Base-Load Nuclear with Heat Storage and Combustion Turbine for Dispatchable Electricity with Infinite-Duration Assured Peak Power More than Twice Reactor Output

(Applicable to Other Heat Sources: Fusion, Geothermal and CSP)

LDES National Consortium Annual Workshop: Short Summary

University of Utah

Salt Lake City, UT 84112

July 14, 2026

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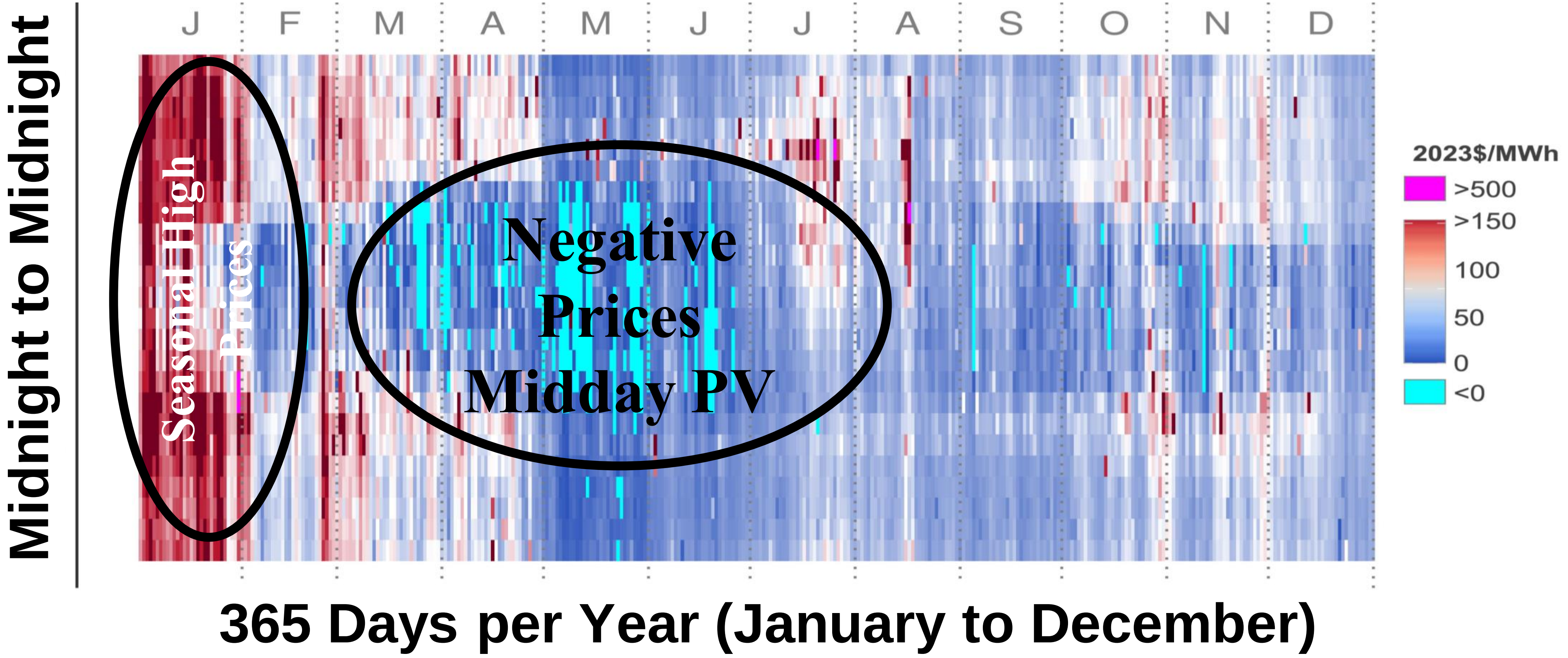
Massachusetts Institute of Technology

MITei

Summary Plus Backup Information: Updated July 19, 2026

The Addition of Wind and Solar Create Times of Very Low and High Prices and the Incentive for Electricity Storage

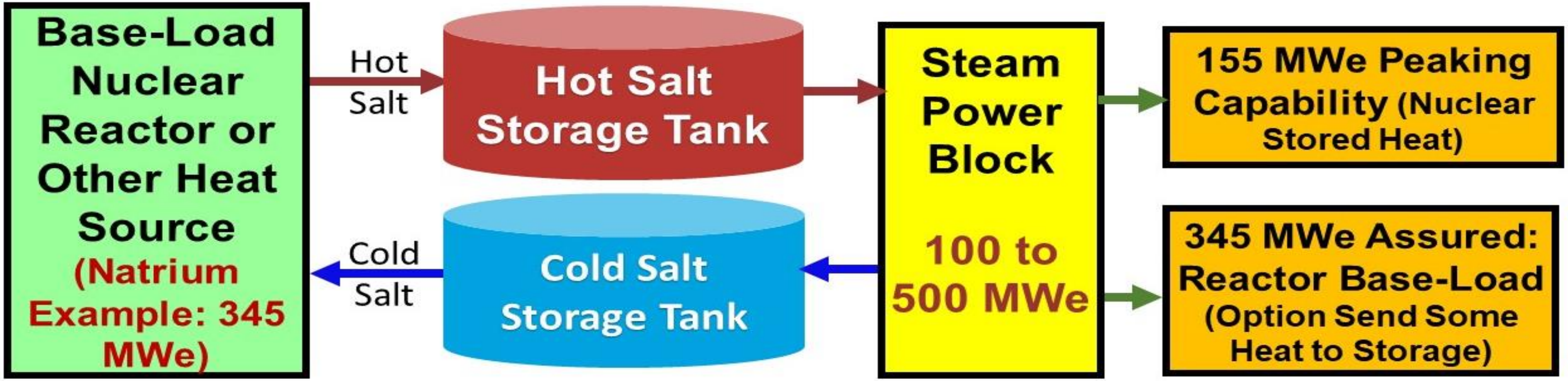
Hourly 2023 California Wholesale Electricity Prices



D. Millstein, E. O'Shaughnessy and R. Wiser, Exploring Wholesale Energy Price Trends, Lawrence Livermore National Laboratory, 2024. https://eta-publications.lbl.gov/sites/default/files/rewep-2024update_tech-brief_20240429.pdf

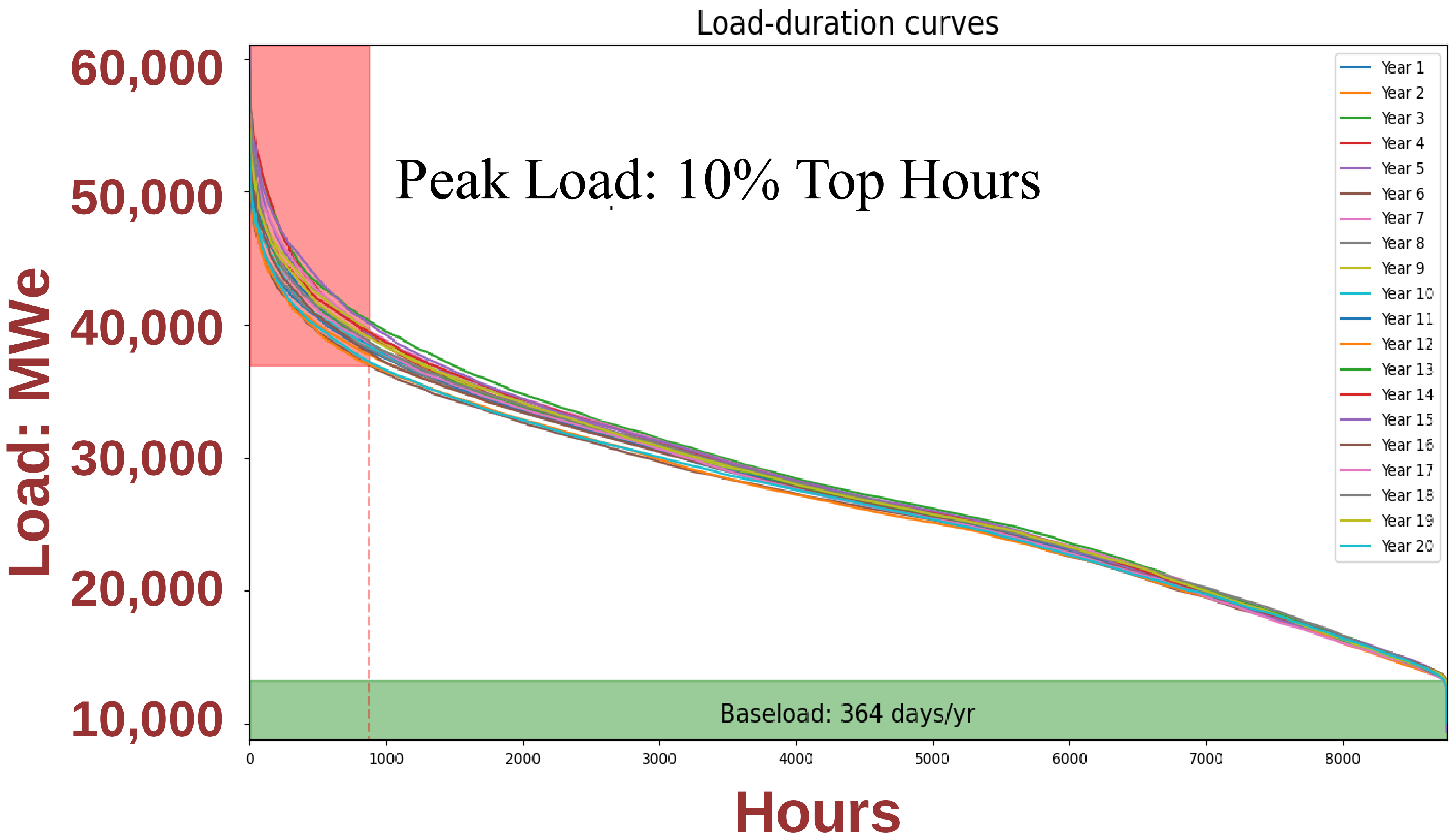
TerraPower is Constructing the Natrium Nuclear Reactor in Wyoming: First Reactor with Nitrate-Salt Heat Storage

- Base-load reactor heats salt. Steam turbine with variable electricity output
  - Base-load reactor: 345 MWe
  - Peak: 500 MWe
  - Minimum output: 100 MWe



Peak Power: Hourly New England Electricity Demand Curve Over One Year: 20 Simulations for the Year 2050

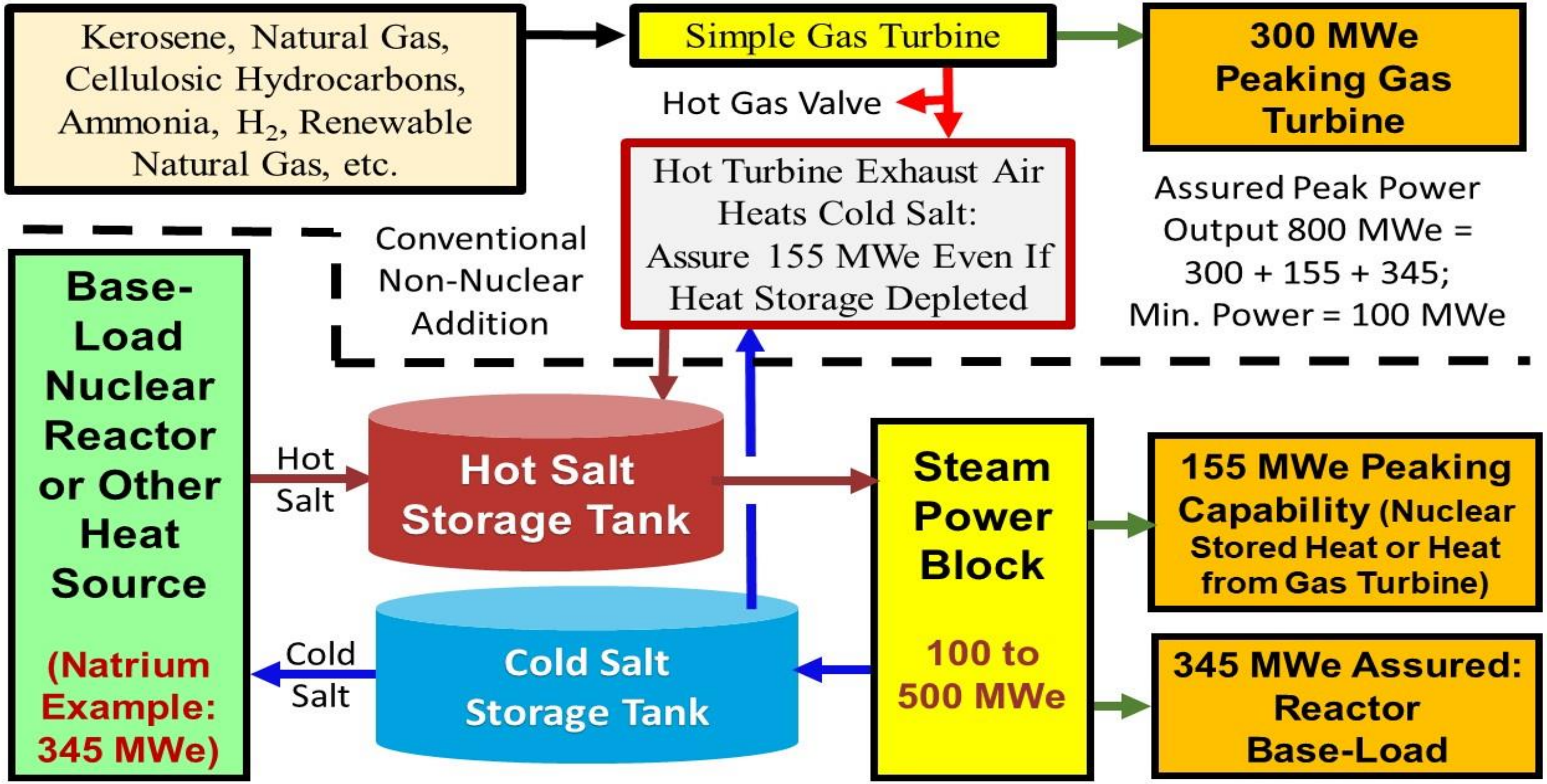
- Long-duration cold spells
- Many events correspond to extended low wind and solar
- Extreme events such as Level 4 hurricanes, need option to operate 1000s of hours at peak power while repair



Armstrong et al., 2024. The role of fusion energy in a decarbonized electricity system. Report by MIT Energy Initiative, see section B.2.2.

We Add Gas Turbine to Base-Load Reactor with Heat Storage:

Hot Gas-Turbine Exhaust Heats Salt for Full Generation Capacity



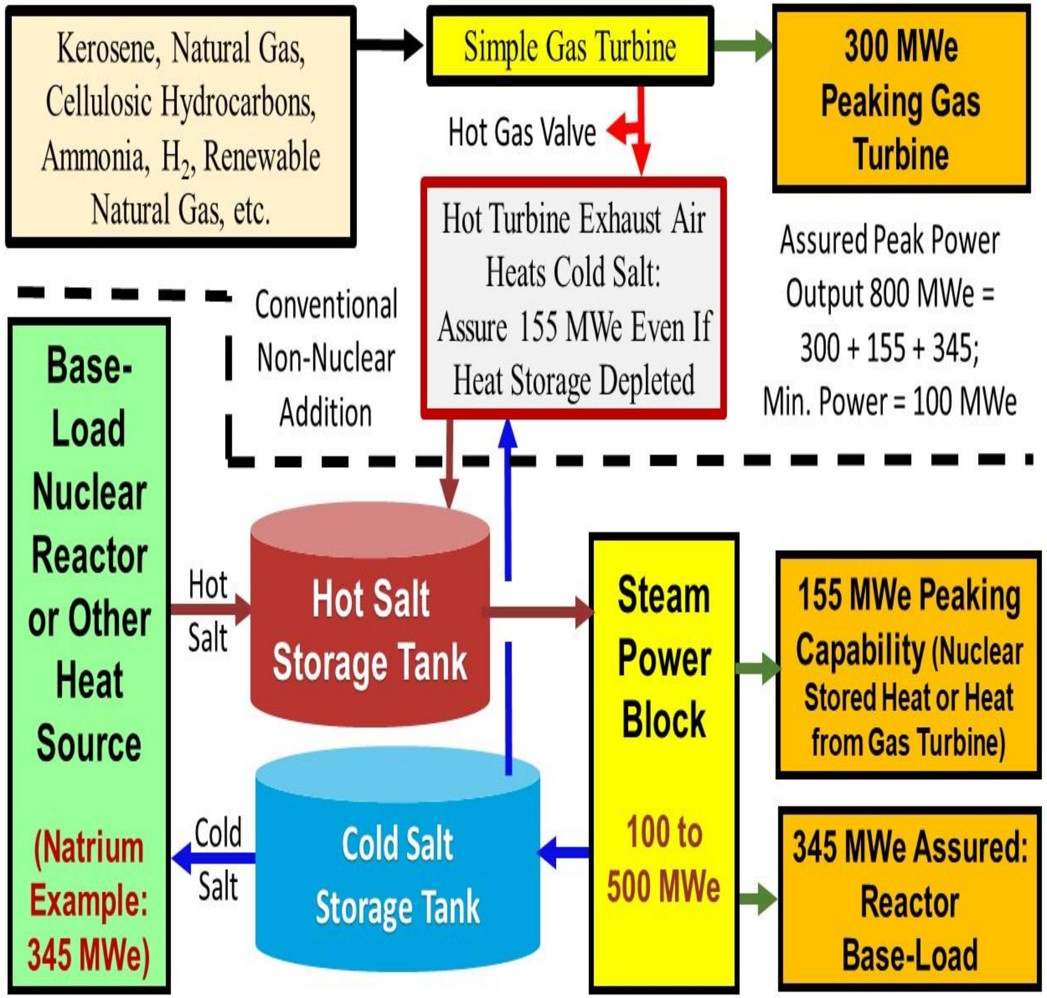
Electricity Output: 100 to 800 MWe

Capacity 800 MWe when Heat Storage Empty: >Twice Reactor Output

Heat Storage Operates 70% of the Time, Gas Turbine 5 to 10% of the Time

System Provides Ancillary Services to Prevent Grid Collapse

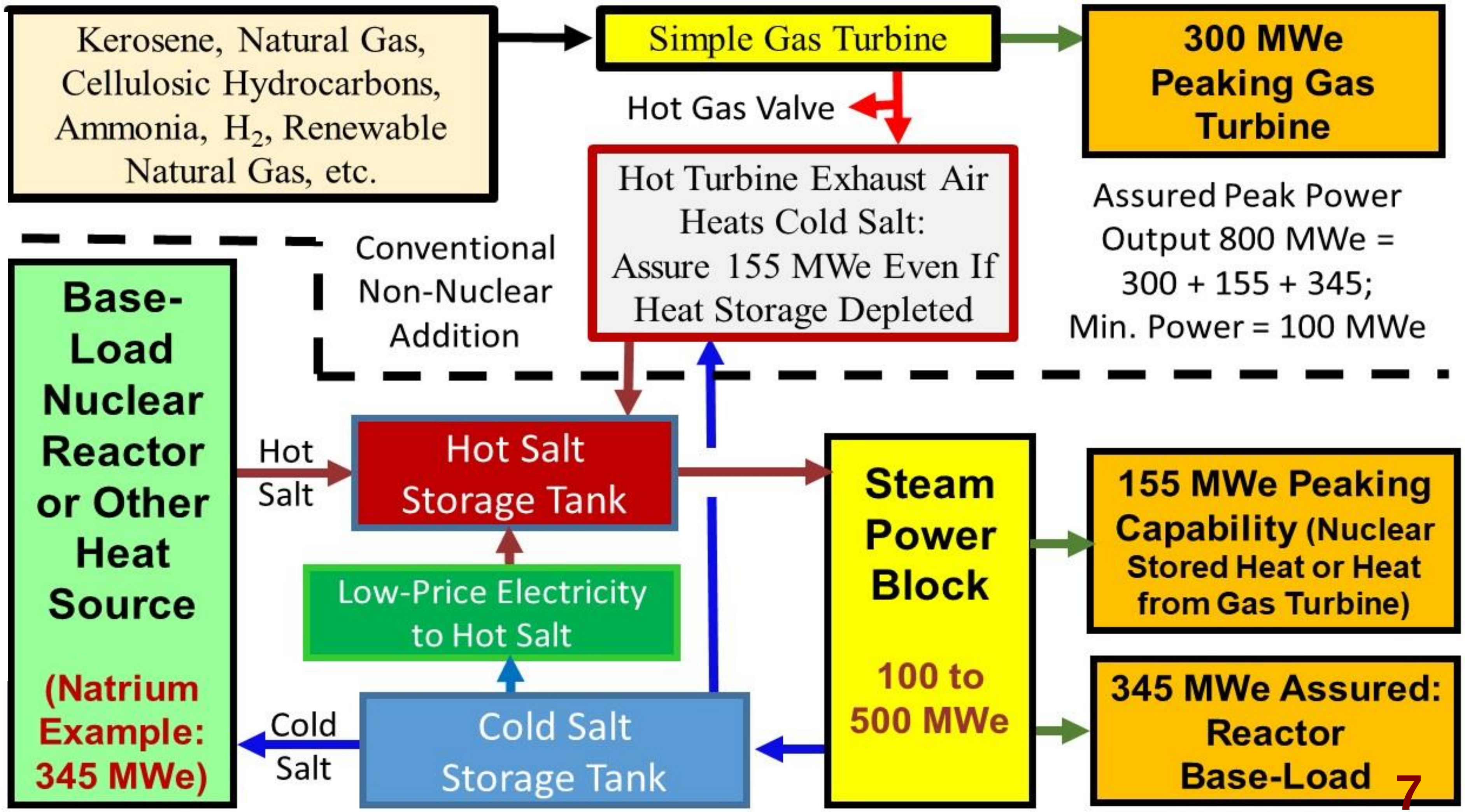
- Frequency control
  - ➢ Wind/solar do not provide frequency control—highest need for frequency control when high wind/solar
  - ➢ At same time low output (100 MWe), system has 500 MWe turbine generator inertia at part load for frequency control
- Backup capacity if loose other electric generators on grid: Power block operating part load most of the time
- Black-start capacity, reactor operating even if grid down with heat to storage



Ancillary Services are 25 to 50% of Battery Revenue

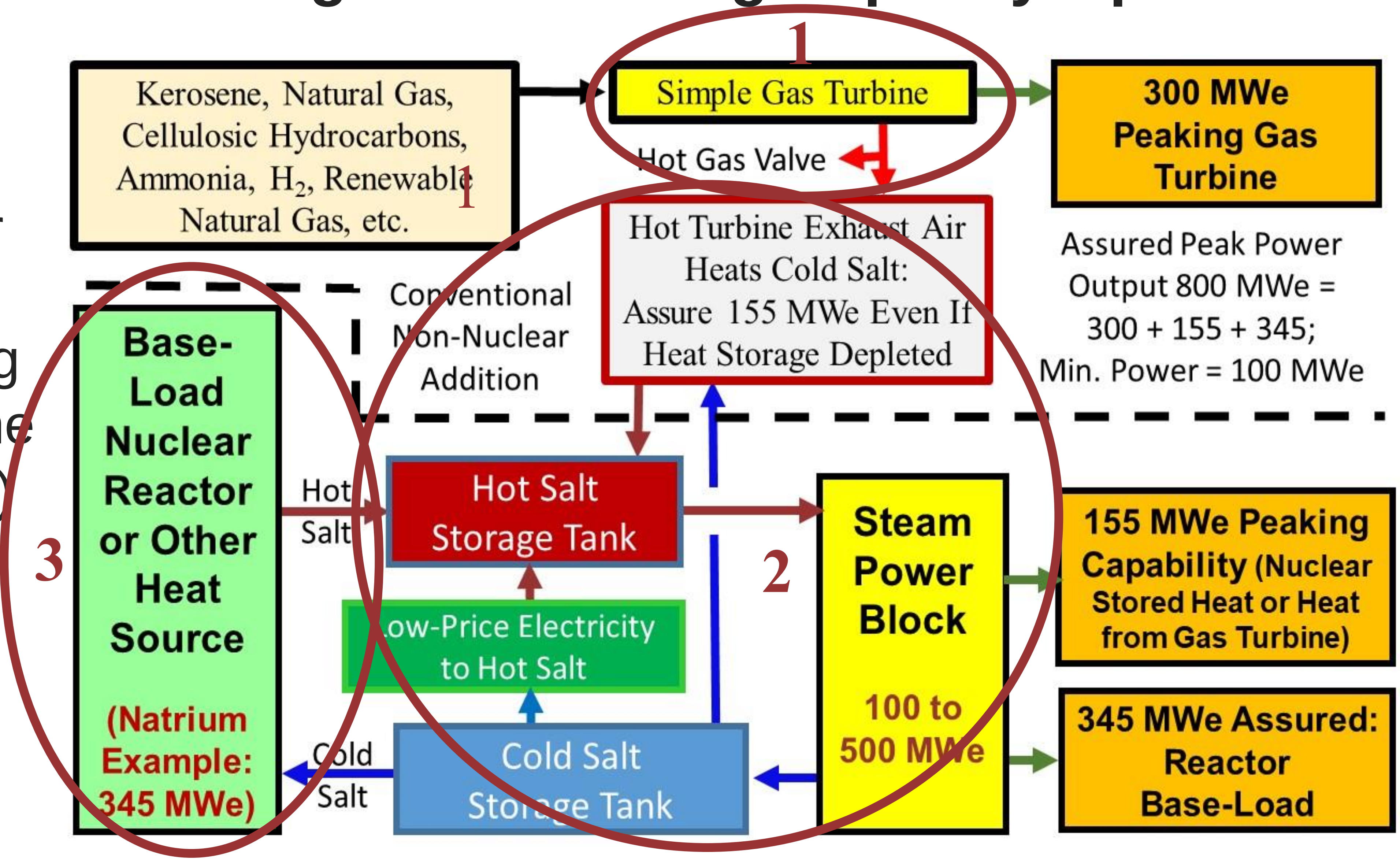
Fast-Build Gas Turbine, Then Non-Nuclear Steam Plant Can Produce Dispatchable Electricity Before Nuclear Plant Is Complete (300 +155 MWe + Low-Price Electricity to Heat)

- Meet tight schedule
- **Option to include salt heater to convert low-price electricity into hot salt**



Design Creates Staged Generating Capacity Options

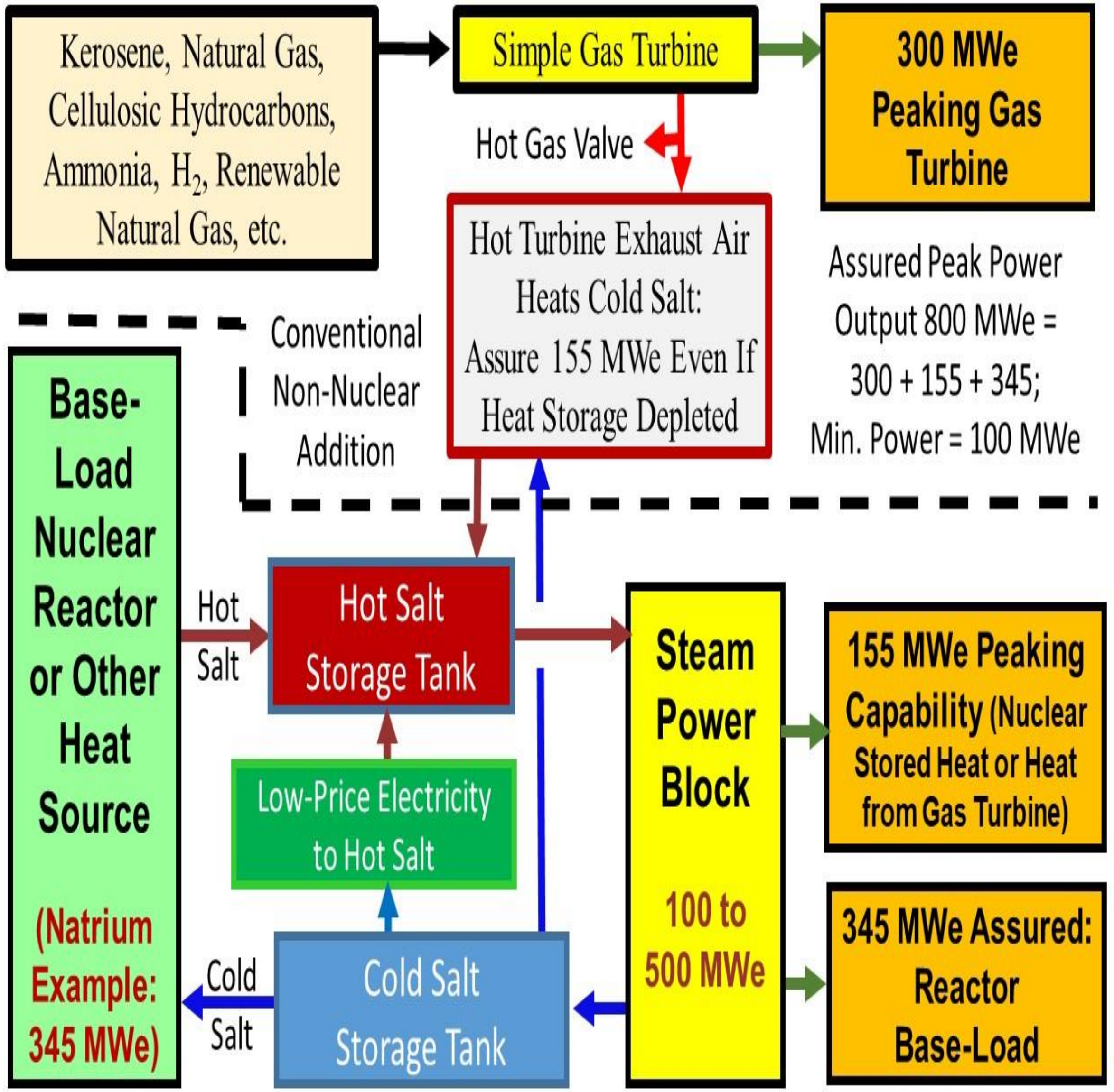
- Phased generation addition over time
- China looking at stand-alone (non-nuclear) combined cycle plant with nitrate-salt heat storage



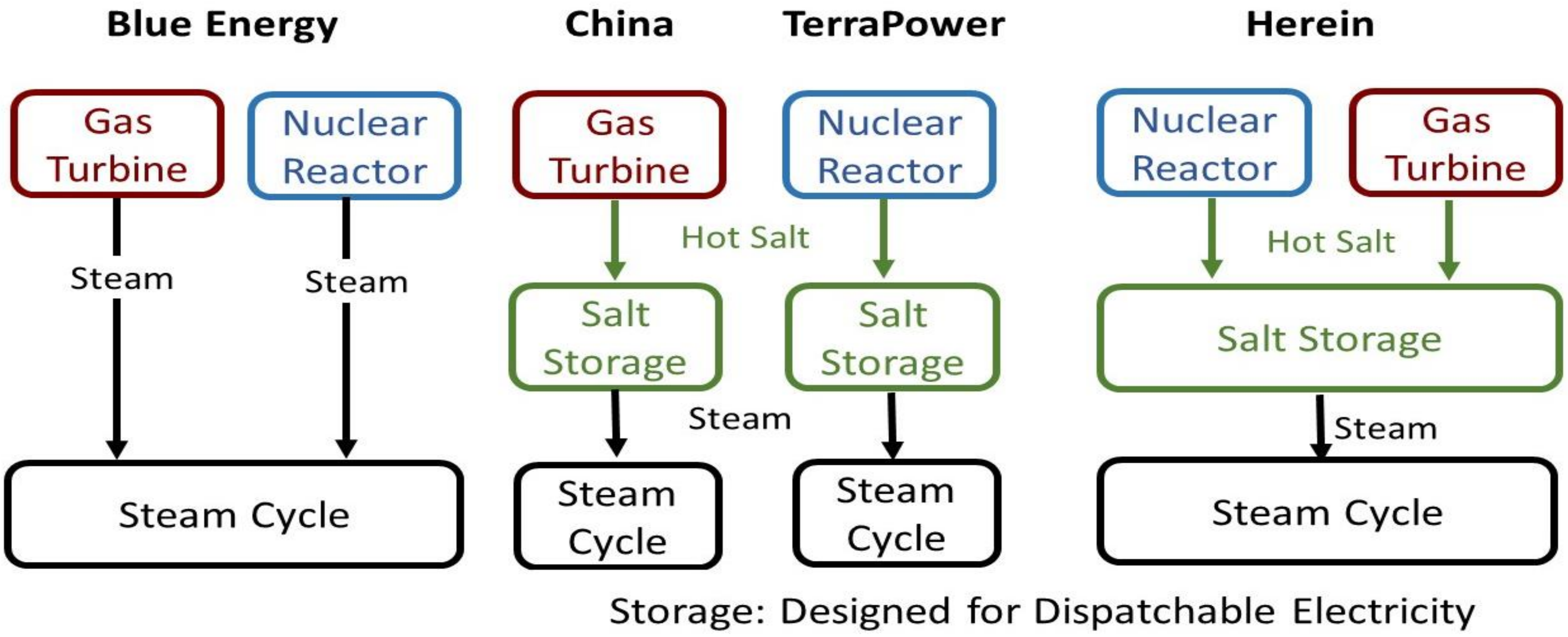
L. J. CAO, J. YU, L. WANG and X. XU, 2025. Combined Cycle Gas Turbine System with Molten Salt Energy Storage: Peak Regulation and Flexibility, *Process*, 13 (604). https://doi.org/10.3390/pr13030604

Functional Goals of Each System Component

- Reactor: Primary energy source, low-carbon heat supply
- Heat storage: Cycles ~300 times per year for daily variations in electricity demand
- Gas turbine
  - ➢ Normal year operate 5 to 10% of time for peak demands
  - ➢ Operate after extreme events (hurricanes, massive earthquakes, etc.) that are once in several decades that destroy significant generation (PV or wind) for many 1000s of hours assuring electricity

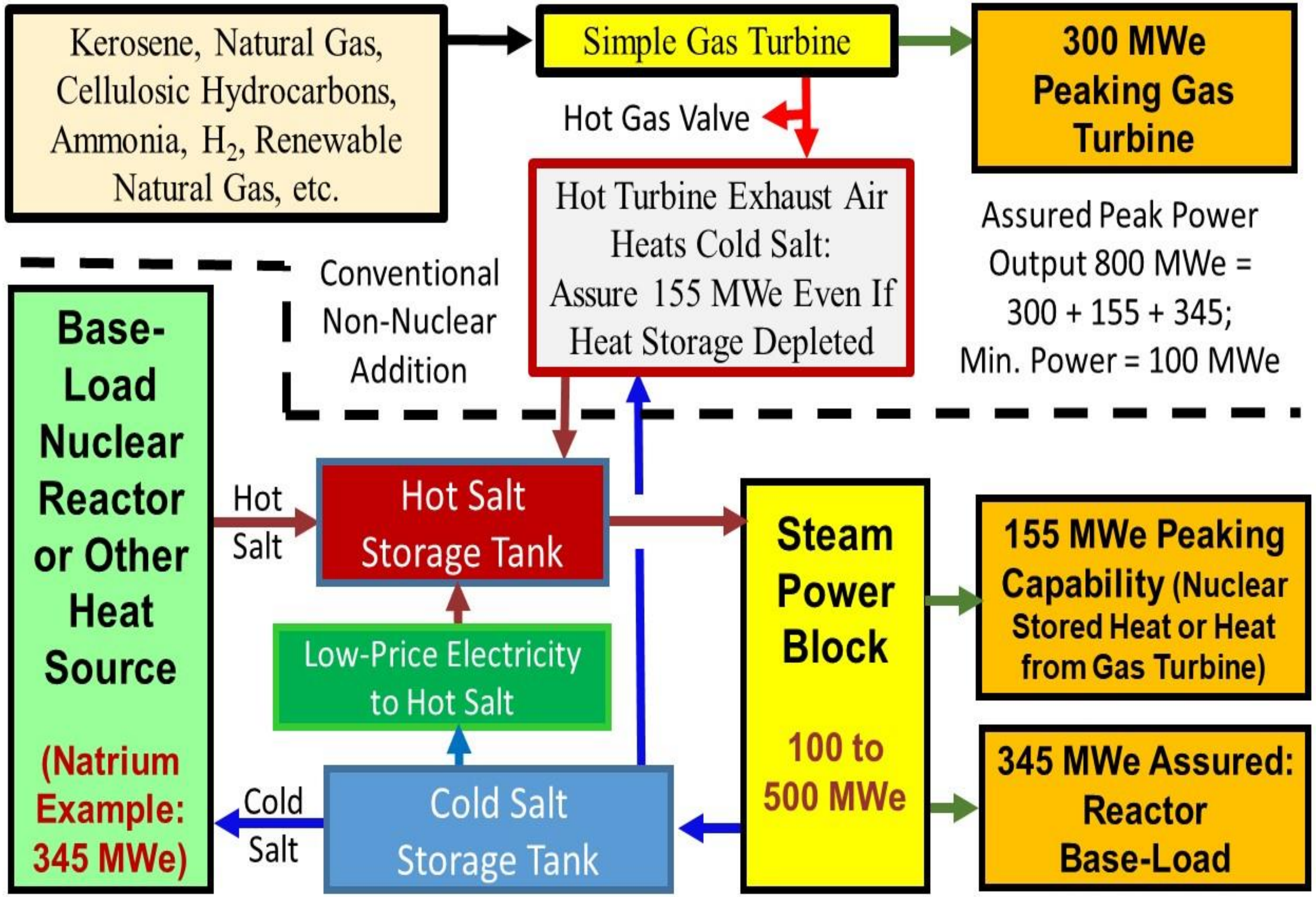


There Is Related Work on Alternative Power Cycle Configurations



Conclusions: Require Solutions for All Events

- System designed for any level of wind or solar (buy if cheap)
- Simple gas turbine operates as efficient combined-cycle gas turbine with heat storage steam cycle
- Full power when heat storage is depleted
- **Minimizes use of combustible fuels**



Buy/Sell Electricity and Can Operate for Unlimited Time at Full Power

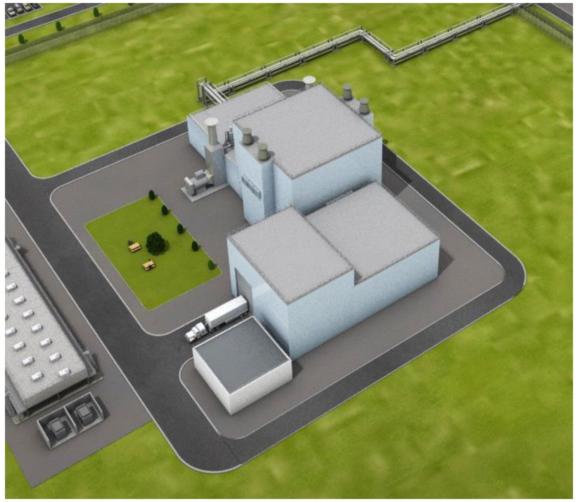
Biography: Charles Forsberg

Dr. Charles Forsberg is a principal research scientist at MIT. His research areas include (1) Fluoride-salt-cooled High-Temperature Reactors (FHRs), (2) utility-scale heat storage including Firebrick Resistance-Heated Energy Storage (FIRES) and 100 GWh Crushed Rock Ultra-Large Stored Heat (CRUSH) systems and (3) nuclear cellulosic hydrocarbon biofuels to replace crude oil. He teaches the fuel cycle and nuclear chemical engineering classes. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory and earlier worked for Bechtel Corporation.

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 former Director of the ANS. He is one of the three originators of the FHR (Kairos Power) and co-inventor of electrically conductive firebrick to enable electricity to heat firebrick to 1800° C for long-duration high-temperature heat storage (Electrified Thermal Solutions). 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 13 patents (excluding foreign patents) and published over 300 papers.

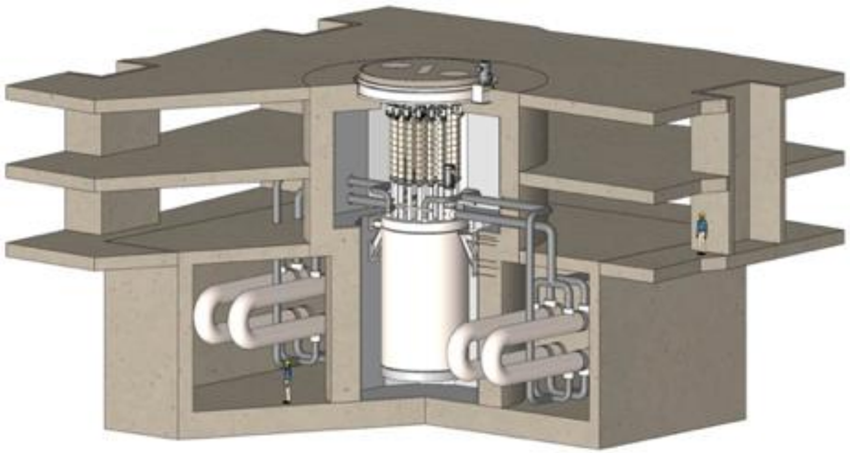
Three Reactors With Salt Intermediate Loops That Can Couple With Nitrate Salt Heat Storage Systems

Sodium Cooled Metallic Fuel



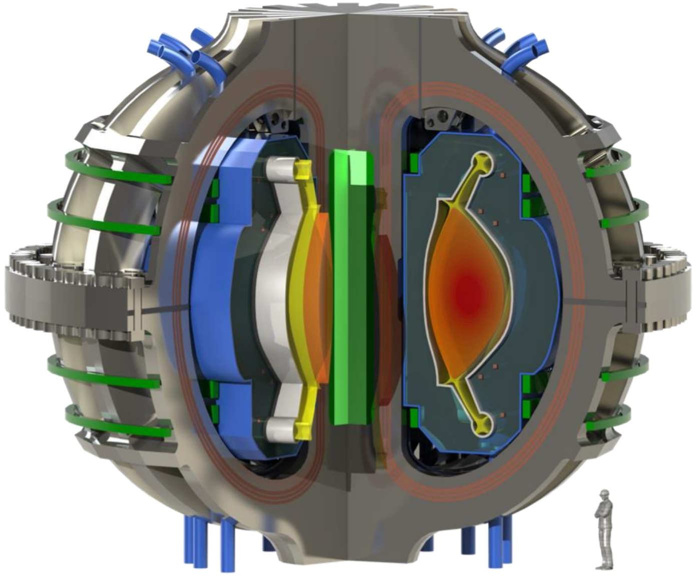
Under Construction TerraPower Natrium Reactor With Nitrate-Salt Heat Storage, Wyoming

Fluoride salt cooled Triso Solid Fuel



Under Construction Kairos Power 35 MWt FHR Hermes, Oak Ridge

Salt-Cooled Fusion Reactor



Commonwealth Fusion

2026 American Nuclear Society Winter Meeting, #11906
Phoenix, Arizona, November 15-18, 2026

Base-load Nuclear Reactors with Heat Storage and Gas Turbines for Unlimited Dispatchable Electricity

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[2]Fulbright PhD Candidate for HEXANA at CentraleSupélec, Gif-sur-Yvette, France

INTRODUCTION

We propose a new system design of nuclear reactors with heat storage systems and a gas turbine that enable a baseload reactor to provide assured dispatchable electricity to the grid. In our example, we use the TerraPower Natrium reactor with a base-load output of 345 MWe that is designed provide dispatchable electricity from 100 to 500 MWe using heat storage. We propose adding a gas turbine provides an additional 300 MWe with its hot exhaust providing heat to enable the Natrium turbine to produce its peak 500 MWe when heat storage is fully depleted. The gas turbine, burning a combustible fuel, operates a limited number of hours per year. The system can provide the 800 MWe for any length of time. The system is a low-carbon replacement of the natural-gas fired turbine.

The system provides ancillary services to the electricity grid to control frequency and provide assured generating capacity. Historically, the value of ancillary services was low because the massive rotating inertia of turbine-generators provided these services at low cost. However, neither solar or wind can provide such services and thus other technologies such as batteries provide ancillary services. Today, a quarter to half the revenue of utility batteries is from ancillary services—revenue this system can capture.

Last, the system can trap and recover tritium for those future fusion and fission systems that generate large quantities of tritium and need a tritium trapping capability.

We describe the market, the system, and its capabilities to enable base-load nuclear plants to functionally replace natural-gas-fired turbines and provide other grid services.

THE ELECTRICTY MARKET

Electricity markets are changing. The addition of large amounts of wind and solar result in times of low or negative electricity prices and times of very high prices when low wind and solar outputs. Because wind and solar operate as fuel savings technologies [1], they must be backed up with dispatchable electricity generating technologies that may include nuclear, hydroelectricity, geothermal and fossil. Furthermore, wind and solar technologies do not provide ancillary services such as frequency control or assured generating capacity. This requires other technologies to provide these services.

Separately, the demand profile for electricity is changing. Applications such as use of electric heating create larger swings in electricity demand over periods of hours, days and seasonally. High winter loads occur at times of low solar output and often low wind output in the U.S., Canada and Europe. Many of these peaks in dispatchable electricity demand are infrequent multi-day events. Such times are less than 5% of the year but today impose very high costs to assure reliable electricity supplies at all times.

These changes require new technologies. Renewables plus batteries are not a solution [2] because the battery costs are measured in hundreds of trillions at the required scale to address longer duration storage including seasonal. They are a technology for short-term energy storage. The geographical availability of pumped hydro sites limits storage capacity. Geothermal energy is also geographically limited by geothermal resources. This paper describes a nuclear option to address the changing electricity grid requirements.

HEAT STORAGE FOR DISPATCHABLE ELECTRICITY

Heat storage was developed for Concentrated Solar Power (CSP) plants where the plant heats cold oil or nitrate salt and sends it to a hot-fluid storage tank. The power conversion system converts the heat to dispatchable electricity with the resulting cold fluid sent to a cold fluid storage tank. The system is shown in Figure 1. All existing such heat storage systems have the heat source, hot and cold storage tanks, and the power block. We identified three additional options that can be added to the simple heat storage system as is also shown in the Figure 1.

The first nuclear reactor to be coupled to large-scale heat storage will be the TerraPower Natrium nuclear reactor that is under construction in Wyoming [3]. It will store heat in the form of hot and cold nitrate salt in two tanks based on the existing heat storage technology developed for CSP. The power plant is coupled by transmission lines to the California electricity grid with its large variations in electricity prices. The base-load power plant output is 345 MWe. The power plant output can be varied from 100 MWe to 500 MWe with about 5.5 hours of heat storage. We use it herein as an example system

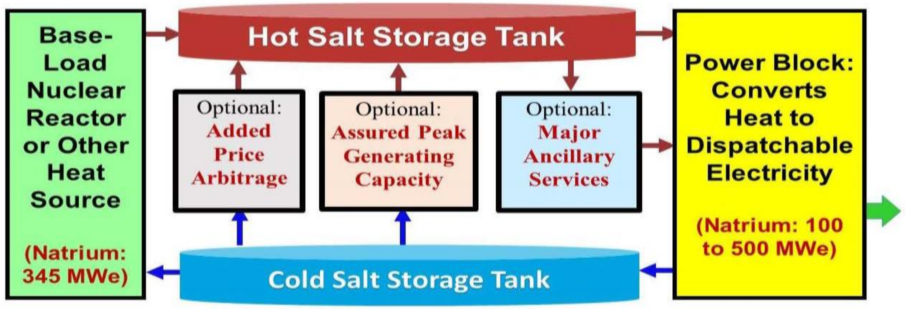

Fig. 1. Base-Load Nuclear Power Plant Producing Dispatchable Electricity with Two-Tank Heat Storage System and Optional Capabilities

There are engineering constraints. First, the minimum stable output of the power block is about 20% of its peak capacity. Steam turbines can operate from 20% to 100% power with some loss of efficiency at very high and low power levels. If the power block is operating at 20% load, it can rapidly increase its power level. In the case of the Natrium reactor, it can increase power output at 50 MWe/minute—that is the power block output can go from 100 to 500 MWe in eight minutes. If the power block is shut down and cold, it may take several hours to bring it up to full power. If the utility wants the capability to quickly increase electricity output, it needs to operate the power block at 20% of full power so equipment is hot and running. If a utility buys a Natrium reactor and has a need to meet a higher peak power demand, it could buy a 700 MWe turbine with a minimum power level of 140 MWe with the same size reactor.

In an electricity grid with large quantities of wind and solar, there will be times of low or negative wholesale electricity prices. At such times it may be economically preferable to buy electricity to heat cold salt to hot salt to provide added peak electricity generation at later times with higher electricity prices. If the turbine is operating at minimum load due to low prices, its electricity may be used to heat salt. Siemens Energy [4] and others are developing systems to enable economic heating of cold salt to hot salt.

For the electricity grid, preventing blackouts is a high priority. If large-scale deployment of wind and solar, the major challenges are long periods of low wind and solar electricity output. Using the Natrium example, the peak power is 500 MWe; but, when heat storage is depleted, the output matches the base-load reactor output of 345 MWe with 155 MWe of steam turbine-generator capacity left unused.

We examined adding a simple gas turbine (Fig. 2) that produces about 300 MWe of peak electricity integrated into heat storage. The hot exhaust heat from that gas turbine heats cold salt to hot salt to allow the production of 155 MWe of electricity--the difference between base load (345 MWe) and peak electricity production with stored heat (500 MWe) by the steam plant. Total plant output is 800 MWe. One has created a high-efficiency combined cycle gas turbine by adding a simple low-cost gas turbine to the pre-existing steam plant associated with the reactor and heat storage system. The assured generating capacity more than twice the base-load reactor. The gas turbine enables base-load output of 455 megawatts (155 MWe + 300 MWe) and dispatchable electricity when the reactor is shut down for refueling and plant output before reactor construction is complete. The gas turbine can burn natural gas, kerosene or low-carbon fuels (biofuels, e-fuels, ammonia and hydrogen). There have been limited studies [5] with stand-alone combined cycle plants using nitrate storage between the gas turbine and the Rankine steam cycle to provide more dispatchable electricity.

Most dispatchable electricity is from the stored heat produced by the reactor. The size of storage depends upon the demands of the local grid. Limited studies typically have peak discharge using heat from storage of about 10 hours per day. The gas turbine is used a limited number of hours per year. There is a tradeoff between the size of the heat storage system and the hours per year the gas turbine is used. The larger the heat storage capacity, the fewer hours per year the gas turbine operates. The gas turbine addresses multiday times of low wind, low solar or very high electricity demand from extreme weather events such as very long cold spells.

ANCILLIARY SERVICES

Electricity grids require ancillary services to assure grid stability, that is, avoid grid collapse. Historically, the value of ancillary services has been low because almost all electricity was generated by massive rotating turbine-generators. The rotating inertia helps to control frequency. It is a nearly free service provided by the generating technology. Solar and wind do not provide such services; thus, other technologies such as batteries are required to provide these services. A quarter to half of the revenue of utility lithium-ion batteries is from providing ancillary services.

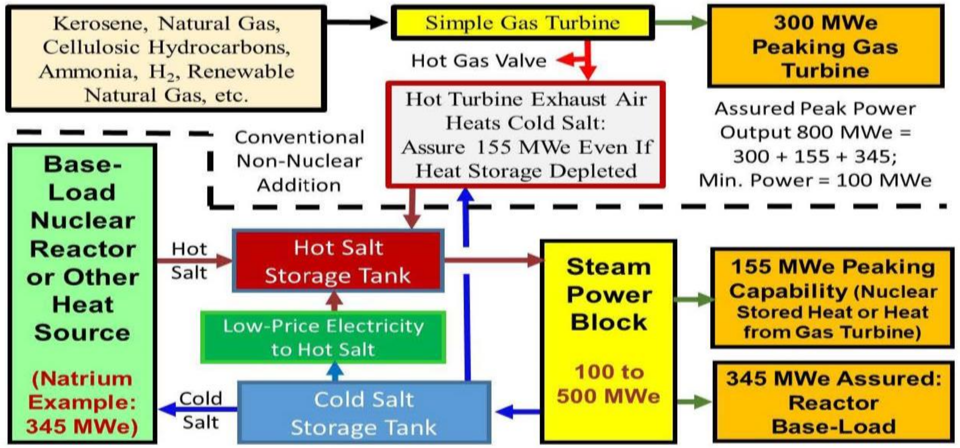

Fig. 2. Providing Assured Peak Generating Capacity Twice Base-Load Reactor Capacity: Natrium Example

Reactors with heat storage can provide these services and receive revenue for providing these services [6]. Using the Natrium reactor example, a 500 MWe steam power system operating at 100 MWe has large capabilities to provide ancillary services. While operating at 100 MWe, the turbine generator has a capacity of 500 MWe and the massive rotating mass of a 500 MWe turbine generator that can help stabilize grid frequency—an ancillary service. If the frequency begins to drop, the rotational inertia of the turbine generator resists frequency changes that would change the rotating speed of that equipment. Equally important is when this ancillary service is available. The need for frequency stabilization increases as the fraction of electricity from wind and solar increases and the number of plants with turbine generators decreases. It is at exactly these times that correspond to times of lower electricity prices when the Natrium power plant output is 100 MWe with 500 MWe of rotating inertia.

The second ancillary service is providing assured generating capacity—the ability to provide more electrical generation when demand goes up or other generating units drop off line. In several grid markets [7], this requires assured added generating capacity for 10 hours—that may define heat storage requirements. Separately, there are requirements for rapid ramp rates. The competition for this assured generating capacity includes batteries, diesel engines (15 seconds), fast-response hydro facilities (90 seconds), gas turbines on hot standby, and other technologies. As described above, the existing design can go from 100 to 500 MWe in 8 minutes. It may be viable to reduce this to as little as 15 seconds if a demand for such a capability using steam accumulators for very fast ramp speeds as shown in Figure 3.

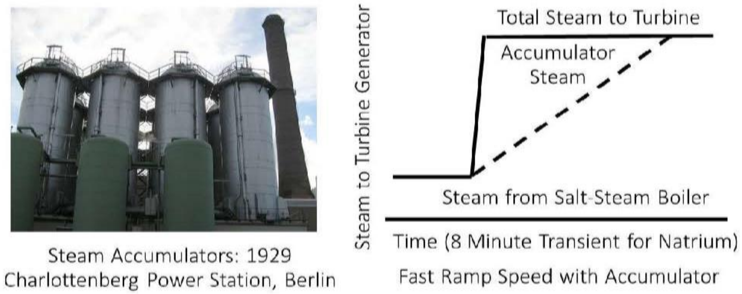

Fig. 1929 Steam Accumulators and Steam Supply to Steam Turbine Generator with Steam from (1) Slow-Response Salt-Steam Boiler and (2) Fast-Response Steam Accumulator

The power ramp speed is limited by the steam boilers that convert heat from hot salt into high-temperature high-pressure steam. If the amount of steam produced is increased rapidly, the thermomechanical stresses generated during the transient cause the hot salt-steam boiler tubes to fail. The technical solution for fast ramp rates is the steam accumulator [6], a second storage device that injects steam into the steam turbine to accelerate it to fully power while the salt-steam boiler output increases more slowly over time. In the case of the TerraPower Natrium reactor, the steam accumulator would provide added steam stored in accumulators for eight minutes. Steam accumulators are an old technology. In 1929 a set of steam accumulators were built in Berlin to quickly provide steam to a steam turbine to enable rapid increases in electricity production. In that case, the steam accumulators were charged with heat from a coal plant at times of lower electricity demand. The accumulators and its turbine operated independently of the coal plant turbines. The best-known application of steam accumulators is accelerating aircraft off the decks of aircraft carriers. Detailed studies by the turbine-generator original equipment suppliers are required to determine limits to ramp rates from 100 to 500 MWe.

TRITIUM REMOVAL

Several types of fission reactors produce sufficient tritium that its release to the environment must be controlled. This includes the Fluoride-salt-cooled High-temperature Reactor being built in Oak Ridge, Tennessee with a nitrate salt intermediate loop by Kairos Power [8] and most molten salt reactors with fuel dissolved in the salt. All fusion reactors produce orders of magnitude more tritium that is also their fuel where there are real challenges in controlling tritium.

Nitrate salt storage systems provide a method to capture this tritium. Tritium escapes reactors by diffusing through metal heat exchangers as atomic hydrogen. However, if tritium escapes into the nitrate salt it is oxidized to water that can't diffuse through metals. The solubility of water in molten salts is extremely low [9] and thus the tritiated water migrates to the cover gas where it can be recovered.

If very low inventories of tritiated water in the salt are desired, the salt can be sparged with an inert gas that moves the tritium to the gas space [10] to be captured. Alternatively, steam can be added to the nitrate salt where the non-tritium-containing water in the salt displaces tritiated water and moves that tritium into the cover gas zone for removal.

CONCLUSIONS

The markets and technologies for the electricity grid are changing. That requires rethinking of the design of nuclear power plants to match requirements. This may require base-load nuclear reactors going from supplying base-load electricity to the grid to base-load nuclear reactors providing fully dispatchable electricity to the grid under all conditions—including rare events requiring peak generating capacity for extended periods of time. Going forward, major engineering studies are required of the system that is proposed herein. Grid economic models that are currently based on price arbitrage must be updated to include economic benefits such as ancillary services and grid requirements to address extreme weather and other events [11].

ACKNOWLEDGEMENT

With support from the Future Energy Systems Center th rough the MIT Energy Initiative and the Claiborne Handlem an Trust We also thank many reviewers.

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Added Information on Power Block Options

Heat storage applicable to most reactor types

Many alternative heat storage technologies

Electricity Grid is Changing: Creates Massive Uncertainties

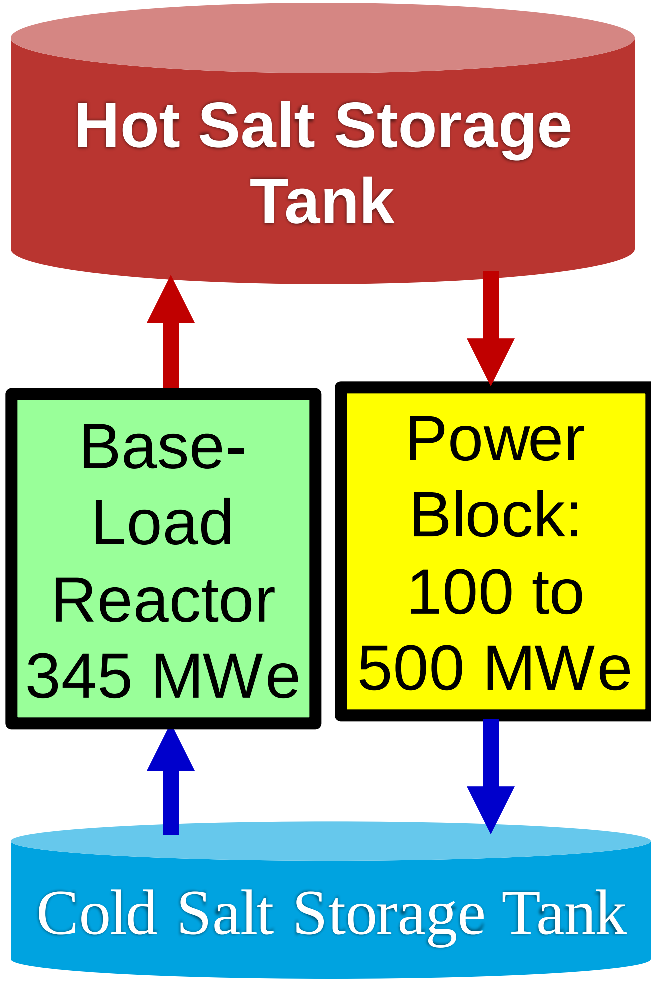
- Historical grid
  - – High-capital-cost low-operating-cost base-load power plants
  - – Low-capital-cost higher-operating-cost dispatchable power plants (gas turbines)
- New grid
  - – Non-dispatchable (electricity sometimes) wind and solar
  - – Gas turbines and nuclear

Gas Turbine Combined Cycle Mitsubishi 501J Grand River Dam Authority

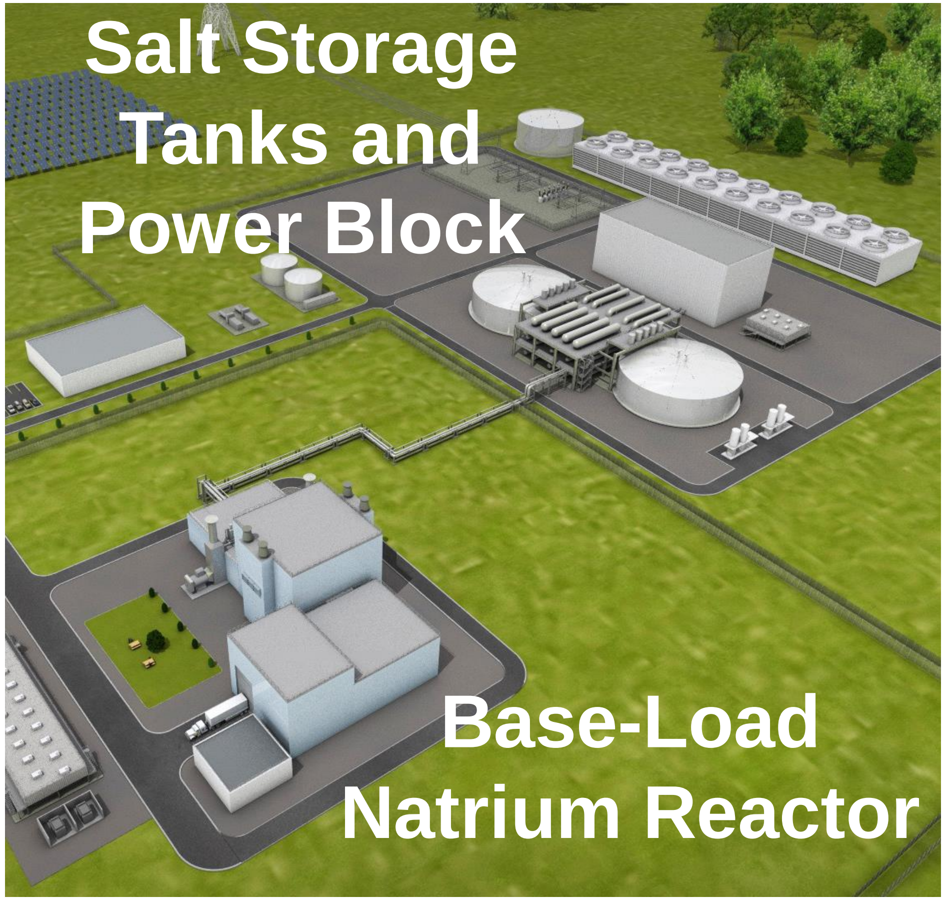
Two Changes to the Grid: Rapidly Varying Wholesale Electricity Prices and Grid is Brittle Against Failure

- Rapidly changing wholesale electricity prices
  - When wind and solar output exceeds demand, wholesale price of electricity may go to zero or be negative—no fuel cost
  - When low wind and solar, electricity prices are higher because other power plants operate fewer hours per year (not operate when high solar / wind output)—pay for these plants over less electricity output
- Electricity gird stability against failure decreases
  - Old electricity grid stabilized with massive rotating inertia of turbine-generators that control frequency—”free” service from the intrinsic characteristic of the technology. Solar does not stabilize grid against failure. If frequency not controlled (60 cycles per second), grid collapses
  - Non-dispatchable wind and solar do not provide <u>assured</u> generating capacity. Must build other systems to provide assured capacity

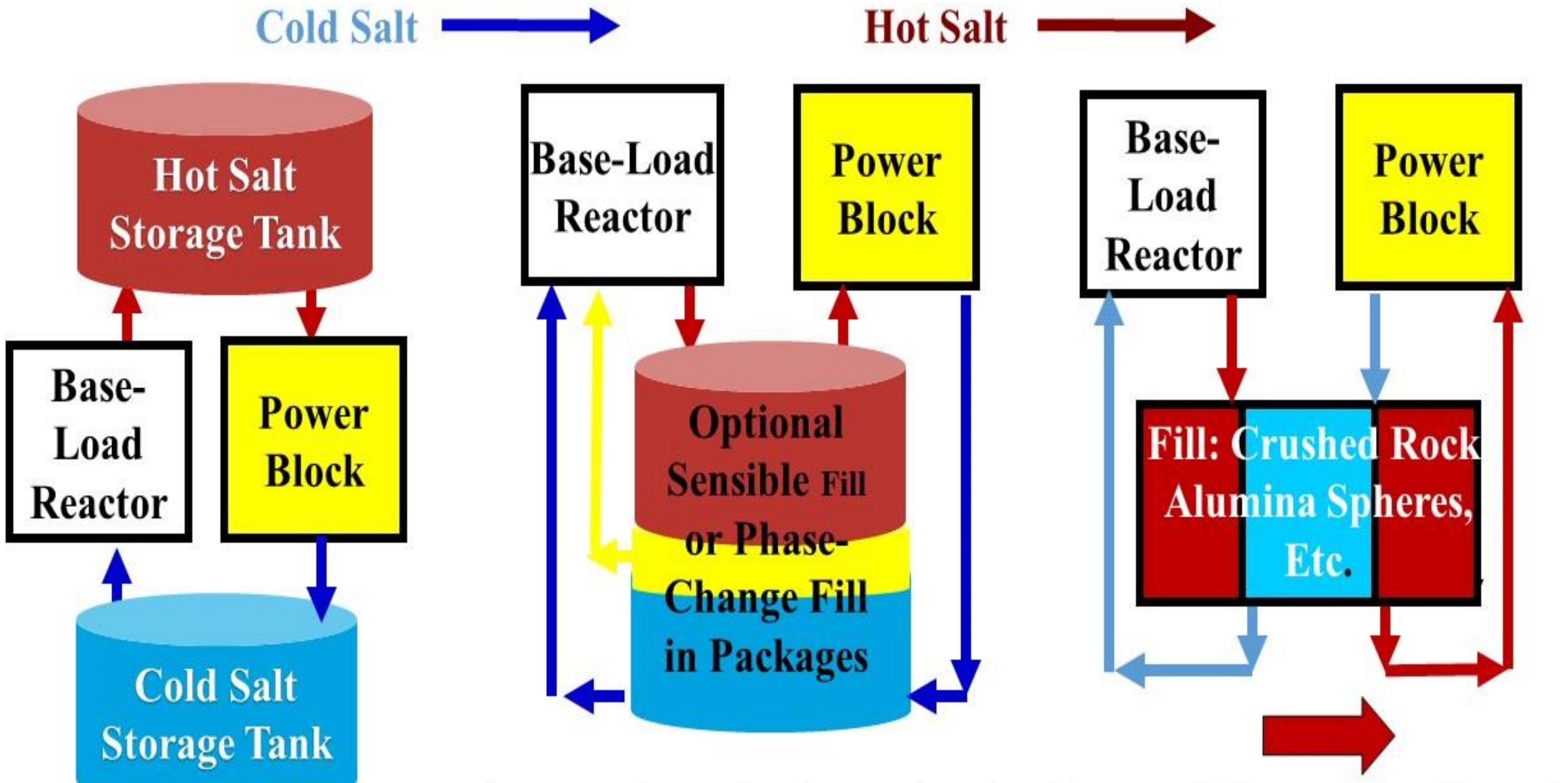
TerraPower is Constructing the Natrium Nuclear Reactor in Wyoming: First Reactor with Nitrate-Salt Heat Storage



- Base-load reactor heats salt. Steam turbine with variable electricity output
  - Base-load: 345 MWe
  - Peak: 500 MWe
  - Minimum output: 100 MWe
- Deliver electricity at times of highest prices
- **Reactor assures a minimum of 345 MWe to grid all times** (vs non-dispatchable wind & solar)



There Is The Potential of Major Reductions In the Cost of Heat Storage with New Technologies



Two-Tank Liquids: Commercial

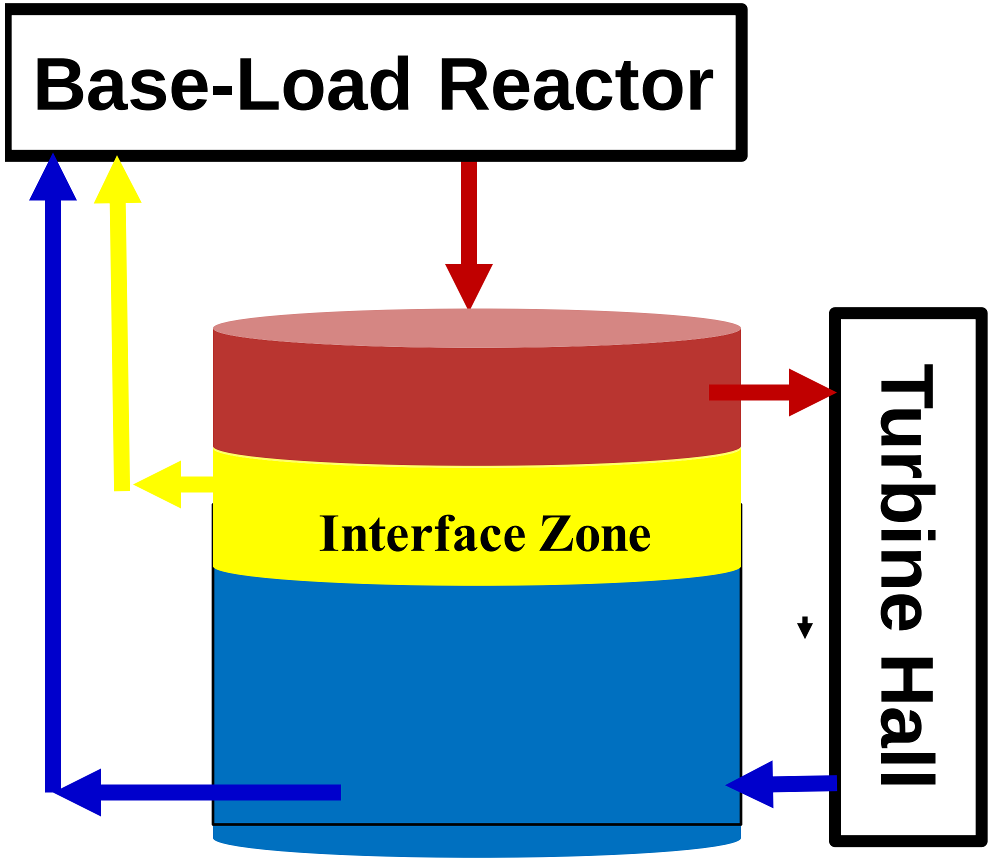
Thermocline Single-Tank Liquid With (Reduced Liquid) or Without Fill Material

Building with Fill and Gravity Trickle of Heat Transfer Fluid

- Base-case two-tank hot and cold nitrate salt system
- Second generation single tank thermocline system
- Third generation: Crushed Rock Ultra-large Stored Heat (CRUSH)

Next-Generation Thermocline Heat Storage Capital Cost Potential 60 to 70% of Two-Tank System

- Single tank with hot salt on top and cold salt on bottom
  - Reactor dumps hot salt into top of tank
  - Power cycle gets hot salt from top of tank
  - Hot-cold interface goes up and down with inventory of hot salt with size control
- Major capital cost reductions
  - One tank full versus two tanks partly full
  - **Option for low-cost fill material to replace up to 60% of salt for storing heat**



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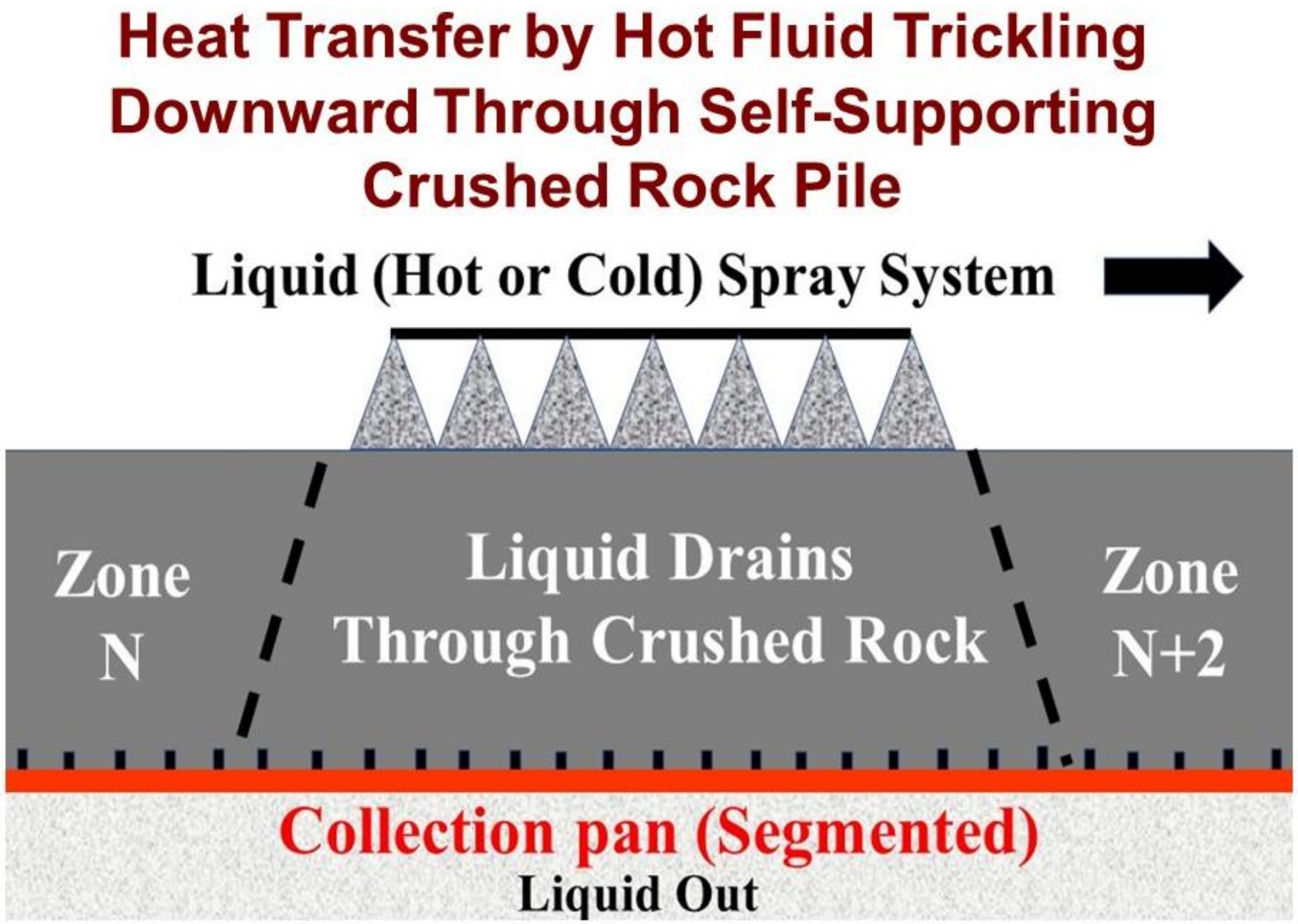
3ed Generation Crushed Rock Ultra-Large Stored Heat (CRUSH) Systems Enables Long Duration Heat Storage

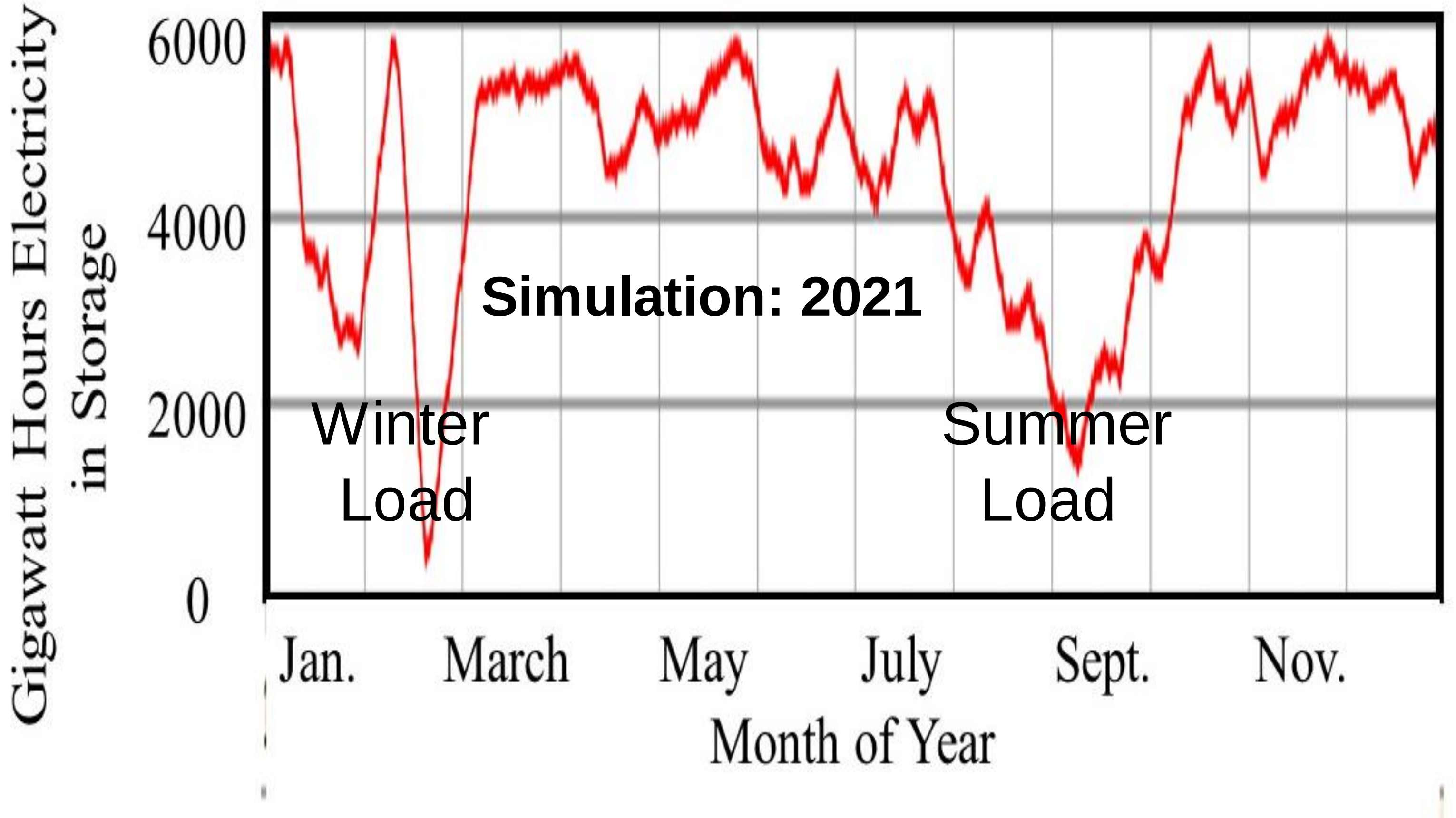
- **Reduce storage costs by factor of three to five**
- **TRL=4+**
- Two tank system costs
  - Salt
  - Expensive tanks
- CRUSH
  - Replace salt with crushed rock
  - Replace tank with insulated building



C. W. Forsberg, Low-cost Crushed Rock Heat Storage with Oil or Salt Heat Transfer, *Applied Energy* 335 (10). 120753, April 2023. https://doi.org/10.1016/j.apenergy.2023.120753

If Third-Generation Heat Storage (CRUSH) Meets Goals, Yearly Heat Storage: Stored Heat Inventory Over One Year in Texas

- Peak electricity: 80 GWe
- Nuclear
  - Base-load: 30 GW(e)
  - Turbines: 63 GW(e)
  - **Heat Storage Capacity: 200 GWh(e) per GW(e) base-load nuclear**
- Solar: 58 GW(e)
- Wind: 38 GW(e)
- **No fossil fuels**

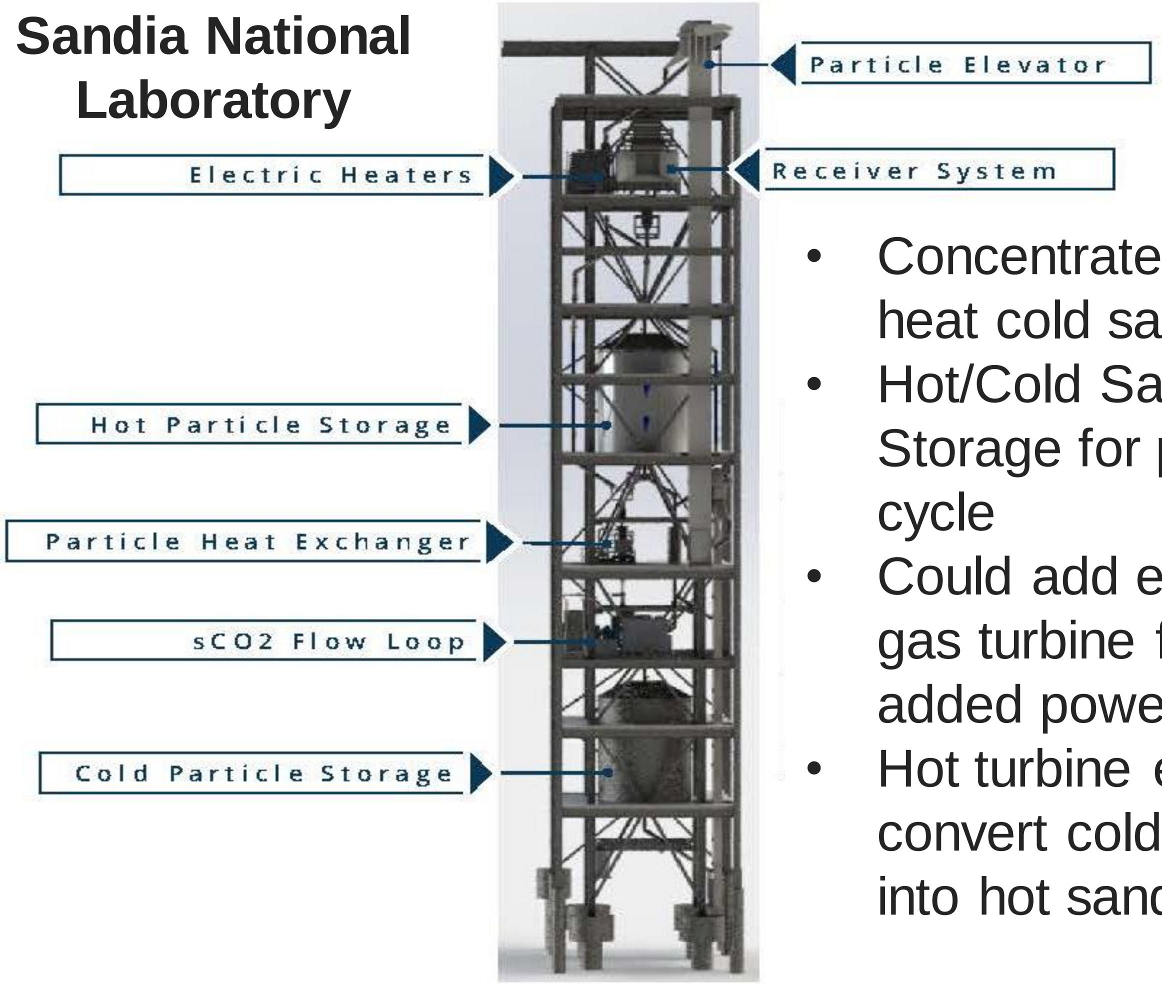


Preston E. and C. Forsberg, Decarbonize ERCOT with Large Thermal Energy Storage, *2025 IEEE Power and Energy Society: Achieving Deep Decarbonization in the Electric Power System*, 25PESGM-000433, Austin, Texas, 27-31 July 2025. https://egpreston.com/ERCOT22C.xlsx

There Are Analog Options for Other Heat Storage Systems

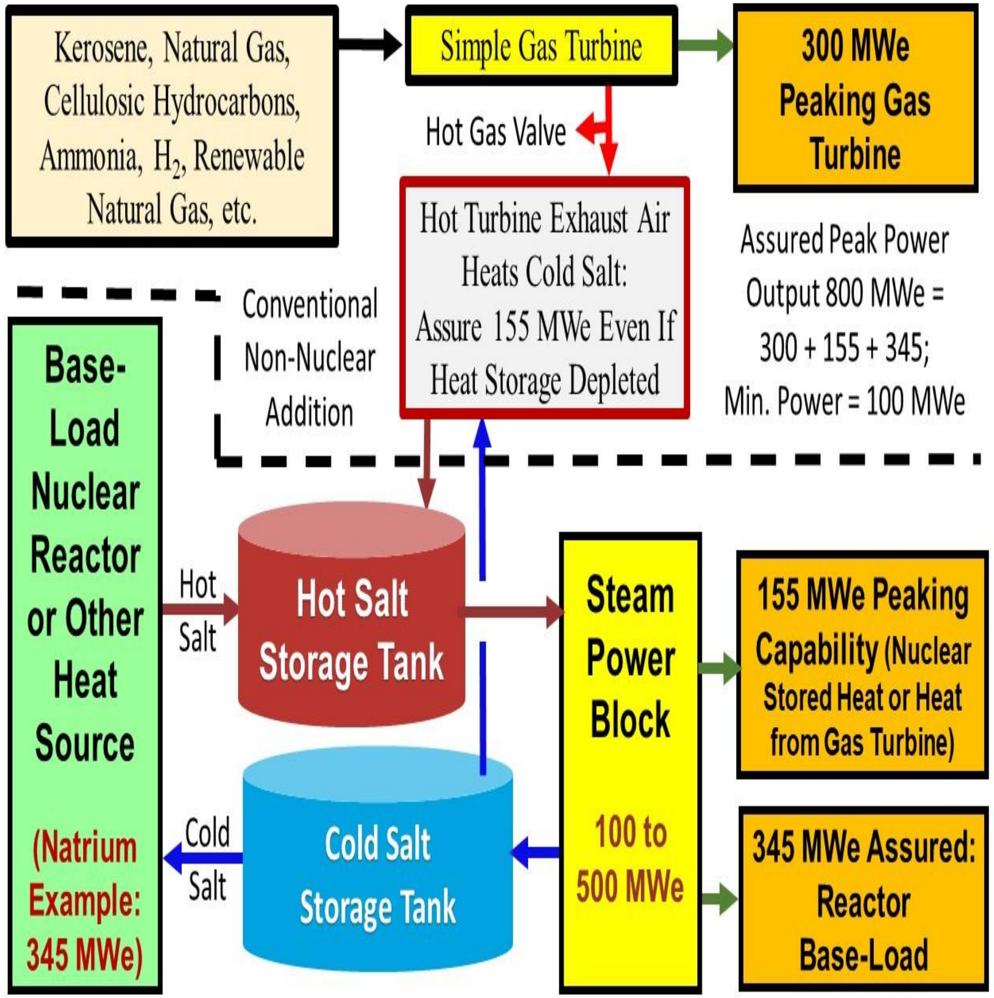
CSP with Sand Heat Storage

Sandia National Laboratory



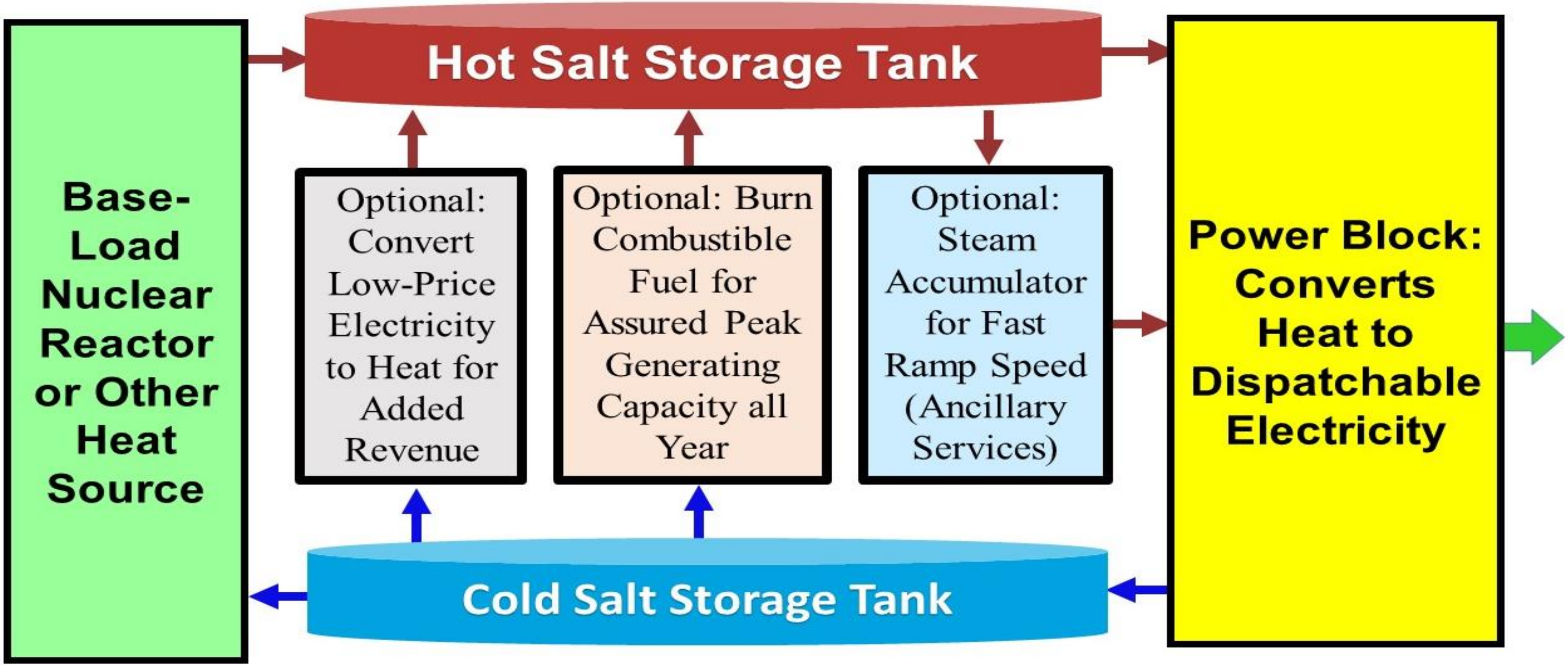
- Concentrated solar heat cold sand
- Hot/Cold Sand Storage for power cycle
- Could add external gas turbine for added power
- Hot turbine exhaust convert cold sand into hot sand

Nuclear with Salt Heat Storage



Added Options for Base-Load Nuclear with Heat Storage

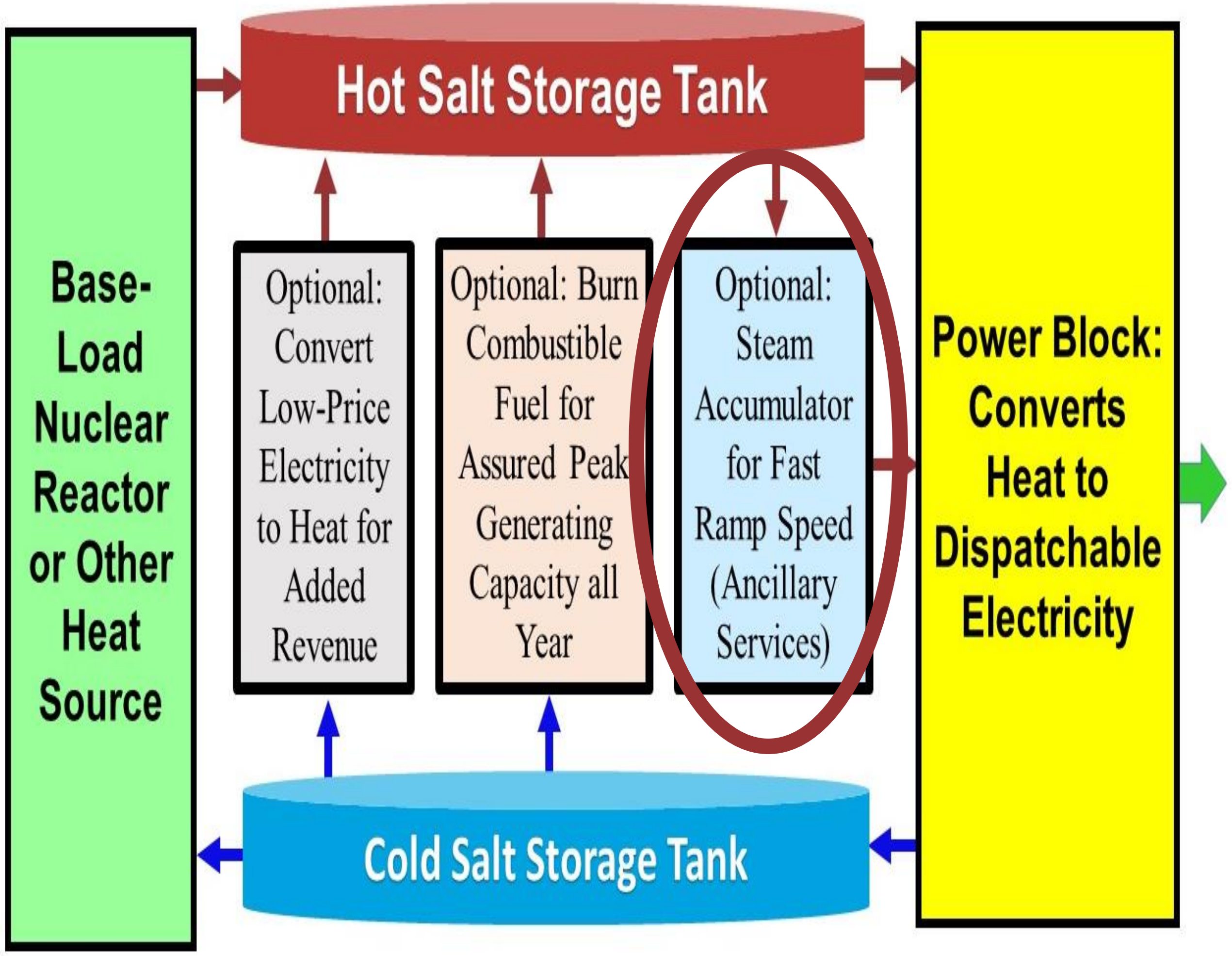
Natrium Reactor Includes Storage Tanks But Not Other Options



Applicable to Many Other Two-Tank Heat Storage Options (Oil, Sand, etc.)

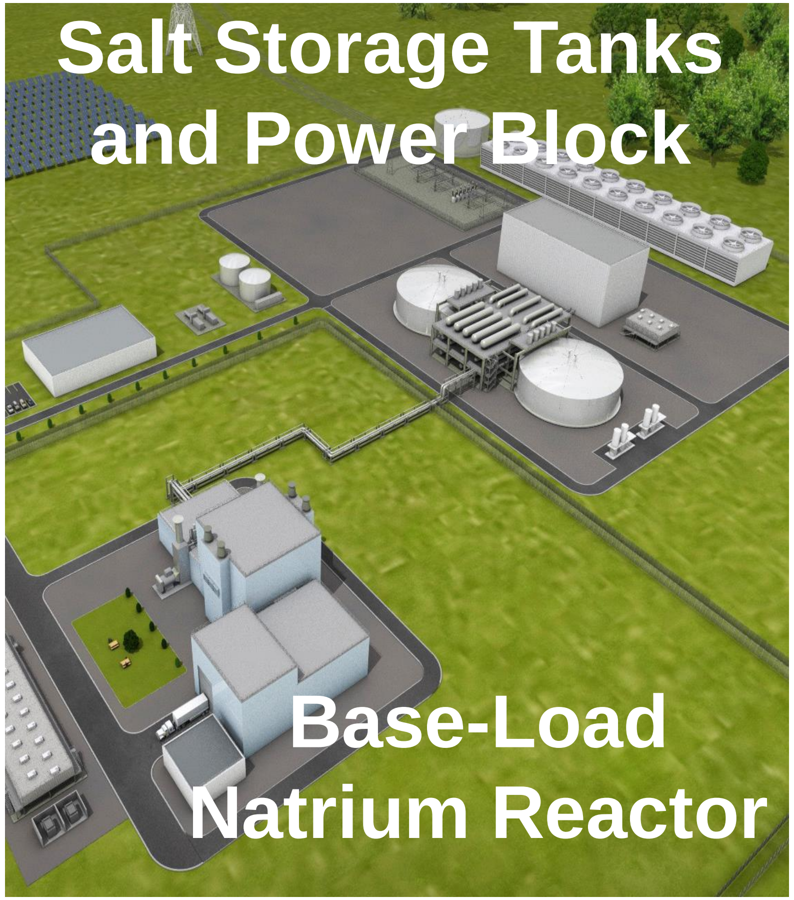
Option to Provide Most Ancillary Services

- Grid pays for ancillary services to assure grid stability against failure (frequency control, assured generating capacity)
- Historically low prices because rotating generators provided nearly free frequency control
- Wind and solar do not provide grid stability services
- Up to half battery revenue to provide these services



Ancillary Benefits Create Economic Incentives for Electricity Output at 20% at Times of Low Electricity Prices

- Electricity grid pays for services to stabilize against grid collapse: Frequency stabilization and capacity to provide added electricity
- Minimum power output of turbine for stable operation is 20% with several grid benefits (Natrium: 100 to 500 MWe)
  - Can accelerate to full power (8 minutes) versus 1-2 hours from cold start—grid capacity payments
  - Add steam accumulator for fast start and may accelerate to full power in 15 seconds
  - Rotating inertia of 500 MW turbine generator to control frequency rather than buy expensive



If Very Low Electricity Prices, 100 MWe Heats Salt for Later Use

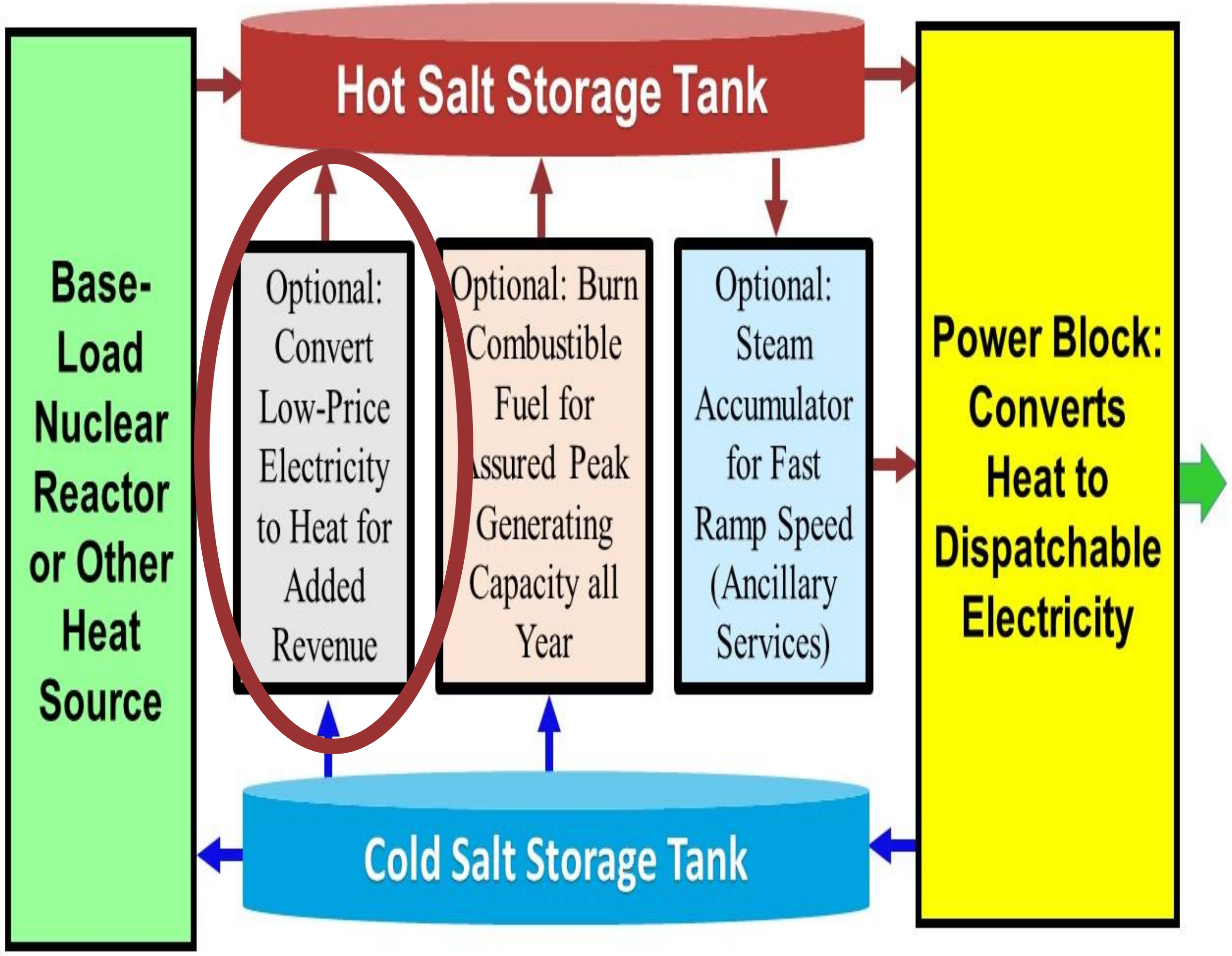
Steam Accumulators: 1929 Charlottenberg Power Station, Berlin: 67 MWh

- Steam accumulator technology
  - Heat water in pressurized vessel with steam
  - Release pressure and flashing of steam sent to turbine, most energy stored in the hot water (Can also store just steam)
- *With salt storage system, add small steam accumulator to quickly ramp up turbine power while the salt-steam boiler more slowly ramps up*

Sources: I. Kanakaris-Wirtl via Structurae, Science News Letter, A. G. Ter-Gazarian

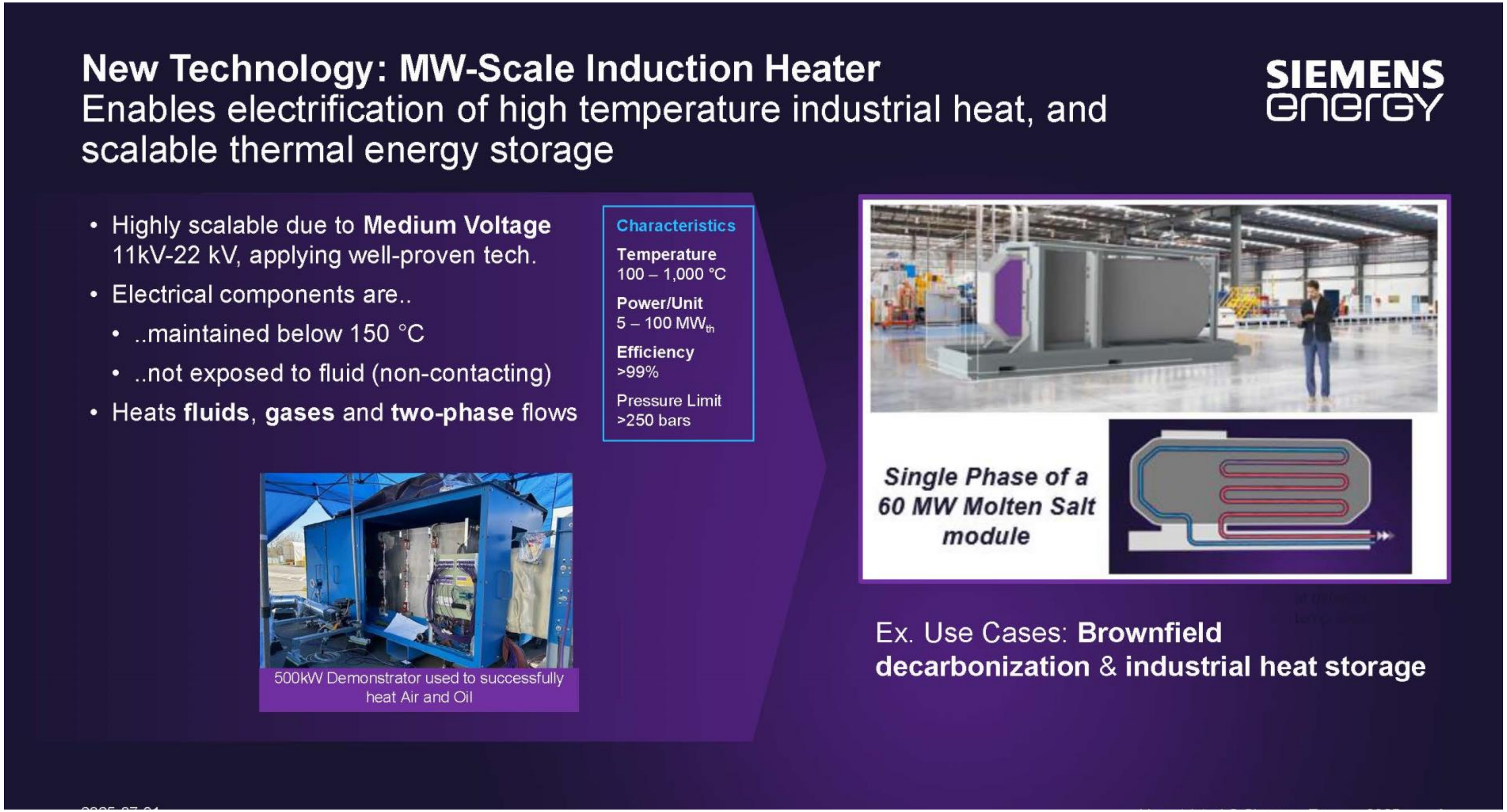
Option to Increase Arbitrage Capability: Buying Low-Price Electricity to Heat Nitrate Salt

- May run turbine (Natrium) at minimum electricity (20%) and heat cold salt with electricity when low electricity prices.
  - Obtain ancillary services payments with turbine on line
  - Value of more hot salt is higher than selling low-price electricity
  - Buy added low-price electricity from the grid
- Market may favor incrementally larger tank and turbine for the benefits of added revenue



Siemens is Developing Salt Heating System That May Cut Salt Heater Capital Cost in Half

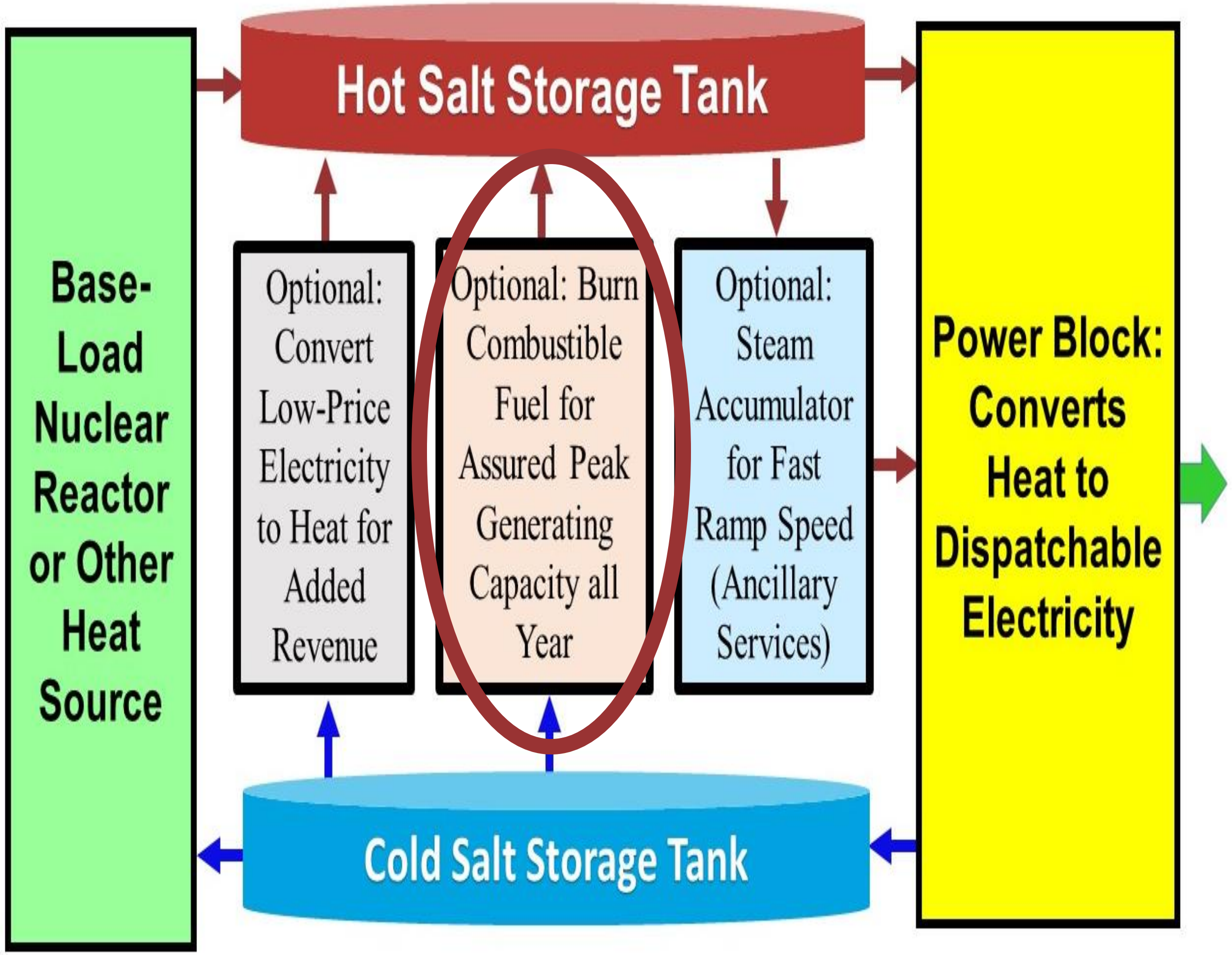
- Boosts incentives to convert low-price electricity to hot salt
- Nominal 60 MWe input
- 99% electricity to heat efficiency



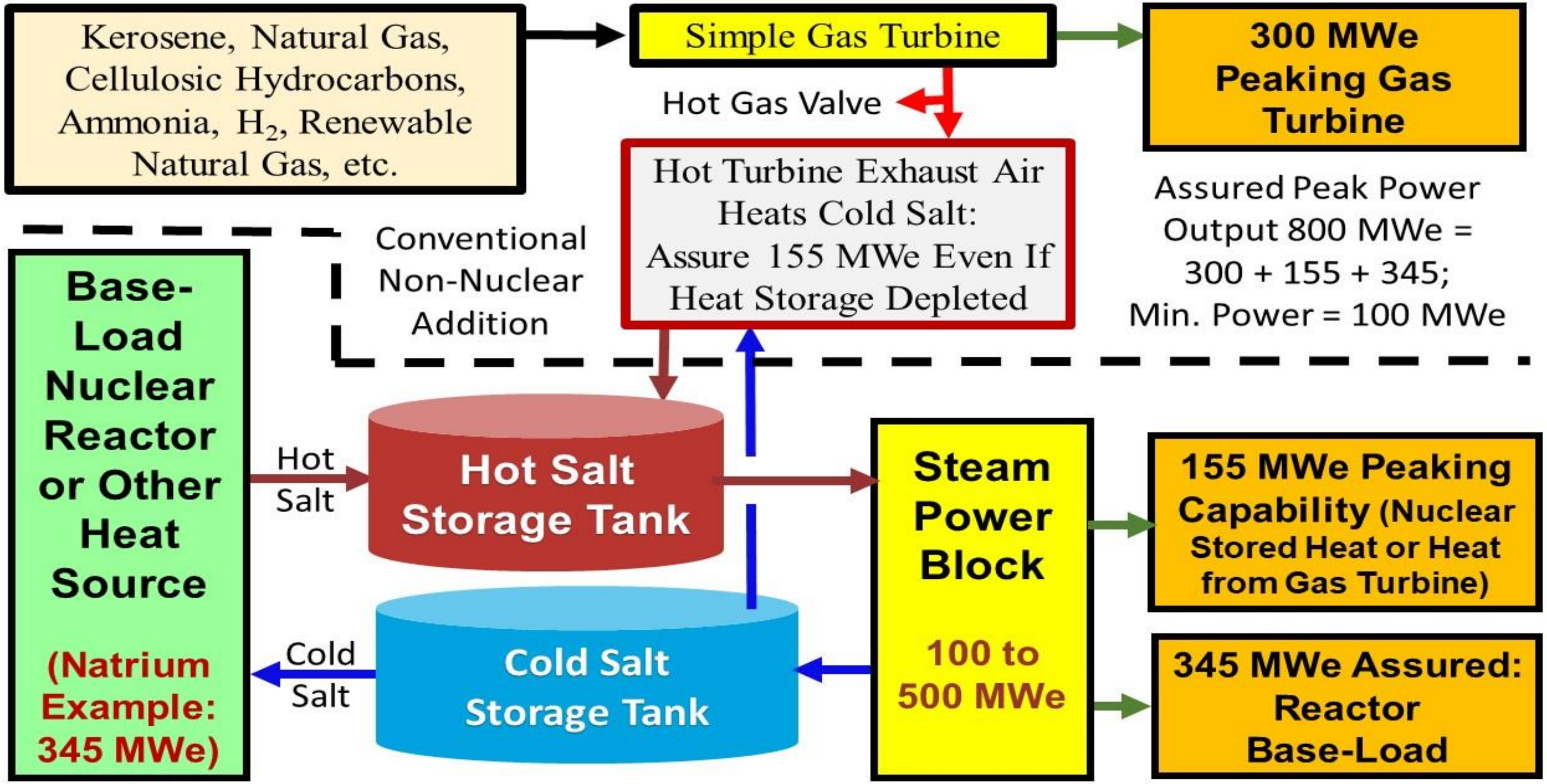
- J. VanKampen, Siemens, Proceedings of the 2025 Thermal-Mechanical-Chemical Energy Storage (TMCES) Workshop, 30-31 July 2025. https://www.swri.org/events/proceedings-of-the-2025-thermal-mechanical-chemical-energy-storage-tmces-workshop

Options to Enable Full Power Output With Depleted Storage for Assured Peak Electricity Production

- Two options
  - Heat cold salt with combustible fuel if out of stored heat
  - Buy gas turbine to produce added electricity with hot exhaust to heat cold salt if out of stored heat
- System minimizes use of combustion fuel for disputable electricity production



We Added Gas Turbine & Salt Heater to Base-Load Reactor with Heat Storage: Hot Gas-Turbine Exhaust Heats Salt for Full Generation Capacity



Electricity Output: 100 to 800 MWe

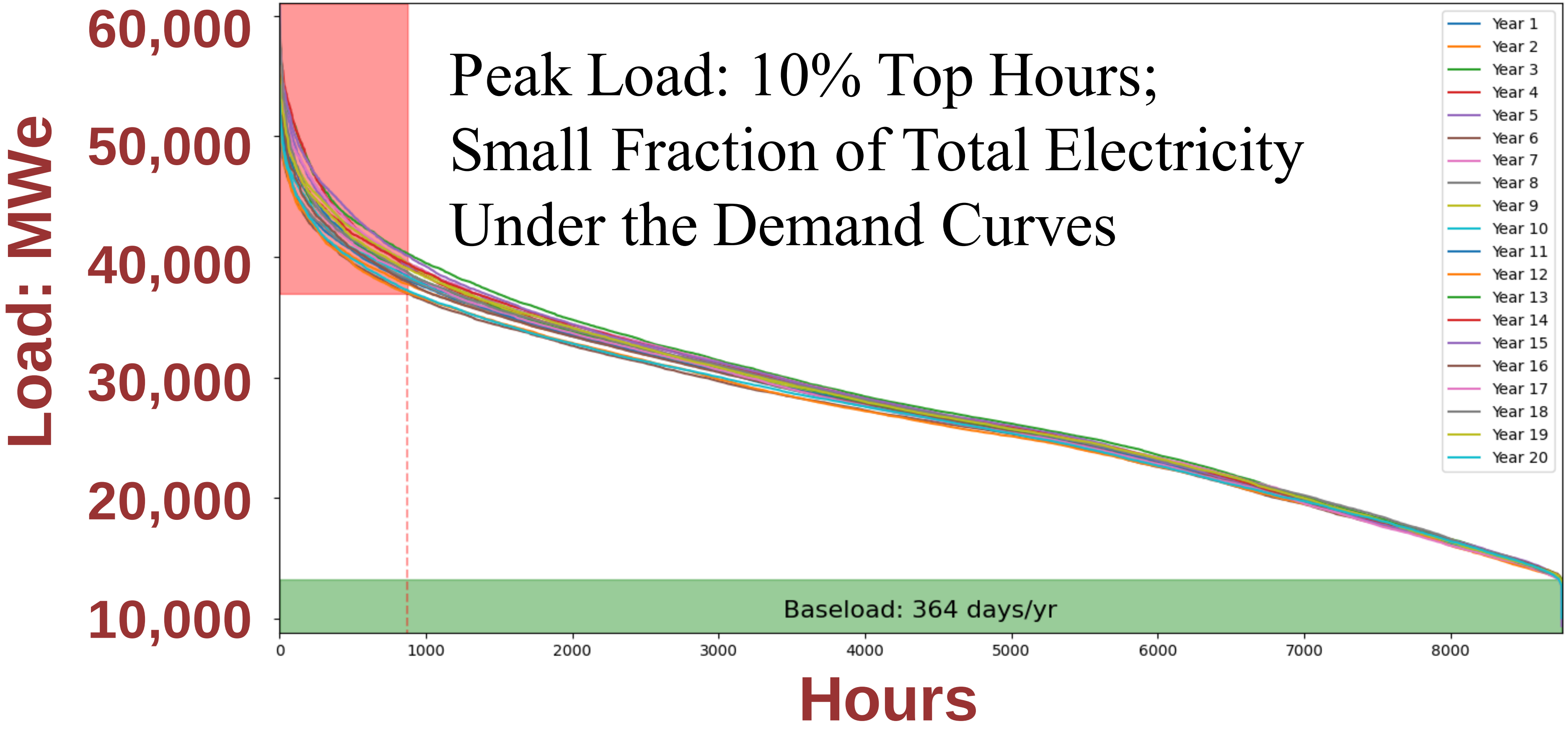
Capacity When Depleted Heat Storage More than Twice Reactor Output

Heat Storage Operates 70% of the Time, Gas Turbine 5 to 10% of the Time

Gas Turbine Addresses Peak Electricity Demands

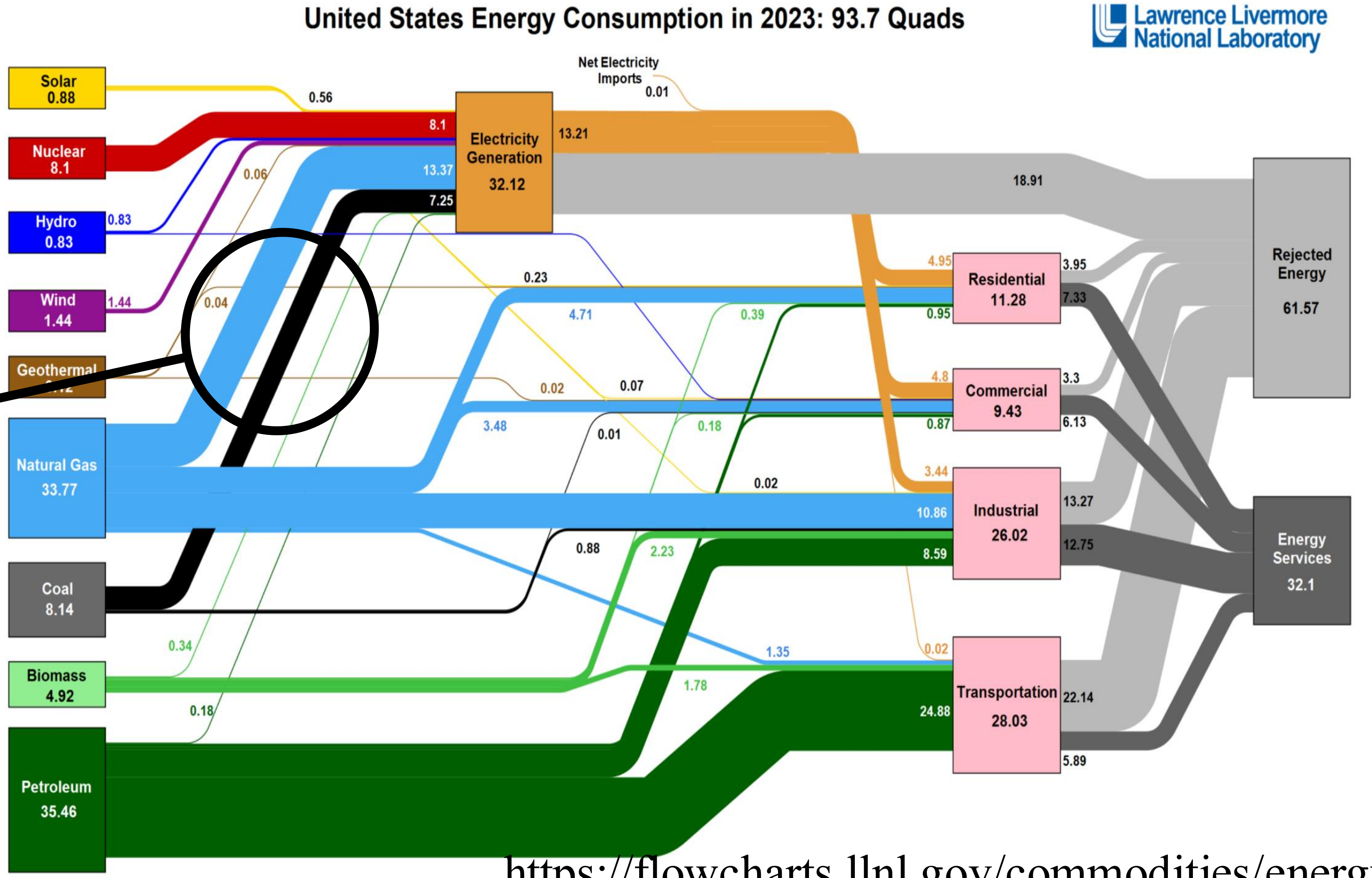
- Long-duration cold spells
- Long-duration heat waves
- Extreme events such as Level 4 hurricanes, need option to operate 1000s of hours at peak power while repair

Hourly New England Electricity Demand Curve over One Year: Highest to Lowest 20 Simulations for the Year 2050



Armstrong et al., 2024. The role of fusion energy in a decarbonized electricity system. Report by MIT Energy Initiative, see section B.2.2.

Base-Load Nuclear with Heat Storage and Gas Turbine Can Eliminate Most Combustible Fuel Use in Electricity Grid



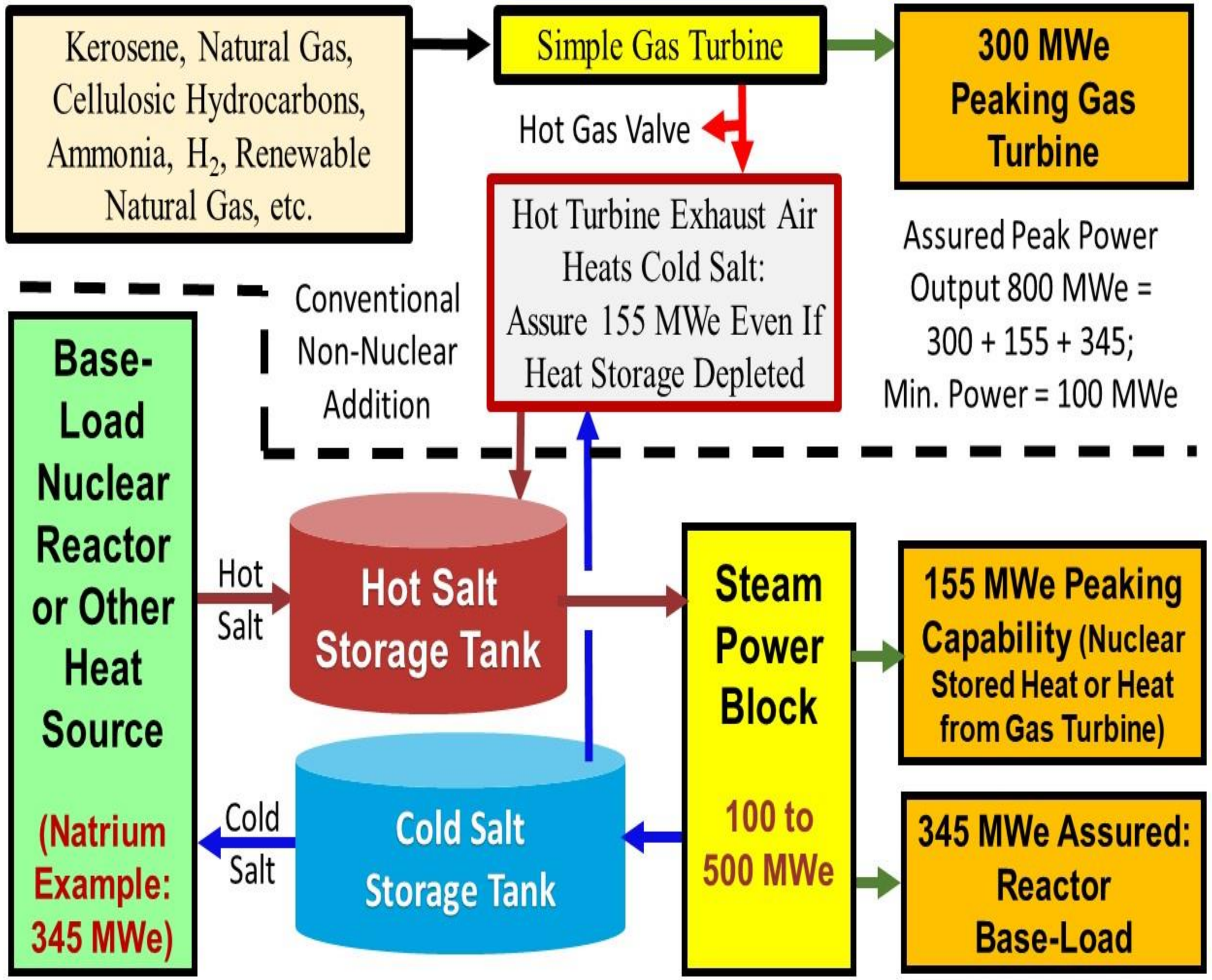
Electricity Storage Today: Coal Piles, Underground Natural Gas Facilities and Oil Tanks

Massachusetts Institute of Technology

https://flowcharts.llnl.gov/commodities/energy

With Gas Turbine Coupled to Bottoming Steam Cycle with Storage, Unique Versatile Operating Modes

- May operate gas turbine (GT) when do not need full power output and charge heat storage
  - Operate GT at peak efficiency
  - Power when needed
- Operate as dispatchable generator when reactor or other heat source (CSP) is shutdown *including start-up power cycle while reactor is under construction*



Studies are Underway to Add Nitrate Salt Heat Storage to Combined Cycle Plants Between Turbine and Steam Plant

- Incentives include:
  - Greater peak power from steam plant
  - Operate gas turbine at maximum efficiency—less operating time in hot standby
  - Faster ramping response
- Our case with nuclear heat
  - Minimize greenhouse gas emissions
  - Build combined cycle gas plant with storage on shorter time schedule with added time for nuclear plant construction
  - Phased construction

L. J. CAO, J. YU, L. WANG and X. XU, 2025. Combined Cycle Gas Turbine System with Molten Salt Energy Storage: Peak Regulation and Flexibility, *Process*, 13 (604). https://doi.org/10.3390/pr13030604

Production of Combustible Turbine Fuel

Need Long-Duration Energy Storage for Grid

Options for Long-Duration Stored Energy for Grid

Lowest Cost to Highest Cost

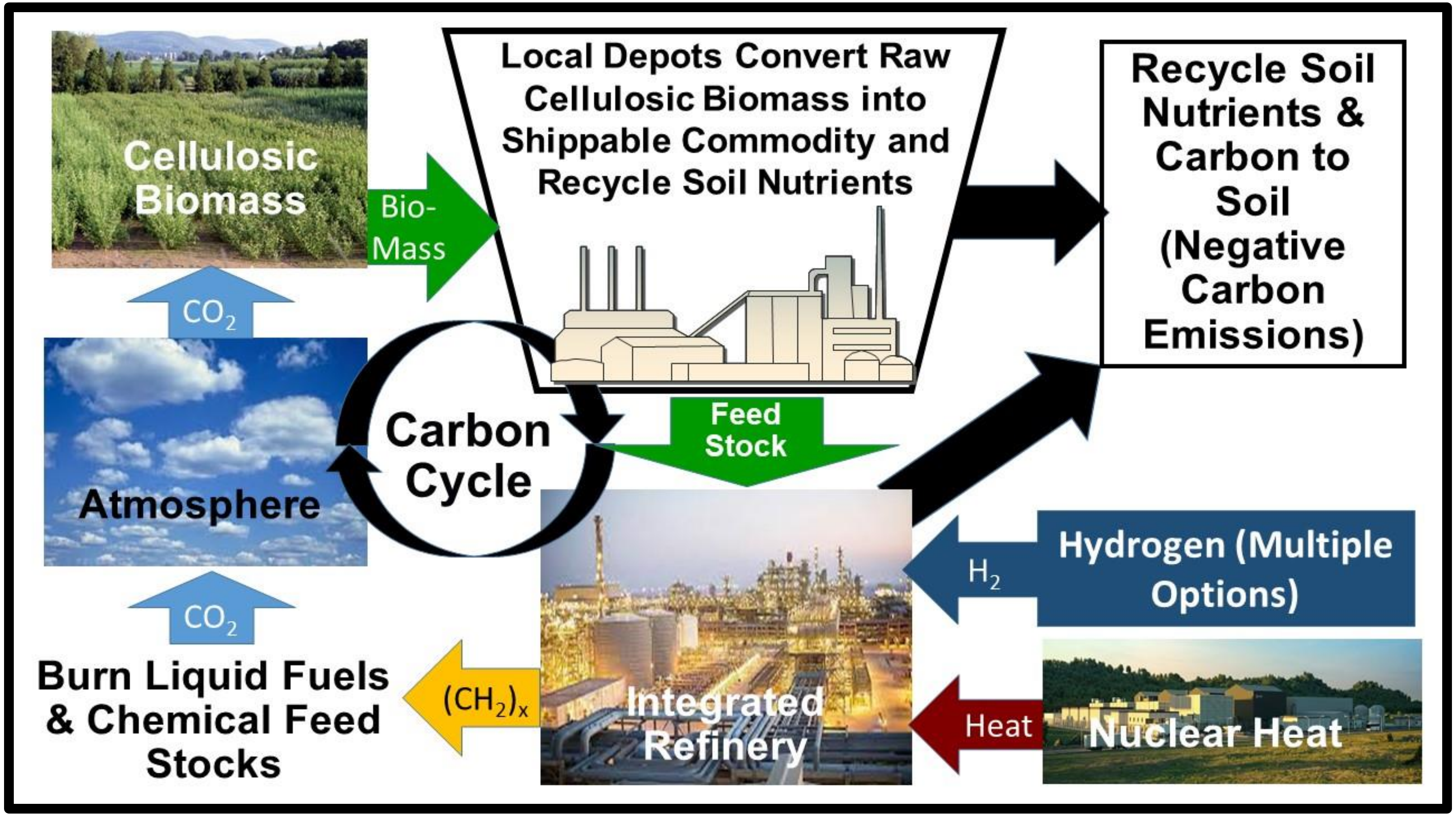
- Underground storage of natural gas (Current, Lowest Cost)
  - Geological constraints—need right types of rock
  - Low-carbon versions are renewable natural gas and hydrogen
- Liquid hydrocarbons in tanks: Low-cost transport
  - Currently jet fuel or diesel mostly made from crude oil
  - Same hydrocarbons can be produced from many other feed stocks including cellulosic biomass to replace all crude oil
- Stored heat: Non-transportable over long distances
- Electrochemical cells (batteries)
  - Costs several times gross national product—unaffordable
  - Non-transportable at scale

Requirements for Combustible Turbine Fuel

- Requirement 1: Low-cost long-term storage on site to assure availability under all conditions
- Requirement 2: Low-cost transportation of combustion fuel to power plant site to enable resupply if required for long periods of time (Hurricanes, etc.)
- Requirements met by (1) existing fossil fuels and (2) cellulosic liquid hydrocarbon fuels (jet, diesel, etc.) that are available at required scale in a low-carbon economy.
- Recent studies indicate sufficient cellulosic biomass to globally replace all crude oil—the competition to other long-duration storage technologies

System for Cellulosic Drop-In Hydrocarbon Biofuels Replacing All Crude Oil Products: Including Fuel for Combustion Turbines

- Gasoline, diesel and jet fuel can be made from any carbon feedstock
- If there was no crude oil, we would have invented diesel and jet fuel made from other feed stocks
- Cellulosic liquid hydrocarbons are the competition to other storage technologies



Low-Carbon Strategy Using Domestic Resources

Replacing All Crude Oil with Cellulosic Hydrocarbon Biofuels with Sustainable Agriculture and Negative Carbon Emissions

Based on studies and workshops, we conclude that there is sufficient cellulosic biomass (corn stover, forest debris, kelp, etc.) to replace all crude oil with cellulosic liquid hydrocarbons (gasoline, diesel, jet fuels and chemical feed stocks) provided the cellulosic biomass is used as a carbon source—not primarily as an energy source. This is without major impacts on food and fiber prices, improving long-term soil productivity and negative carbon emissions. Cellulosic biomass contains about one oxygen per carbon atom. There is sufficient cellulosic biomass if add massive quantities of external heat and hydrogen for the chemical conversion process to hydrocarbon liquids. There is not sufficient biomass if use the biomass as a carbon source in the final product and an energy source to produce the hydrogen and heat for the conversion process. In the near-term if the goal is a low-carbon world, the economic hydrogen source is natural gas converted to hydrogen with sequestration of the byproduct carbon dioxide and heat from nuclear reactors. There is the potential to economically competitive with crude oil

Summary of Cellulosic Biofuels Production Option

1. Cellulosic liquid hydrocarbons (gasoline, diesel, jet fuel, chemical feed stocks, etc.) produced using massive external sources of hydrogen and some external sources of heat can fully replace all liquid hydrocarbons made from crude oil and most chemical feed stocks
2. Hydrogen is the largest cost followed by cellulosic biomass. In the near term, the economic source of hydrogen for large-scale deployment will be primarily from low-price natural gas with wind and other sources depending upon location. Nuclear energy may become the primary heat source
3. The system design is carbon-negative with (1) recycle of soil nutrients incorporated in refractory carbon forms from the production process to improve long-term soil productivity and sustainability and (2) sequestering of carbon dioxide from the production of hydrogen by the auto-thermal process when using natural gas.
4. There is the potential to be economically competitive with crude oil with major economic benefits for the U.S. economy enabled by the strengths of American agriculture and the oil/gas industry (refineries, natural gas, etc.).

C. Forsberg and B. Dale, What is the Future of Liquid Hydrocarbon Fuels and Feedstocks, *Chemical Engineering Progress*, 121 (4), 48-53, April 2025. https://www.aiche.org/sites/default/files/cep/202504048.pdf

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