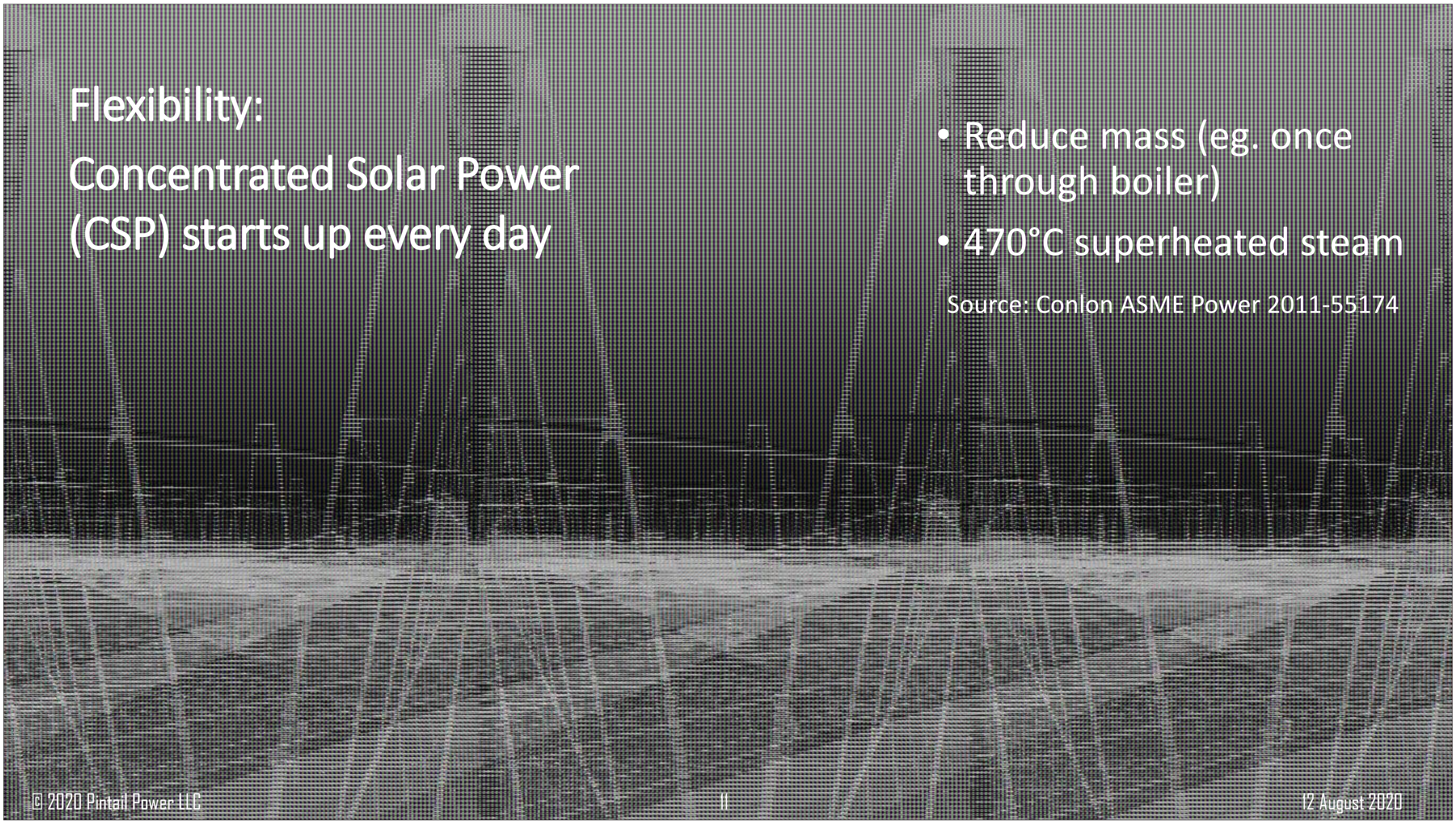
Source: EIA 2020 Updated Cost Report
https://www.eia.gov/analysis/studies/powerplants/capitalcost/



Steam Conditions Are Critical

- Simplicity reduces CAPEX and Maintenance
  - Eliminate reheater
  - Minimize regenerative feedwater heating
  - Single casing turbine
- Low-cost power can accelerate startup
  - Electric heating blankets on casing
  - Electric steam generation
    - Maintain condenser vacuum
    - Keep turbine rolling
- Superheat in a nuclear plant?
  - Indian Point 1?
  - Topping cycle?





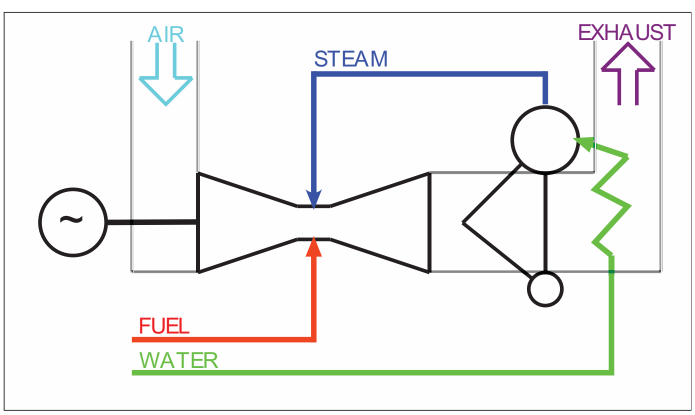
Flexibility: Concentrated Solar Power (CSP) starts up every day

- Reduce mass (eg. once through boiler)
- 470°C superheated steam

Source: Conlon ASME Power 2011-55174

Flexibility: Boiler Start up

Apply Compressor Discharge Pressure to suppress steam drum level swell



Source: Hamill, Digumarthi, Conlon, Cheng, Chang US Patent No. 4,790,269

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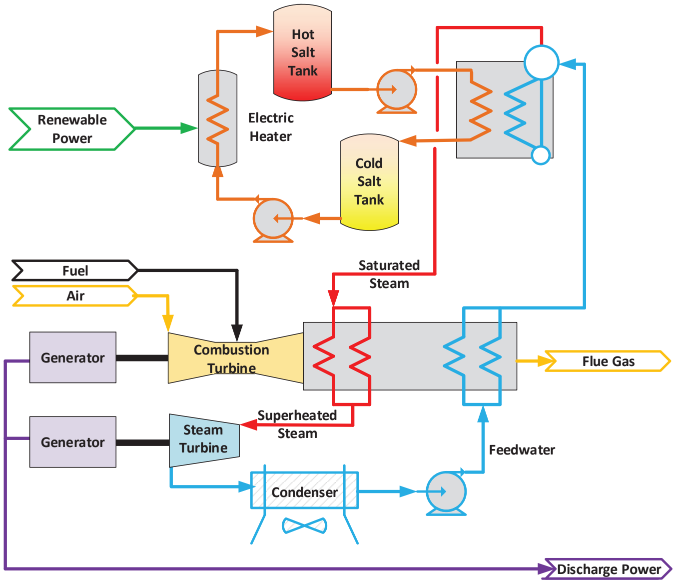


Sources: Pintail Power, U.S. Patent No. 10,113,535
POWER Magazine, Dec. 2019

Liquid Salt Combined Cycle™

- Superheat using aero CT Exhaust
  - Fuel Heat Rate < 5000 Btu_{in}/kWh_{out}
- Efficient use of low-cost renewable energy
  - Electricity Rate <1 kWh_{in}/kWh_{out}
- Flexibility
  - Hot standby, fast startup
  - No rate- or state-of-charge constraints
- Installed Cost < $150/kWh (100MW x 12 hour)

How LSCC Cuts the Cost of Storage

Hot salt temperature <427°C

[redacted]

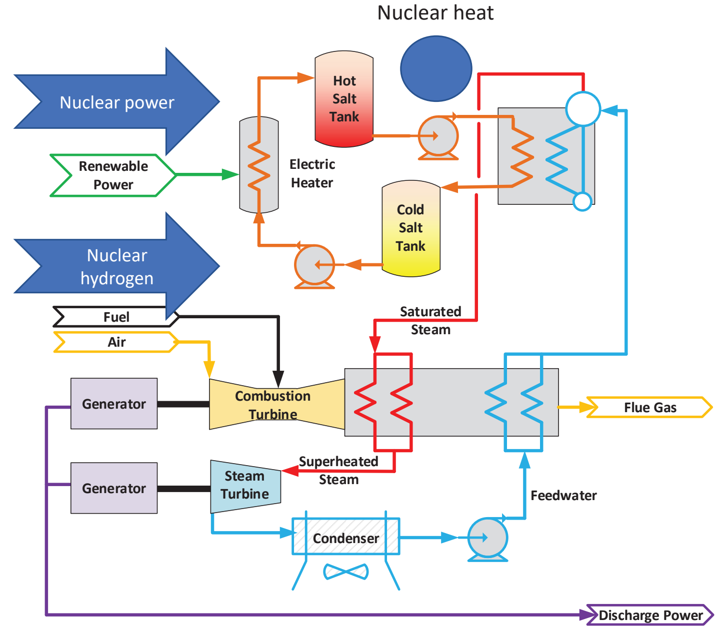
- Carbon steel tanks and piping
  - Lower cost than stainless steel
  - Simpler construction (no PWHT) than stainless steel
  - Lower thermal expansion and thermal stresses than stainless steel
- Perpetual salt life
  - No corrosion
  - No degradation

Hybrid synergy with Combustion Turbine

- 5x-6x less salt than CSP
  - 12.5 kg/kWh_e
  - <$25/$kWh_e$
- Fewer tanks and pumps, less piping, less heat loss and heat trace

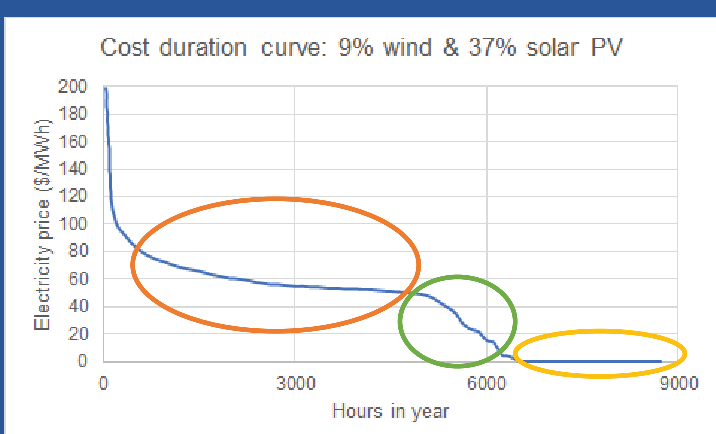
Nuclear Salt Combined Cycle™

- Nuclear steam or electricity heats the salt
- Nuclear Hydrogen fuels the CT



Sources: Pintail Power, U.S. Patent No. 10,113,535

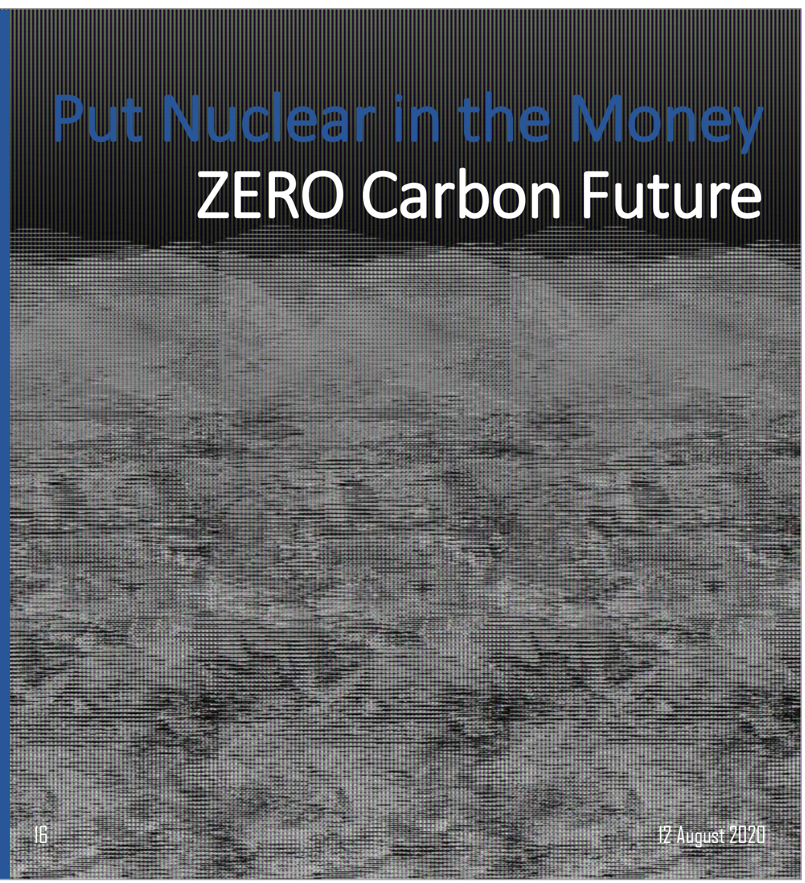
- Make hydrogen and charge thermal storage
- Flexible start up and load following
- Run carbon free high-efficiency power cycle



https://energycentral.com/c/ec/fuel-after-oil

Put Nuclear in the Money

ZERO Carbon Future



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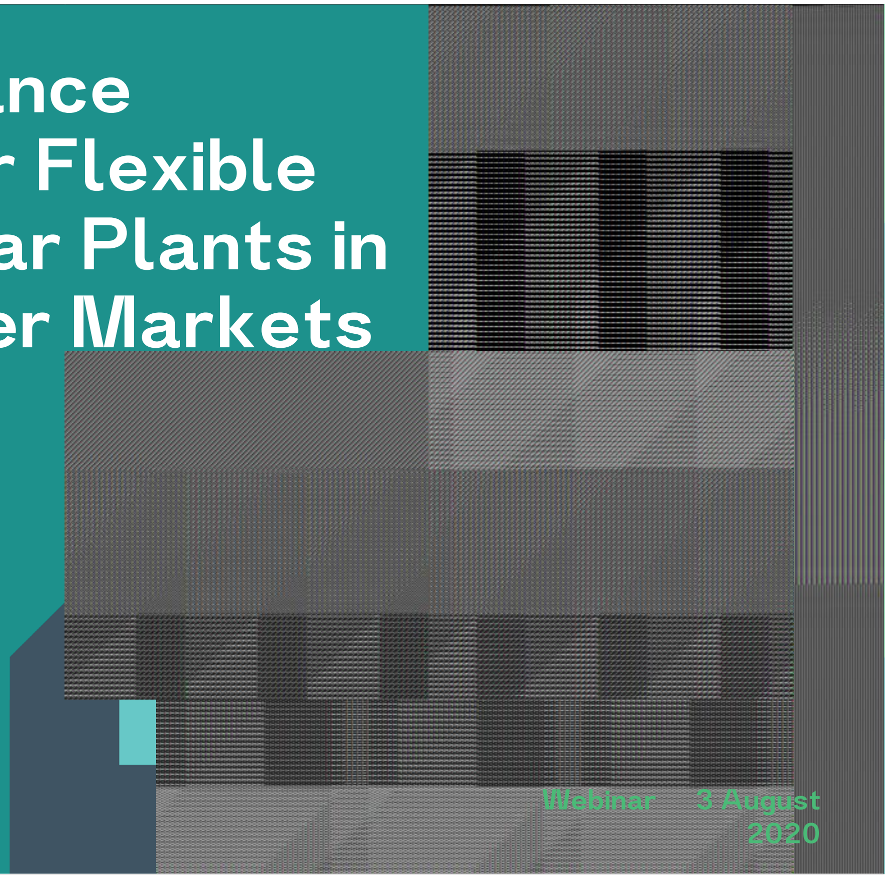
@pintailpower

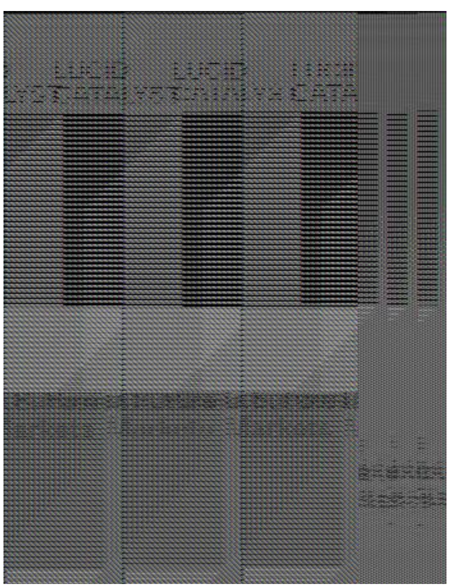
Cost & Performance Requirements for Flexible Advanced Nuclear Plants in Future U.S. Power Markets

Eric Ingersoll



Webinar 3 August 2020

Motivations for the study



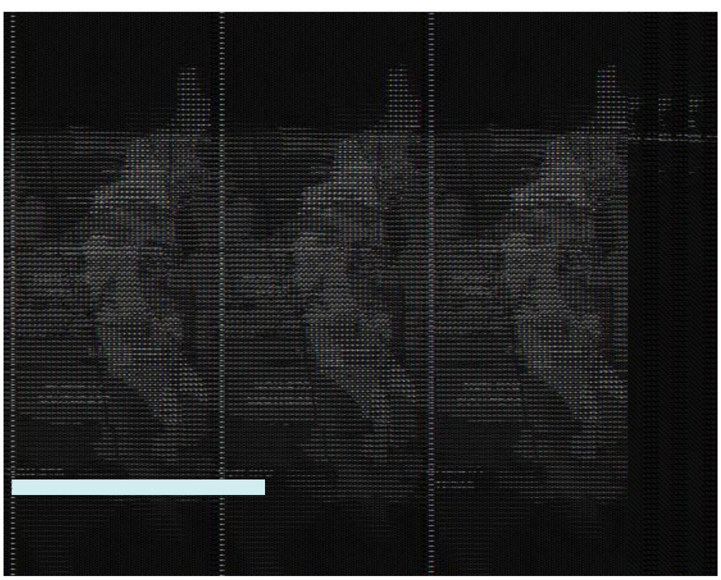
- Derive, rather than justify a capital cost
- Based on likely market conditions at the likely time of deployment
- Whole system perspective — looking at whole system performance
- New role for advanced reactors as providers of flexible firm capacity
- Derive the value of a flexible plant
- Not a policy study — the effect of market conditions on 'maximum allowable capital cost'

Setting up the model

- PLEXOS grid model simulates dispatch and prices
- 'Black box' advanced nuclear plant is dispatched and earns revenue for energy sold
- Financial model for plant calculates OpEx (fuel and O&M) and gross margin
- Financial model calculates 'maximum allowable capital cost' for assumed rate of return

Setting up the market scenarios

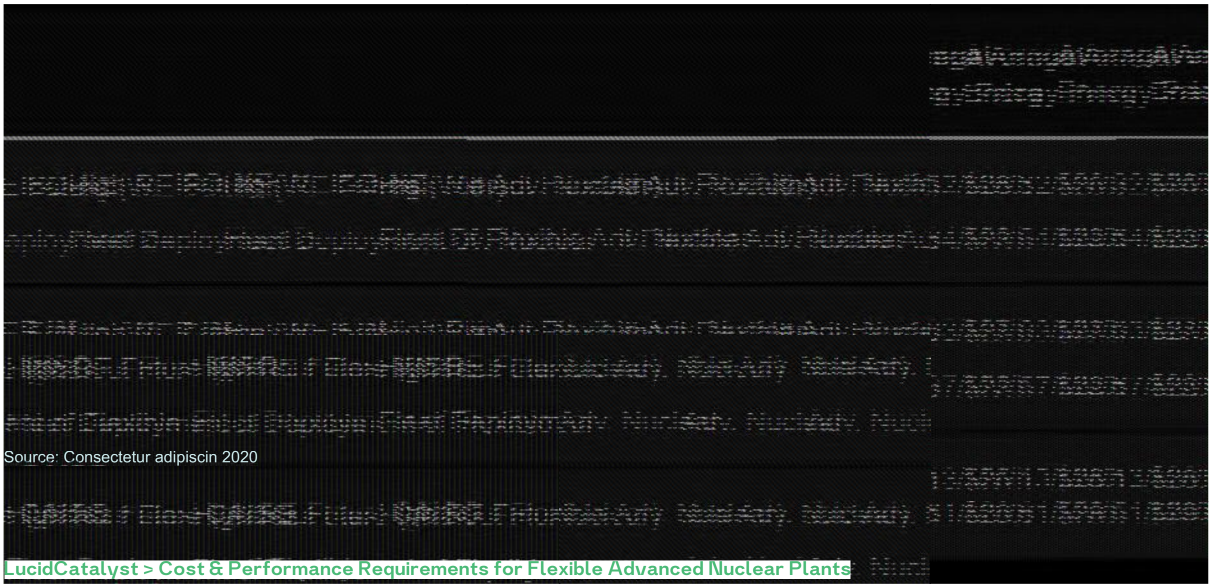
U.S. regional power markets



- Four markets
  - CAISO — Strong solar
  - MISO — Strong wind
  - ISO-NE — Offshore wind
  - PJM — Mixed portfolio
- Two Generation Mixes
  - High RE — NREL ReEDS: low-cost renewables, low gas price
  - Lower RE — PLEXOS built-in based on announced plans and interconnection queue
- NOT a capacity addition model

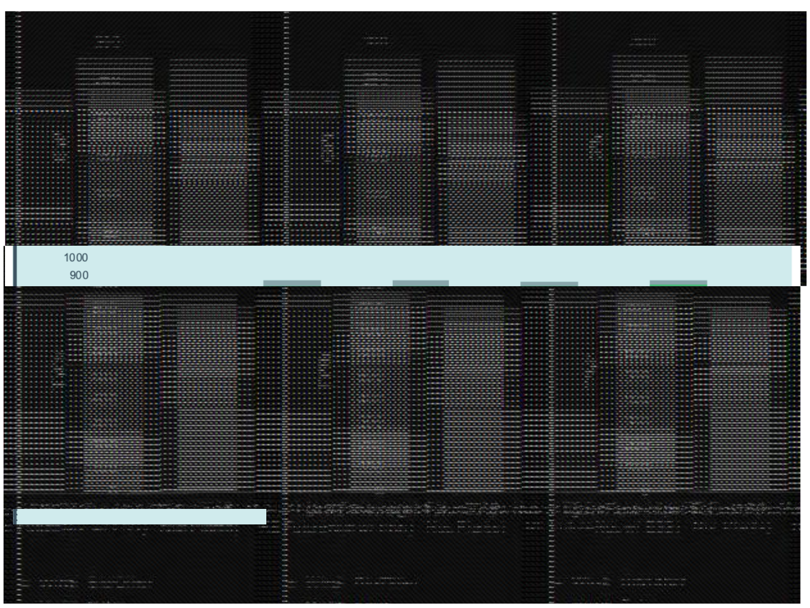
Resulting power prices are very low

Model results for key scenarios and regions



Source: Consectetur adipiscin 2020

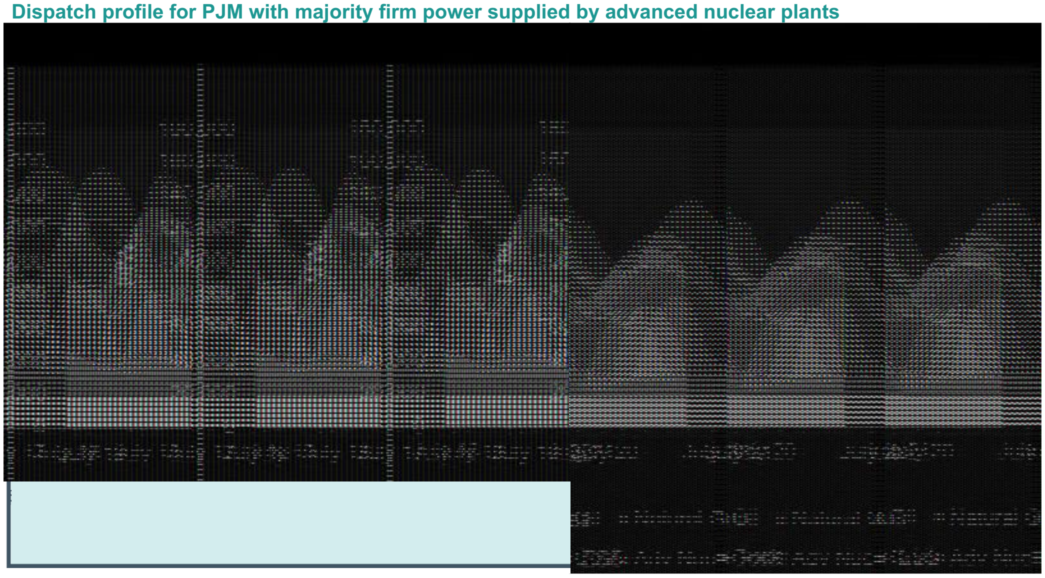
Example PJM: Capacity and Generation



Model results for key scenarios and regions

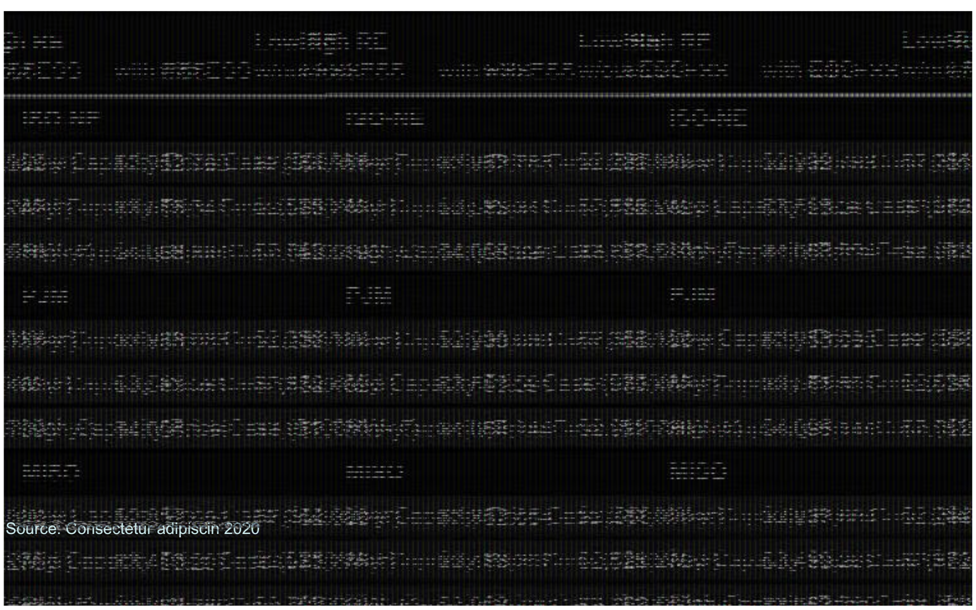
Daily dispatch

Dispatch profile for PJM with majority firm power supplied by advanced nuclear plants



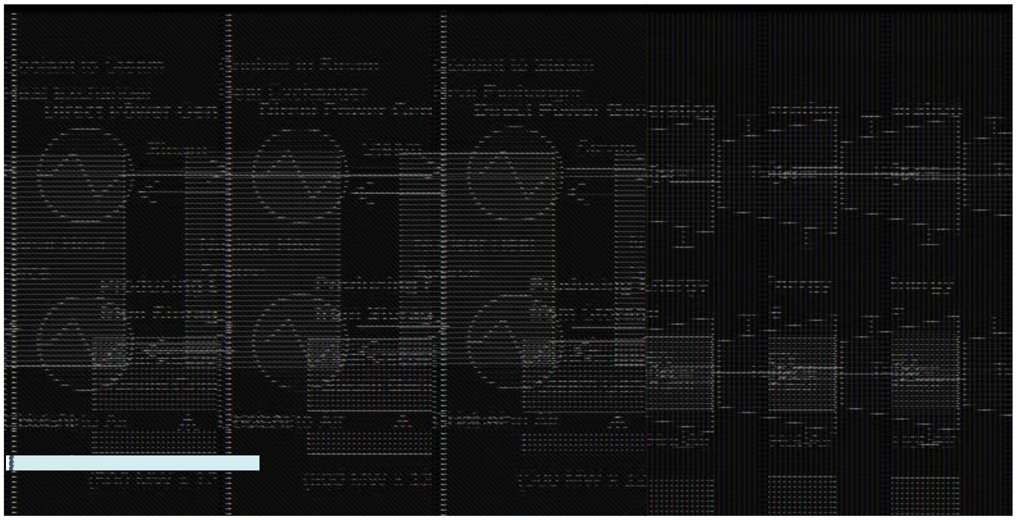
Projected maximum allowable capital costs

Maximum allowable CAPEX ($/kW) by ISO, configuration, and RE scenario



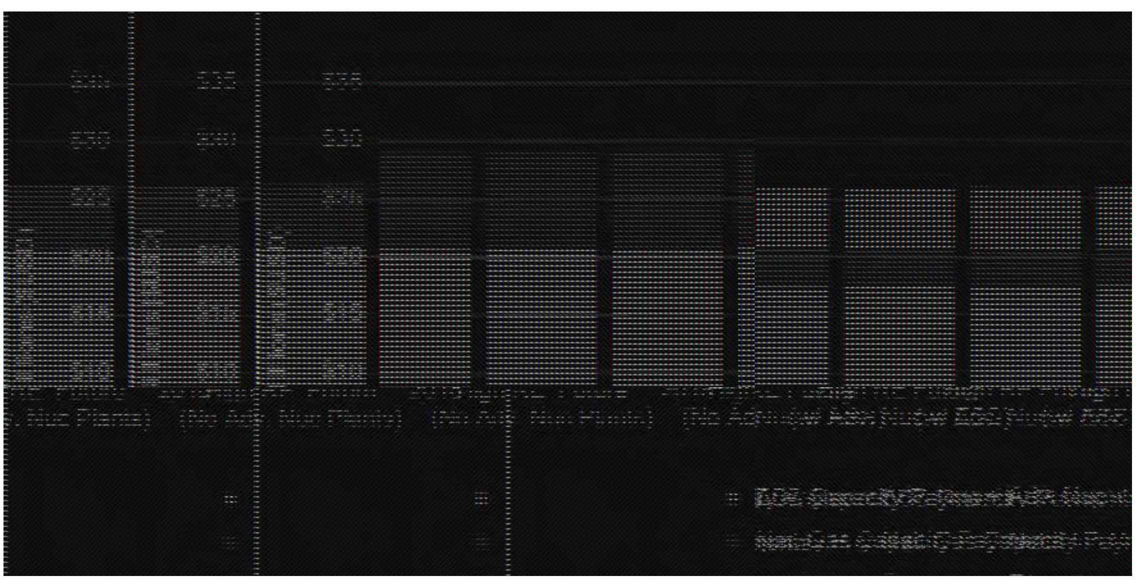
System diagram and high level costs

Charging and discharging configuration of advanced nuclear plant with thermal ESS



- Nuclear Island (heat source) separate from balance of plant
- All BoP is conventional (DOE costs)
  - $880/kWe
- Estimate for thermal ESS and additional power block
  - $1,100/kWe
  - $92/kWh (storage)

The cost of serving load was lower with advanced nuclear



Total payments for energy and capacity for 2018 and two scenarios

Recommendations for technology developers

Flexibility

Flexibility (without storage) may be good for the grid but it does not necessarily benefit a plant's revenue. Making flexibility economic for nuclear producers will require either the inclusion of ESS or major market reforms.

Cost Reduction

Delivering plants for less than $3,000/kW requires meaningful cost reduction in all systems and components, and all aspects of the delivery process.

Key strategies include standardization and reuse of designs, and separation of the heat source (nuclear island) safety case from the rest of the plant to enable use of off-the-shelf balance of plant.

Advanced nuclear plants can supply a large fraction of dispatchable power without raising the overall cost of electricity.

Recommendations for other stakeholders

ISO operators, public utility commissioners, policymakers, utilities, and other stakeholders

This study should motivate these actors to further investigate of the role that these advanced nuclear plants could play in the grids of the future. And in particular to continue and increase their support of advanced nuclear commercialization efforts.

This study should also motivate organizations responsible for national and international energy modeling to include flexible, advanced nuclear with energy storage in their projections for future energy systems.

LucidCatalyst delivers strategic thought leadership to enable rapid decarbonization and prosperity for all.

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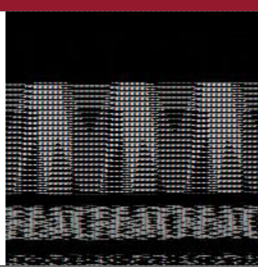
VALUE PROPOSITIONS



JOHN PARSONS
August 24, 2020
EPRI Webinar: Separating Nuclear Reactors from the Power Block with Heat Storage: A New Power Plant Design Paradigm

NUCLEAR OVERNIGHT COST

Reducing the Unique Overnight Cost of Nuclear.

- **Separating the nuclear island from the power island potentially enables a lower cost power island.**
  - Savings on nuclear quality standard requirements.
  - Increases the options for turbines.

SEPARATE OPTIMIZATION OF CAPACITIES FOR HEAT AND POWER

Solar Thermal Plant Capacity Optimization.

- **In a solar thermal plant, the size of the heat generation and the power block are different.**
  - Enabled by storage.
- **Solar thermal plants need storage for this purpose.**
  - For any given capacity of solar collectors, a fluctuating production of heat.
  - Directly coupling power generation without heat storage produces a very inefficient utilization of power generation capacity.
  - Heat storage uncouples the two capacities and enables scaling of power generation for more efficient utilization.

Not Electricity Arbitrage.

- **Optimizing solar thermal storage and capacities against fluctuating wholesale power prices is, to date, a smaller source of value.**
- **But wholesale power markets are changing dramatically, so this could become a significant source of the value of storage.**

What About For Nuclear?

- **Nuclear plants in most countries have not needed to decouple the two islands.**
  - Most have been built for baseload generation, and the system has needed sufficient quantities of baseload to provide a market for nuclear.
- **Load following with nuclear.**
  - Classic example is France, where the scale of total nuclear capacity means it is essential that some units are cycled to follow load. Elsewhere, too.
  - Cycling a nuclear plant raises the unit capital cost.
  - In current design, lose value on both the idle power block and the idle reactor.

Lower Total Capital Cost by Optimizing Separately

- **Uncoupling the two islands enables a more efficient utilization of both sets of capex in the face of fluctuating electricity demand.**
  - Reactor is scaled to fit aggregate heat requirement, without needing to fit peak generation requirement.
  - Power island is scaled to fit a larger peaking requirement.
  - Reactor operates at full capacity. Power island operates at fluctuating capacity, and with a higher peak capacity.
  - But, with the additional cost of storage.

COGENERATION

Classic Cogeneration.

- **Coupled electricity and heat production.**
- **Extra investment, but improved energy efficiency**
  - As compared to the uncoupled production of the same quantities of the two commodities.
- **Economic efficiency is not assured by energy efficiency.**
  - Depends upon the relative capital cost and relative fuel prices.

Joskow and Jones. "The simple economics of industrial cogeneration." *The Energy Journal* 4.1 (1983).

Business Model Problem

- **One machine, two products, two customers.**
  - Works for district heating.
  - Industrial customer usually scales cogen plant to its own heat needs, and sells the electricity as a by-product.
    - Small generation relative to power system capacity.
- **But there are difficulties in serving two customers.**
  - Features of the optimized system for pair of products is very sensitive to economic variables.
  - Industrial customers do not want to be captive to another business.
    - The “hold-up” problem.
  - Long-term contracts have limited value.
  - Realization of cogeneration scale has always fallen far short of engineering calculations of the opportunity.

Parallel Cogeneration

- **Separating the nuclear island and the power block yields new cogeneration opportunities.**
  - Cogeneration is simpler, but really just parallel operations now.
  - Exploits the ability to separately optimize the scale of the different elements.
    - Optimize power block for electricity load profile.
    - Optimize heat generation for combined heat load profile.

THANK YOU

U.S. DEPARTMENT OF ENERGY

NATIONAL ENERGY TECHNOLOGY LABORATORY

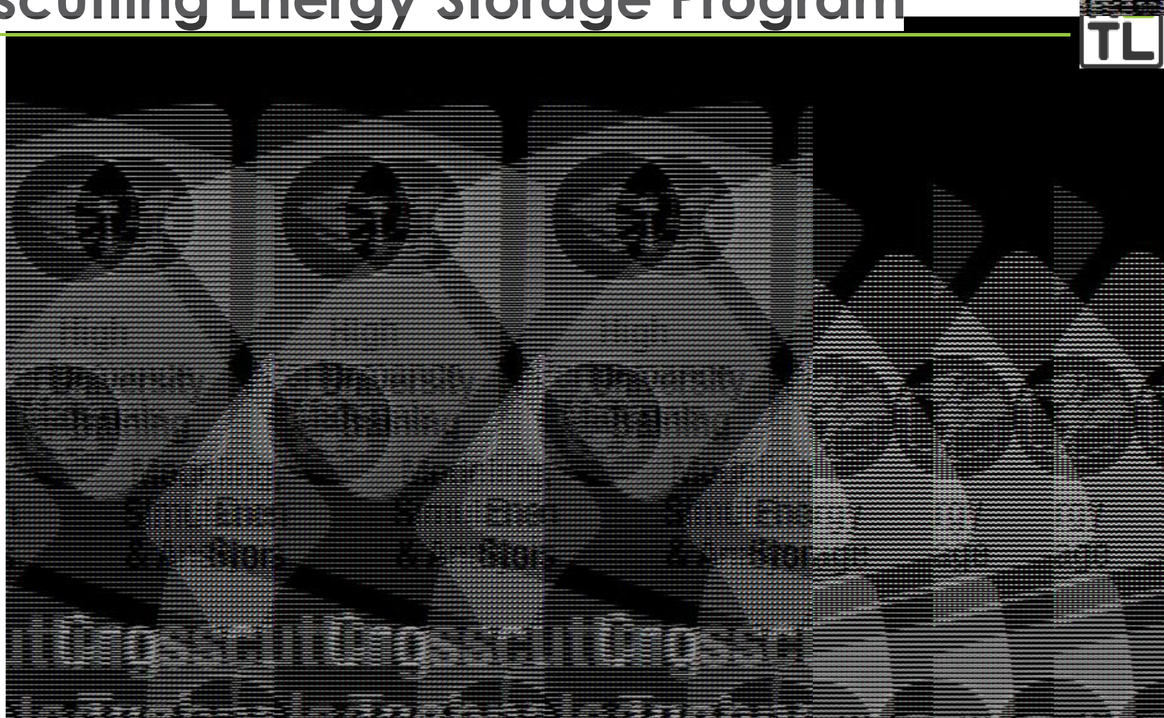
Implications of heat storage systems design for fossil fuels with CCS

MIT INL EPRI Workshop | August 26th, 2020

Briggs White

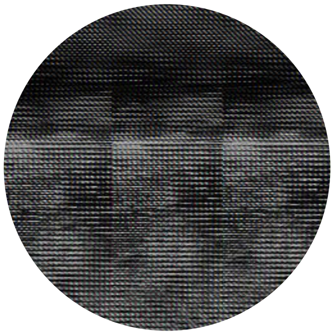
Image source: Adobe Stock

Crosscutting Energy Storage Program

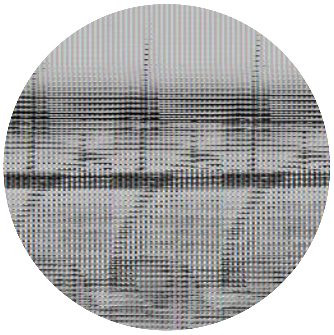


Program Mission

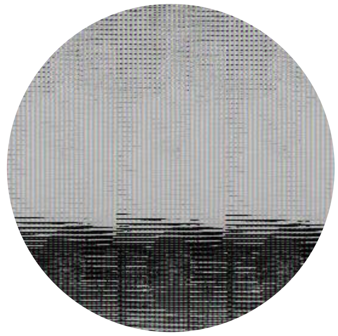
Asset Flexibility | Grid Reliability | Environmental Performance



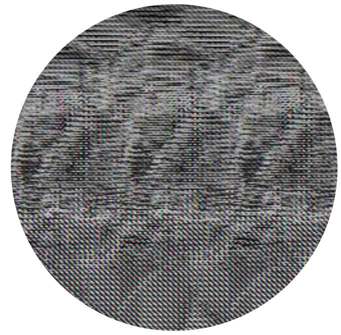
Thermal



Mechanical



Chemical



Hybrid

Image Sources: Adobe Stock

Program Scope

Electricity Generating Units (EGUs)

Fossil-fueled Smaller-Scale Assets

Fossil-fueled Industrial Facilities

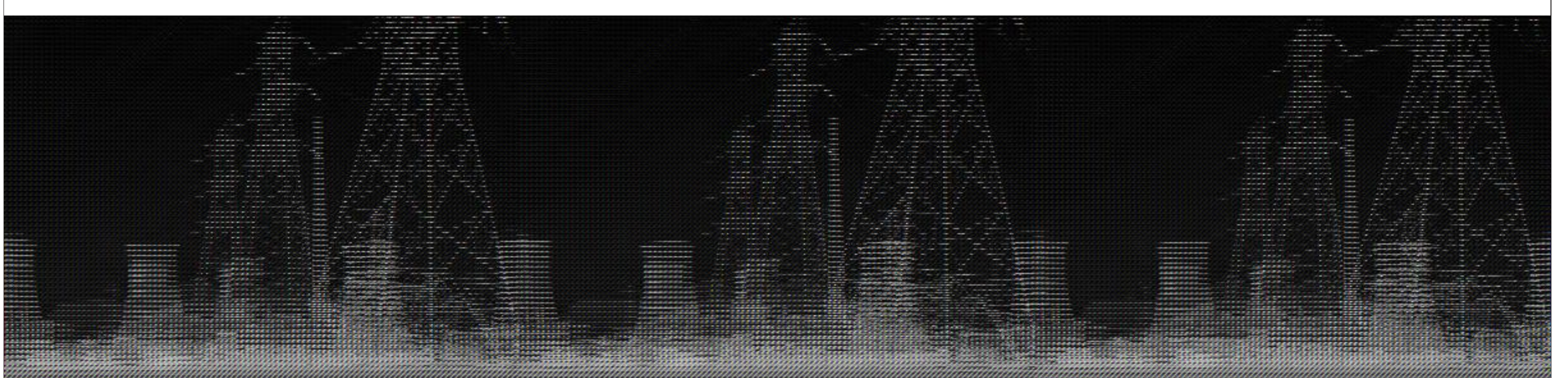
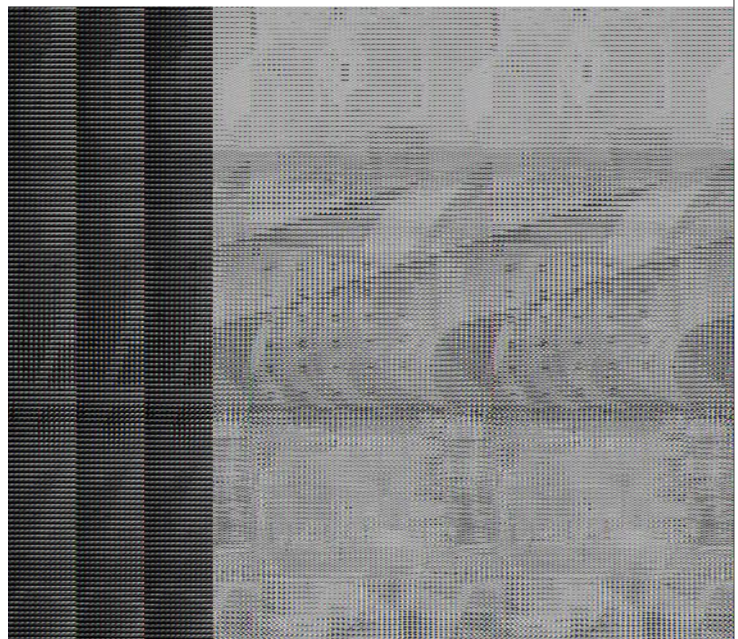


Image Source: Adobe Stock

ES and thermal power considerations

Additional benefits are derived from long duration storage

- **Cleaner** emissions
- **Reliability** in a changing grid
- **Flexibility** for dispatch
- **Fewer** component stresses



Beyond Batteries

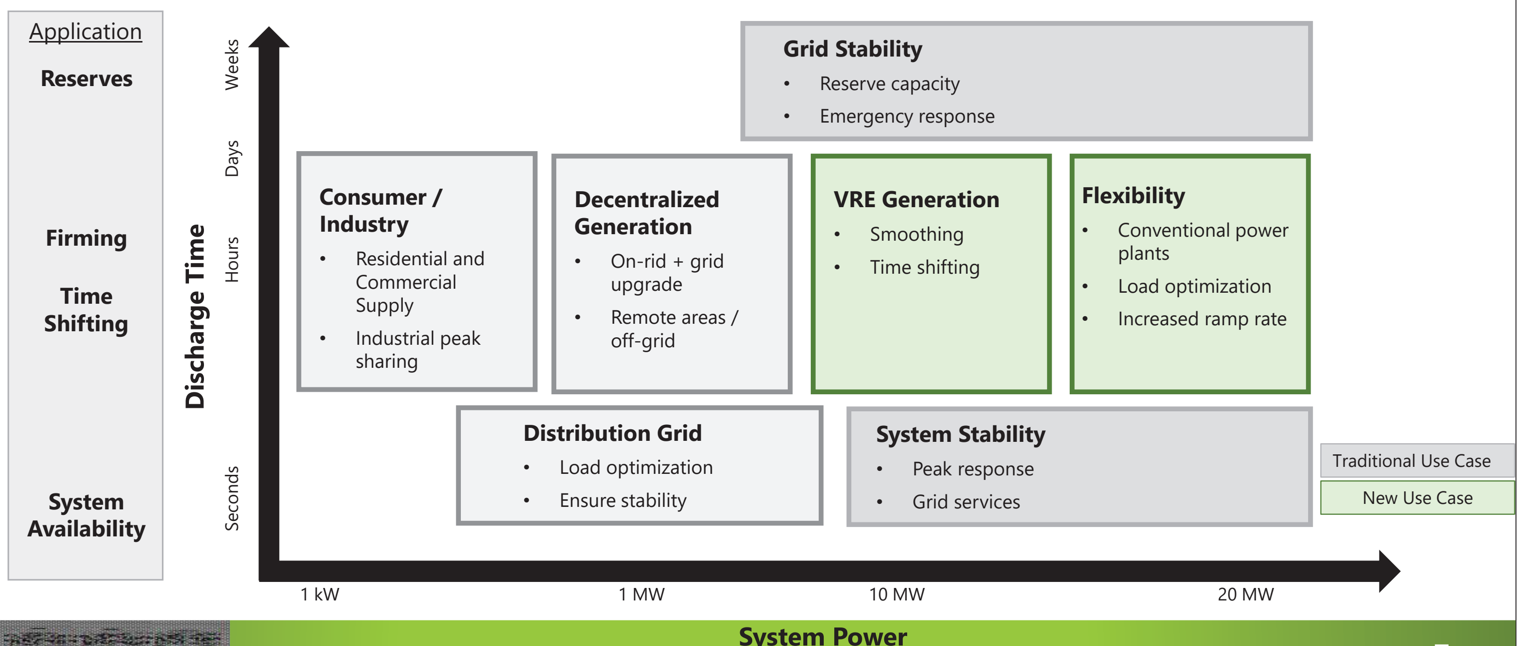
Batteries have a time and place, but…

Energy storage technologies expand far beyond batteries alone.

Image Source: Adobe Stock

Segmentation by Use Case

Mapping use cases on technology requirements

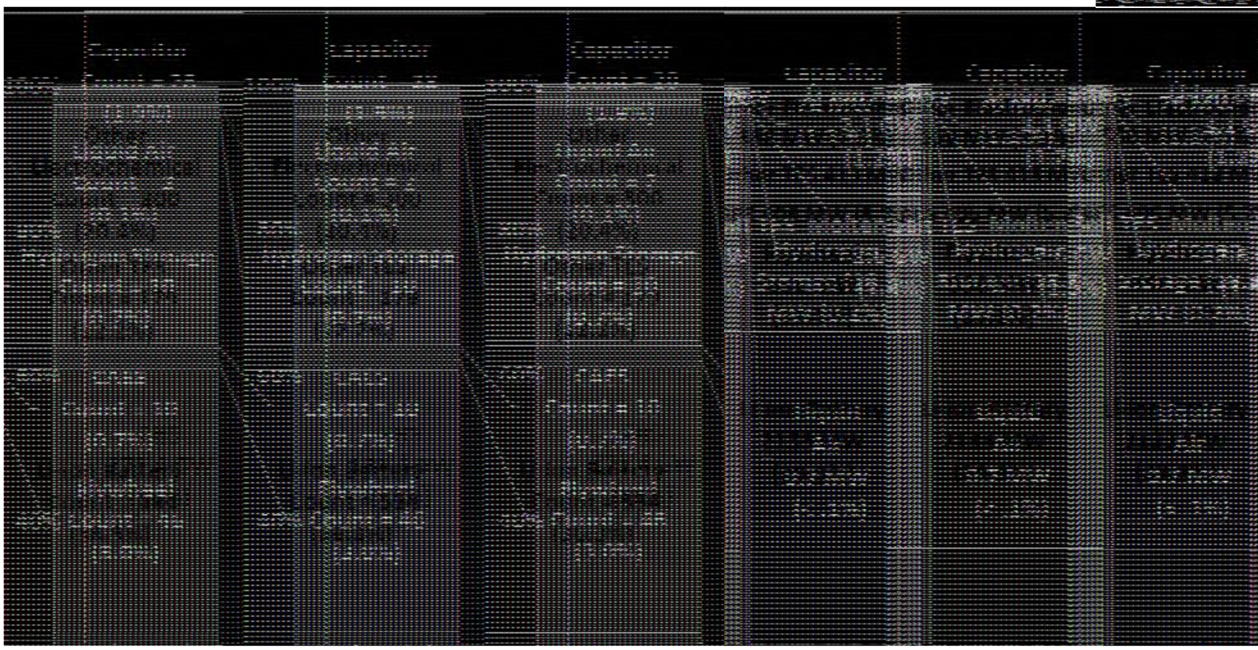


Fossil Market Size

Fuel	Prime Mover	Dispatch Type Category	No. of Units	Summer Capacity (GW)
NG	GT	Peaking	2,332	127
NG	CC	Peaking	32	0.3
NG	CC	Cycling	150	15.5
NG	CC	Must Run	547	254
Coal	all	Peaking	10	0.08
Coal	all	Cycling	18	2.2
Coal	all	Must Run	475	221
Coal	all	Baseload	278	6
Gas	IC	Peaking	1,250	5.2
Gas	IC	Cycling	14	0.37
Petro	IC	Peaking	3,308	5.9
Renew	IC	Peaking	1,866	2

Renew IC fuels include Landfill gas, Biogas, Bioliquids, Agriculture byproducts

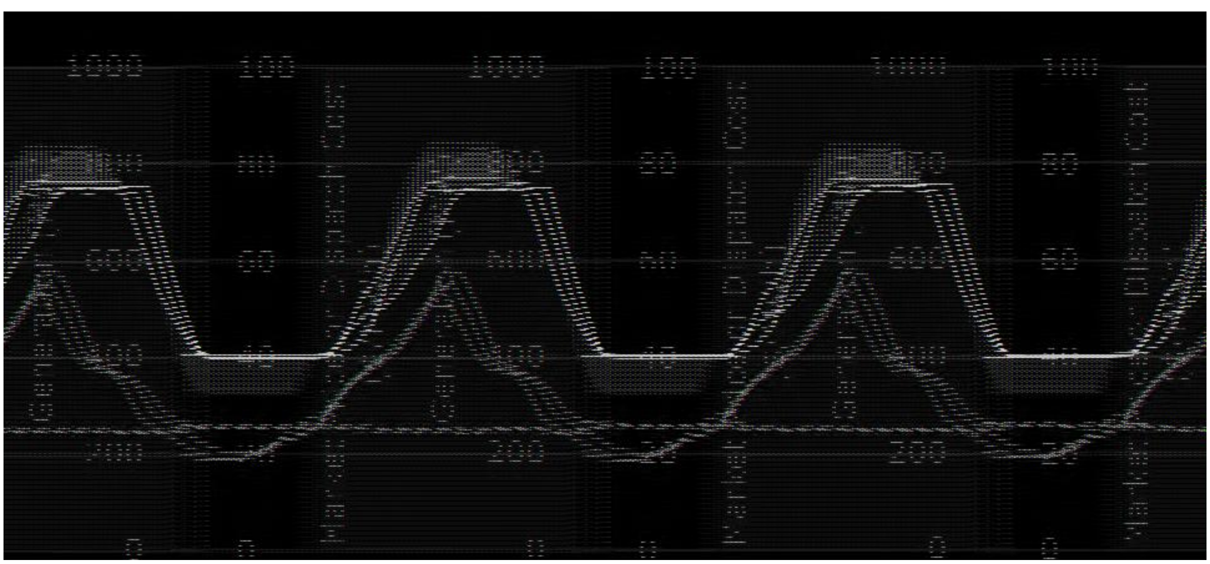
Global Operational Energy Storage Projects



Sandia National Laboratories, "DOE Global Energy Storage Database," Department of Energy, 2018. [Online]. Available: https://energystorageexchange.org/projects. [Accessed 1 February 2019].

Fossil Plant Energy Storage Benefit

Illustration of Energy Storage Enabling Financial Benefit (Plant and 'Grid')



Storage Benefit

- Actual unit data for generation, market price and estimated dispatch cost
- Simulation illustrates 8-hour energy storage option (store, withdraw)
- Day 1: higher morning ramp rate to increase revenue and capture peak power
- Day 2: running out of storage due to design capacity

Source: NETL

ES and fossil power are integrating now

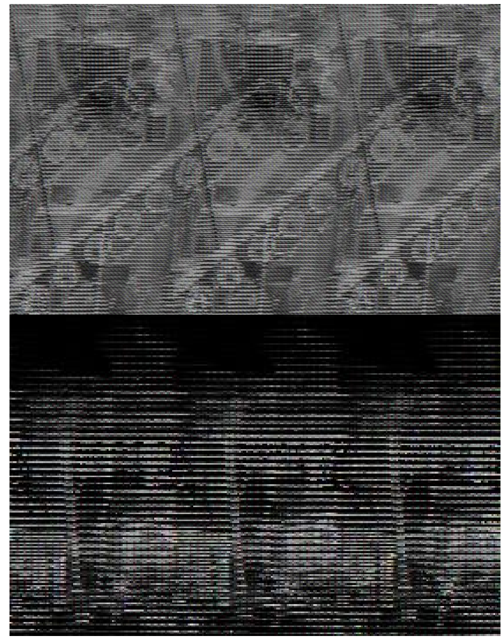
Coal power and batteries integrated in 2015

AES Warrior Run Power Station (Cumberland MD)

- 180 MW circulating fluidized bed (CFB) combustion technology; commenced operation in 2000
- In 2015, AES deployed a **10 MW Li-ion energy storage** at this facility (Advancion™ 4)

Edison International & GE's LM6000 Hybrid EGT

- Integrates battery energy storage with the LM6000 gas turbine
- In March 2017, Edison International integrated a **10 MW Li-ion battery with a gas turbine** in Norwalk and Rancho Cucamonga, California



https://www.aes.com/investors/press-releases/press-release-details/2015/AES-Reveals-AdvancionTM-4-with-First-Commercial-Deployment/default.aspx#:~:text=AES%20Reveals%20AdvancionTM%204%20with%20First%20Commercial%20Deployment&text=ARLINGTON%2C%20Va.,Run%20facility%20in%20Cumberland%2C%20Maryland%20.
https://www.ge.com/power/services/gas-turbines/upgrades/hybrid-egt

Thermal Energy Storage (TES)

Definition

- Sensible: sensible heat is stored and released by heating and cooling a storage medium
- Latent: the storage medium (also called phase change materials [PCMs]) change state (e.g. from solid to liquid)
- Thermochemical: relies on chemical reactions to store and release heat

Benefits

- ✓ Uniquely suited to thermal power generation
- ✓ Relatively large storage capacities
- ✓ Relatively long operating lifetimes

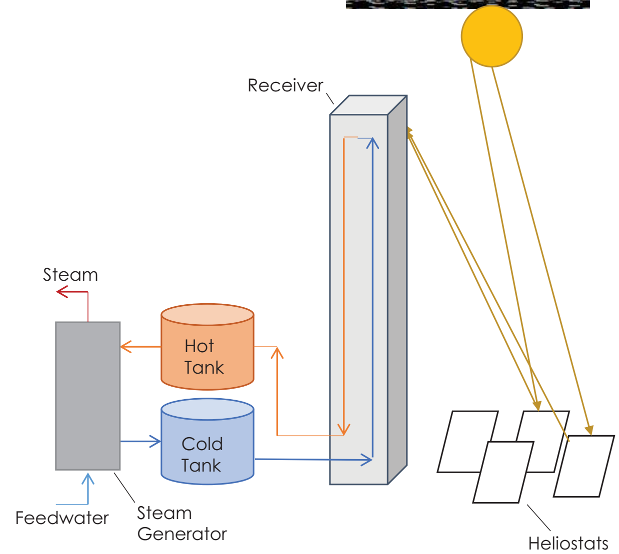
TES Technology Development

Current Technology Status

- Sensible heat widely utilized at concentrated solar power (CSP) plants
- Cold storage widely utilized for cooling
- Thermochemical and PCMs less developed

Technology Developer Examples

- PCM Systems: Terrafore Technologies, Sunamp, Phase Change Energy Solutions, BgtL
- Electrothermal systems: Malta
- Thermochemical: Southern Research Institute
- Sensible systems: Bright Energy



Sensible TES system commonly used for CSP plants

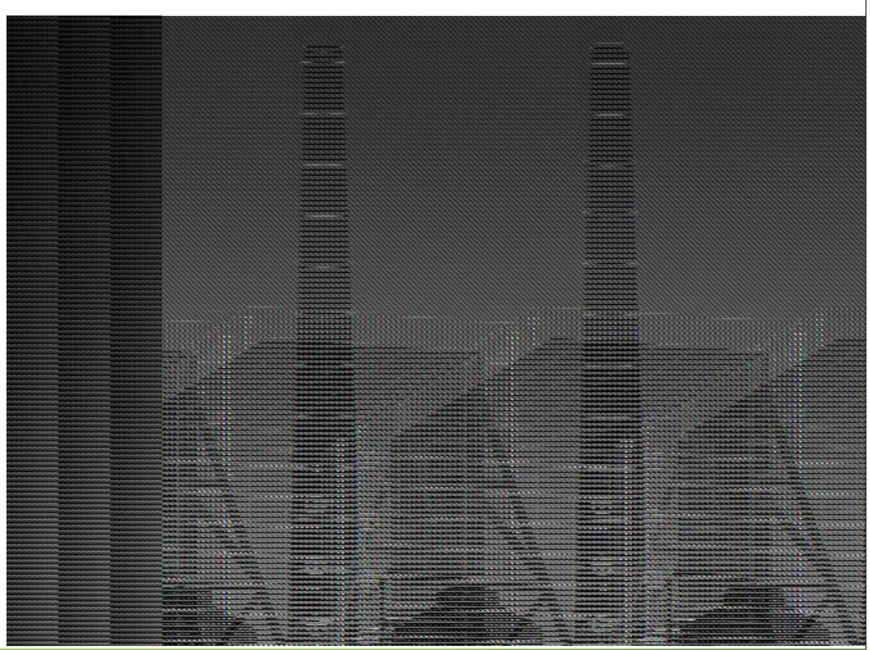
https://www.powermag.com/the-latest-in-thermal-energy-storage/

Current NETL TES Projects: EPRI

Concrete thermal energy storage enabling flexible operation

Without coal plant cycling

- Pilot scale concrete thermal energy storage system (CTES)
  - Tube-in-concrete heat exchange modules charged with steam
- Key innovation: high conductivity, high-temperature, low-cost concrete and novel arrangements of steam tubes



Current NETL TES Projects: Lehigh

Flexible coal power plant operation with thermal energy storage

Utilizing thermosiphons and cementitious materials

- Develop solid media thermal energy storage concept
  - Thermosiphon technology embedded into cementitious matrix
  - Combined sensible/latent heat thermal energy storage
- Key innovation: increase efficiency of coal power plants while reducing carbon emissions

Current NETL TES Projects: West Virginia University

Techno-economic optimization of advanced energy plants with Integrated thermal, mechanical, and electro-chemical storage

- Evaluate the transient response to various system concepts
- Minimize the levelized cost of electricity for storage technologies, specifically:
  - Thermal
  - chemical
  - Mechanical
  - Electro-chemical
- Key innovation: novel mixed-integer nonlinear programming algorithm to down select the most promising technologies

Collaboration: Coal-First Projects

Sponsored by other programs in DOE FE

TES Challenges and Opportunities

Challenges

- Material challenges
  - Waste disposal
  - Corrosive (especially at higher temperatures)
  - Lifetime (possible degradation over time)
  - Ambient temperature effects (e.g. heating required during downtime?)
- Integration challenges
  - Temperature limits (e.g. molten salt limited to 1,050°F)
  - Area requirements
  - Additional power generation capacity needed

Technology Development Opportunities

- Integrated system research
- Materials (sensible, PCM and thermochemical)
- Continued demonstration

https://www.powermag.com/the-latest-in-thermal-energy-storage/

A range of competing alternatives

ES hybridization with thermal power

TRL 2-3 Basic Technology Research
- Advanced Sensible Heat Storage
- Latent Heat: Other Phase Change Materials
- Forest Waste Wood
- Formic Acid Production
- Thermal-chemical Hybrid (TCES)
- Electro-thermal Hybrid

TRL 4-5 Components Tested
- Geothermal
- Advanced Chemical Energy

TRL 6-8 System Tested
- Latent Heat: Liquid Air Energy Storage (LAES)

TRL 9 Commercialized
- Compressed Air Energy Storage
- Redox Flow Battery
- Molten Salt
- Chemical Energy (H_2, NH_3, SNG, etc.)

Key
- *Thermal Energy Storage*
- *Chemical Energy Storage*
- *Mechanical Energy Storage*
- *Other Technology Type*

Technology Development Vision

TRL 2-3 **TRL 4-5** **TRL 6-7** **TRL 8+**

- **Innovative Concepts**
- **Component-Level ES Tech**
- **Integrated Systems**
- **Demonstrations (Future as Needed)**

Outcomes
- Mature Long-Duration Energy Storage technologies
- Field Test Near-term Energy Storage Tech with Fossil Assets
- Support Commercialization and Deployment

NETL's Focus

- **Feasibility studies/Pre-FEEDs**
  - Market studies
  - Economic assessments
  - Technology reviews
  - Integration challenges
- **Technology Demos/Pilots**
- **Component level R&D**
- **Energy Storage Tracking**
- **Use Cases**
  - Integration challenges
  - Maturation
  - Cost & Performance
  - Valuation
- **Webinars**
  - Stakeholder engagement

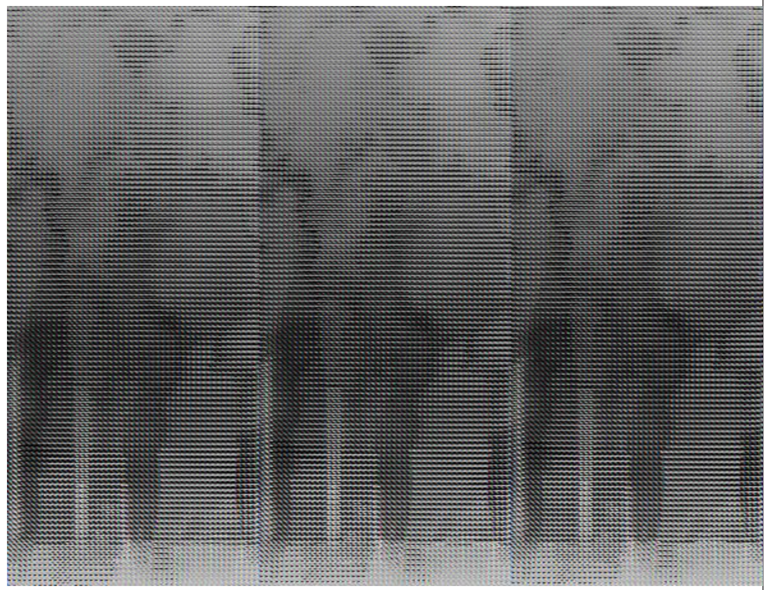


Image Source: Adobe Photostock

Planned Engagement

Summer 2020

Energy Storage Grand Challenge draft Roadmap developed for release and feedback

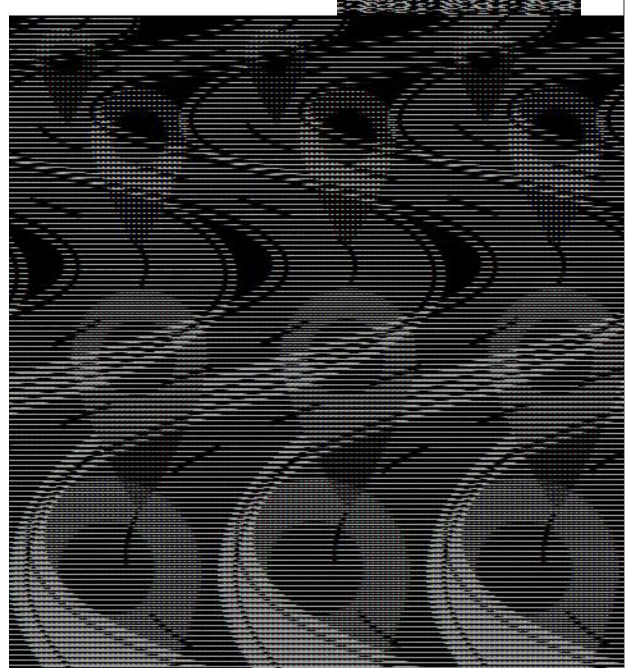
FE Program panel discussion – Sept. 21

Winter 2021

In January, the Crosscutting Energy Storage program will host a webinar to discuss new FOA awards

More at:

https://netl.doe.gov/events
https://www.energy.gov/energy-storage-grand-challenge/energy-storage-grand-challenge



Calls to Action

- **Feedback on ESGC roadmap**
- **Response to the Hydrogen RFI**
  - Topics: natural gas hydrogen, production, transport, storage, gasification from waste, turbines, etc.
- **Partner with MIT/INL/EPRI Workshop groups**
  - Energy storage tech
  - Lessons learned
  - Co-funding R&D
  - Metrics
- **Annual project review meeting**
  - Held in September 2020

More at:
https://www.fedconnect.net/FedConnect/default.aspx?ReturnUrl=%2ffedconnect%2f%3fdoc%3dDE-FOA-0002369%26agency%3dDOE&doc=DE-FOA-0002369&agency=DOE

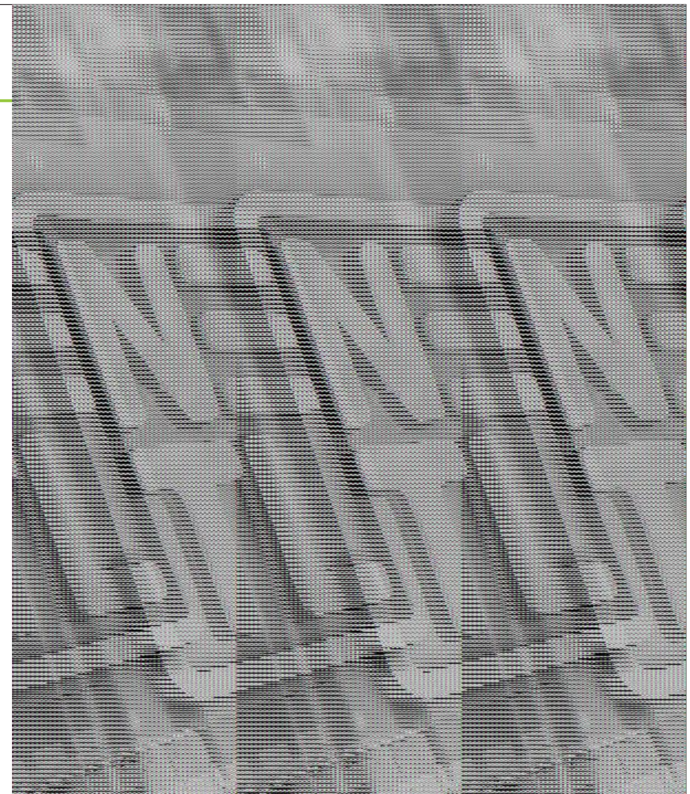


Image Source: NETL

Thank You!

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Learn more:

netl.doe.gov/coal/crosscutting/energy-storage

netl.doe.gov/business/solicitations

energy.gov/energy-storage-grand-challenge/energy-storage-grand-challenge

Stable salt reactors

Basis for Heat Storage to Enable Peak Electricity Production in the United Kingdom – Case Study

August 26th, 2020

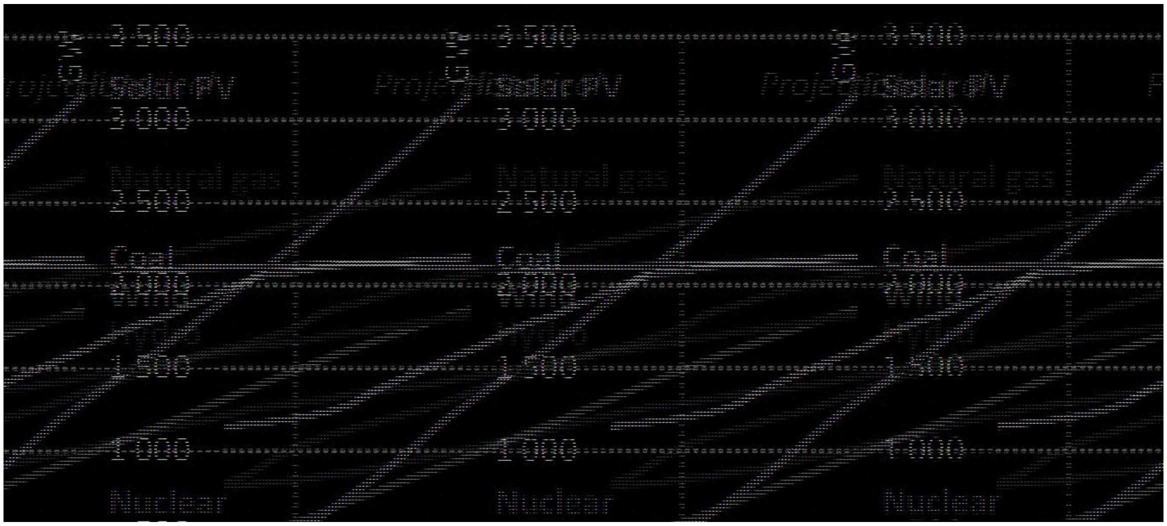
Ian Scott, M.A., Ph.D., Founder and Chief Scientist

Moltex Energy Ltd | 13 The Courtyard | Timothy's Bridge Road | Stratford-upon-Avon | Warwickshire | United Kingdom | CV37 9NP | info@moltexenergy.com | **www.moltexenergy.com**

Moltex Energy mission

- To reduce the cost of nuclear fission energy so that it economically beats burning coal and gas and **the world** is powered with renewables and nuclear

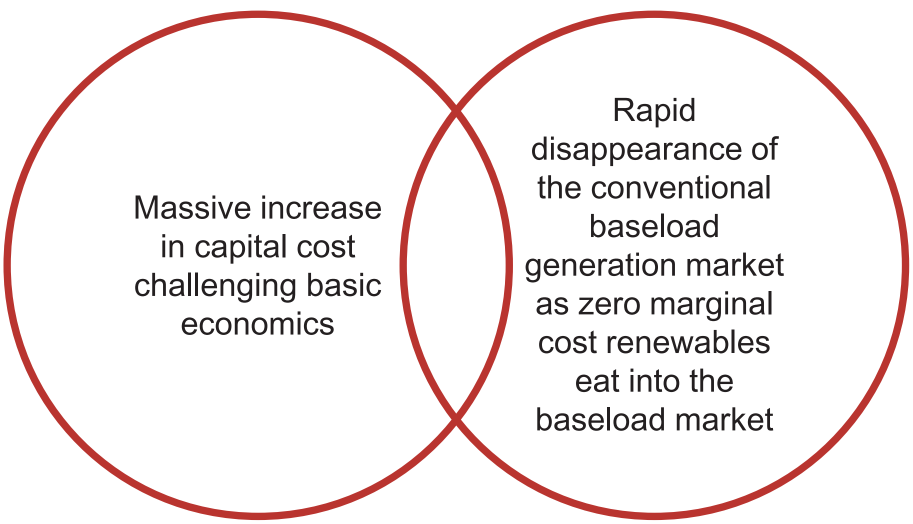
The slow death of nuclear energy



International Energy Agency – World Energy Outlook 2019

3

The twin drivers of the slow death of nuclear energy

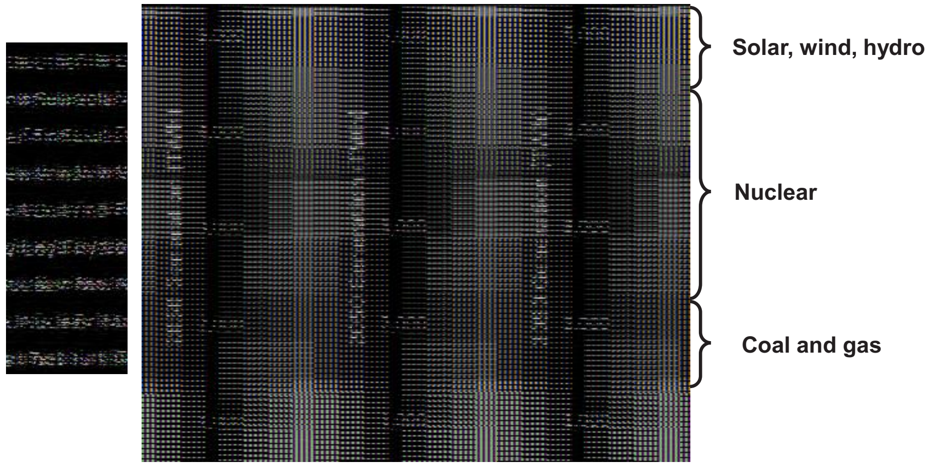


4

The importance of capital cost

- At $3,000/kW, nuclear is viable; at $2,000/kW, it is dominant
- New PWRs are $7,000-$8,000/kW and counting

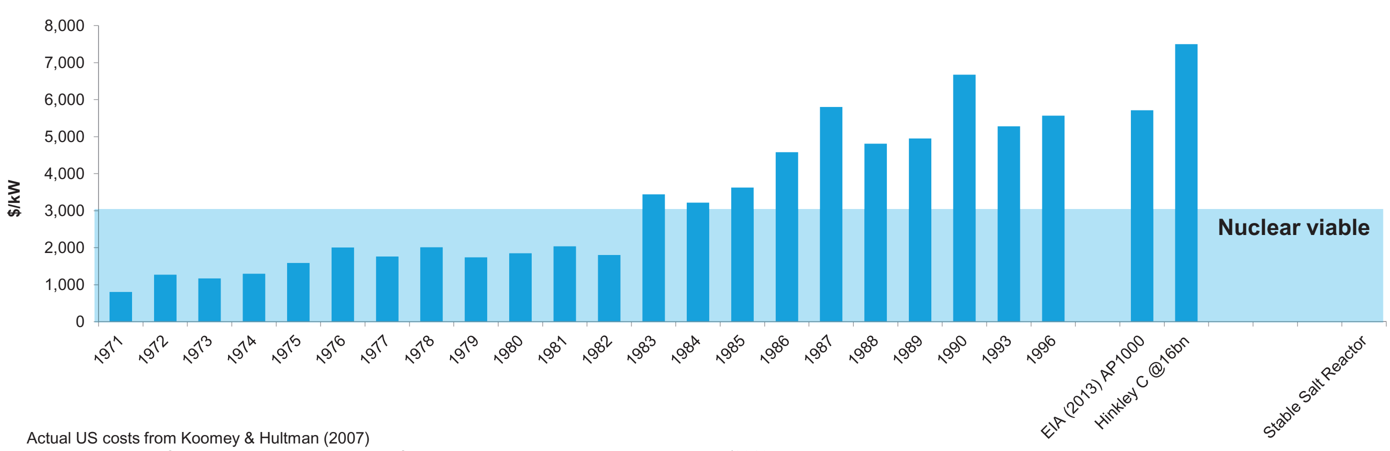
Energy mix in US in 2050 at different price points



Ref: EPRI - Exploring the Role of Advanced Nuclear in Future Energy Markets (2018)

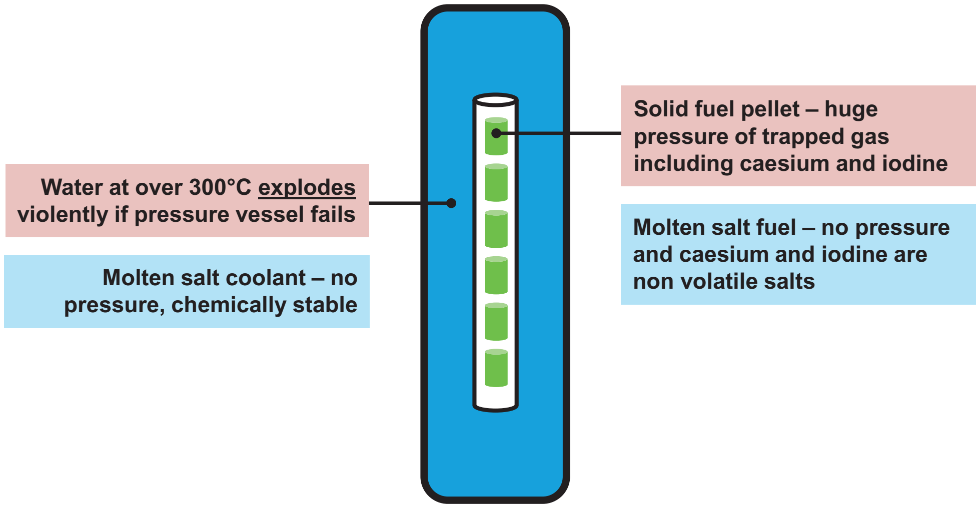
Achieving safety drives nuclear cost escalation

Overnight capital cost of nuclear reactors – Constant 2014$, by date of completion



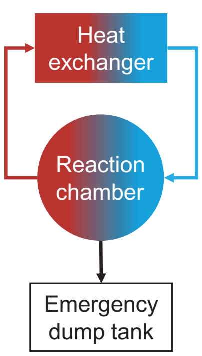
Actual US costs from Koomey & Hultman (2007)
Nuclear viable cost from EPRI -Exploring the Role of Advanced Nuclear in Future Energy Markets (2018

Eliminating hazards with molten salt



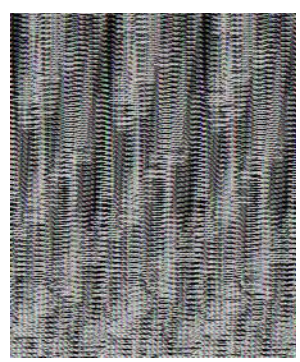
Two ways to use molten salt fuel

Conventional MSRs



- Intensely radioactive fuel salt pumped at pressure round an engineered system which can never be approached by a human being

Stable salt reactor platform



- Fuel salt placed in fuel assemblies
- New concept, patent now granted worldwide

Stable salt reactor platform

Fast spectrum “Wasteburner” SSR-W

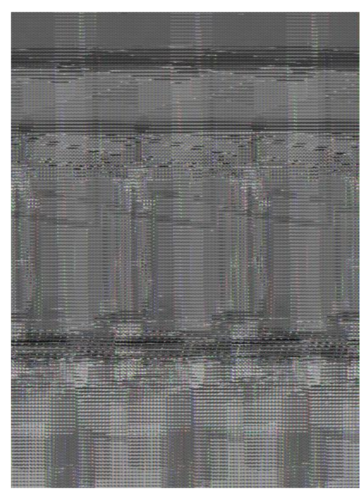
- Fueled by higher actinides from conventional oxide fuel
- Chloride salt fuel
- ZrF_4 coolant salt
- On power refueling
- Passive EHRS to atmosphere

Thermal spectrum <5% LEU SSR-U

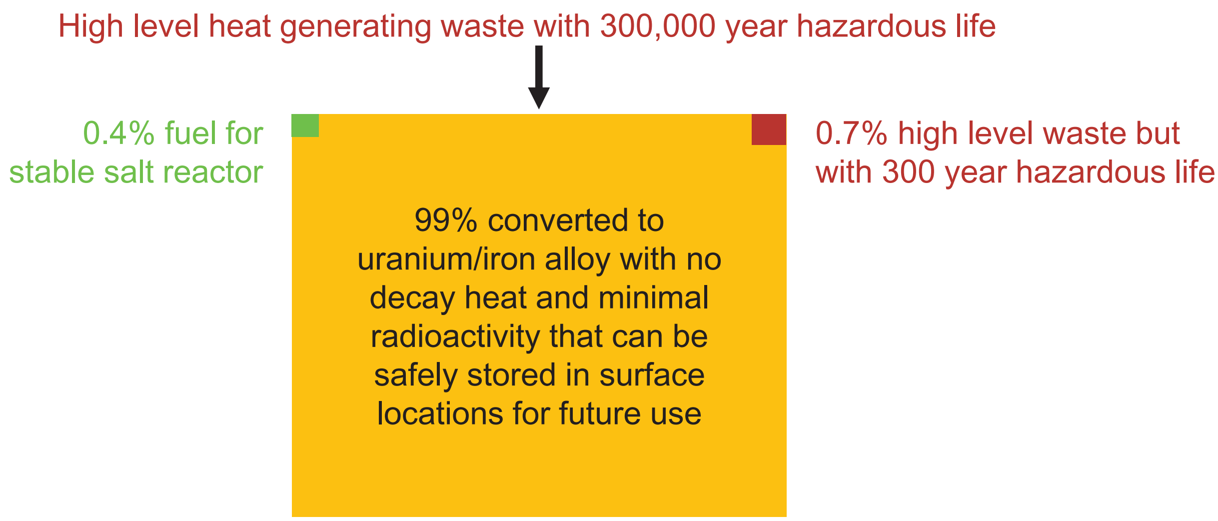
- Graphite moderated - graphite does not contacting fuel
- Uranium/sodium fluoride fuel salt
- Proprietary coolant salt
- Output temperature >800C
- Passive EHRS to atmosphere

SSR-W “Wasteburner”

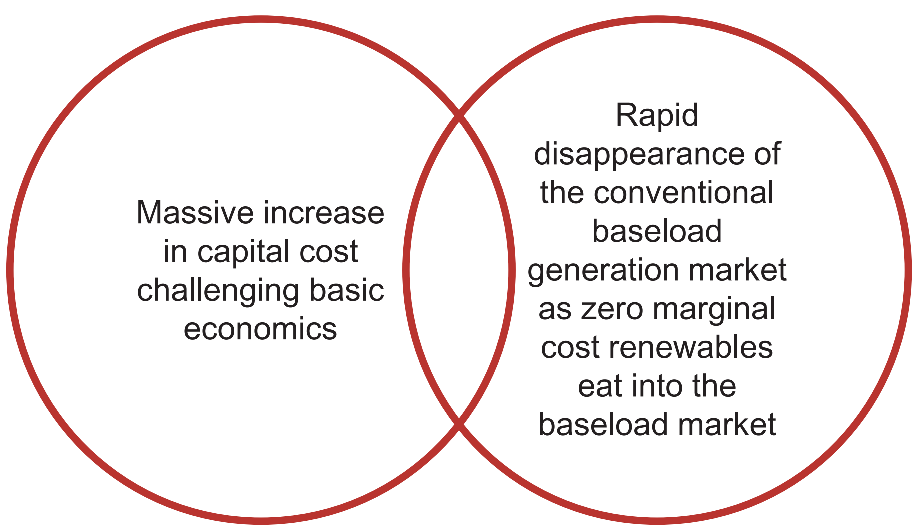
- Fuel salt is uranium/plutonium chloride based, coolant is ZrF_4/KF
- Fuel tubes are vented to prevent tube pressurization
- Hexagonal fuel assemblies with 271 fuel tubes
- Approximately circular core with assemblies supported on a diagrid
- Fuel assemblies replaced with reactor at power using vertical lift crane that never contacts the molten salt coolant
- Spent fuel assemblies decay for up to a year in peripheral locations inside coolant tank but outside the reactor core before being batch removed through airlock into transport flasks
- Novel, patented, heat exchangers permit elimination of intermediate coolant loop – heat passes directly from primary coolant to “solar salt” thermal storage system



SSR-W fuel from CANDU waste (Waste To Stable Salts – WATSS)

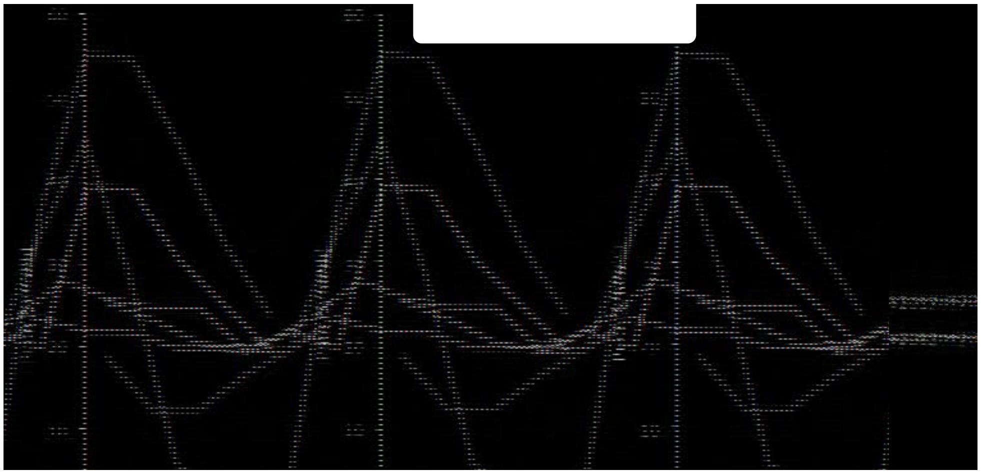


The twin drivers of the slow death of nuclear energy



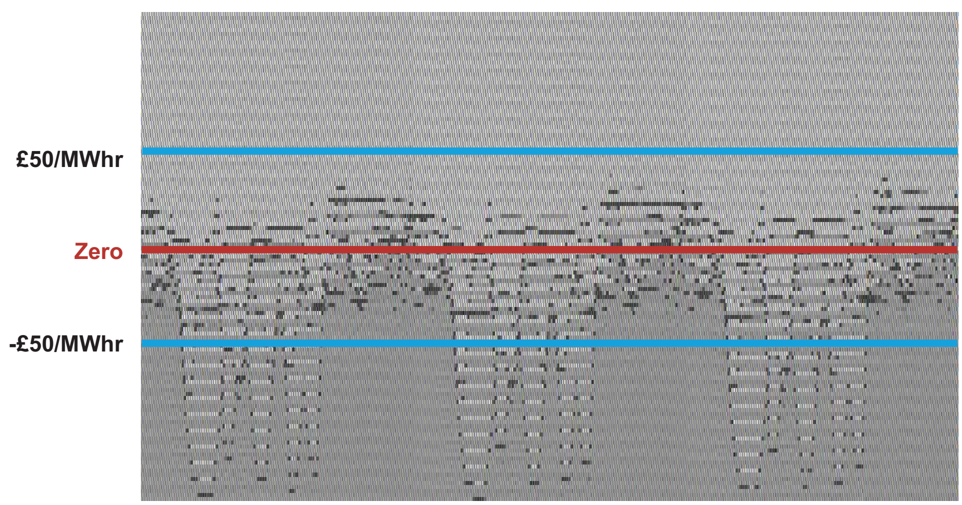
Disappearance of baseload generation as renewables increase

Southern California SP15 day ahead prices – Second day in April



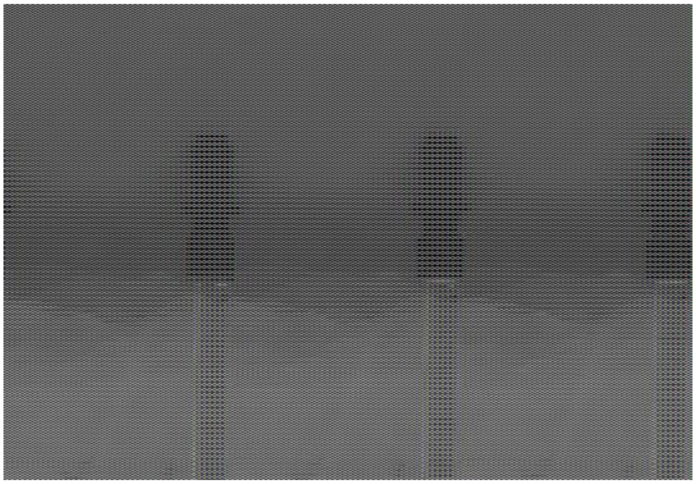
UK wholesale prices – Period 20-27 May 2020

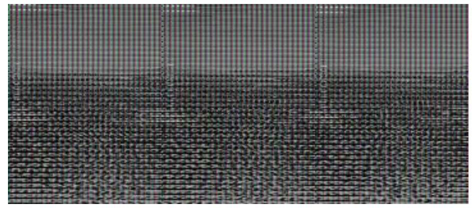
- Average day ahead price for 22 May was minus £9.92/MWhr
- Early hours of 22 May prices reached minus £52.03/MWhr
- Who is paying? Nuclear and renewables with strike prices

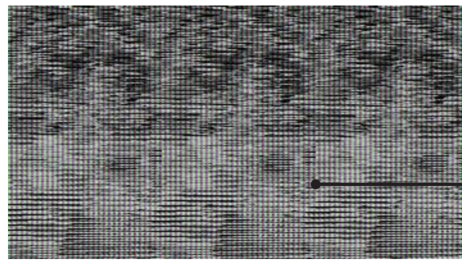


Ref: Drax Electric Insights

Cheap thermal energy storage at grid scale from solar industry



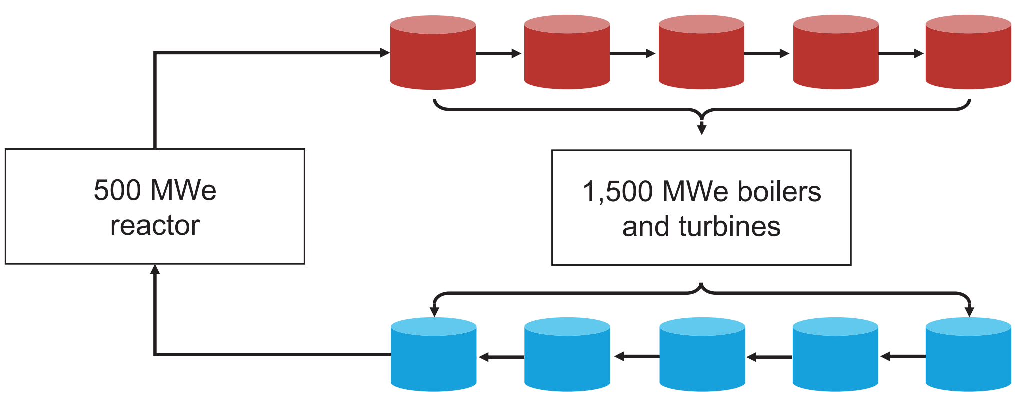




Crescent Dunes solar power station, Nevada

Preferred deployment model

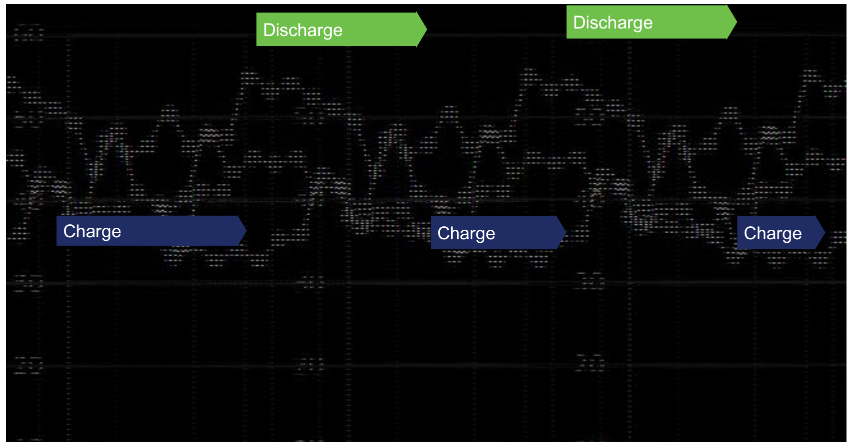
- Operates at 33% capacity factor peaking plant – typical of CCGTs



Operation on average UK day

- Averaged over 2017-2019, UK 30-min interval system selling price as baseload is £47/MWhr
- Sell into the best 8 hours each day £70/MWhr – good for high solar renewable market
- Sell into the best 24 hours each 3 days £87/MWhr – good for high wind renewable market

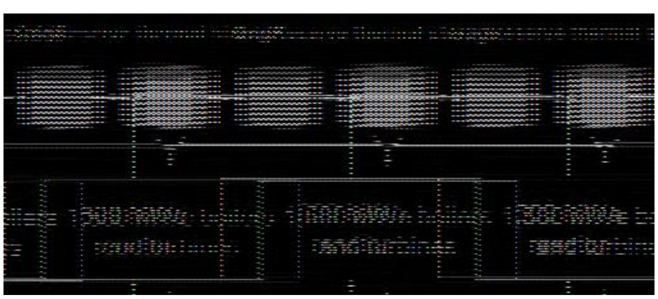
2019 average price at each half hour interval



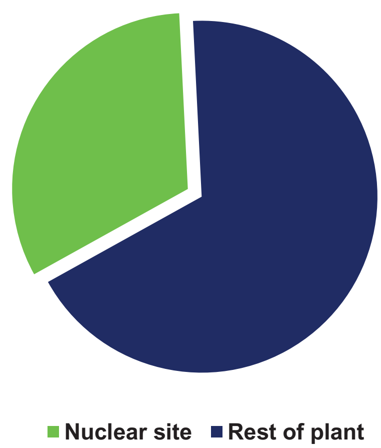
UK price data is transparent, publicly available and a relatively free market

Impact of GridReserve on capital cost

- Rest of plant costs are **high confidence** as similar to CCGT and CSP plants and not subject to nuclear regulation. Errors, optimism bias, etc. in nuclear island costs have relatively little impact on total cost.

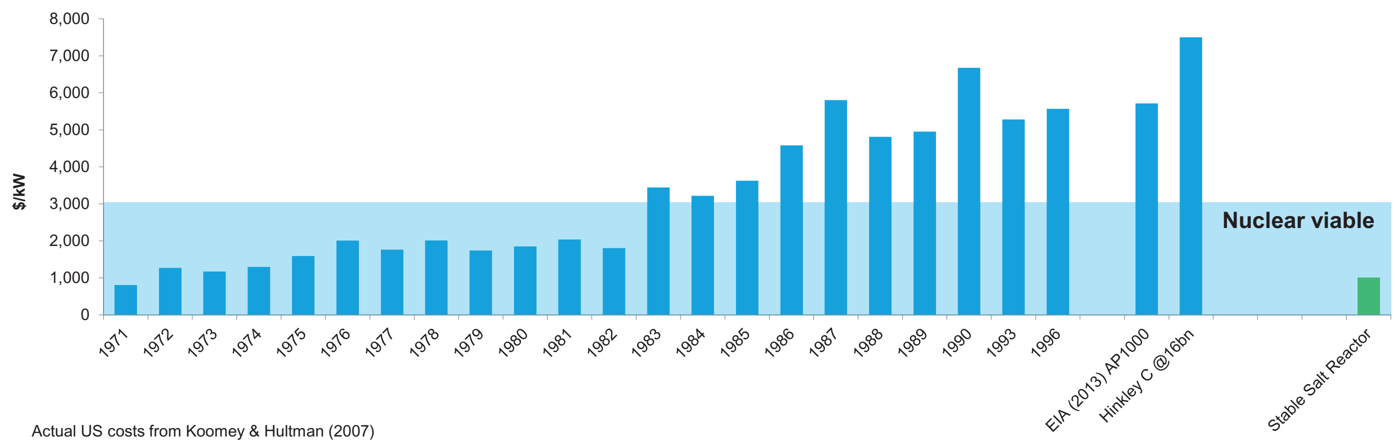


Overnight capital cost



Economic benefits of intrinsic safety and using GridReserve

Overnight capital cost of nuclear reactors – Constant 2014$, by date of completion



Actual US costs from Koomey & Hultman (2007)
Nuclear viable cost from EPRI -Exploring the Role of Advanced Nuclear in Future Energy Markets (2018

Summary of key points

- Molten salt fuel in essentially conventional fuel assemblies is a genuinely new concept that eliminates most of the technical challenges pumped fuel salt MSR's face
- SSR-W profitably eliminates most of the hazard of spent nuclear fuel from the first nuclear era
- Low nuclear island costs, combined with GridReserve thermal energy storage brings plant capital cost well below $2000 per kWe capacity - with high confidence in the cost because most is non nuclear
- GridReserve makes nuclear energy a true partner to intermittent renewable energy sources operating highly profitably over both 24 hours and multiday periods

Thank you

Ian Scott, MA, PhD, Founder and Chief Scientist

ianscott@moltexenergy.com

Non-Technical Aspects of Integrating Thermal Energy Storage with Nuclear

Perspectives and Cautionary Lessons from History

Andrew Sowder, Sr. Technical Executive
Advanced Nuclear Technology

August 26, 2020

Lessons from the Past

- Cogeneration missions are not new to nuclear

- Two case studies in brief:
  - Midland Nuclear Power Plant designed for steam supply to neighboring Dow Chemical facility in Midland, MI (1970s – 80s)

  - Planning for OPPD's Fort Calhoun extended power uprate (EPU) coincided with opportunity for steam sales (~17% of thermal output) to adjoining Cargill corn mill

OPPD = Omaha Public Power District serving eastern Nebraska along Platte and Missouri rivers

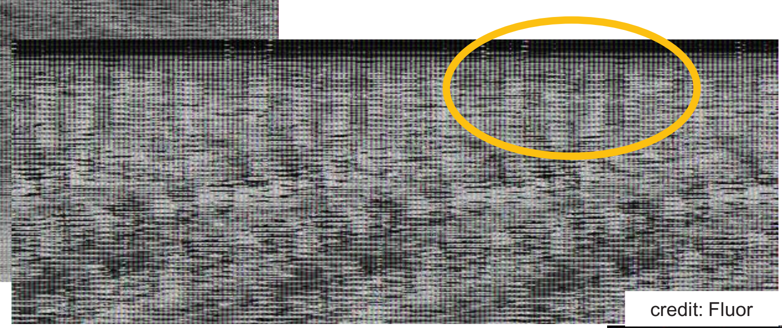
References and Credit

- Midland history:
  - C.E. Gatlin, Jr. et al. Repowering of the Midland Nuclear Station. Proceedings from the Tenth Annual Industrial Energy Technology Conference, Houston, TX, September 13-15, 1988.
  - A look back at Midland's brush with nuclear energy. Midland Daily News. May 16, 2008.
  - Fluor Projects: Midland Gas-Fueled Cogeneration Power Plant Refurbishment. http://www.fluor.com/projects/gas-fueled-power-plant-epc-commissioning

- Fort Calhoun history:
  - Joe Gasper. *Fort Calhoun-Cargill Proposed Steam Sales and Lessons Learned*. Presentation at MIT LWR Heat Storage Workshop, Cambridge, MA. June 27-28, 2017.

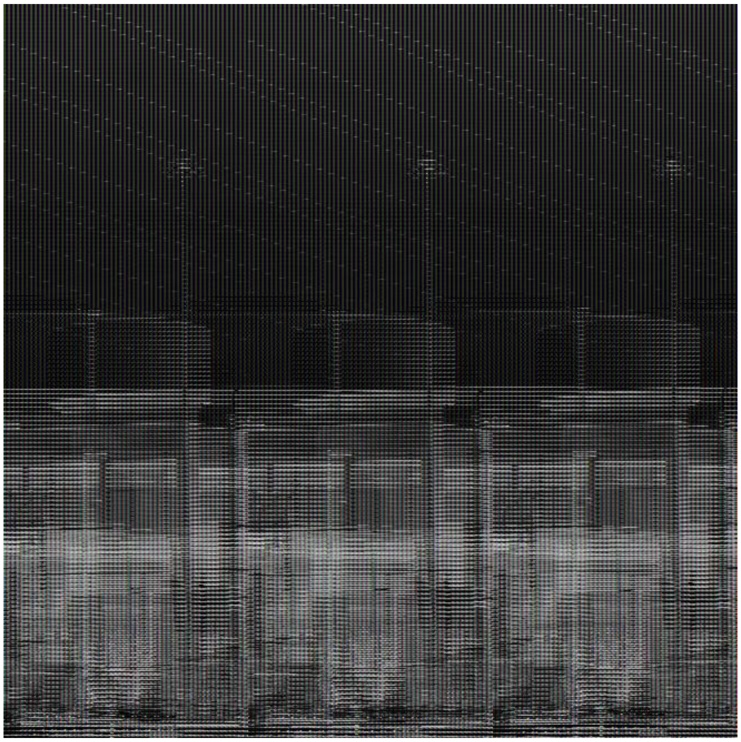
Midland Cogeneration Station

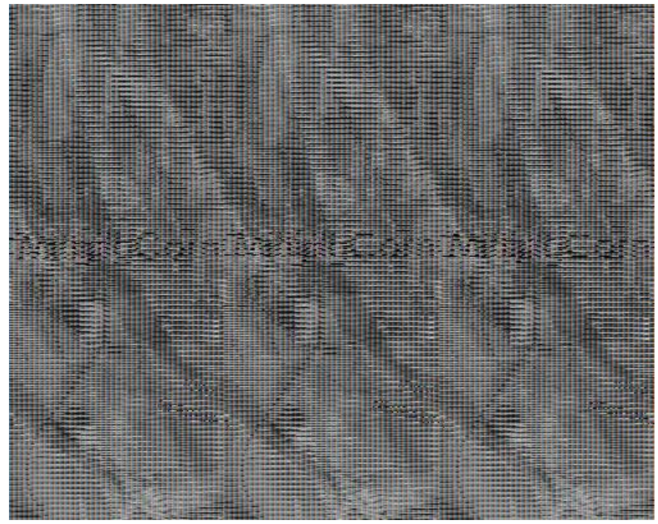
- Started in 1967 as two-unit PWR for electricity generation and steam supply to neighboring Dow Chemical facility
- Halted in 1984 at 85% complete with $4.1bn invested after chronic delays, escalating costs
- Repowered as a 12-unit combined-cycle, natural-gas-fired cogen plant; online in 1991

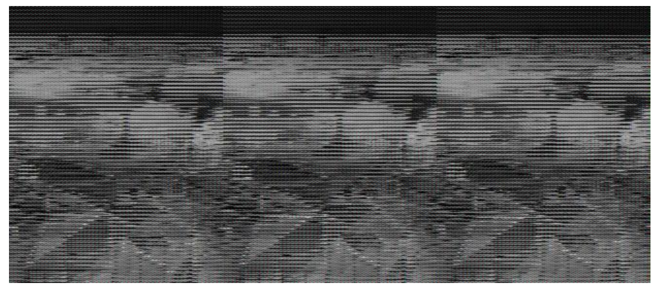


credit: Fluor

Fort Calhoun Nuclear Station







2000s: Convergence of Opportunities for Fort Calhoun

- Smallest operating NPP at 2016 retirement
- 17% planned extended power uprate (EPU) to 1755 MWt
- 2005-2006 major refurbishment project anticipated EPU with replacement of:
  - Steam generator
  - Pressurizer
  - Condenser
- 2004: Interest from Cargill in Fort Calhoun steam to support expansion of neighboring corn mill facility in lieu of additional natural gas

Regulatory and Licensing

- Midland Nuclear Plant received Part 50 Construction license from AEC but project was plagued by delays from internal and external factors, including:
  - Significant impacts from evolving U.S. nuclear regulatory authority and regulations for projects that spanned the late 1970s and early 1980s*
  - Major changes to oversight and regulation following 1979 Three Mile Island accident

- Evaluation of Fort Calhoun steam sales to Cargill included early engagement with USNRC
  - Technically feasible
  - **No licensing show stoppers**
  - Adequate safety margins maintained even with planned EPU

*Energy Reorganization Act of 1974 established a new independent U.S. Nuclear Regulatory Commission

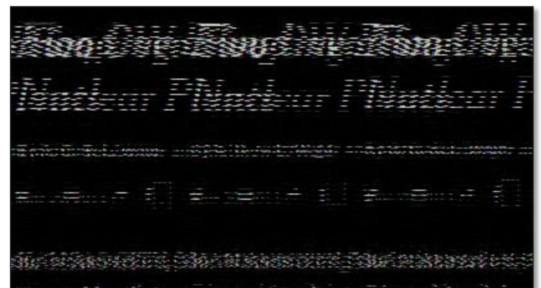
Business Risk, Liability, and Insurance

- Midland NPP: $4.1 billion invested at 85% completion in 1984
  - **Financial burden risked solvency of Consumers Power (= 45% of capitalization)**
  - **Dow withdrawal from project in 1983**

- Fort Calhoun: Steam sales to Cargill passed each test until liability…
  - Configuration of corn mill process proved problematic
    - *Cargill could not sufficiently isolate food process lines*
    - *Possibility that tritium could migrate to corn sweeteners and ultimately end up in soft drinks (J. Gasper, 2017)*
  - **SHOW STOPPER: Unresolvable nuclear insurance issue for OPPD - how to prove a negative, i.e., tritium detected in consumer produce did NOT originate at Fort Calhoun**

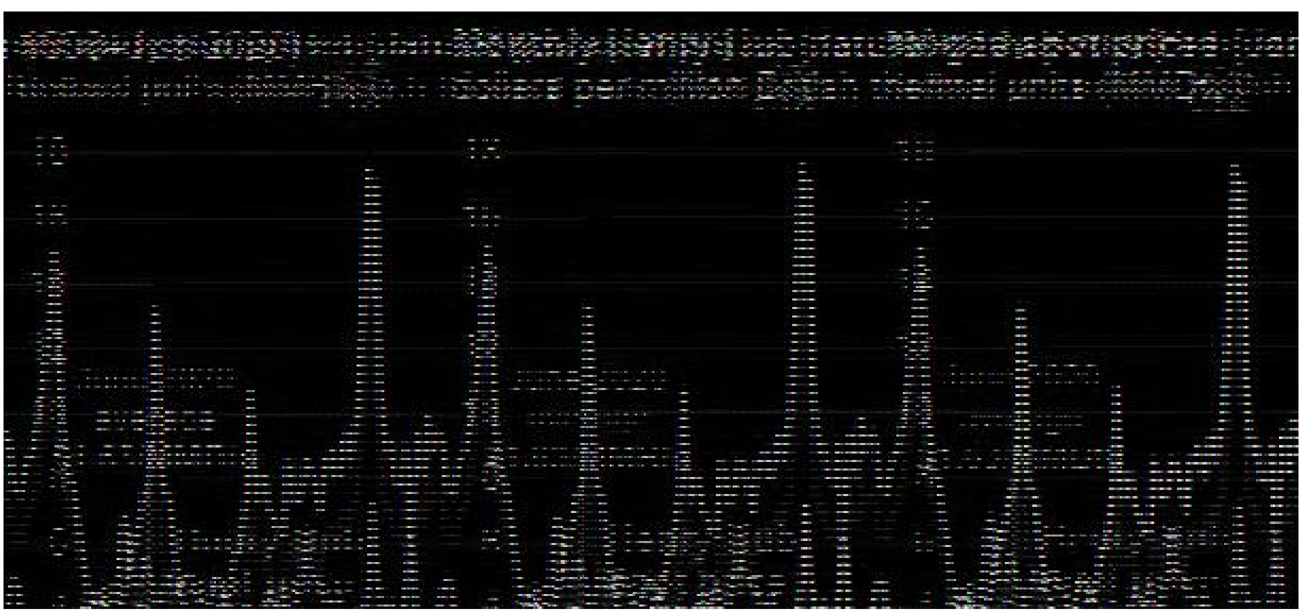
Timing and External Events

- Extended Midland plan construction timeline (unrelated to cogeneration mission) intersected with two consequential developments in late 1970s and early 1980s for nuclear industry
  - Broad economic downturn
  - Three Mile Island and subsequent changes to regulatory environment
- Fort Calhoun opportunity for EPU and steam sales to Cargill also coincided with seismic shift in electricity market
  - Shale gas revolution in United States
  - Increasing penetration of renewables
  - Grid congestion
  - 2008 "Great Recession"
  - Later…2011



New York Times, 2011 https://www.nytimes.com/2011/06/21/us/21flood.html

The Ever Present Threat of a Disruptor



Source: US Energy Information Agency

Workshop Observations and Conclusions: A Personal Perspective

Three Workshops: MIT, INL and EPRI Webinar (3 parts)

Charles Forsberg

Massachusetts Institute of Technology Cambridge, MA 02139,
Email: cforsber@mit.edu

Separating Nuclear Reactors from the Power Block with Heat Storage:
A New Power Plant Design Paradigm

Session 3: WebEx Workshop: August 26, 10:00 AM to 1:00 PM Eastern

Low-Carbon Resilience Requires Massive Storage

- Experience results in an energy system with more than a month of storage. In the U.S.:
  - Coal, oil and natural gas: 45 to 90 days with seasonal variation
  - Nuclear: 9 months
- U.S. Low-carbon storage future
  - Nuclear: 9 months (fuel) + hydro (seasonal) + biofuels
  - PV / Wind: zero
- U.S. Annual energy consumption: 25,155 TWh
  - 1 day storage: 69,000 GWh; 1 month storage: 2,000,000 GWh
  - Greater than 80% of energy use by the consumer is heat
- **Serious storage strategies are at the million GWH Scale**

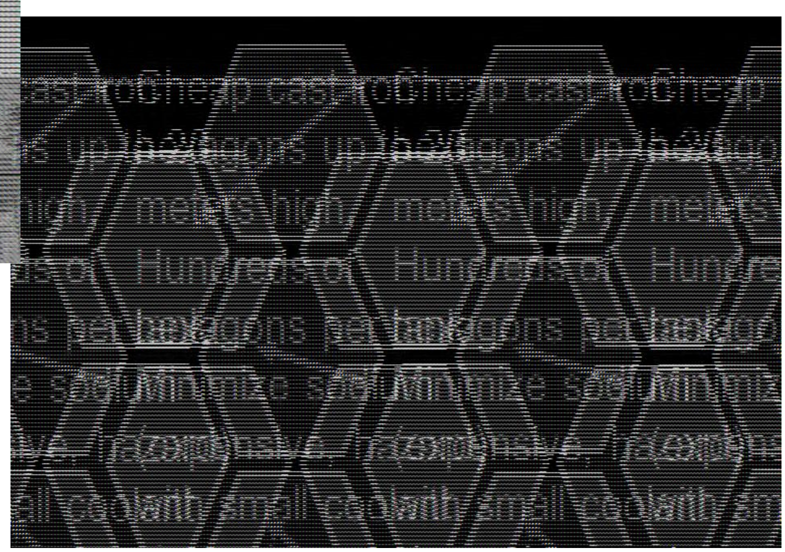
Large Incentives for Joint Nuclear / Solar / Fossil Heat-Storage Development Programs

- **Heat storage systems do not know what the heat source is**
- Significant improvements in cooperation across energy sources in the last several years; but we have some way to go
- More than 400 people attended this workshop—across nuclear, CSP and fossil energy sources

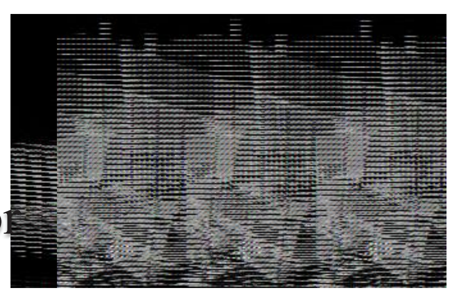
Example: Planned Sodium-Cooled Systems:

Potential Common Cast-Iron Heat-Storage Technology

National Solar Thermal Test Facility (Sandia)



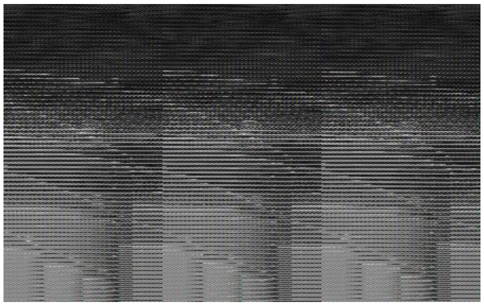
Versatile Test Reactor (INL)



Heat Storage Has the Potential to be 10 to 100 Times Cheaper than Electricity (Battery) Storage

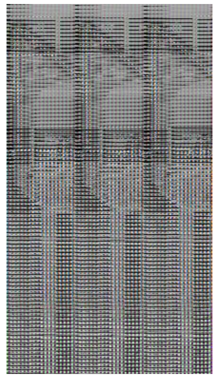
Lower-Cost Materials of Construction and Advancing Designs

Nitrate Salt (Today)



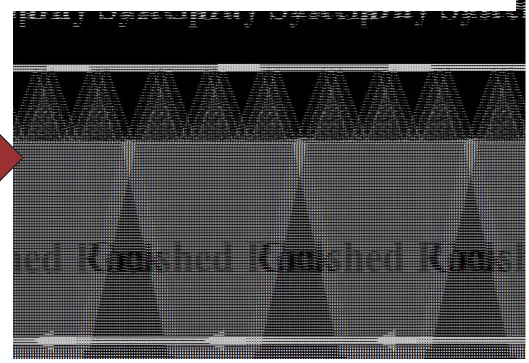
Solana Generating Station (2013, U.S., ~4200 MWh(t))

Crushed Rock in Nitrate Salt



DLR

Crushed Rock with Salt Heat Transfer



MIT

Higher Temperature Salts Are Coming

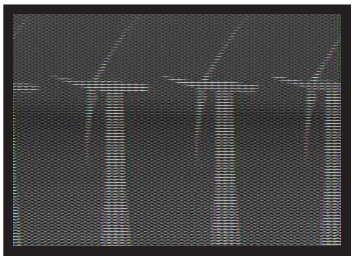
Heat Storage May Enable Low-Cost Assured Generating Capacity

- Two electricity system requirements
  - Energy (kWh)
  - Capacity (kW)
- **California rolling blackouts because of insufficient generating capacity**
  - High demand
  - Sun went down

The Guardian

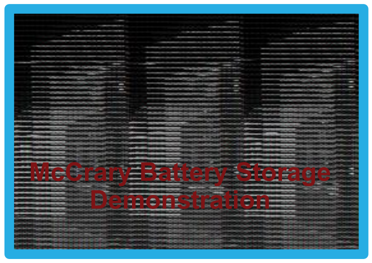
Buy Several KW(e) Generating Capacity if Electricity Storage vs 1 KW(e) Capacity if Heat Storage

Electricity Storage



Generation

+



Electricity Storage

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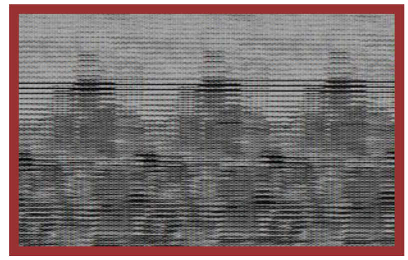


Backup Gas Turbine for Depleted Storage

Heat Storage

Turbine-Generators Sized to Peak Demand

Reactor / Other

Heat Storage

Low-Cost Peaking Boiler or Furnace

Heat Storage Creates Option to Design Low-Cost Peak Generating Capacity

- Efficient
- High Capacity Factor
- Higher Capital Cost

"Base-Load" Turbine-Generator

Peaking Turbine-Generator

- Low Capacity Factor
- Low Capital Cost
- 2-3 X Capacity

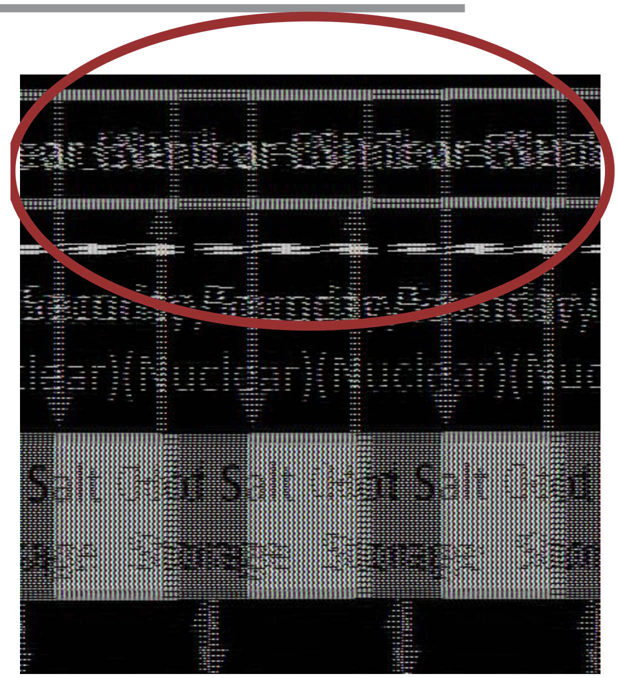
Heat Storage

Assured Generating Capacity: Low-Cost Furnace

Reactor

Implications for Reactor Island

- Smaller security boundary and fewer people with plant access
- No grid/reactor interactions or safety implications—rethink design
- Only reactor island designed, regulated and built to nuclear standards
- Separate non-nuclear balance of plant design and construction team
- Change in licensing



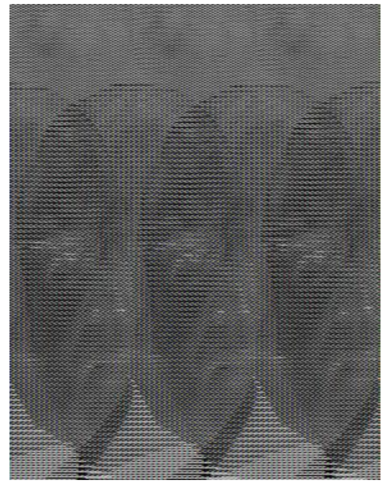
Conclusions

- Market changes have created the incentives for storage
- We are early in research, development and deployment of
  - Heat storage technologies
  - Power conversion technologies
- Large incentives for coupled nuclear, solar, and fossil heat-storage demonstration programs
- Heat storage implies major changes in nuclear plant design

Biography: Charles Forsberg

Dr. Charles Forsberg is a principal research scientist at MIT. His research areas include Fluoride-salt-cooled High-Temperature Reactors (FHRs) and utility-scale heat storage including Firebrick Resistance-Heated Energy Storage (FIRES) and 100 GWh heat storage systems. He teaches the fuel cycle and nuclear chemical engineering classes. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory.

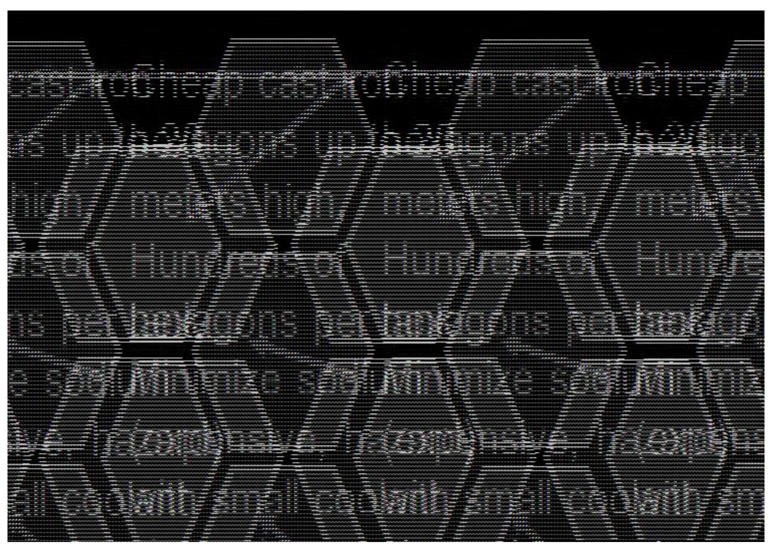
He is a Fellow of the American Nuclear Society (ANS), a Fellow of the American Association for the Advancement of Science, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in waste management, hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design and is a Director of the ANS. Dr. Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. He has been awarded 12 patents and published over 300 papers.



http://web.mit.edu/nse/people/research/forsberg.html

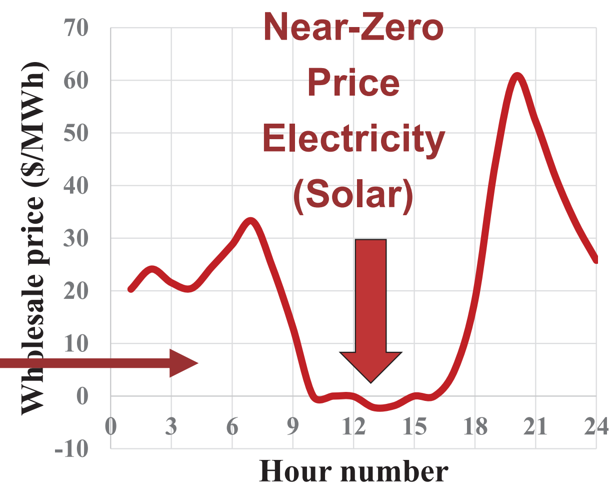
Cast-Iron Storage for Sodium Systems

- Cast iron is cheap, greater than 98% of tank inventory
- Geometry is similar to sodium fast reactor core with massive design experience
- Minimum sodium inventory to minimize cost and hazard
- Option of inserts in cast iron to minimize vertical heat transfer



Electricity Markets are *Changing*

- **Electricity prices in fossil-fuel systems are relatively constant because most of the production cost is in the fuel.**
- **Volatile electricity prices in high-capital-cost low-operating-cost electricity systems (nuclear, wind, solar, etc.). Operating costs set minimum electricity prices**
- Changes in markets create incentives for energy storage: sell electricity at times of high prices

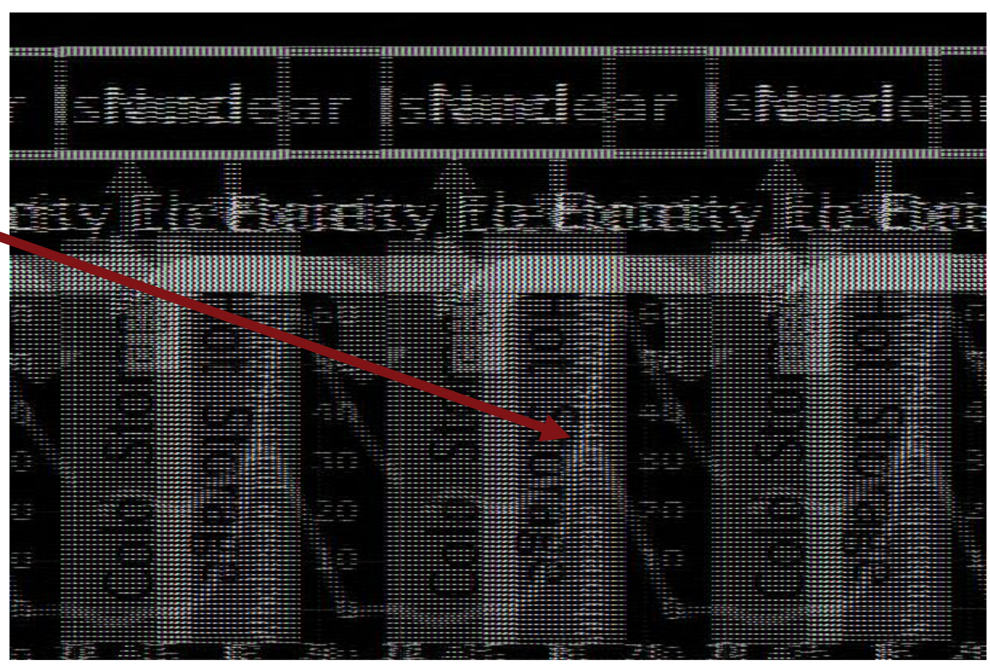


California Wholesale Electricity Prices With Midday Solar Price Collapse: 31 March 2019

13

Heat Storage Enables Large-Scale Wind and Solar PV

- Lowest cost storage system
- Buy low-price electricity to set minimum electricity prices when excess wind or solar
- Incremental capital cost is the cost of resistance heaters



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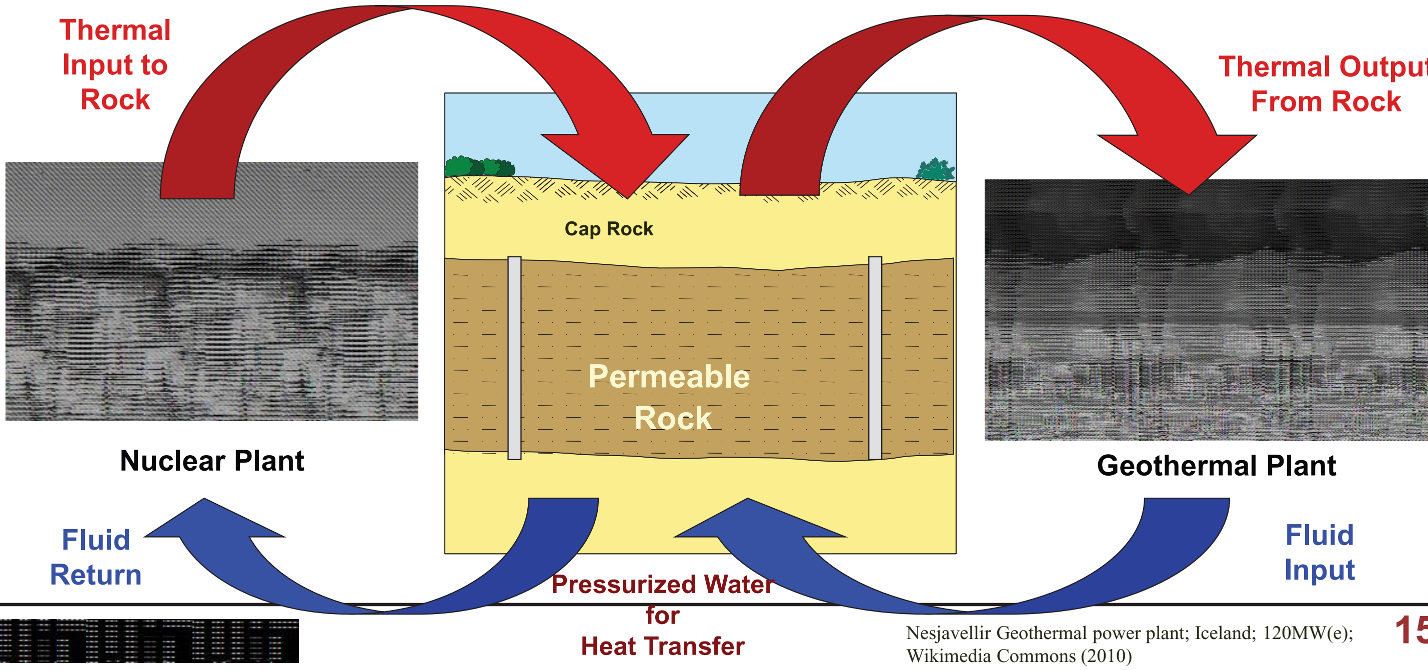
Hourly to Seasonal Geothermal Heat Storage

Create Artificial Geothermal Heat Source



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Nesjavellir Geothermal power plant; Iceland; 120MW(e); Wikimedia Commons (2010)

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