Long-Duration Hot-Air Supply from Electrically-Heated High Temperature (1800˚C) Firebrick

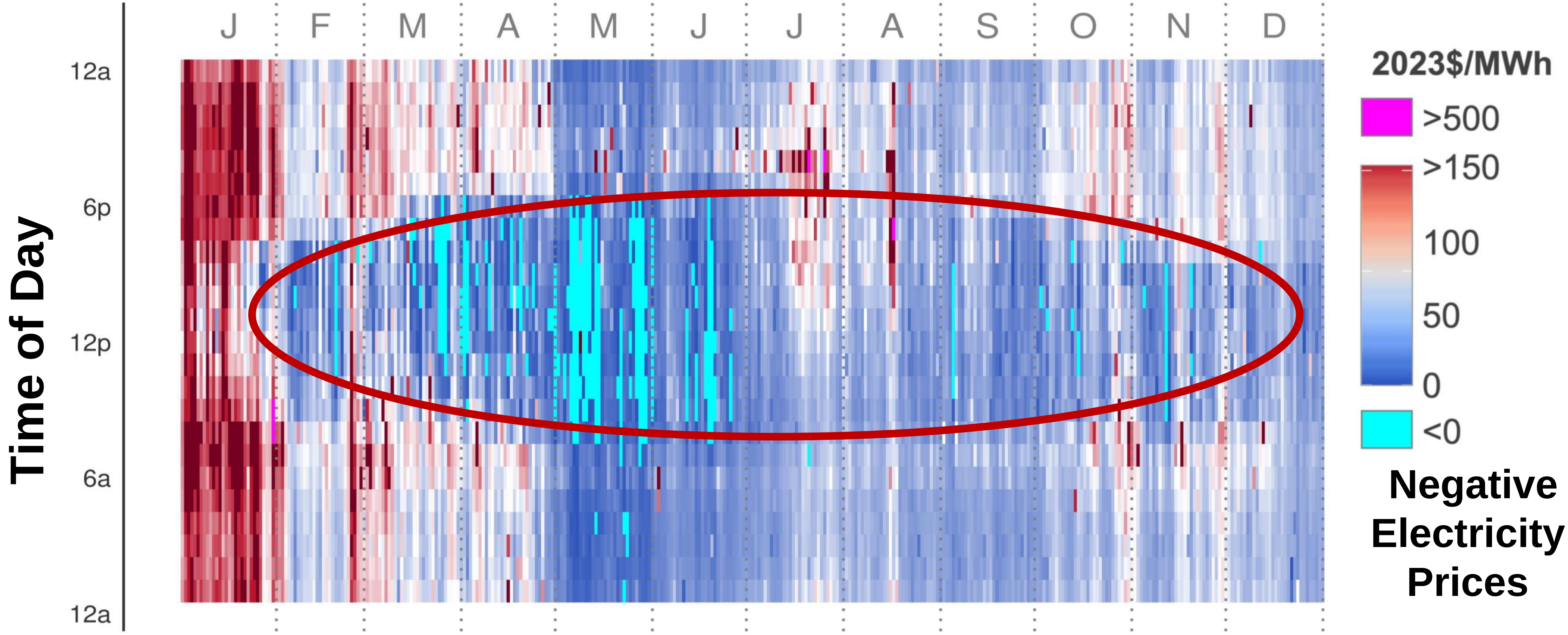
Charles Forsberg

Massachusetts Institute of Technology, Cambridge, MA, USA, cfosber@mit.edu

2025 TMCES Workshop
San Antonio, Texas
July 31, 2025

Charles Forsberg
cforsber@mit.edu

Goal: Productively Use All Low-Price Electricity Less Than Fossil Fuels (2023 California Wholesale Electricity Prices)



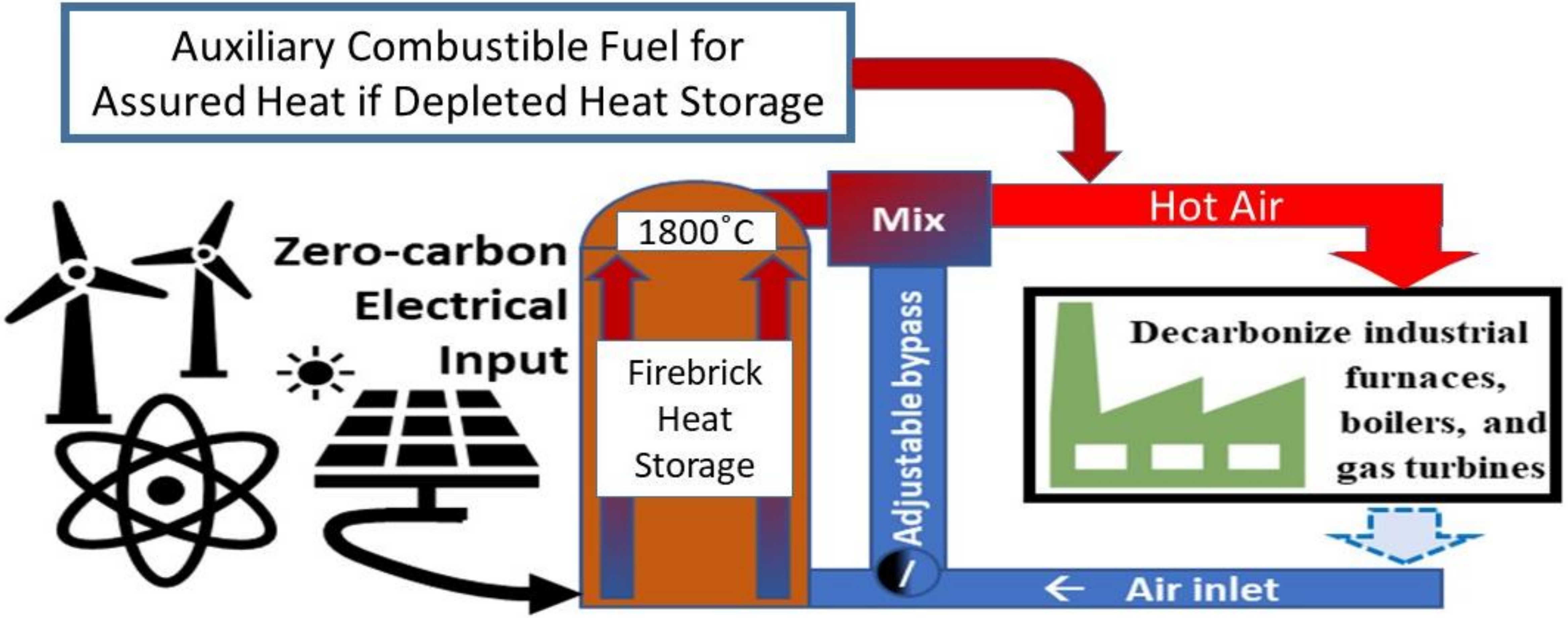
D. Millstein, E. O'Shaughnessy and R. Wiser, Exploring Wholesale Energy Price Trends, Lawrence Livermore National Laboratory, 2024. https://eta-publications.lbl.gov/sites/default/files/rewep-2024update_tech-brief_20240429.pdf

We Are A Hot-Air Society: Produce Hot Air by Burning Fuels

Technology Has Changed Over A Million Years But Not the Basics

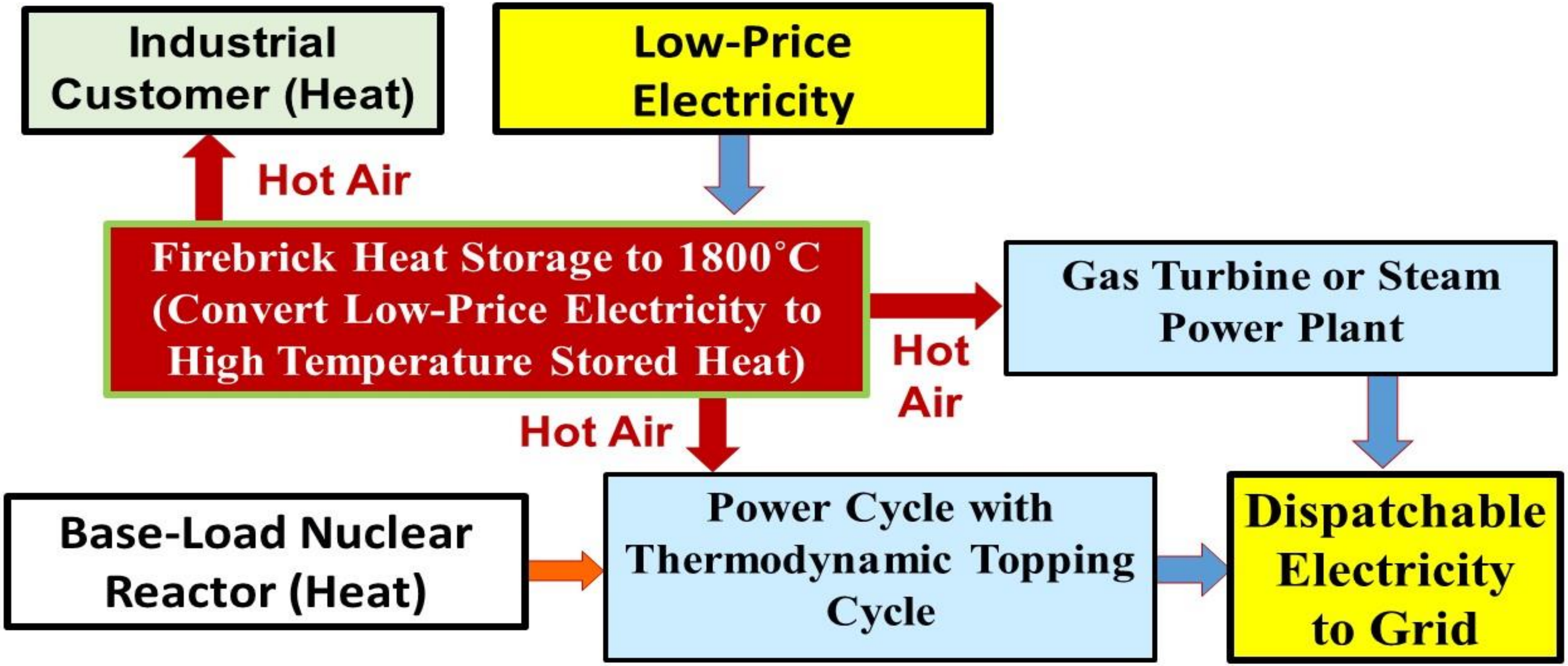
If Excess Electricity, Most Useful If Store and Deliver as Hot Air

Convert Low-Price Electricity into High-Value High-Temperature Stored Heat in Firebrick: Blow Air Through Firebrick Channels to Deliver Heat as Hot Air to Customer

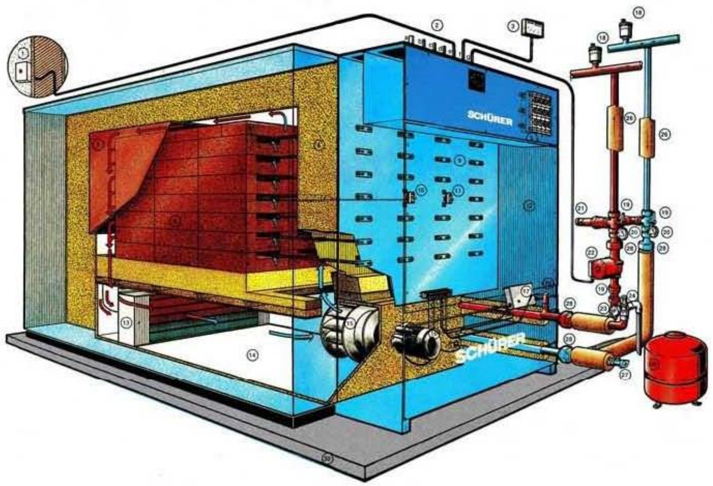


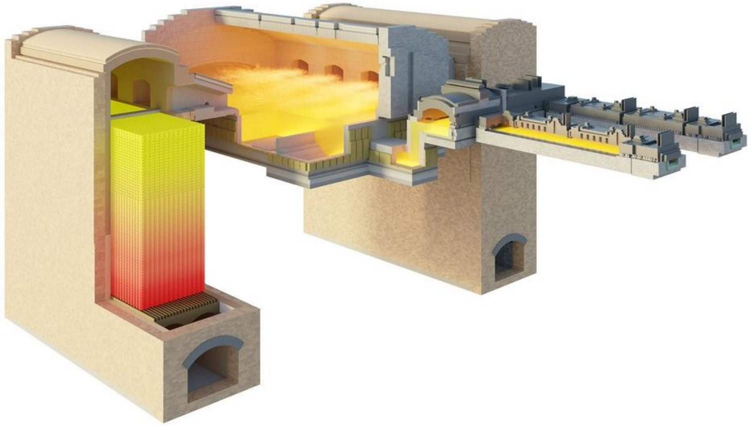
Recycle of Warm Air (No Stack) Improves Efficiency

System Design to Efficiently Use All Low-Price Electricity

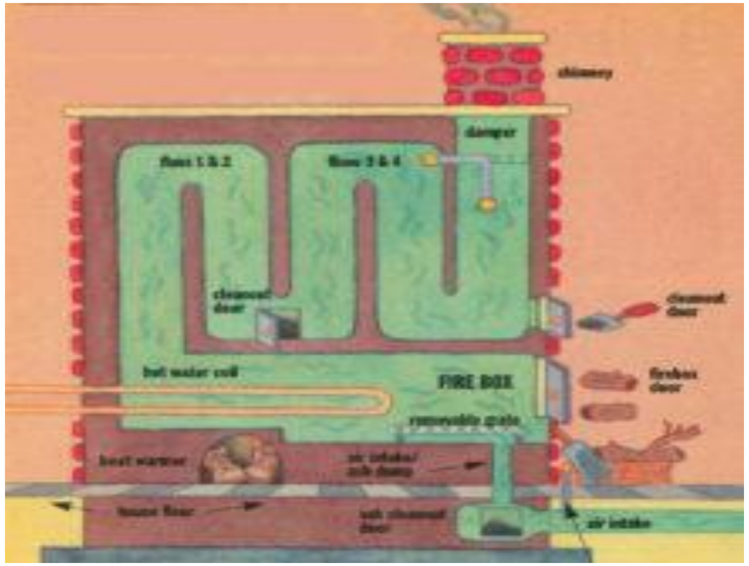


Storing Heat In Firebrick is an Old Technology





Glass Plant Regenerator, 30 Minutes to One Hour Storage, Natural Gas Heat, Gigawatt Hour, Massive Industrial Facilities

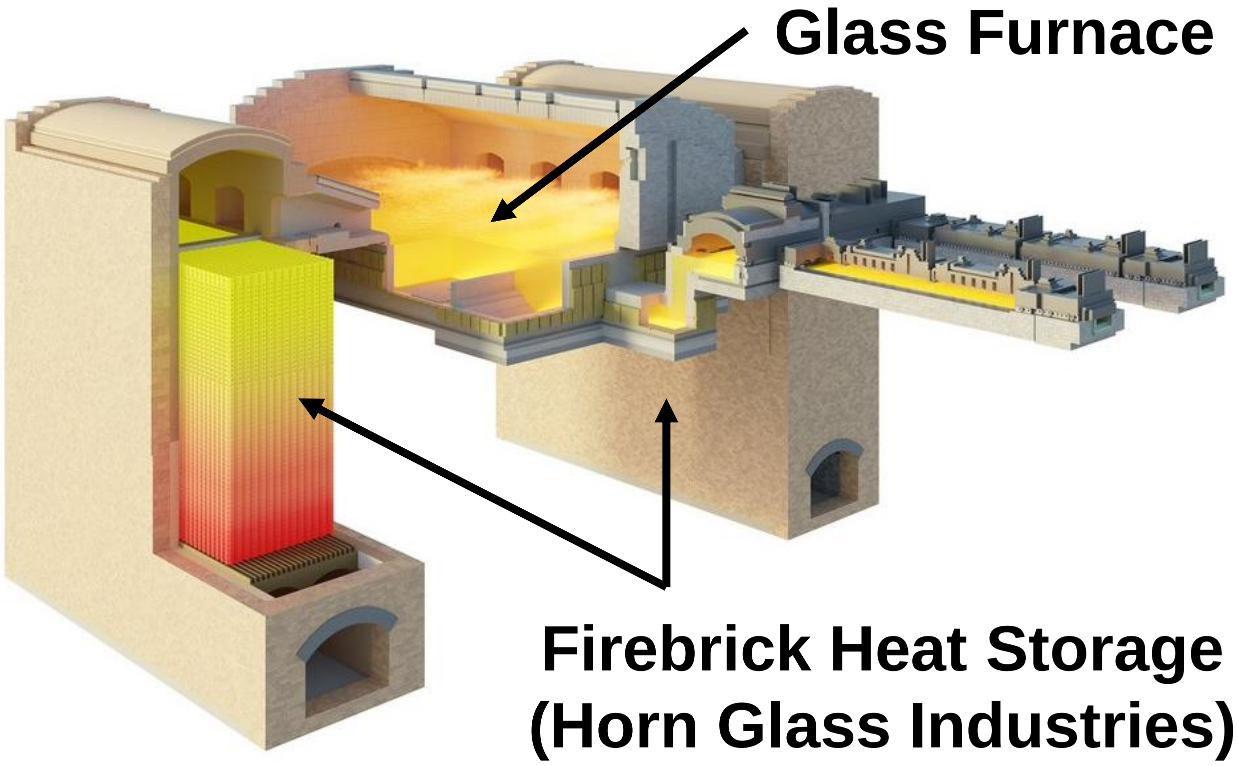


Siberian Fireplace, Wood heat, 15th Century, Store Heat Up to One Week

Factory Fabricated for Apartment Building, One Day Heat Storage, China, Electric Heat, Up to 8 MWh

Firebrick: A Gigawatt-Hour Heat Storage Technology Used in Glass, Steel and Other Industries

- Glass furnace
  - Recover heat from warm gas (up to 1500˚C) exiting glass furnace by heating firebrick before send off-gas to stack
  - Store heat in firebrick
  - Reverse flow ever 30 minutes
  - Heat incoming air, then boost temperature with natural gas
- 1000˚C firebrick temperature swing (minimize firebrick)



https://www.hornglass.com/products/melting-furnaces-and-equipment/cross-fired-furnaces

- M. Zier et al., A Review of Decarbonization Options for the Glass Industry, *Energy Conservation and Management: X*, 2021. https://doi.org/10.1016/j.ecmx.2021.100083

Strategy for Converting Cheap Electricity into Long-term High-Temperature Stored Heat for Industry and Power Cycles

- Fossil fuels deliver heat to industry as hot air—storage device must deliver heat to industry as hot air to match customer demand (Natural gas combustion)
- **Customer can swing between stored heat and fossil fuels or biofuels**
- Need cheap material—the only cheap high-temperature storage material is firebrick
- Heat storage in modified firebrick regenerators (right)

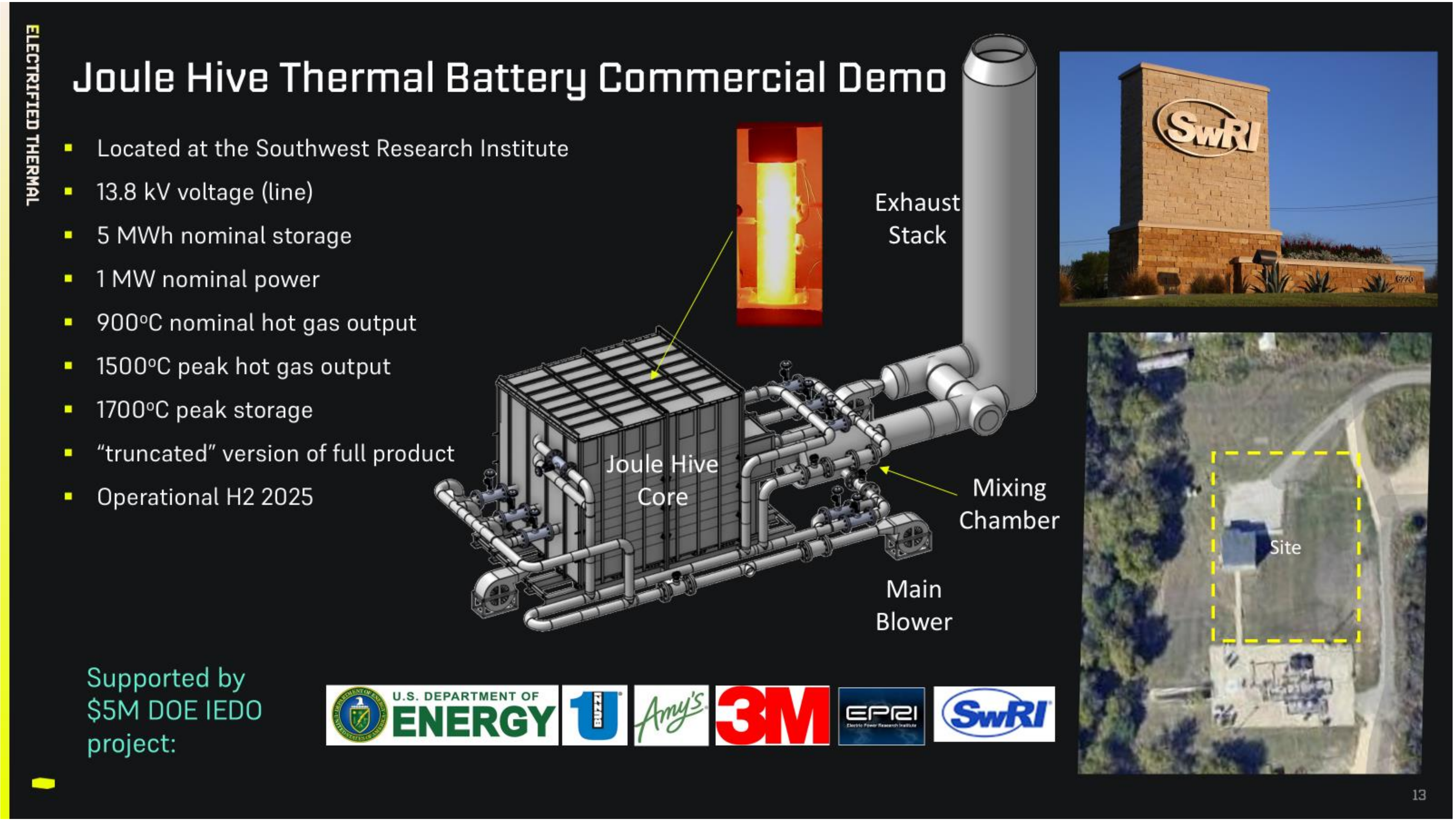
Converting Excess Electricity to High-Temperature Stored Heat in Firebrick

First Challenge: Firebrick Is an Electrical Insulator, We Developed an Electrically-Conductive Firebrick as Resistance Heater

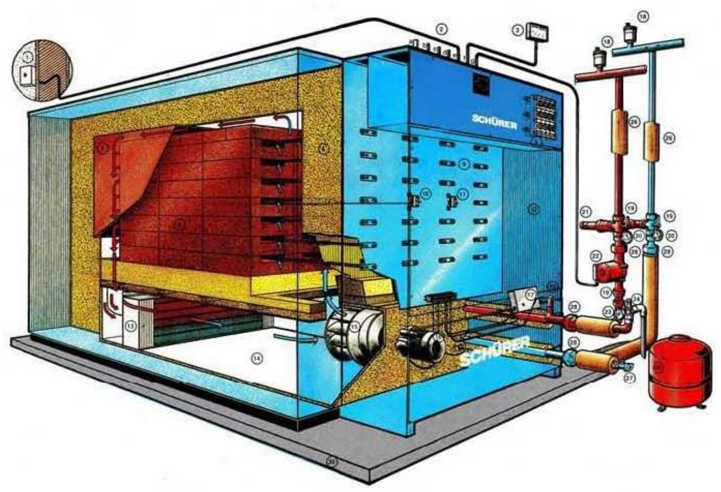
- Only firebrick can withstand very high temperatures but firebrick is an electrical insulator
- *We invented inexpensive doped firebrick to create conductive firebrick with required properties for electric resistance heating—match temperatures of burning natural gas (1800˚C). Small fraction firebrick become heater elements.
- Being commercialized by Electrified Thermal Solutions (D. C. Stack: CEO)
- **Demo under construction at SWRI**

- *C. Forsberg and D. C. Stack, *Electrically Conductive Firebrick System*, U.S. Patent: 11,877,376 B2. January 16, 2024. https://image-ppubs.uspto.gov/dirsearch-public/print/downloadPdf/11877376

Electrified Thermal Solutions Demo

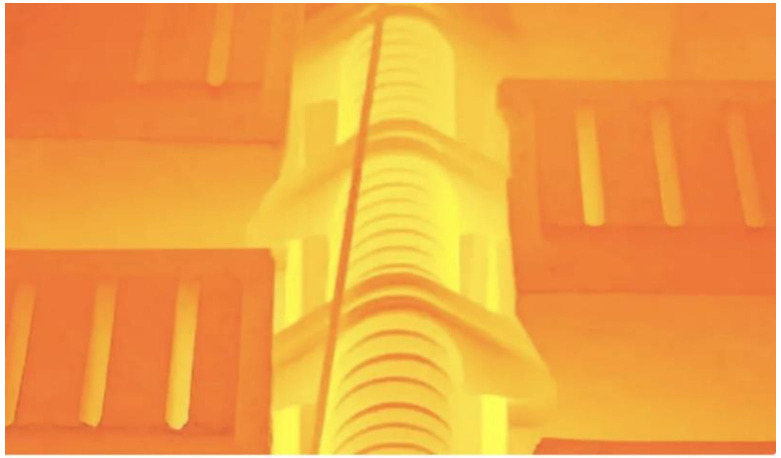


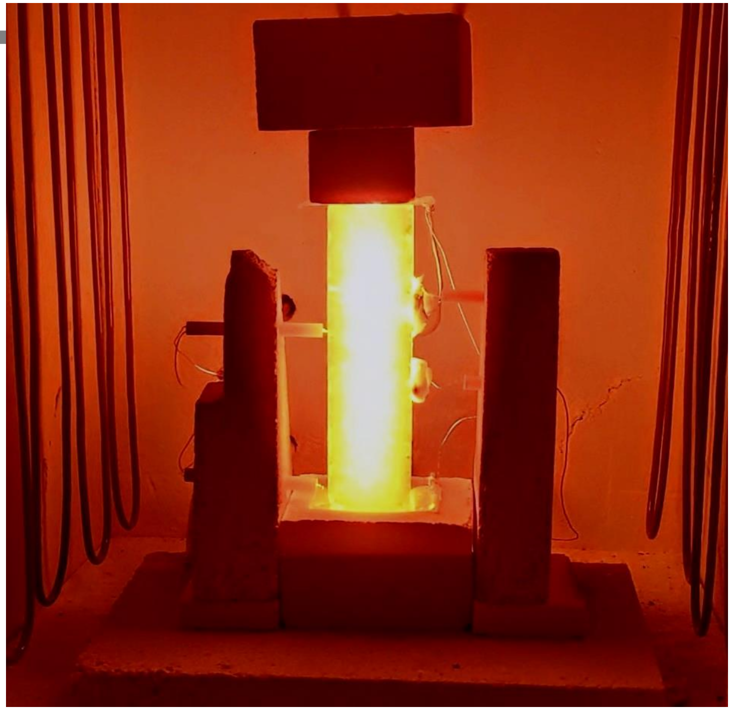
Firebrick Electricity-to-Heat Storage Technologies



Factory Fabricated
600˚C, Conventional
Electric Heaters,
50+ Year old Commercial
Technology

Factory Fabricated
1100˚C
Early Commercialization
Rondo Energy



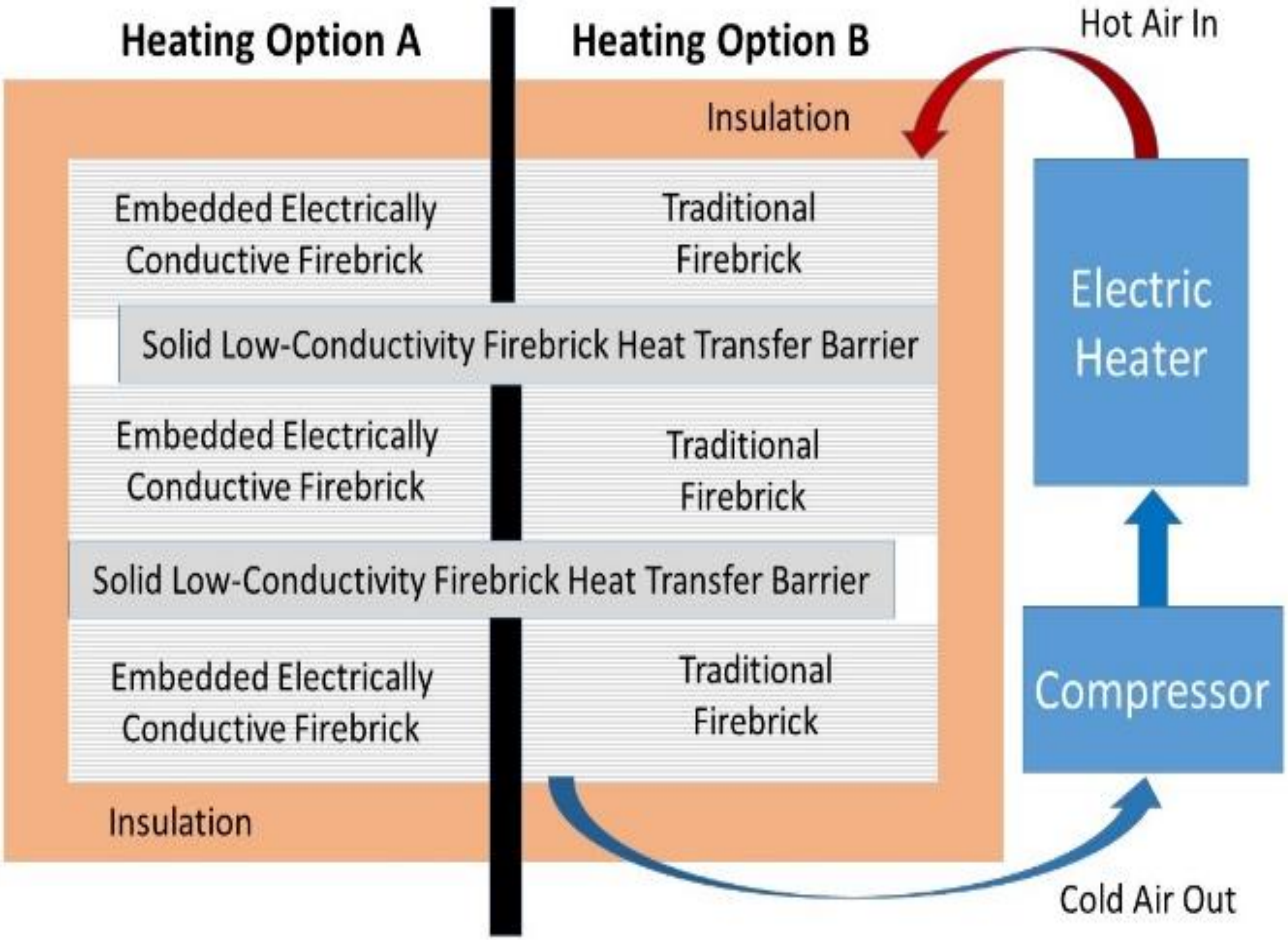


Factory or Field to 1800˚C
Electrically Conductive
Firebrick Being
Commercialized by
Electrified Thermal Solutions

Higher Temperatures, Larger Delta T and Potentially Lower Costs

Alternative Methods to Heat Firebrick Using Electricity

- Directly heat firebrick (Option A)
- Heat air outside of firebrick storage system
  - Electrically conductive firebrick (resistance or induction heating)
  - Conventional resistance heaters (temperature limits)

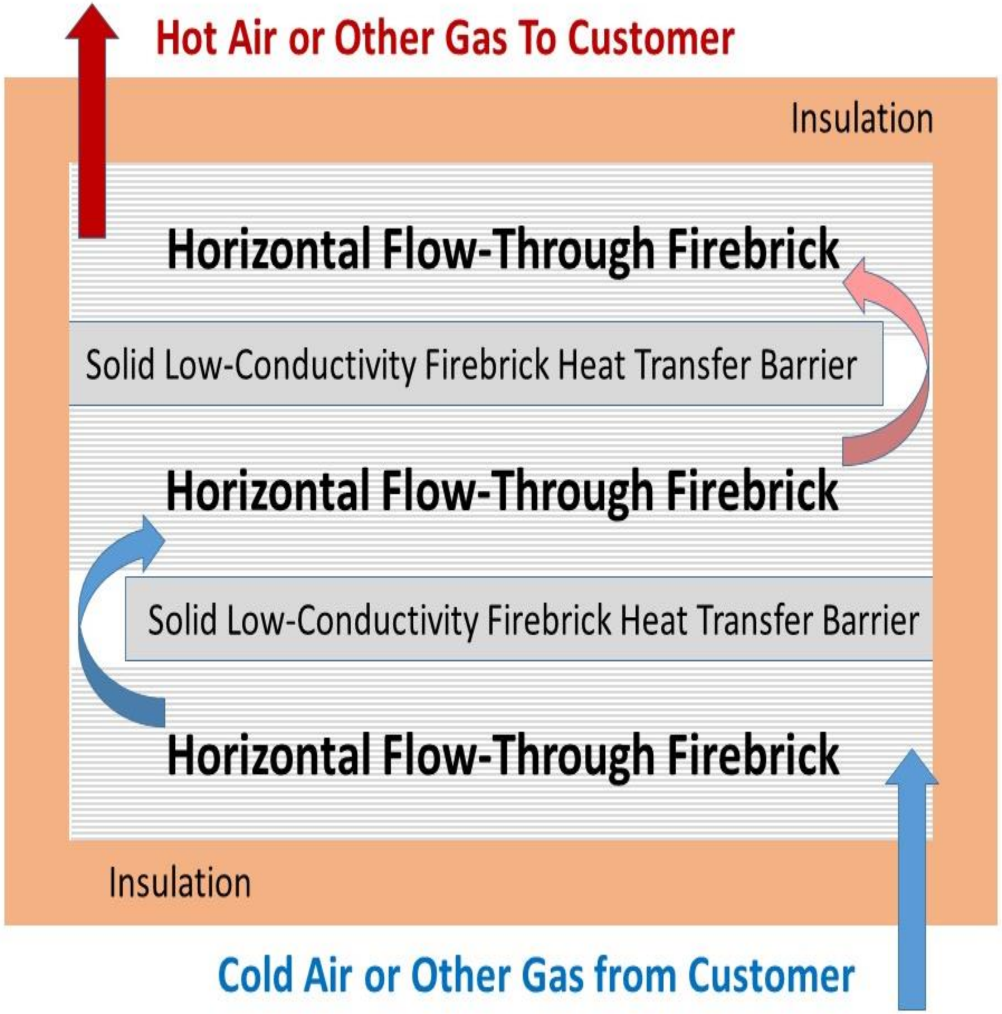


Large Incentives for 1000˚C Delta T to Minimize Firebrick Cost

Second Challenge: Slow Heat Transfer from Hot to Cold Zone During Storage by Heat Conduction and Radiation Heat Transfer

Current vertical gas flow for heat in and out over short times

- Industrial recuperators designed to store heat for hours, not days or weeks. Fast heat flow from hot to cold. Need fix.
- Create longer heat transfer path from hot zones to cold zones with S shaped flow paths (right)
- Horizontal insulator brick layers prevent fast heat transfer and enable long duration storage



Patent Pending

C. Forsberg, Base-Load Nuclear Reactors for Fully Dispatchable Electricity: Nuclear Air-Brayton Combined Cycles, Firebrick Heat Storage, Hydrogen Storage and Hydrocarbon Bio-Fuels, *Energies*, 18(4) 821, 2025. https://doi.org/10.3390/en18040821

Using High-Temperature Stored Heat for Nuclear Peak Electricity Production with Higher Heat-to-Electricity Efficiency

See also Jason Mortzheim (GE Vernova) TMCES Workshop Lighting Talk on Gas Turbines Operating on High-Temperature Stored Heat

High-Temperature Thermodynamic Topping Cycles Enable Efficient Production of Peak Power With Base-Load Reactors

- Heat-to-electricity conversion efficiency increases with peak power cycle temperature
- Add high-temperature heat to boost temperature of the power cycle above that of the reactor coolant with peak power production.
  - Light-water reactors with steam cycles-double output
  - Higher-temperature reactors with Nuclear Air Brayton Combined Cycle-peak output 2 to 5 times base load—longer term option
- **Temperature of added heat must be significantly above the peak temperatures of the reactor coolant—hotter is better**

Nuclear Thermodynamic Topping Cycles are a 1960s Technology

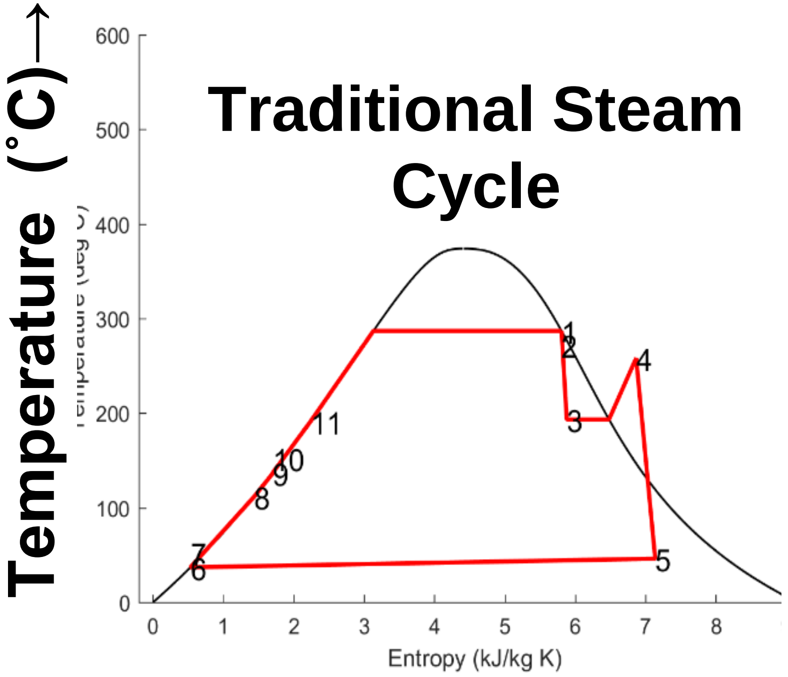
- Indian Point I (1960s) PWR steam superheated with oil-fired burner
- Hot air heats PWR steam to higher temperatures (550°C) before turbine
- Low added capital cost. Water flow rate through power cycle does not change—only the peak steam temperature:
- **Replace oil burner with hot air from firebrick (290°C to >600°C steam)**

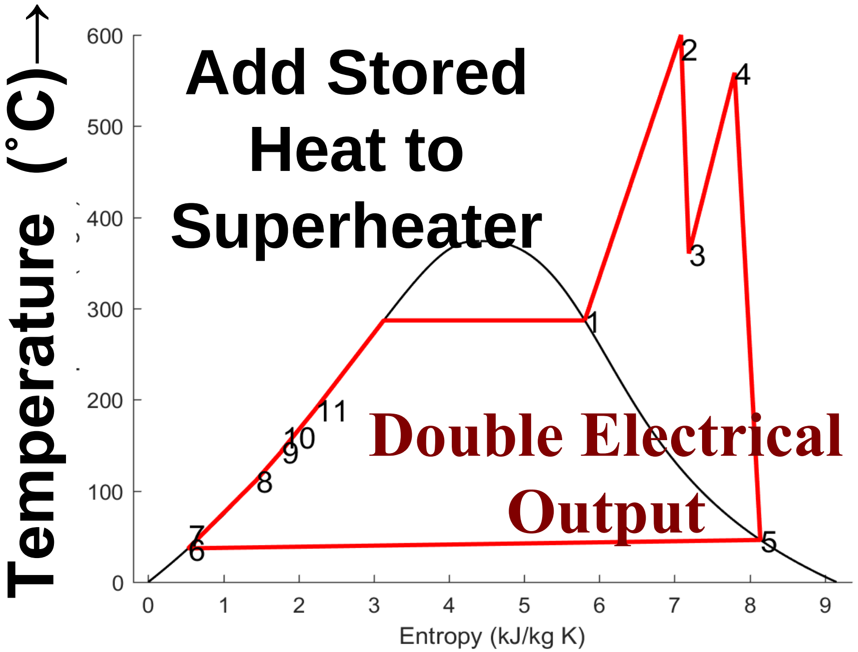
Wibisono, A. F. and E Shwageraus, E. Thermodynamic Performance of Pressurized Water Reactor Power Conversion Cycle Combined with Fossil Fuel Superheater, *Energy*. Volume 117, Part 1, 15 December 2016. https://doi.org/10.1016/j.energy.2016.10.060

Simplest (Lowest Capital Cost) LWR Cycle: Superheat Exit Steam

Updated Version of Indian Point I (1970s) Nuclear Power Plant

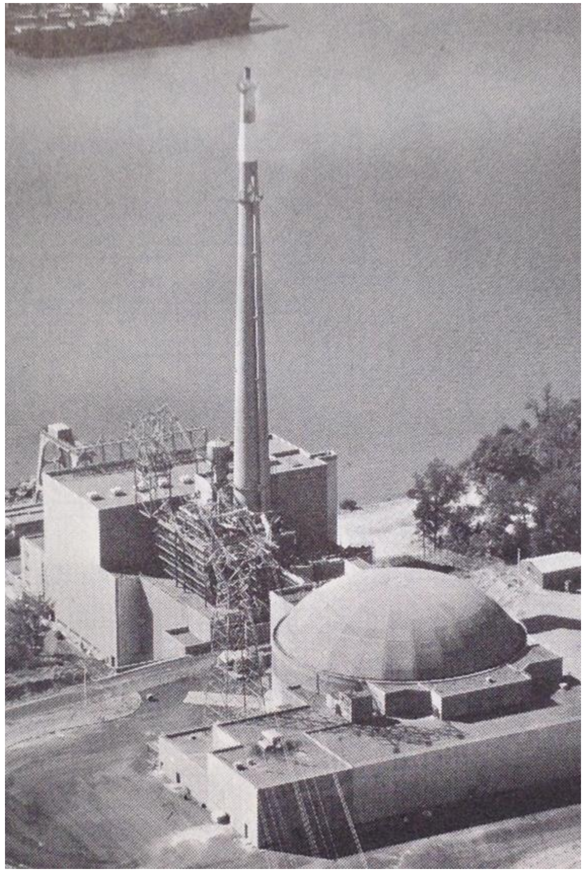
- GE SMR (Ontario Hydro)
- Added Peak Power 102% Base Load
- Fossil: Heat to Electricity Efficiency 46%
- **Firebrick higher efficiency**



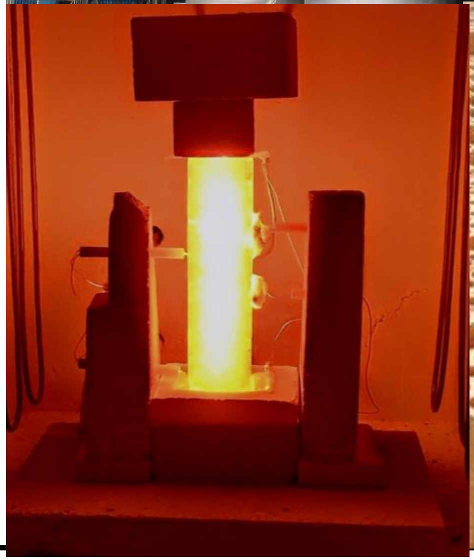


Firebrick heating more efficient: recycle warm air back to reheat rather than to stack with combustion gases and water vapor from combustion [Lower heating value of combustible fuels]

Conclusions



- Firebrick heat storage may set a minimum electricity price equal to natural gas—changes the electricity market
- Provides high-temperature heat to commerce and industry as hot air for one-to-one replacement of fossil fuels
- Heat for gas turbines and nuclear reactor peaking cycles



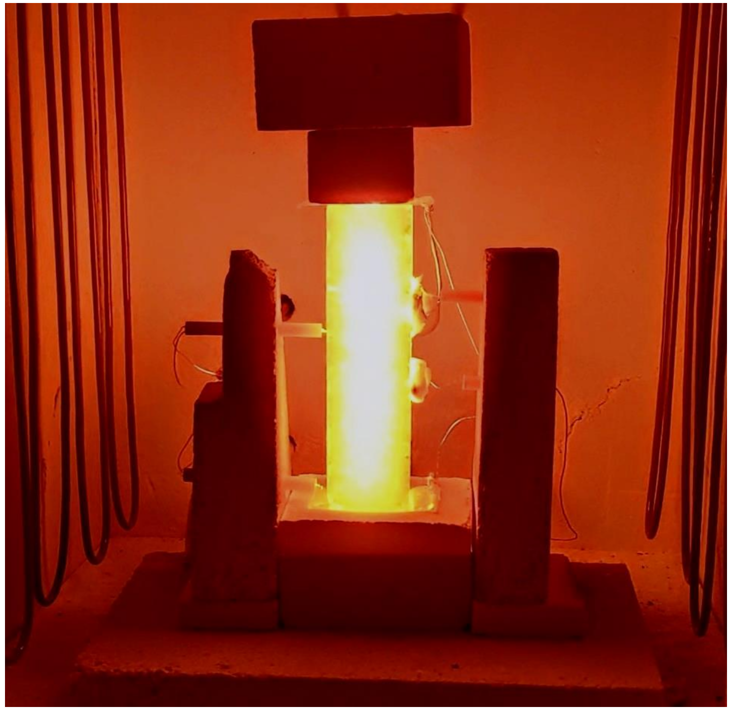
Biography: Charles Forsberg

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), 100-GWh Crushed Rock Ultra-large Stored Heat (CRUSH) systems and nuclear-assisted biofuels production. 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. 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 (excludes foreign patents first filed in the U.S.) and published over 300 papers.

Potentially Lowest-Cost Electricity to Heat System

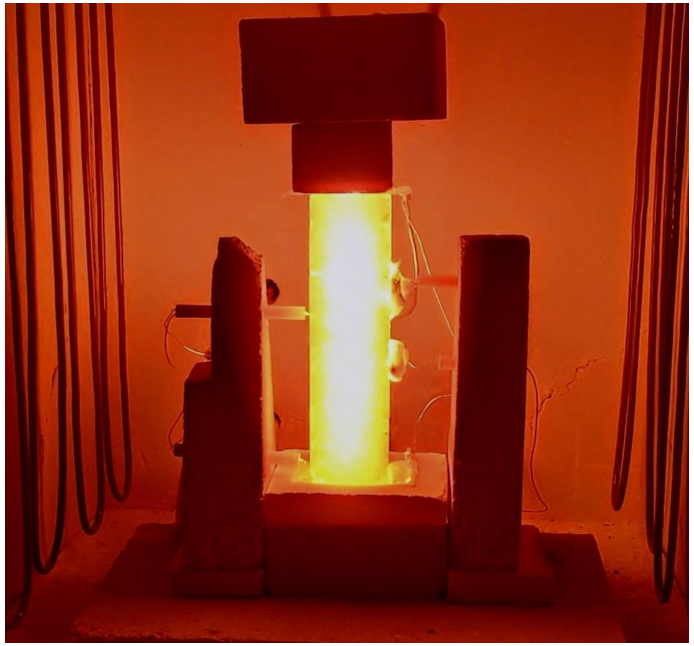
- Low cost firebrick
- Large cold-to-hot temperature swing that maximizes heat storage per ton of firebrick
- Deliver heat as hot air blown through firebrick—no external heat exchanger between firebrick and customer
- Megawatt heating elements minimizing power electronics (Next viewgraph)



Electrically Conductive Firebrick Being Commercialized by *Electrified Thermal Solutions*

Potential for Megawatt Heater Elements to Minimize Cost of Power Electronics

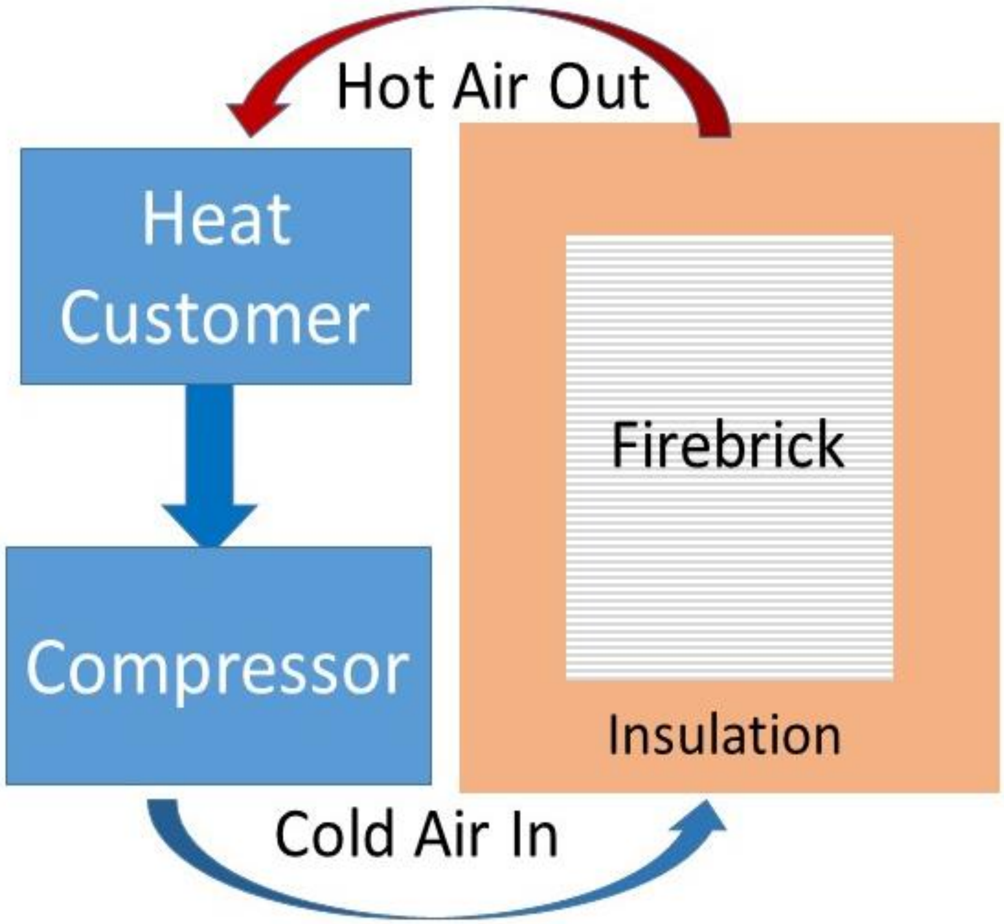
- Traditional resistance heaters at most two meters long with relatively low voltage and many heaters to produce a megawatt of heat
- Conductive firebrick (short brick wall) enables heaters 10s of meters long in large piles of conventional firebrick with small number of power leads into storage system
- Can have high-voltage (22,000 volt) megawatt heater circuits
- Radical simplification and reduction in the cost of the electrical components per unit of energy input



Electrically Conductive Firebrick Being Commercialized by *Electrified Thermal Solutions*

Electricity-to-Heat-To-Customer Efficiency is High

- Efficiency > 95% in many cases
  - Electricity-to-heat 100%
  - Hot air to customer with warm air returned to firebrick to be reheated, no stack gas
  - Heat losses through walls
- Fossil-fuel burner stack gas to remove carbon dioxide and water also removes heat—much lower efficiency



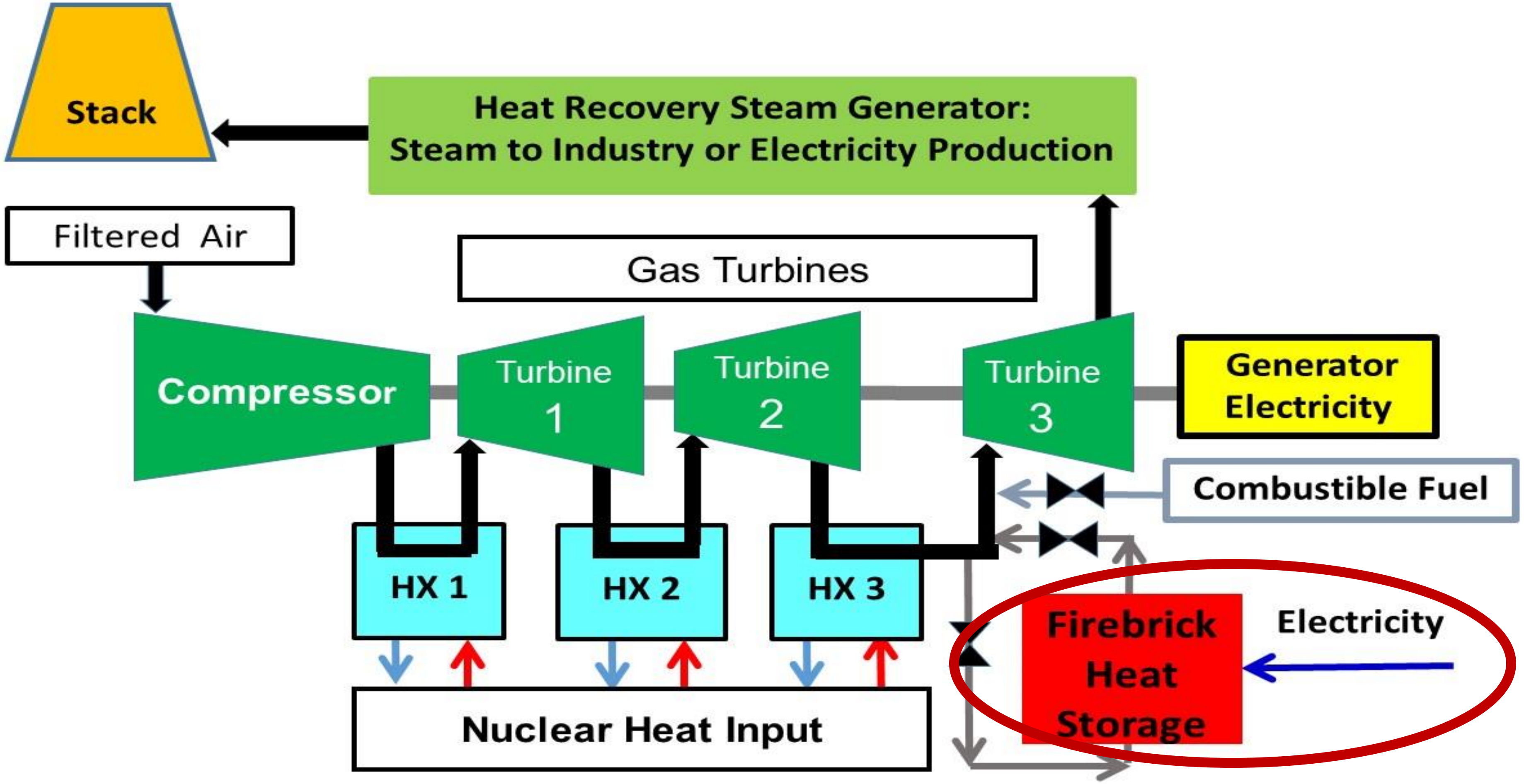
Performance of Simple LWR Thermodynamic Cycles

Parameter	AP-1000		GE SMR	
	No Superheater	With Superheater	No Superheater	With Superheater
HP Turbine Inlet Temperature (˚C)	**271**	**600**	**287**	**600**
Nuclear Power Generated (MWe)	1,031	2,045	289	583
Stored Heat Required (MWt)	_	2318	_	636
Reactor Nuclear Heat (MWt)	3417	3417	840	840
Added Peak Power (%)	_	**98.00**	_	**101.87**
Stored Heat Cycle Efficiency (%)	_	**43.66**	_	**46.23**
Total Cycle Efficiency (%)	30.23	35.66	34.35	39.47

There are More-Complex Higher-Efficiency Peaking Cycles

Nuclear Air-Brayton Combined Cycle with Peaking Power for Higher-Temperature Sodium and Salt-Cooled Reactors

- Sodium Cooled Reactor
- Power Gain: 2.5 to 5.7
- Stored Heat to Electricity Efficiency 71 to 74%



C. Forsberg, Base-Load Nuclear Reactors for Fully Dispatchable Electricity: Nuclear Air-Brayton Combined Cycles, Firebrick Heat Storage, Hydrogen Storage and Hydrocarbon Bio-Fuels, *Energies*, 18(4) 821, 2025. https://www.mdpi.com/1996-1073/18/4/821; https://doi.org/10.3390/en18040821.

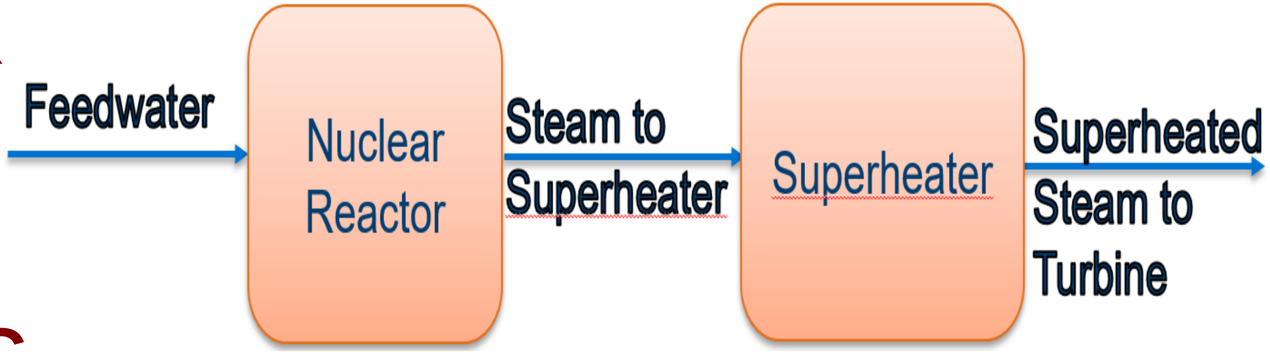
NACC Performance for Different Reactors

Turbine 1&2 Exit Temp.	Turbine 3 Nominal Exit Temp.	Turbine 3 Boosted Inlet Temp.	Base Efficiency	Heat to Electricity Efficiency	Combined Efficiency	Overall Power Gain
Sodium Near-Term System (Nominal Inlet Temperature 773 K (500 ˚C)						
680.5 K	640.5 K	1100 K	32.8%	**71.1%**	48.4%	**2.522**
680.5 K	640.5 K	1700 K	32.8%	**74.2%**	60.4%	**5.744**
Molten Salt Advanced System (Nominal Inlet Temperature 973 K (700 ˚C)						
792.5 K	722.5 K	1100 K	45.5%	**74.5%**	51.1%	**1.403**
792.5 K	722.5 K	1700 K	45.5%	**75.0%**	61.6%	**3.070**

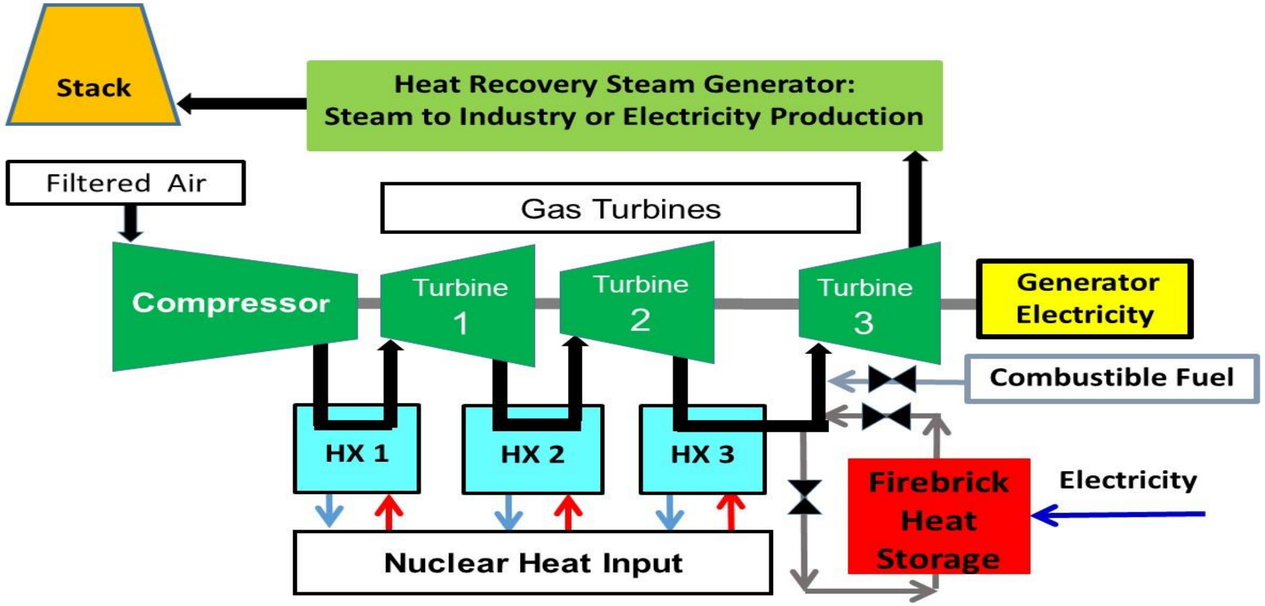
Peak Power Systems Can Provide Auxiliary Services: Stabilize Frequency and Fast-Response Spinning Reserve

- Massive rotating inertia of generator at part load for frequency control
- Fast ramp speed for steam turbine if add steam accumulator for power while steam boiler ramps up
- NACC fast ramp—No change incoming air flow

LWR

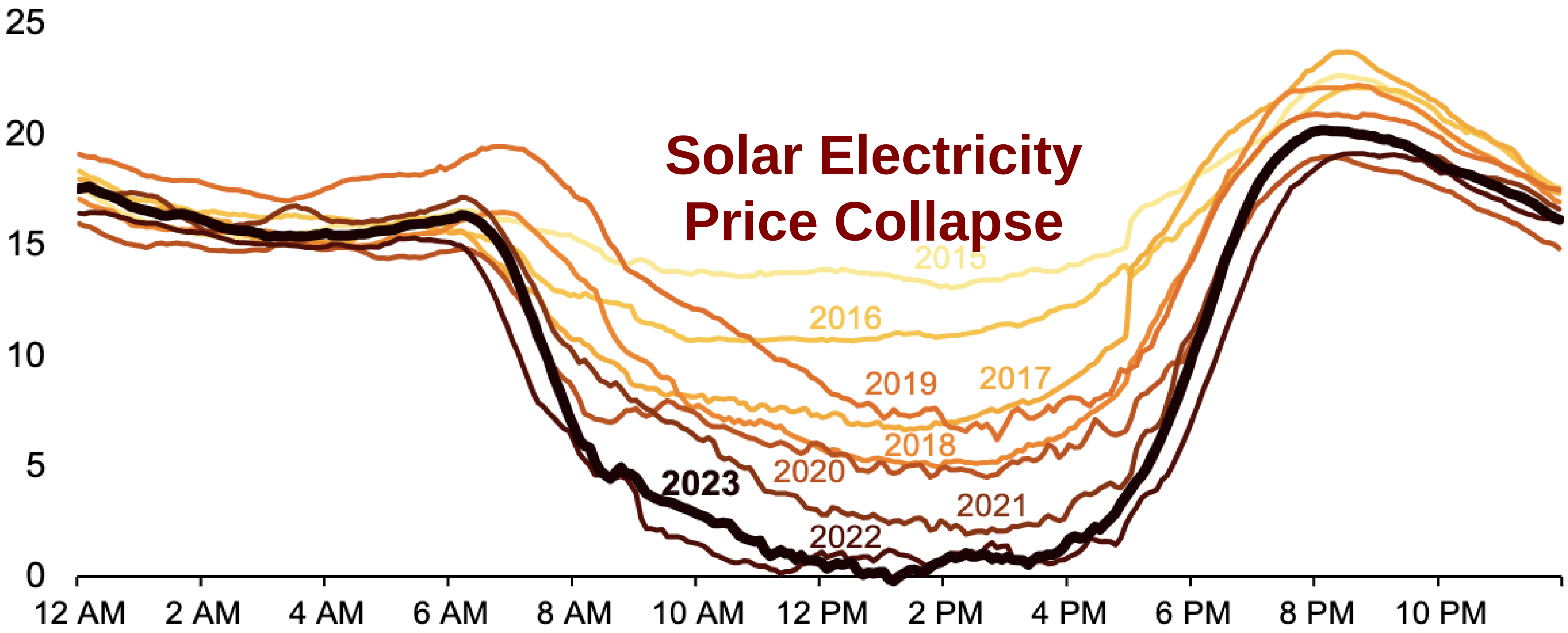


NACC



M. D. Noll, W. N Mann and T. Levin, An empirical analysis of supply offers in the ERCOT operating reserves markets, *Applied Energy*, 381, 2025. https://doi.org/10.1016/j.apenergy.2024.125035

California CAISO Lowest Net Load Day Each Spring in Gigawatts by Year—Demand After Wind and Solar

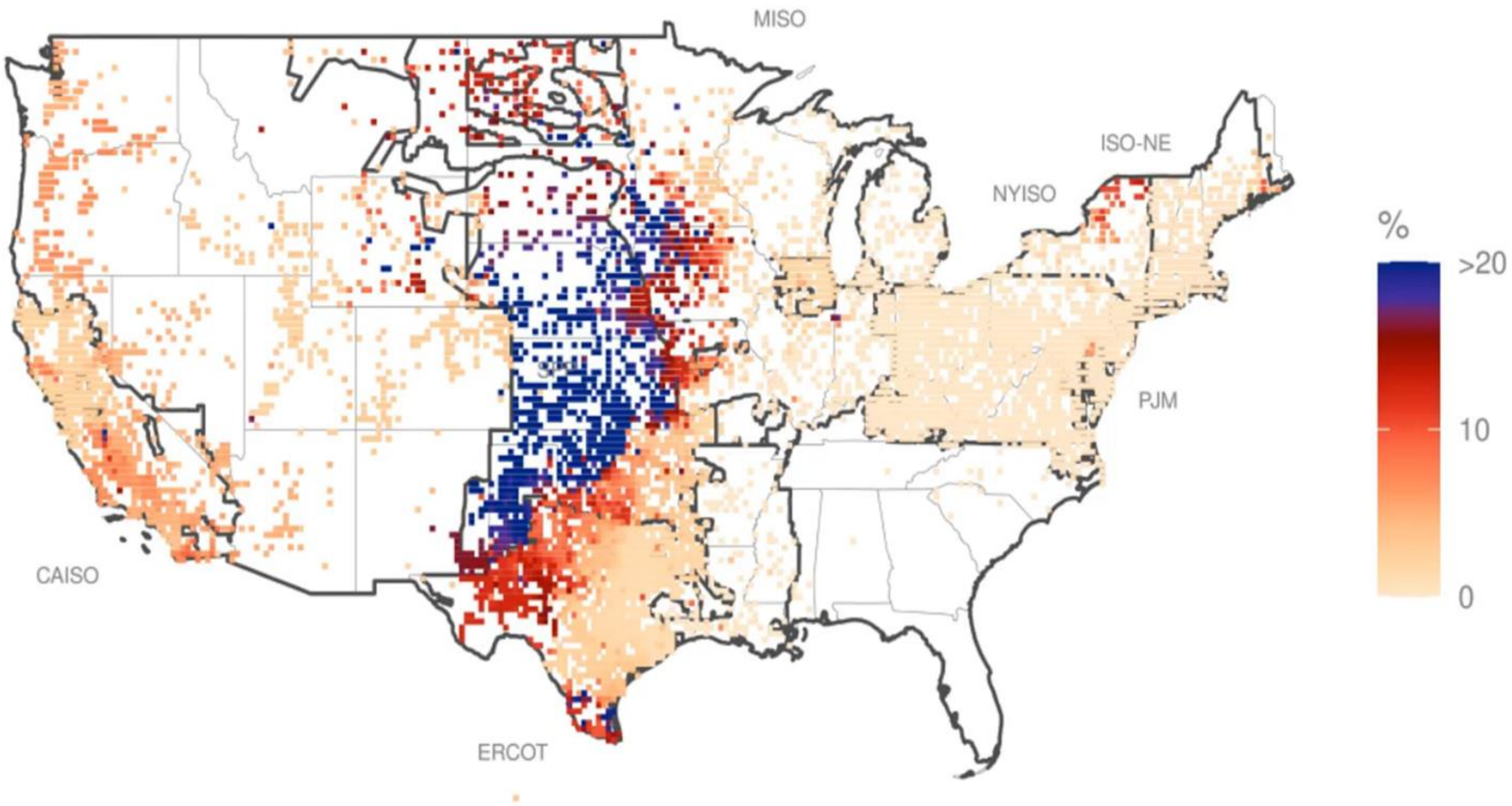


FIRES May Kill Off the Electrical Grid Duck Curve and Any Electricity Less than the Delivered Price of Fossil Fuels

Goal: Productively Use All Low-Price Electricity

Fraction of Time Wholesale Electricity Prices Below Zero (Courtesy of Electrified Thermal Solutions).

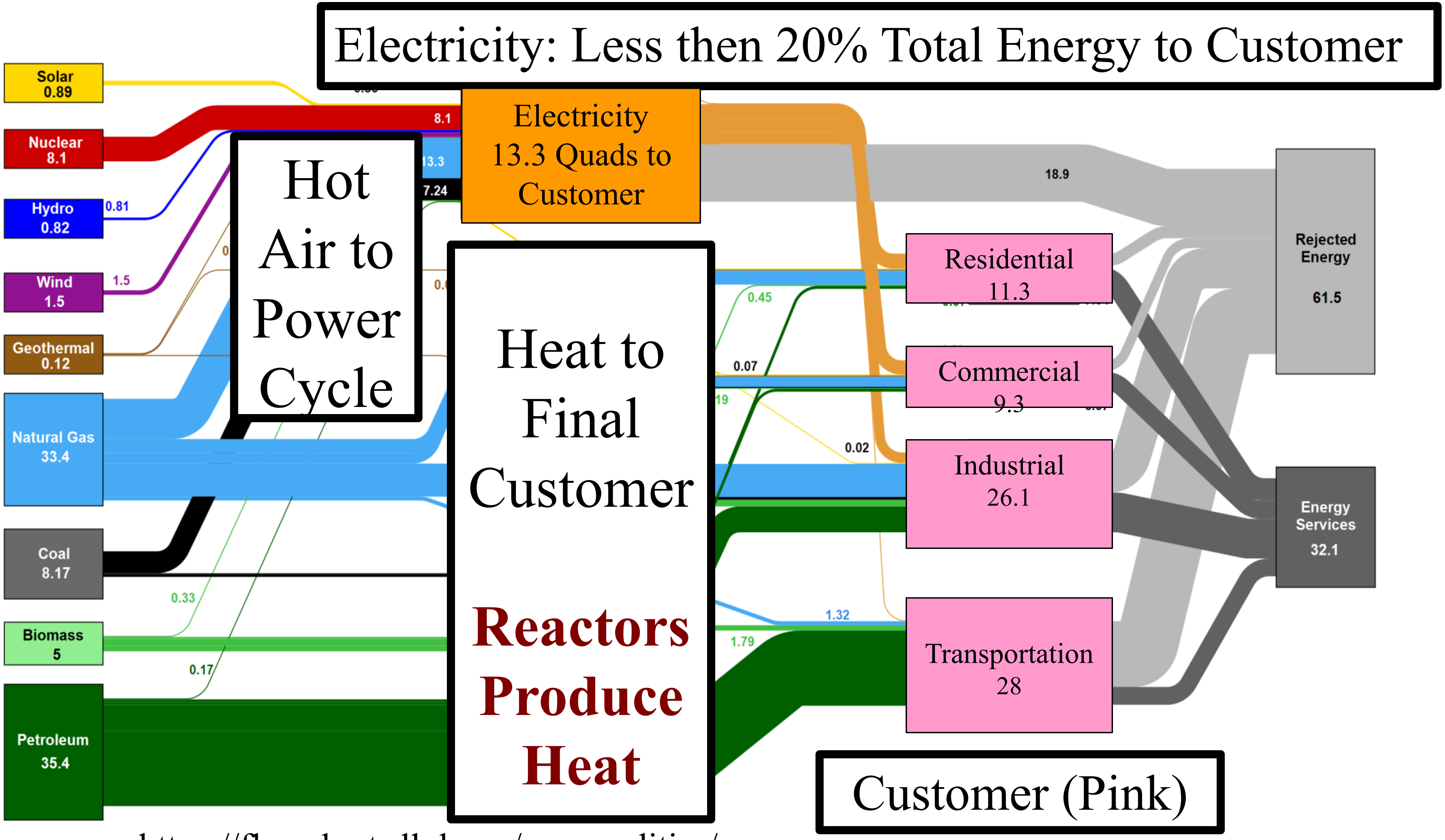
- Convert all electricity less than price of natural gas into stored heat for industry and electricity generation
- Set a minimum price for electricity near that from natural gas



U.S. Energy Consumption in 2023: 93.6 Quads: Mostly Hot Air

Solar
Nuclear
Hydro
Wind
Geo
Nat Gas

Coal
Bio
Oil



Low Cost Heat Storage Requires Low-Cost Materials

Temperature

~1800˚C Flame Temperature of Natural Gas

Firebrick (Electricity-to-Heat Technology: Electrified Thermal Solutions)*

~600˚C Long-Term Chemical Stability of Selected Rock

Crushed Rock (Today's Discussion)

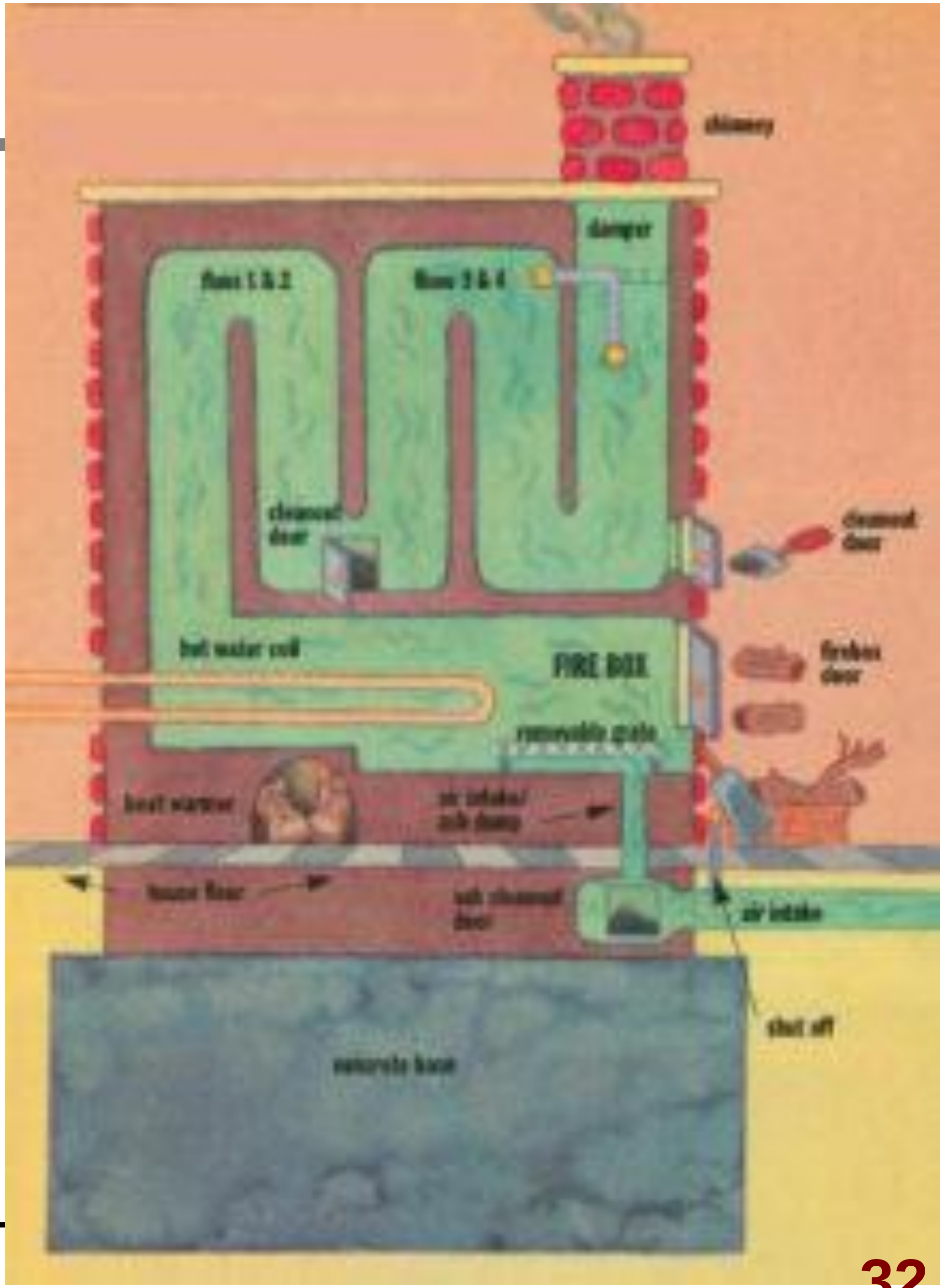
Oil to 400˚C, Salts to 600˚C

100˚C Boiling Point of Water

Liquid Water (District Heating Systems)

*Company: Electrified Thermal Solutions: Patent: C. Forsberg and D. C. Stack, *Electrically Conductive Firebrick System*, U.S. Patent: 11,877,376 B2. January 16, 2024. https://image-ppubs.uspto.gov/dirsearch-public/print/downloadPdf/11877376; Story: https://insideclimatenews.org/news/20052024/mit-electrified-thermal-solutions-decarbonize-heavy-industry/

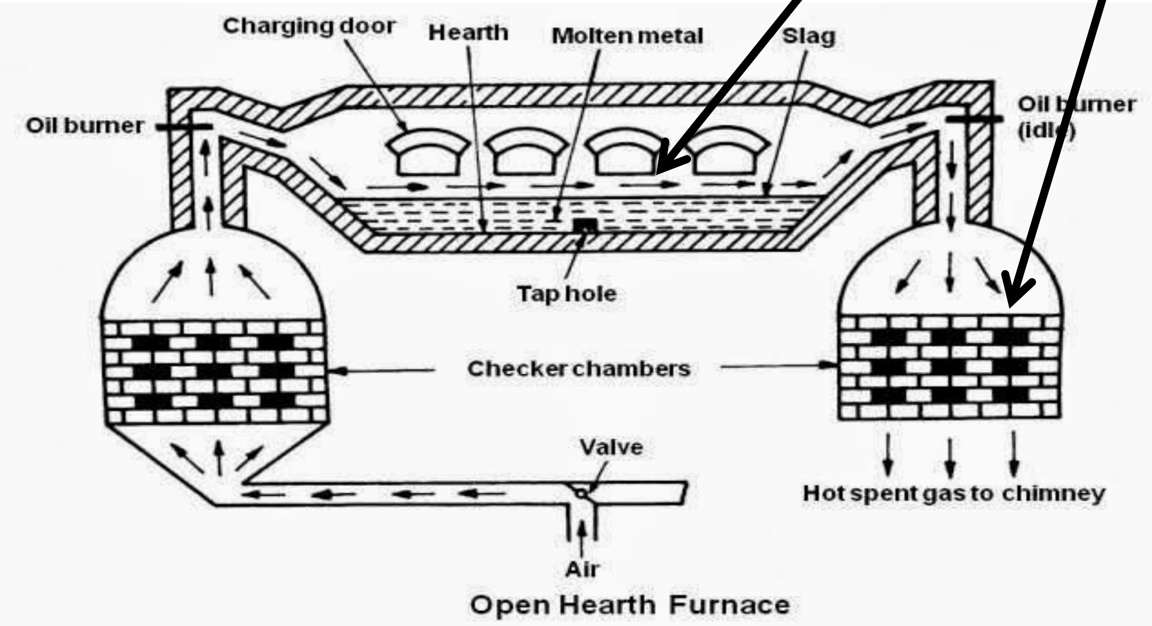
Siberian Fireplace



- Wood fireplace with chimney looping through firebrick
- Heat storage for many days with warm firebrick for cabin
- Earliest versions so far identified: 15th century
- Very efficient conversion of firewood to stored heat

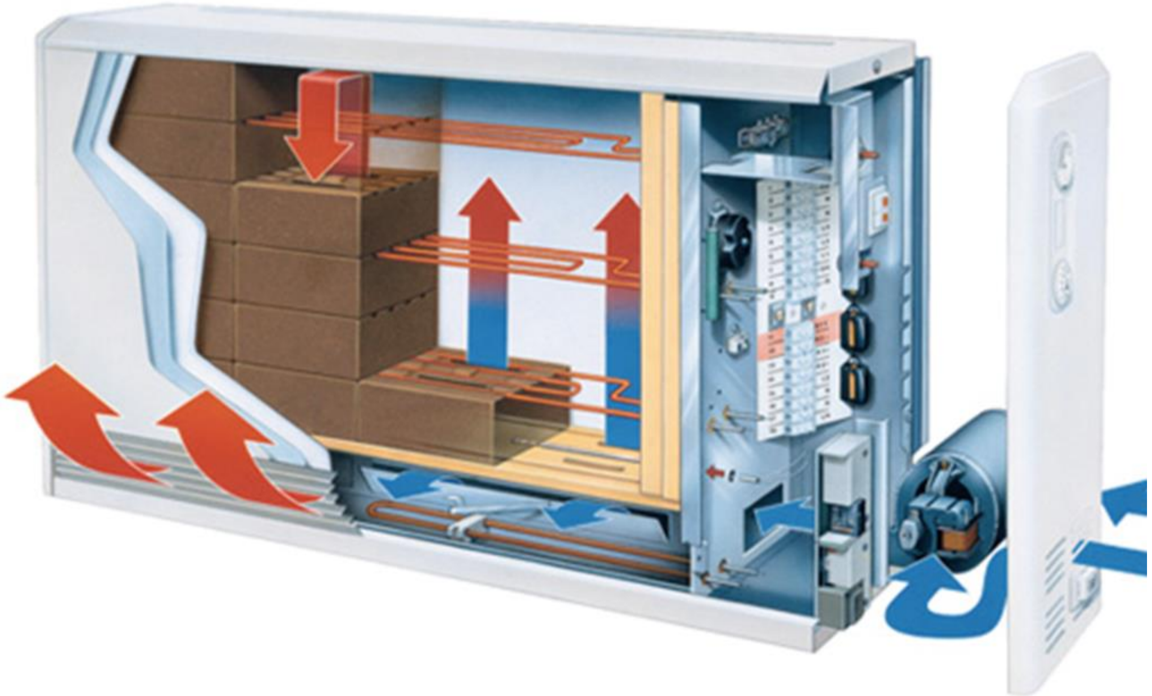
https://www.motherearthnews.com/diy/building-a-russian-woodstove-from-bricks-zmaz97onzgoe/

Firebrick Air Recuperators Developed for Open-Hearth Steel Production (1920s)



- Hot air blown over molten pig iron (>1600C) to remove carbon by oxidation
- Exhaust air through firebrick with air channels to absorb heat, then off gas to stack
- Reverse air direction when heated firebrick recuperator
  - Preheat in-coming fresh air
  - Add oil to boost air temperature
  - Flow over pig iron to remove carbon
  - Exhausted to second firebrick recuperator
- Extreme temperature swings in firebrick with hot corrosive gases

50+ Year Old Residential Heat Storage Units

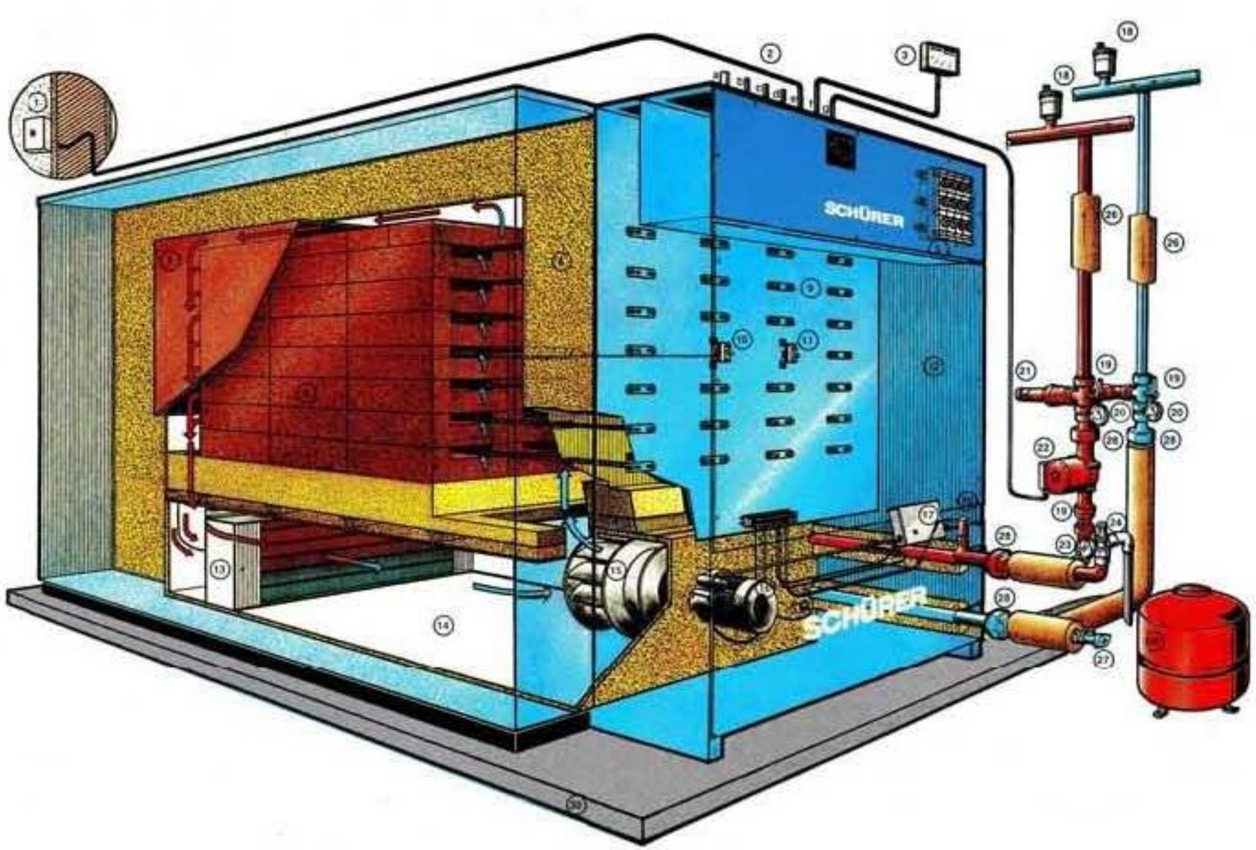


Dimplex® home heat storage unit with resistance heaters

- Some utilities offer night-time electricity discounts for electrically heated homes
- High temperature firebrick with electric heater and fan
  - Buy and store electrical heat when cheaper than fuel
  - Used to heat homes and offices
- Storage temperatures up to ~700C
- Capacity typically 100 kWh
- Discharge and charge 10-20 kW
- **Prices as low as $15/kWh**

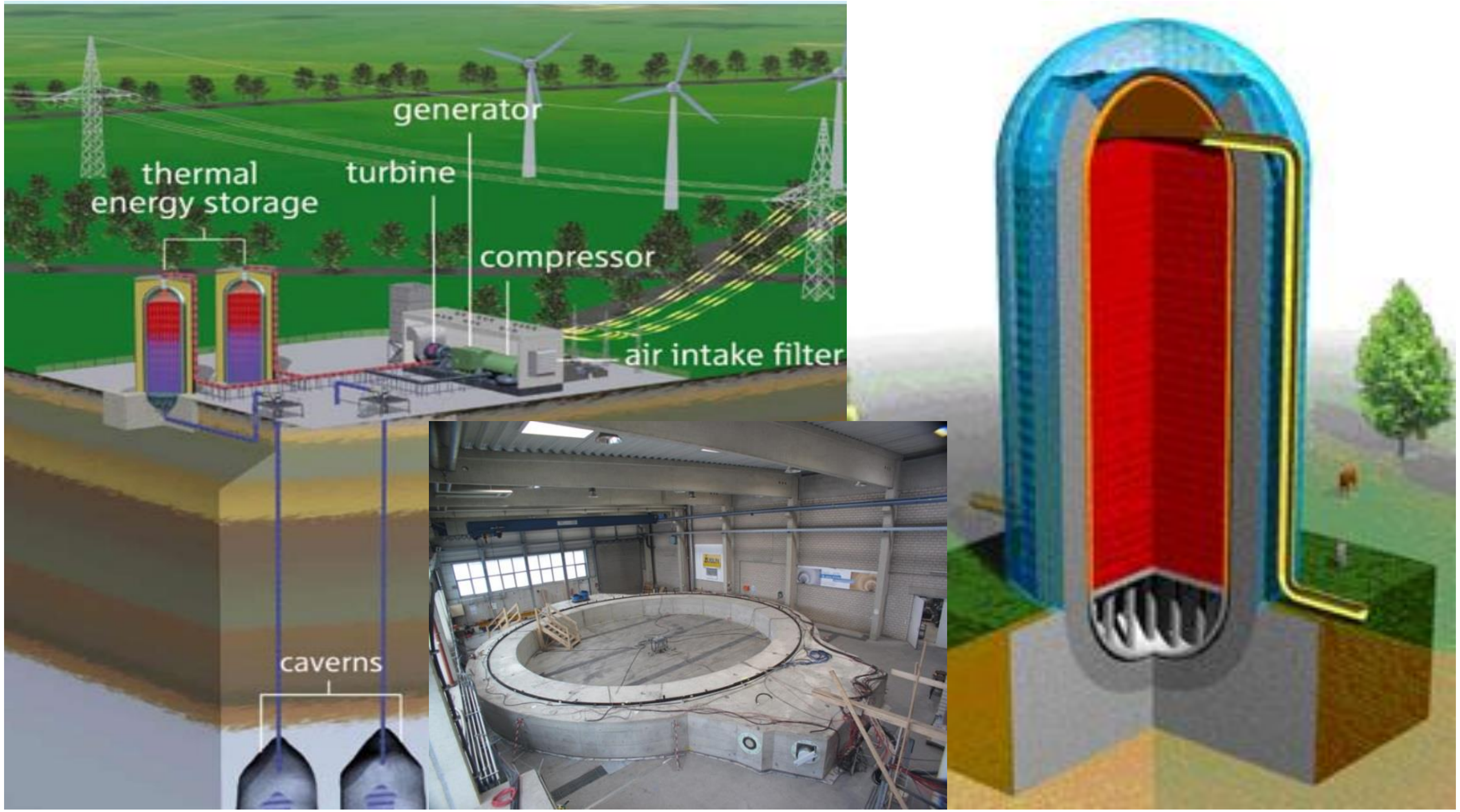
Recent China Experience: Heat Storage Units for Large Apartment Complexes

- Eight-hour night discount rate for electricity
- Units up to 8 MWh storage capacity
- Traditional electric resistance heaters
- Hot air heats hot water for building heat and use
- Hot air circulated between firebrick and water heat exchanger
- Factory fabricated



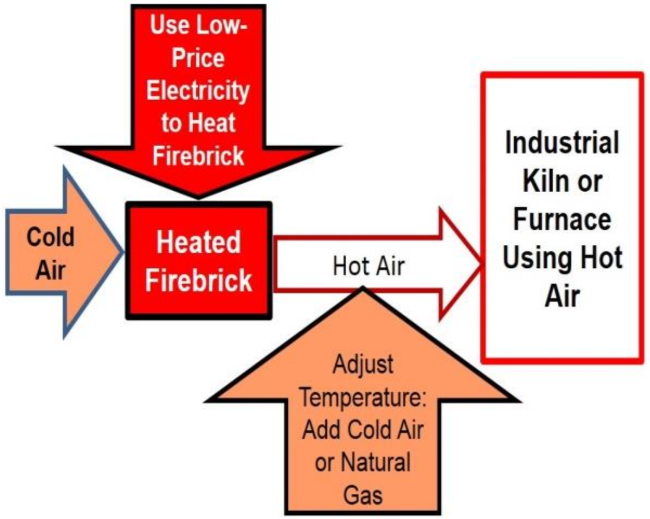
GE/RWE Adiabatic Compressed Air Storage Integration of Firebrick Heat Storage with Gas Turbines (Adele)

- Early development
- Electricity into Storage
  - Compress air to 70 bar and 600° C
  - Cool air by heating firebrick
  - Compressed air to underground storage
- Electricity from Storage
  - Heat compressed air with firebrick
  - Turbine produces electricity

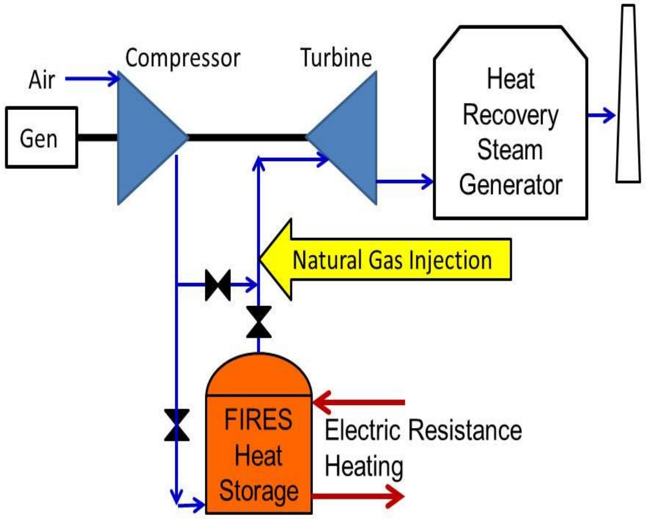


Strategy to Use "Low Value" Electricity for Productive Purposes

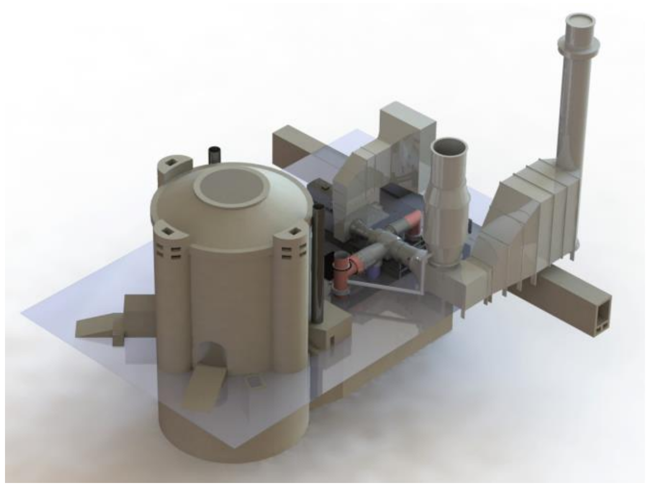
Low-Price Electricity to Industry, Peak Power and Nuclear Plants



Heat for Commerce and Industry



Heat for Electricity



Dispatchable Nuclear Electricity With Base-Load Reactor