Nuclear Heat Uses and Storage

Charles Forsberg

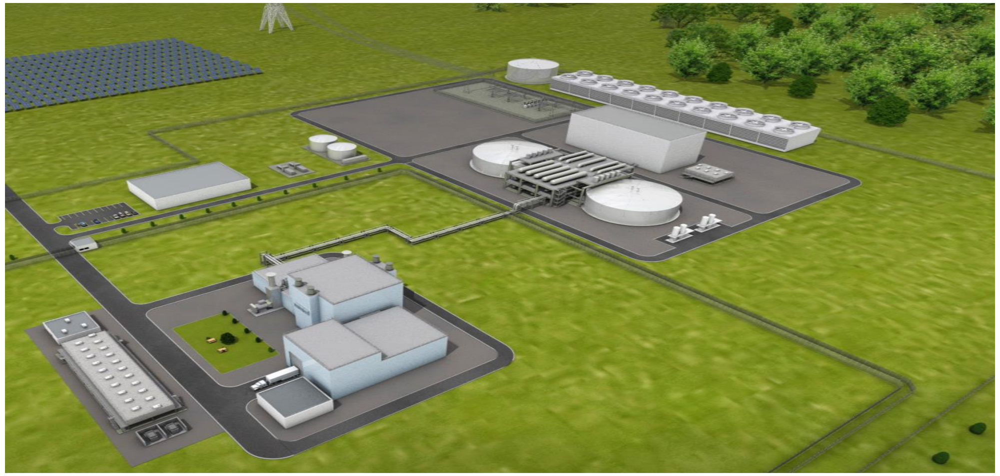
Massachusetts Institute of Technology
Cambridge, MA 02139, cforsber@mit.edu

11 October 2023
11:00 am, Room 4-149

Yogi Berra — It's tough to make **predictions**, especially about the **future**

Next Two U.S. Commercial Nuclear Power Projects

- GE/Terrapower reactors in Wyoming with heat storage for base-load reactor operation and variable electricity to the grid



- Dow Chemical and X-Energy high temperature reactors to provide heat to Dow Seadrift chemical complex in Texas

Neither “Conventional” Nuclear Electric Generating Plant

Outline

- Heat Versus Work
- Nuclear Direct Heat Use
- Future Heat Markets
- Hydrogen
- U.S. Energy Storage Challenge
- Nuclear Air Brayton Combined Cycle
- Conclusions

Heat Versus Work (Thermodynamics)

Heat Generating Technologies

- Fossil Fuels
- Nuclear
- Concentrated Solar Power
- Geothermal

Work (Electricity) Generating Technologies

- Hydro
- Solar PV
- Wind

Thermodynamics of Power Cycles: Work Energy (Electricity) Expensive, Heat Cheap

Multiple Units of Heat → One Unit Electricity

+ Power Plant

1 Unit of Electricity → One Unit of Heat

+ Electric Resistance Heater

Nuclear Reactor Heat a Factor of Three Less Costly than Electricity

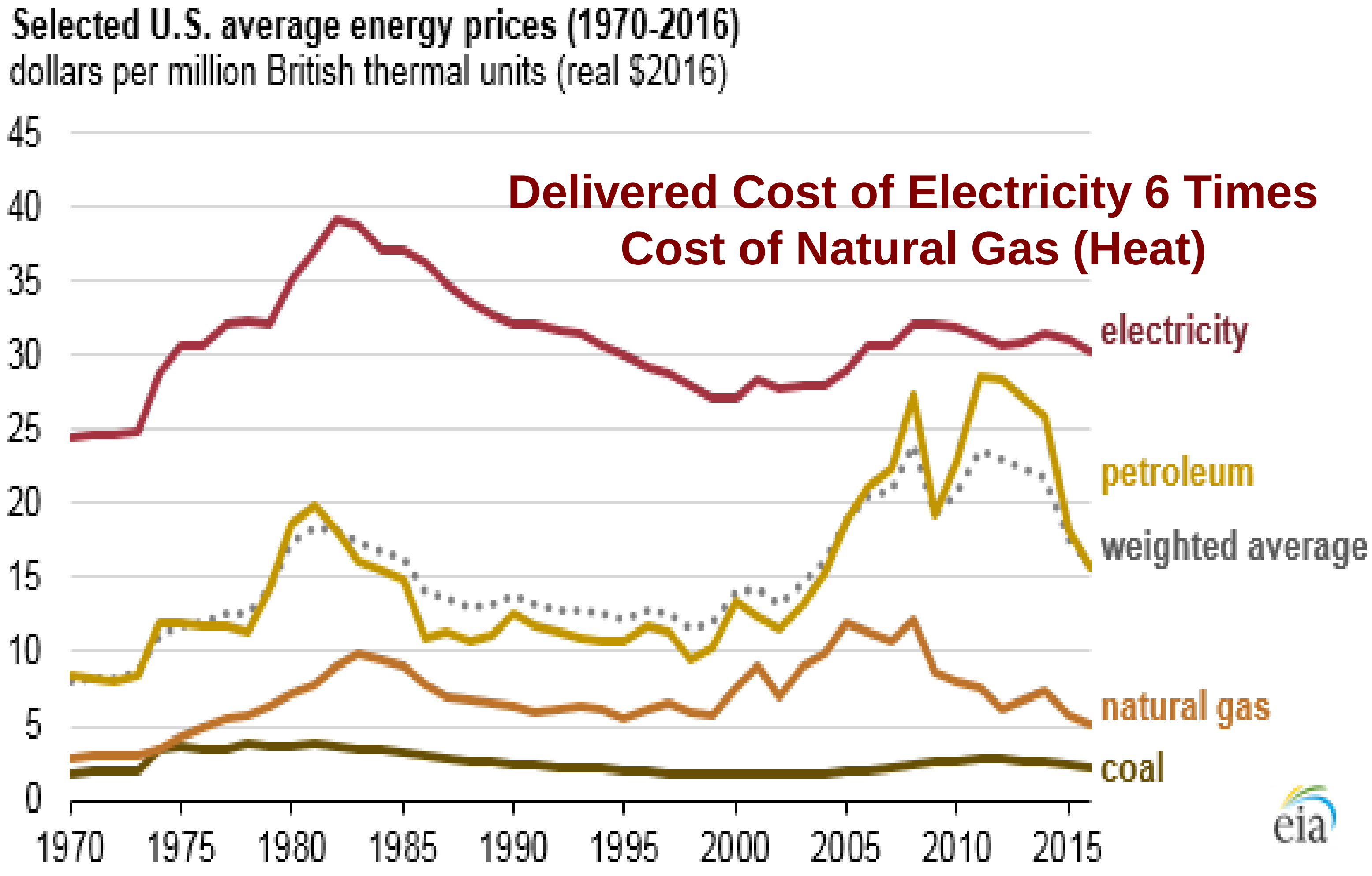
Electricity Can Pump Heat to Higher Temperature; but, Technological and Economic Limits

- Heat pumps such as air conditioners
- Major technological and cost limits if raise temperature more than about 100˚C—not viable for most of the industrial heat market
- Low-capital-cost electric resistance heaters can convert electricity to high-temperature heat
- **Nuclear heat with high-temperature reactors provides heat to ~700˚C**

We Use Heat Because it is Cheap and Storable

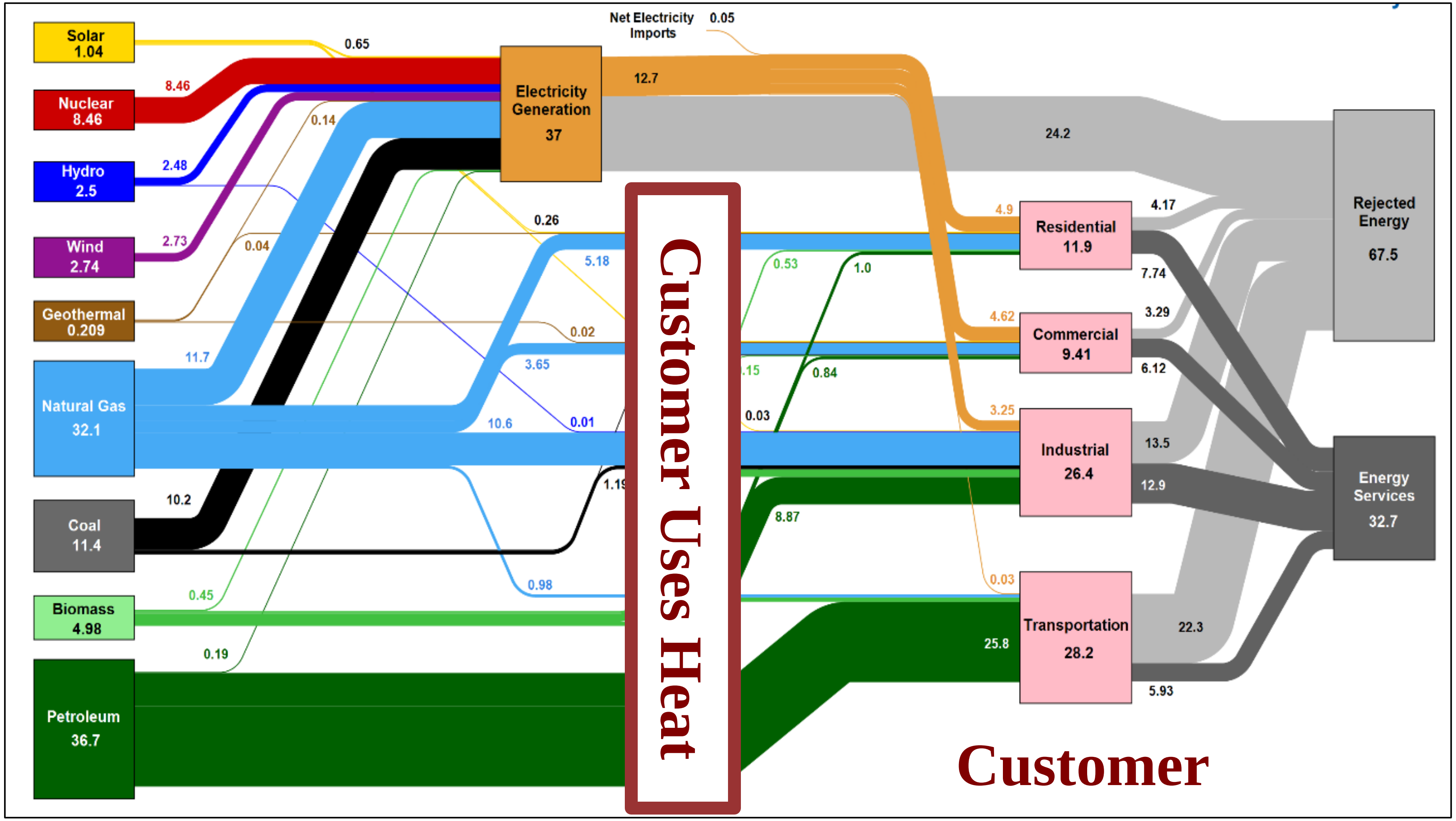
Electricity (Work) Six Times More Expensive than Heat

- Electricity is great except:
  - Expensive to produce
  - Expensive to ship
  - Expensive to store
- Heat is cheap to produce and store; heat storage may replace fossil fuels for energy storage



Fossil Fuels Producing Heat Are Central To The U.S. Economy

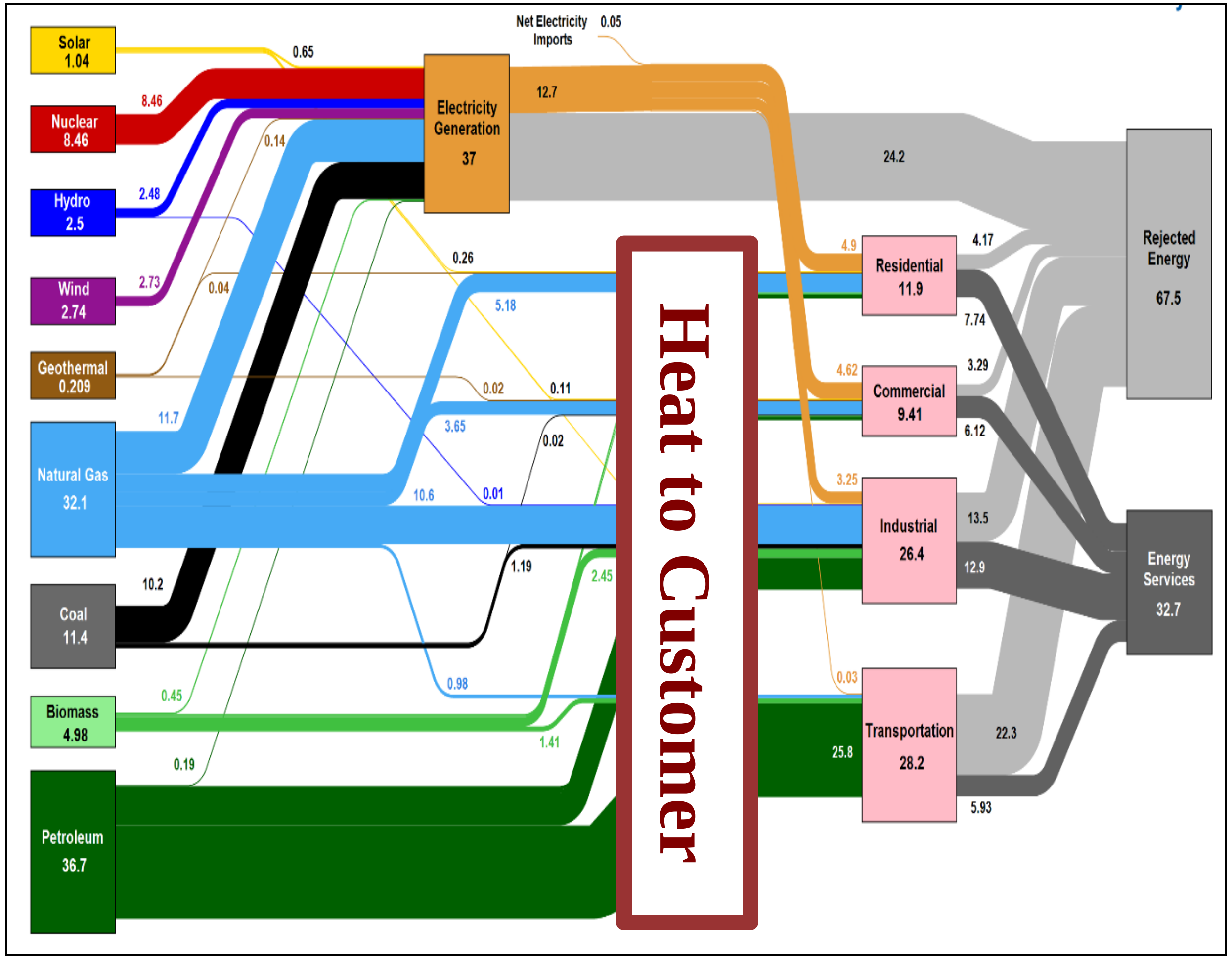
- Oil (dark green), natural gas (blue), and nuclear (red)
- Crude oil: 48% of U.S. energy and feed stocks to the final customer
- Electricity:18% of energy to the final customer; rest is heat



Includes Transportation with Heat Engines

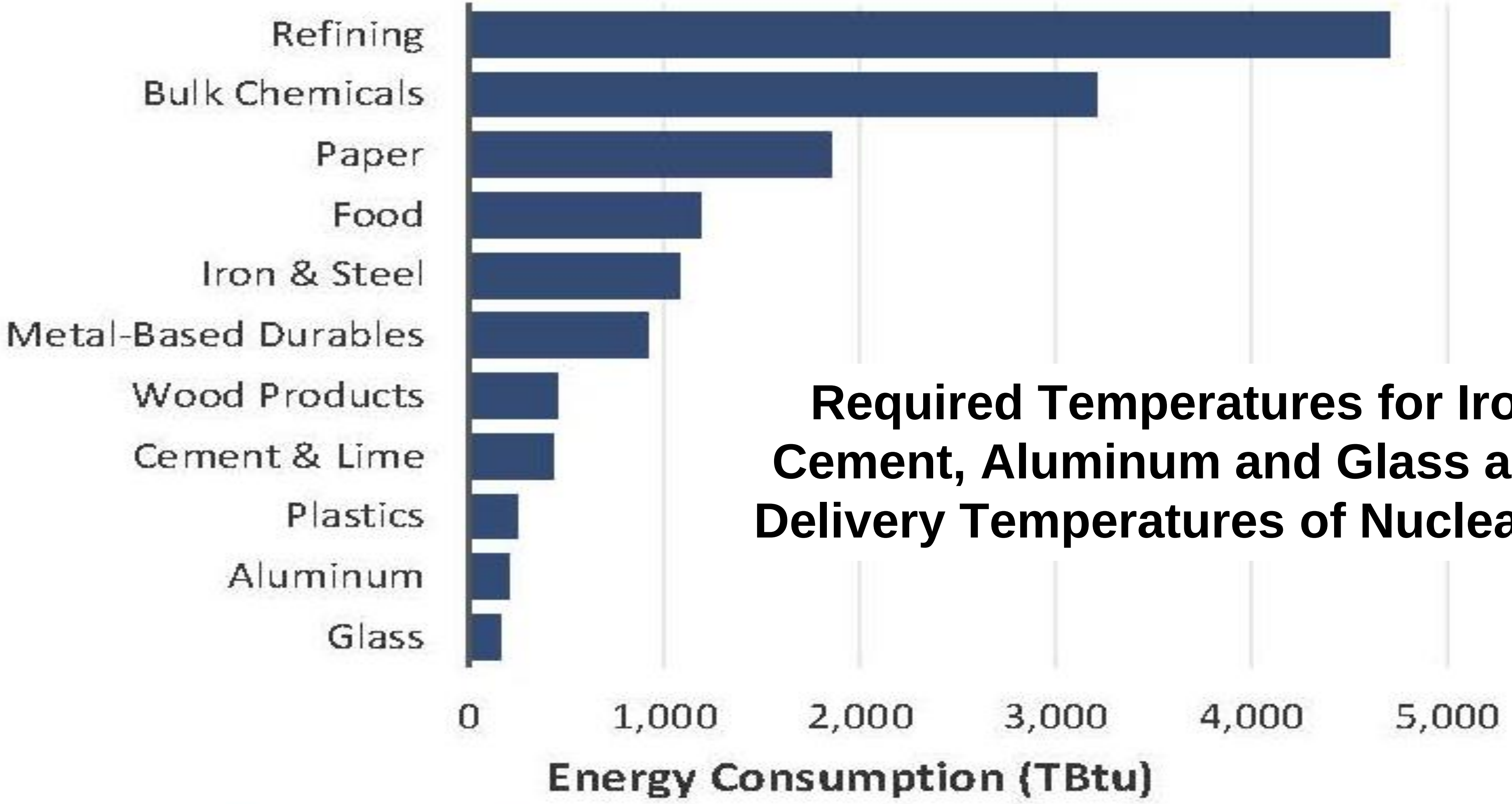
Nuclear Direct Heat Use

Chemical Plants
Liquid Fuels
Hydrogen



Heat: Industry: 23.1 Quad, Transportation: 28.2 Quad

U.S. Industrial Heat Consumption in 2022



Required Temperatures for Iron, Steel, Cement, Aluminum and Glass above Heat Delivery Temperatures of Nuclear Reactors

:: U.S. EIA, Annual Energy Outlook 2023.

Dow Chemical is Buying Four High-Temperature Reactors for Seadrift, Texas Chemical Complex

- Heat for chemical processes: 400 meter evacuation zone
- Reactors designed to deliver process heat—24/7 at constant rate to match chemical plant demand
- 200 MWt per helium-cooled pebble-bed reactor

Dow and X-Energy agreement for nuclear reactors to provide process heat at a Dow Seadrift Texas site

Chemical Plants Have Different Energy Requirements than the Electricity Grid: Steady-State Heat

- Startup times for many chemical plants measured in days—not economically viable to vary heat input with time. Dow buys four reactors to meet demand and for reliability
- Long time perspective, chemical sites operated for a century or more due to supporting infrastructure
- The customer is the chemical company—no external market

Future Heat Markets

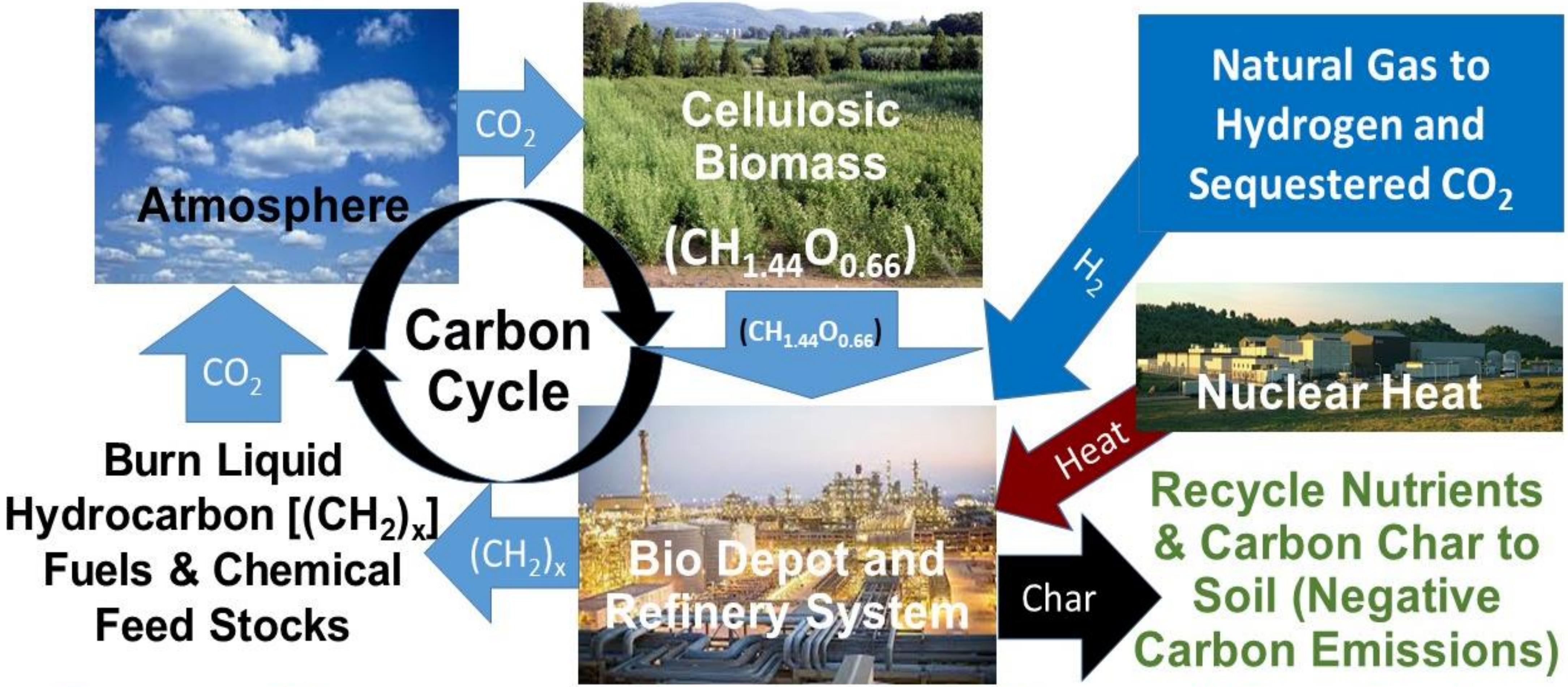
Replacing all Crude Oil with Cellulosic (Corn stover, wood, kelp, etc.) Hydrocarbon Liquids (Gasoline, Diesel, Jet Fuel and Chemical Feed Stocks)

Enable Decarbonize Half U.S. Economy

Largest Potential Heat Market: Refining to Bio-refining

- Can large integrated refineries replace all crude oil with cellulosic feedstocks for drop-in hydrocarbon biofuels? (hydrocarbonprocessing.com

Can Replace All Crude Oil with Cellulosic Hydrocarbon Liquids to Decarbonize Half the Economy



Bio-Oxygen Removed As Water, H_2 to Product, Process Heat

Need to Eliminate Campfire Model of Biofuels Production

Use External Heat and Hydrogen for Conversion Process

Biomass Energy Sources for Conversion Process

Or

(Trade offs between H_2, heat, and biomass)

Reserve Biomass Carbon for Final Products

Increases U.S. Biofuels Potential from 6 to 25 Million Barrels per Day

U.S. Demand Today: 18 $\times 10^6$ B/D, Future Estimates: 10 to 20 $\times 10^6$ B/D

Three Routes to Low-Carbon Hydrocarbon Fuels

Cellulosic Hydrocarbon Biofuels

- Cellulosic is the most common form of biomass: corn stover, trees, kelp, etc.
- Can replace all crude oil with external heat and hydrogen inputs (Minimize feedstock)
- Need two hydrogen atoms per carbon atom to liquid fuels
- **Heat input ~ heat output of existing nuclear fleet**

Traditional Biofuels from vegetable oil, fats, sugars and carbohydrates

- Compete with food; insufficient to replace all crude oil
- Small hydrogen inputs
- Some heat inputs

Electric Fuels made from Carbon Dioxide

- Require 6 hydrogen per carbon
- Expensive hydrogen

Hydrogen Production

Minimum Demand May Exceed 20% of the U.S. Energy Market

Same Scale as Electricity Market

Two Hydrogen Markets: Chemical and Energy

Hydrogen as Chemical Feedstock

- Producing ammonia fertilizer (NH_3) that feeds half the world
- Direct reduction of 2.5 billion tons of iron ore to iron, oxygen leaves as water (replace coal in removing oxygen, 7% CO_2 releases)
- Liquid biofuels—hydrogen to make "hydro"carbons

Hydrogen as an Energy Source (Maybe)

- Replace natural gas, use low-cost underground storage
- Delivery to millions of customers rather than thousands of large industrial facilities
- Lots of competing energy delivery options (electricity, heat, etc.)

Hydrogen Replacing Natural Gas would be Back to the Future, Round Two for Hydrogen

- Original lighting was town gas from coal: mix of carbon monoxide and hydrogen
- In U.S. natural gas replaced town gas in the 1950s. 1970s conversion in the United Kingdom
- Switch to hydrogen would be the second conversion

Low-Carbon Hydrogen Production Options

Low-cost natural gas to hydrogen with sequestration of carbon dioxide underground produces lowest cost H_2

- Methane (CH_4) is a rich hydrogen source: 4 hydrogen per carbon
- Carbon plus oxygen provides energy to break up molecule
- Exxon-Mobil to build billion cubic foot per day hydrogen plant

If no low-cost natural gas, then high-temperature electrolysis (steam plus electricity) of water

- Water poorer hydrogen source: 2 hydrogen per oxygen
- Must input energy to break up water molecule
- Nuclear provides heat (steam) plus electricity

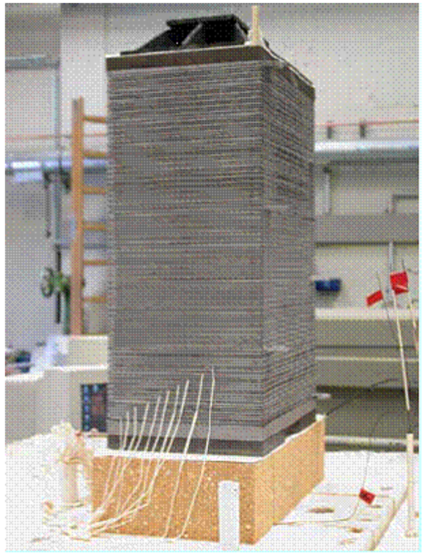
Methane is a "high-assay" hydrogen ore

Characteristics of Electrolysis

- Electrolysis: Electricity + Water yields $2H_2 + O_2$
- High-Temperature Electrolysis
  - Electricity + Steam yields $2H_2 + O_2$
  - Low-cost steam partly replaces more expensive electricity
  - Potentially lower capital costs
- **Early stage of Commercialization**

Pressure electrolyzer (Lurgi System) for hydrogen production, capacity 760 Nm^3/h H_2

Electrolysis

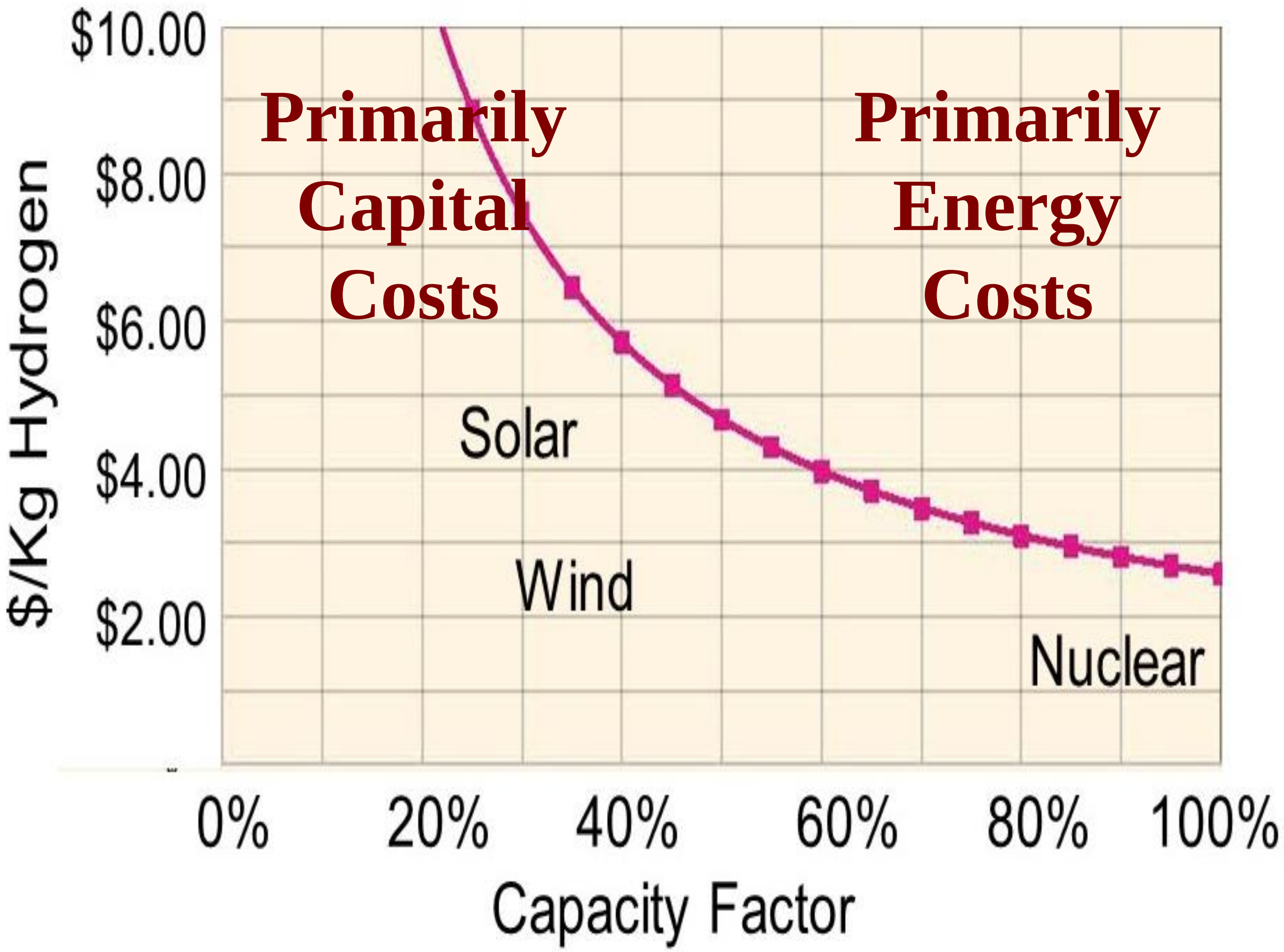


High Temp Electrolysis

Jury Is Out On Long-Term H_2 Production Methods

- Hydrogen today is cheap to store underground so no need for steady-state delivery

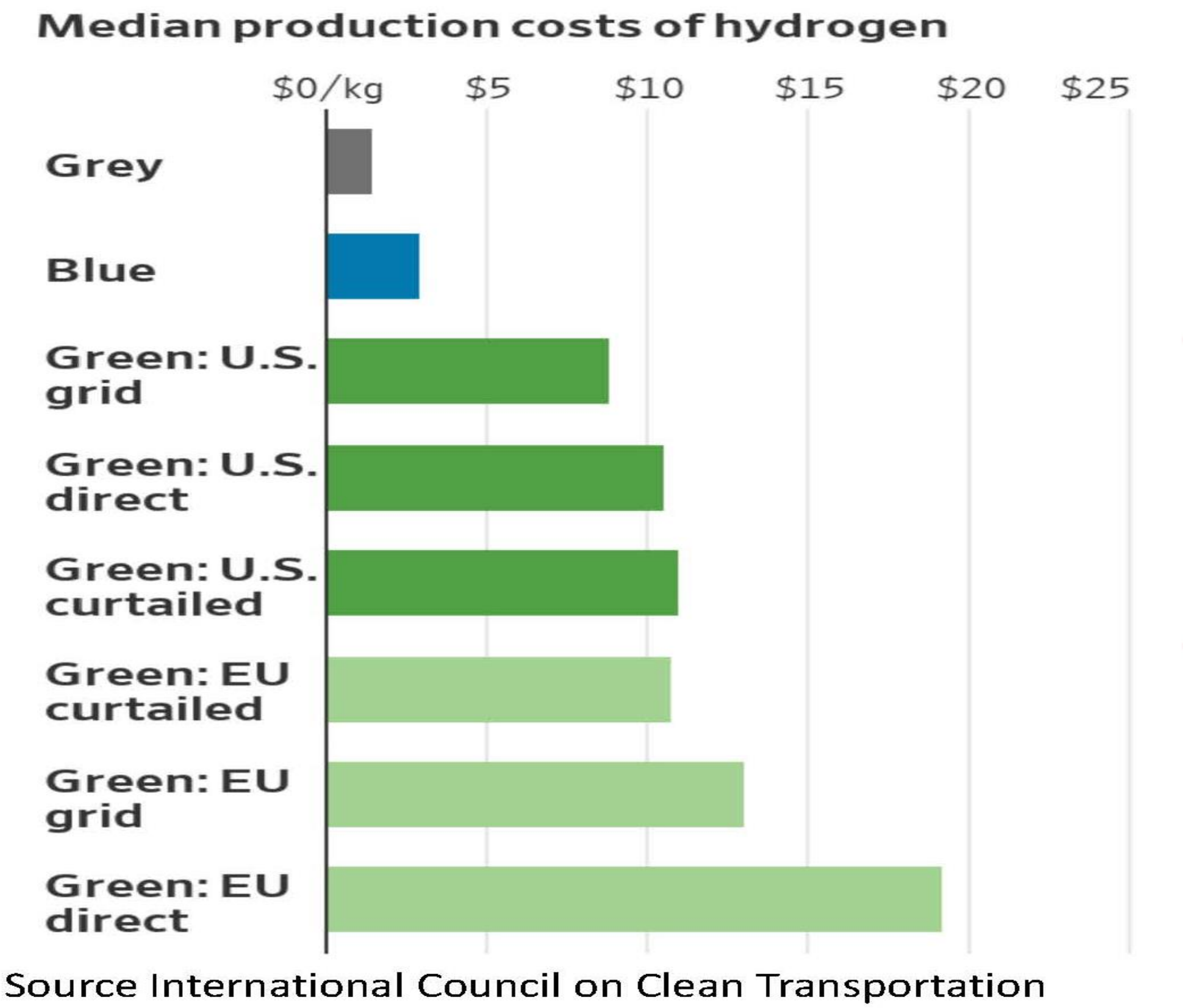
- **Current electricity-to-hydrogen options have high electrolyzer capital costs that drives hydrogen costs if low capacity factors**



Natural Gas to Hydrogen with CCS < $2/kg

Hydrogen from Natural Gas with CCS is Tough to Beat

- Gray hydrogen today from natural gas
- Blue hydrogen (natural gas plus CCS) will likely be the lowest cost option as long as cheap natural gas
- Wind/Solar electricity not competitive even if zero-price electricity—low capacity factor for electrolyzer



Hydrogen Pipeline Capability Enables Radically Different Large-Scale Nuclear Hydrogen Production Systems

- **Pipelines move 10s of gigawatts versus gigawatt electric lines**
- Enables very large (oil refinery size) chemical / hydrogen production
- Build reactor manufacturing plant and then reactors over the next 20 years in series

Steam and Electricity to H_2 and O_2

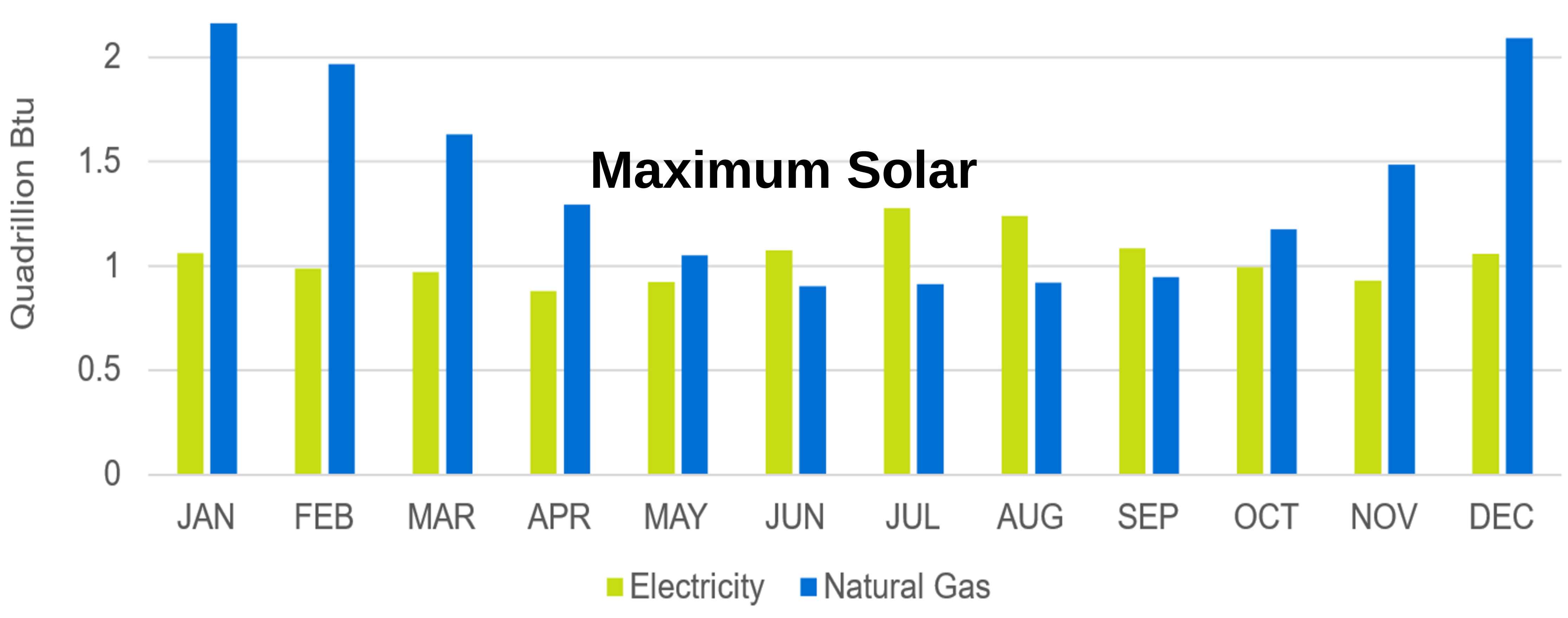
· LucidCatalyst, *Missing Link to a Livable Climate: How Hydrogen-Enabled Synthetic Fuels Can Help Deliver the Paris Goals*, 2020. https://www.lucidcatalyst.com/hydrogen-report

U.S. Energy Storage Challenge

Natural Gas is the Seasonal Swing Fuel

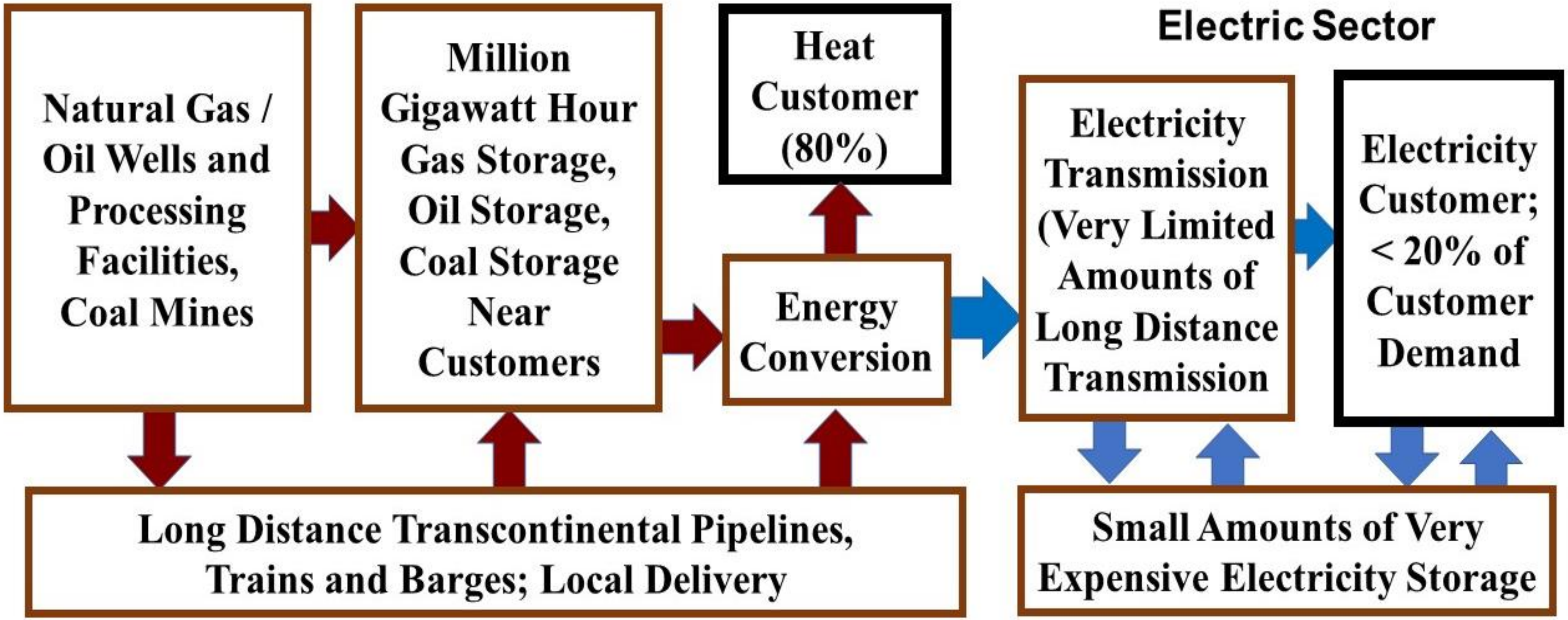
2020 U.S. Electric and Natural Gas Consumption

Winter: Minimum Solar and Wind Decreases with Temperature



American Gas Association, 2021. Net Zero Emissions Opportunities for Gas Utilities.
https://www.aga.org/globalassets/research--insights/reports/aga-net-zero-emissions-opportunities-for-gas-utilities.pdf

Existing Fossil Energy Delivery System: Transport and Storage (Millions of Gigawatt Hours)



Energy Conversion: Power Plant, Car Engine, Home Furnace

Fossil Fuels are Used Today to Store Energy to Meet Variable Demand at Million Gigawatt-Hour Scale

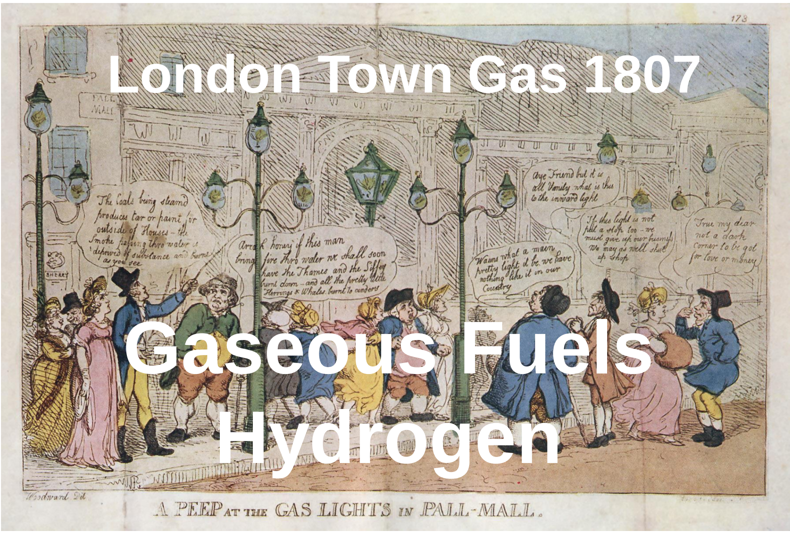
The Scale of the Problem to Be Solved

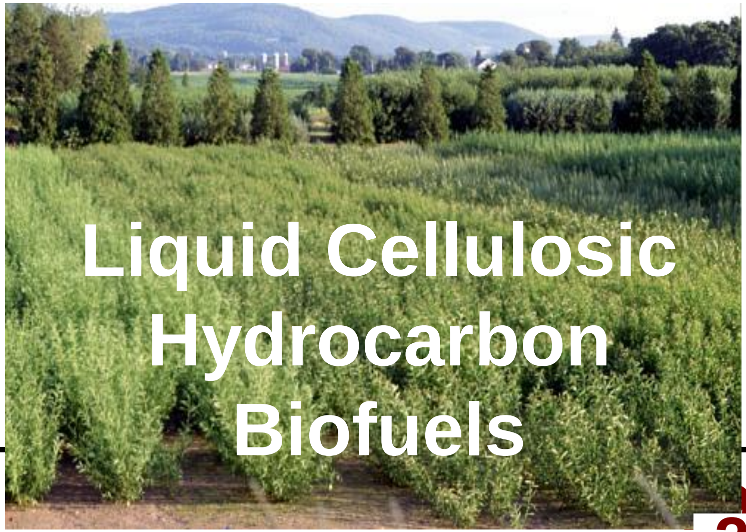
- U.S.: Six weeks storage: 3.4 million gigawatt hours
- Storage forms
  - – Oil: 90 days
  - – Natural gas: 35 days
  - – Coal: 100 days
  - – Nuclear fuel in reactor: 9 months
  - – Everything else round-off error

C. Forsberg, "Addressing the Low-Carbon Million Gigawatt-Hour Energy Storage Challenge", *The Electricity Journal*, December 2021. https://doi.org/10.1016/j.tej.2021.107042

Four Options to Replace the Fossil-Fuel Storage Function at the Million-Gigawatt Hour Scale

- Storage matches energy production with demand
- Must address hourly to seasonal energy storage
- Dependence on weather and climate (PV and Solar) may increase storage

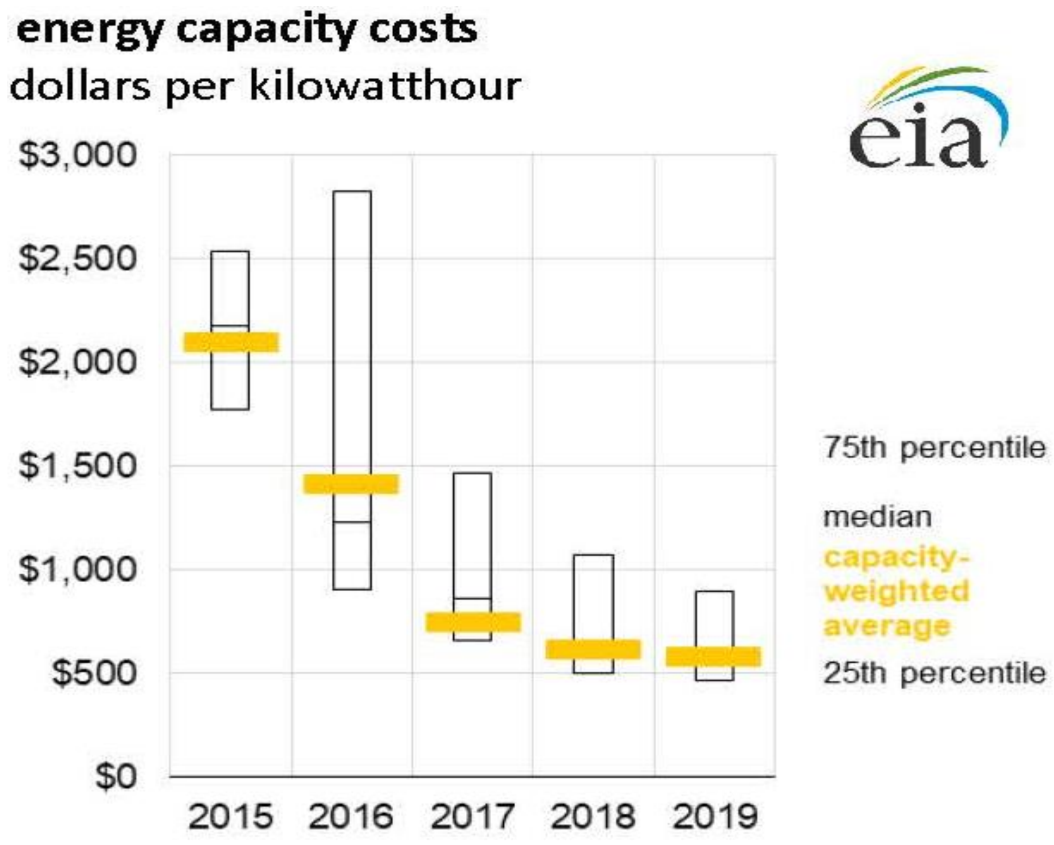




Batteries Are Not a Solution for Hourly to Seasonal Million-Gigawatt-Hour Energy Storage Challenge

- Battery system capital cost leveling off at $500/kWh(e) because made of less-abundant elements
- Only change if new chemistry
- Relative costs
  - Cost solar: $31.30/MWh
  - Cost onshore wind: $31.45/MWh
  - Cost offshore wind: $115.04/MWh
  - Cost storage (daily): $121.86/MWh

C. Forsberg, "Addressing the Low-Carbon Million Gigawatt-Hour Energy Storage Challenge", *The Electricity Journal,* 34 (10) 107042, December 2021. https://doi.org/10.1016/j.tej.2021.107042

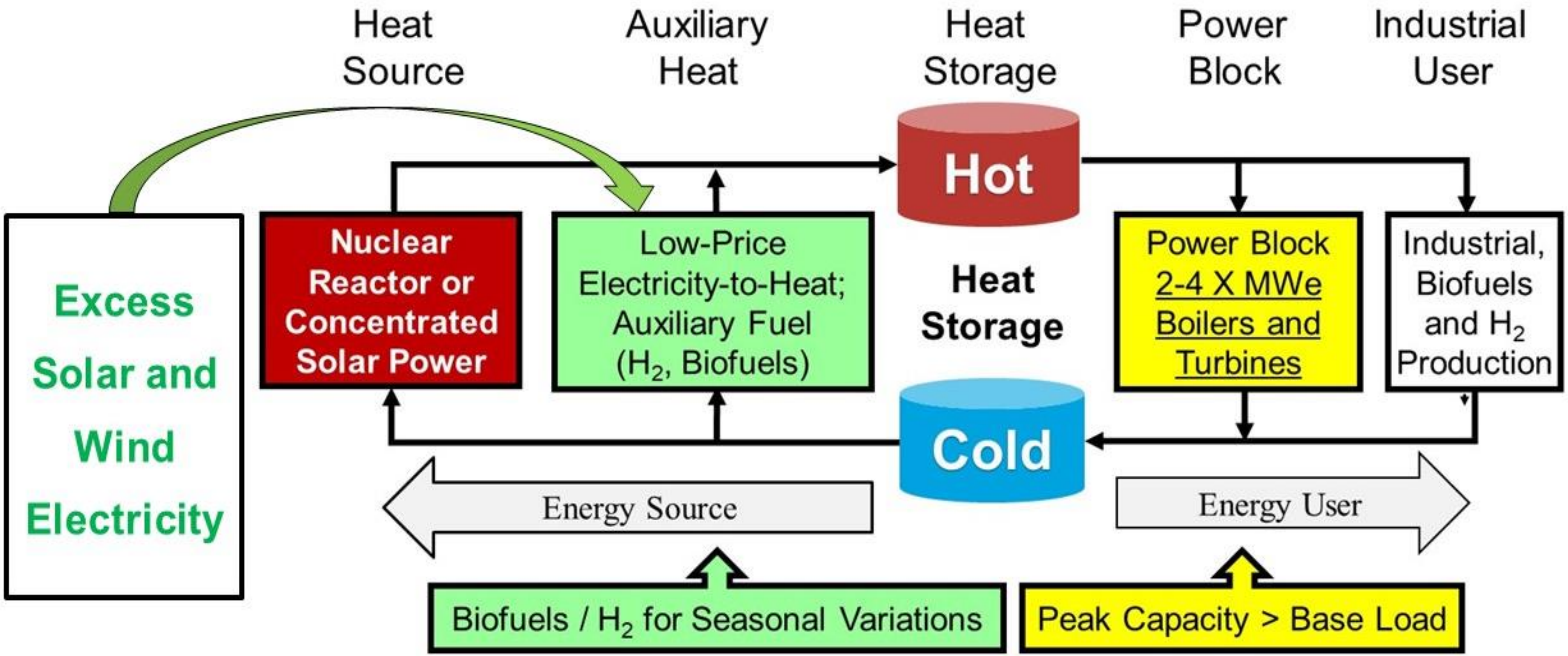


U.S. Energy Information Agency, August 2021. *Battery Storage in the United States: an Update on Market Trends*

Nuclear with Stored Heat for Dispatchable Electricity

Same Systems for Concentrated Solar Power and Geothermal that also Produce Heat

System Design for Nuclear or CSP with Heat Storage



Two Tank System with Salt or Oil

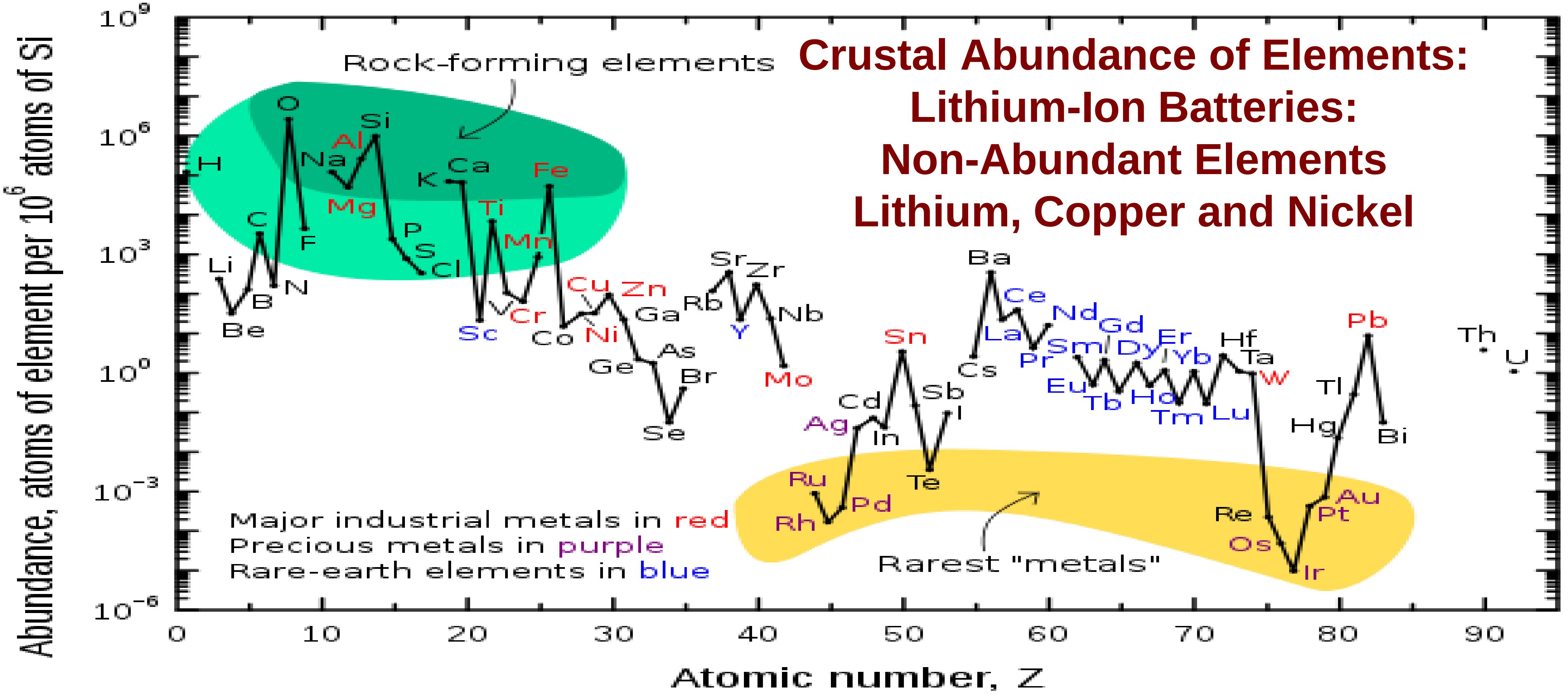
Hot-and-Cold Nitrate-Salt Thermal-Energy Storage Used at Concentrated Solar Power (CSP) Plants

Two-Tank Molten salt thermal energy storage

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

Solar System Heats Cold Nitrate Salt and Puts in Hot Storage Tank

Cheap Storage Starts with Cheap Materials

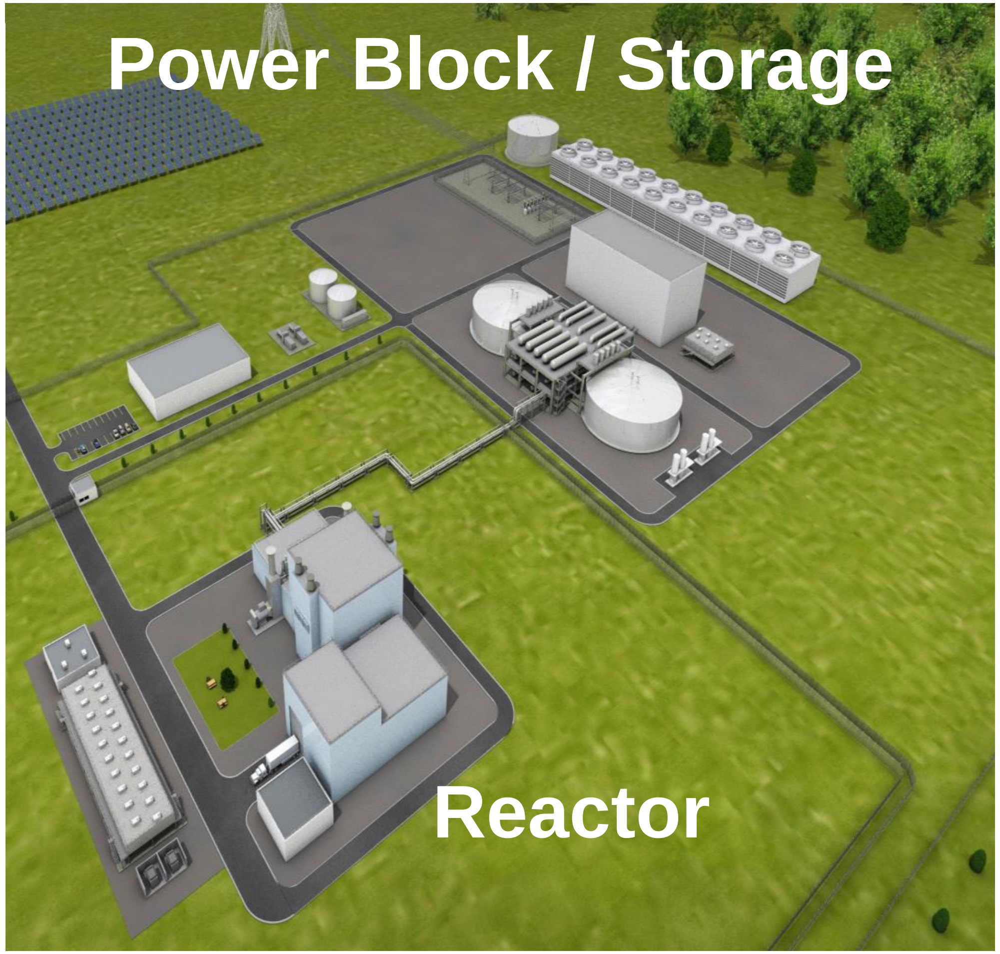


Heat Storage Is Low Cost Because Use Earth-Abundant Low-Cost Materials in Different Forms

- Major forms of heat storage
  - Sensible (heat material by increasing temperature)
  - Latent heat (phase change such as melting)
  - Chemical bonds
- Examples
  - Nitrate salt (liquid)
  - Crushed rock
  - Concrete
  - Iron
- **Its all about cheap materials**

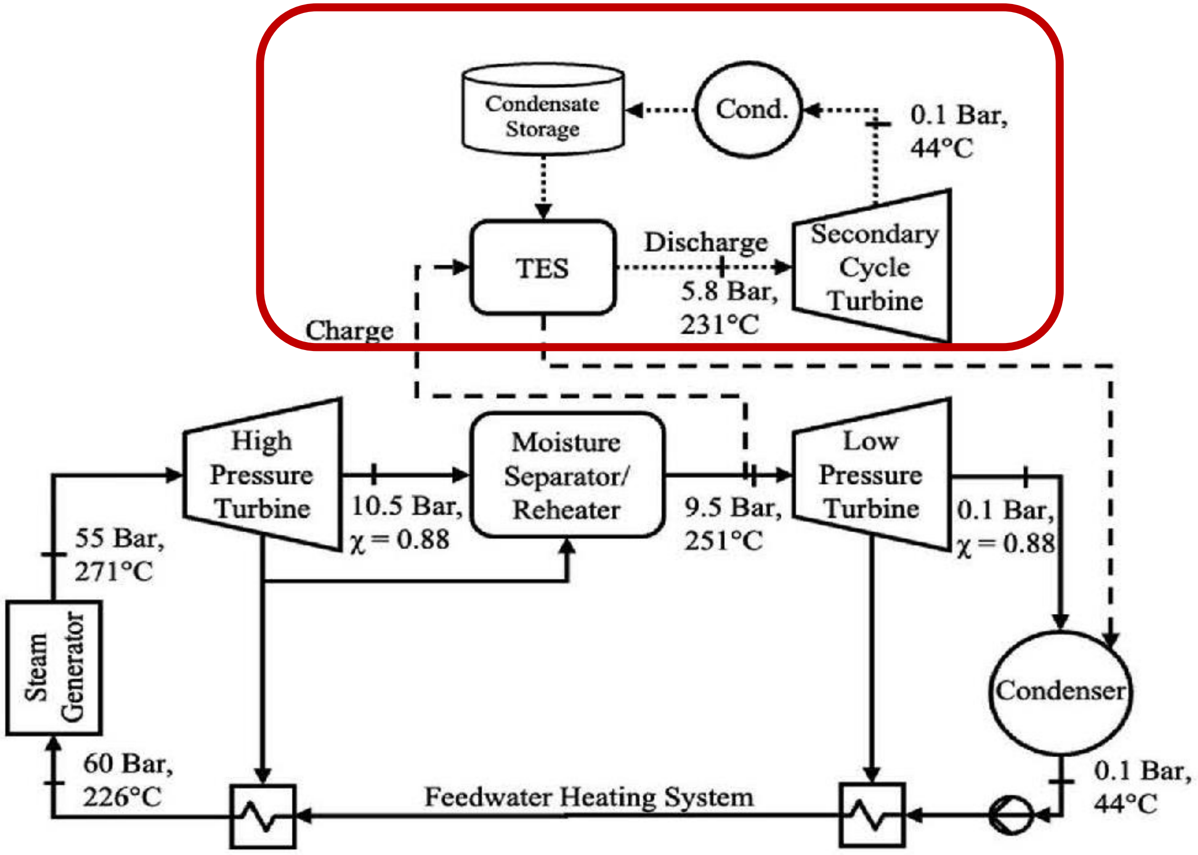
GE / TerraPower Natrium Reactors to Use Nitrate Salt Heat Storage by 2030 in Wyoming

- Sodium-cooled reactor transfers heat to nitrate salt system
- Base-load reactor operation with variable electricity to grid
- Nuclear island regulated by Nuclear Regulatory Commission
- Heat storage and power block commercial non-nuclear standards
- Goal: boost revenue and decrease capital cost with smaller nuclear island



Many Different Ways Being Developed to Include Heat Storage in Light-Water Reactor Power Cycles

- Concepts coupled to reactor or part of power cycle
- Example on left: Part of power cycle (Red Box)
  - Steam extracted after high pressure turbine to heat storage
  - Heat storage to separate power peaking cycle to minimize impacts on existing reactor systems



F. Carlson and J. H. Davidson, "Nuclear Power Coupled with Thermal Energy Storage: Impact of Technical Performance on Economics in an Exemplary Electricity Grid," *ASME Open Journal of Engineering*, Vol. 1, 011006-1, 2022. DOI: 10.1115/1.4053419.

Hot Oil Heat Storage: Lower-Temperature Systems

- Heat-transfer oils are stable to ~400°C
- Demonstrated use of hot oils for heat storage in power systems →
- Solid heat storage materials (concrete, crushed rock, etc.) are cheaper than oil; thus, systems being developed where use oil only for heat transfer

Courtesy of Nevada Solar One

Thermocline Systems:

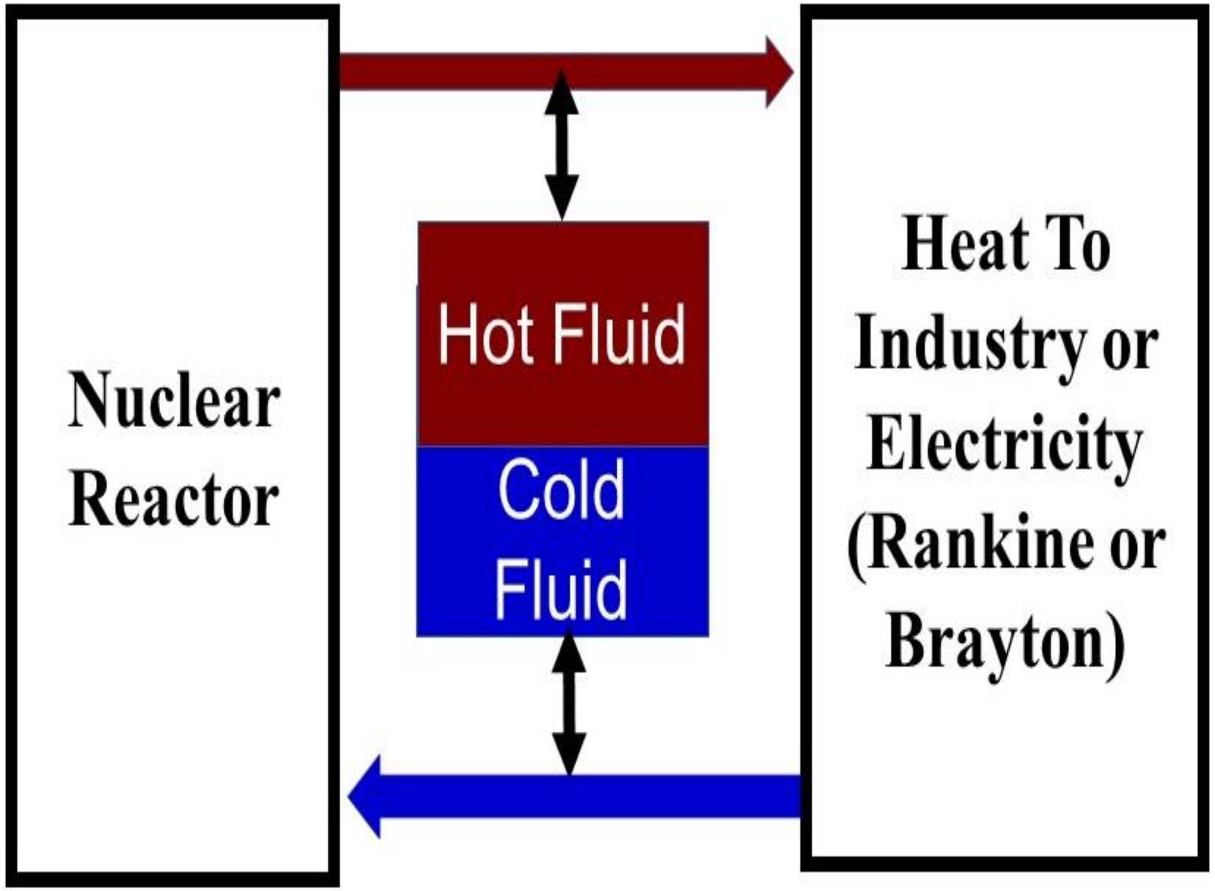
Hot Fluid on Top of Cold Fluid

Second Generation Heat Storage System

Single Tank or Tanks in Series
(First-Generation two-tank system
only half of tank volume filled with Fluid)

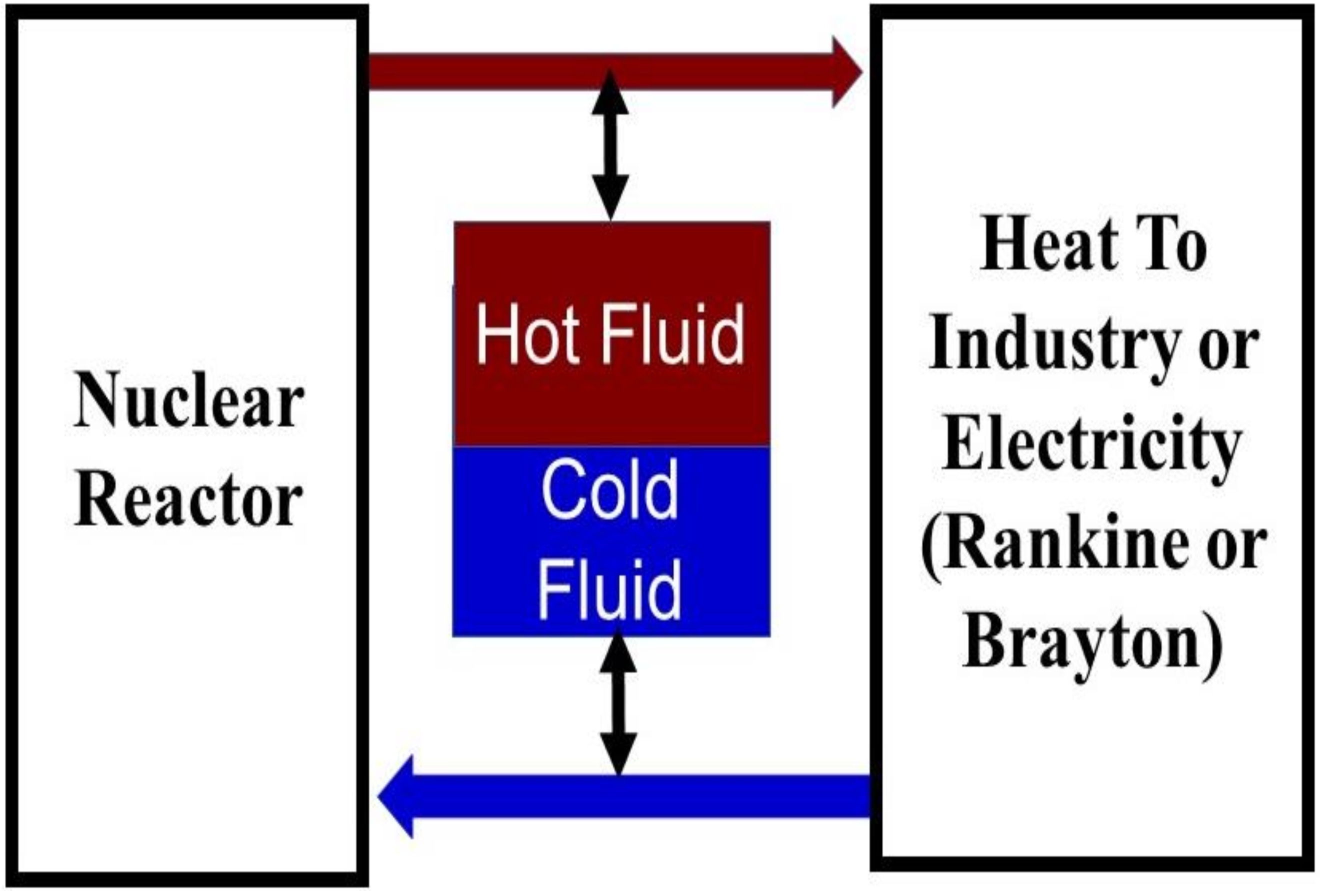
Thermocline Systems: One Full Storage Tank with Hot Fluid on Top of Cold Fluid with Variable Heat to Power Cycle

- Heating: Hot fluid from reactor to power cycle and/or thermocline heat storage
- Cold fluid from power cycle to reactor and/or bottom of thermocline heat storage
- Lower cost with single tank always full of fluid



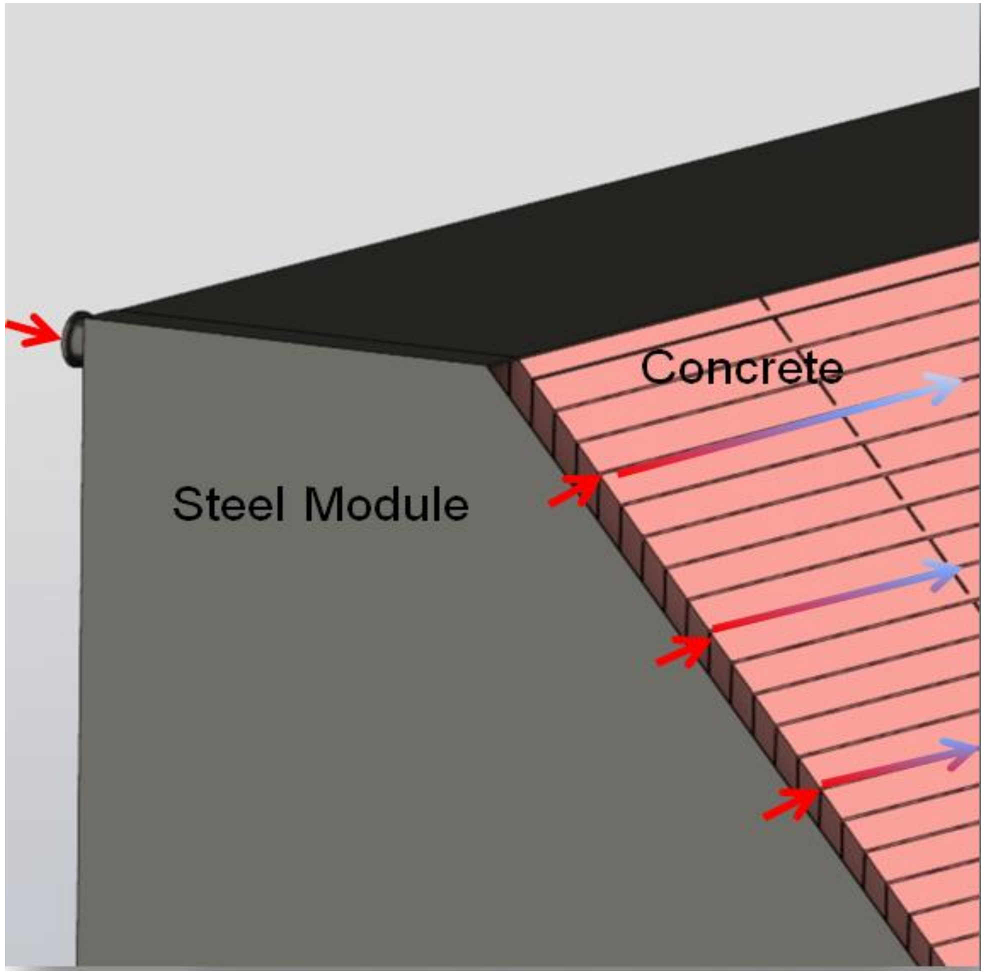
Thermocline Systems Enable Filling Tanks with Low-Cost Fill Material—Cheaper than Fluid

- 60 to 90+% fill material
- Fill materials
  - Crushed rock
  - Concrete
  - Iron
  - Phase-change materials in sealed containers
    - Aluminum
    - Many other chemicals

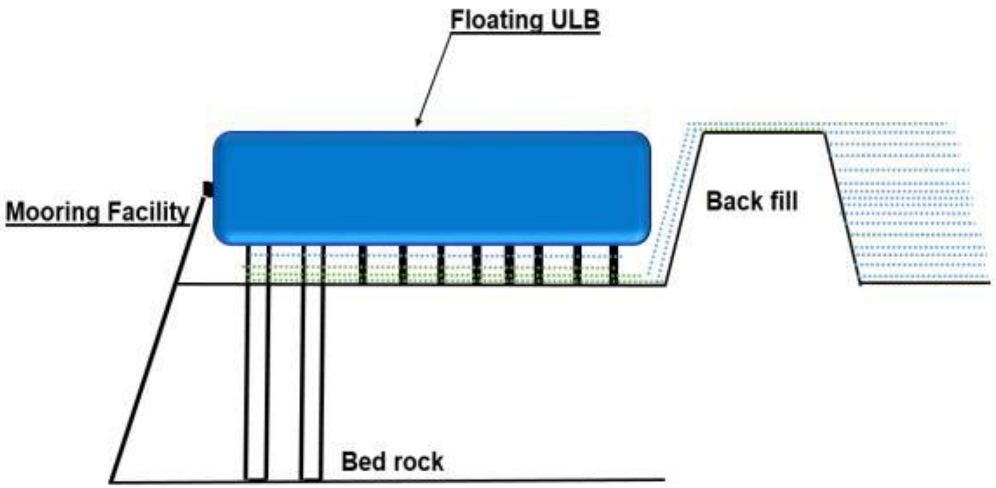


Westinghouse Developing Concrete Heat Storage with Organic Heat Transfer Fluid for LWRs

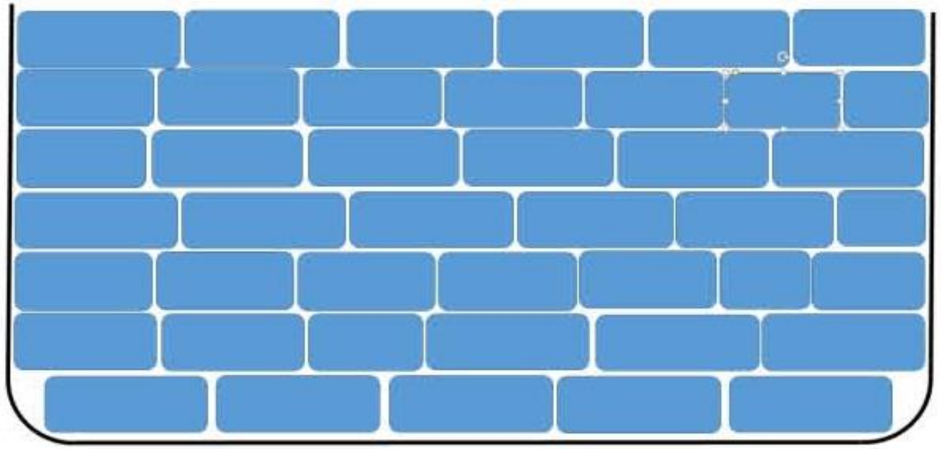
- Low pressure system
- Tanks are the size of shipping containers
- Using thin concrete plates with narrow gaps creates huge surface area relative to volume and minimizes oil fraction



LWR Heat Storage Using Crushed Rock and Hot Oil



- Hot oil for heat transfer between heat storage system and steam cycle. Option to drain oil after heating or cooling rock to minimize fluid inventory
- Hot oil/crushed rock heat storage system
  - Large barge (60 by 450m) with multiple tanks for 20 GWh(e) heat storage (Korean design)
  -



Crushed Rock Ultra-Large Stored Heat (CRUSH) System

Hourly to Seasonal Storage
Eliminate Tanks and Minimize Heat Transfer Fluid

Third Generation Heat Storage System
Technical Readiness Level 3

Two-Tank Salt Systems are Too Expensive for Long Duration Storage: Half the Cost in Salt & Half in Tanks

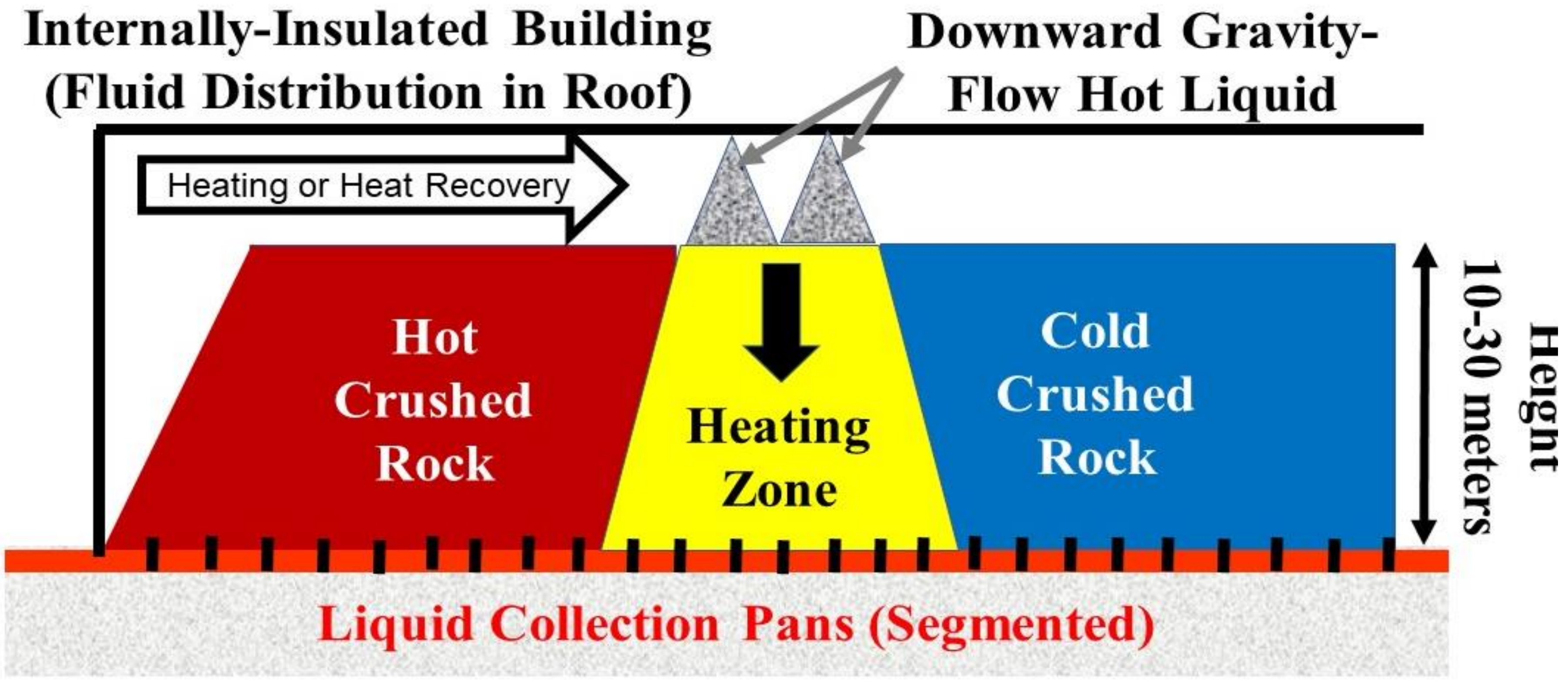
- **Estimated capital costs: $20-25/kWh heat storage**
- **If want to dramatically reduce cost must:**
  - Eliminate most of the salt
  - Eliminate expensive stainless steel tanks that contain hot liquid salt

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

Lower-temperature Oil-Based CSP Systems Use Nitrate Salt Storage Because High-Cost of Oil

Basis for CRUSH Low-Cost Heat Storage

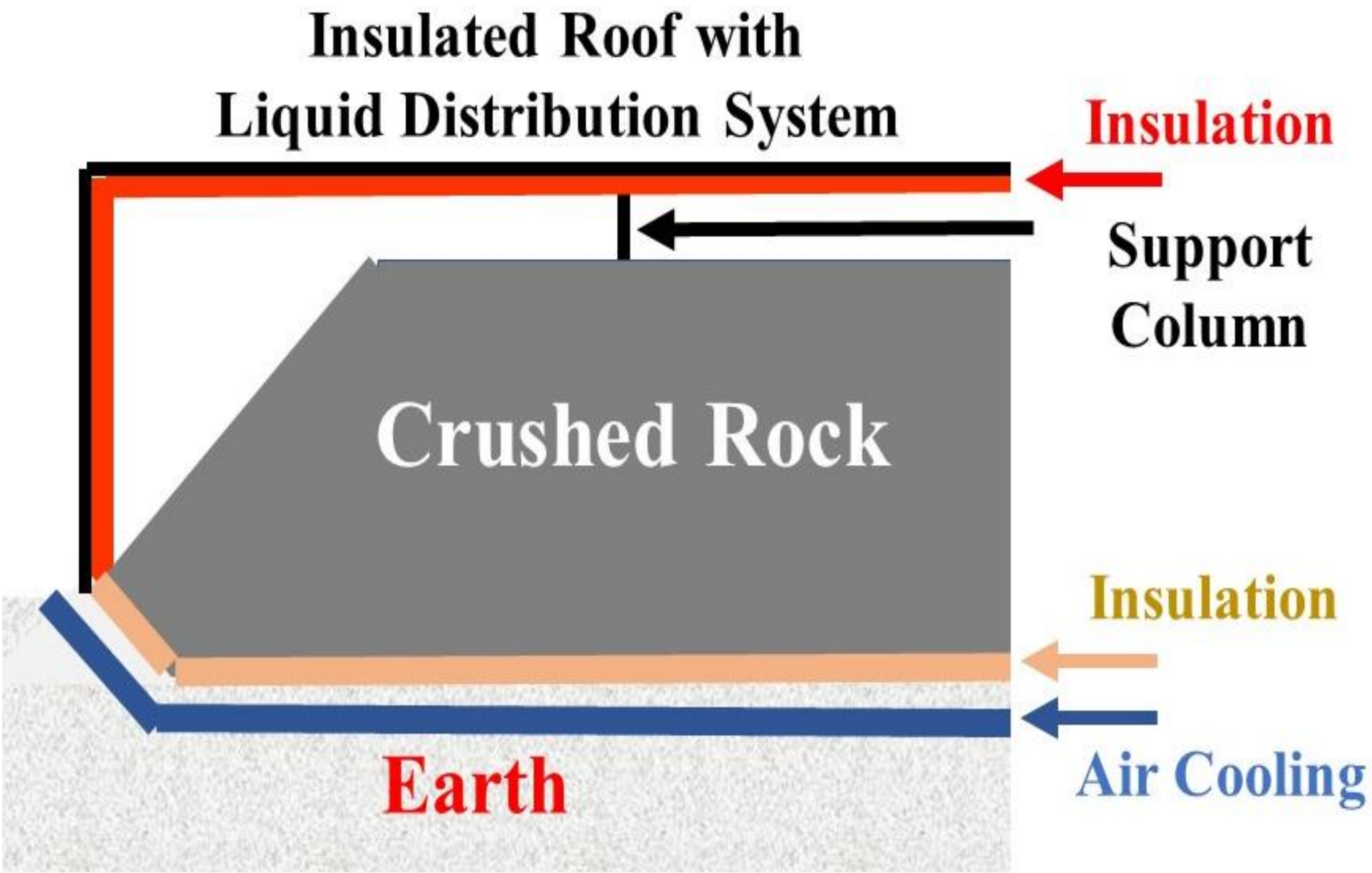
- Crushed Rock is Used for Sensible Heat Storage
- Heat-Transfer Oil or Nitrate Salt for Heat Transfer, <u>Not Heat Storage</u>
- Low-Cost Insulated Building Contains Crushed Rock—No Tanks



Caveat: TRL=3

Sensible Heat Storage in Crushed Rock: The Lowest-Cost Heat-Storage Material

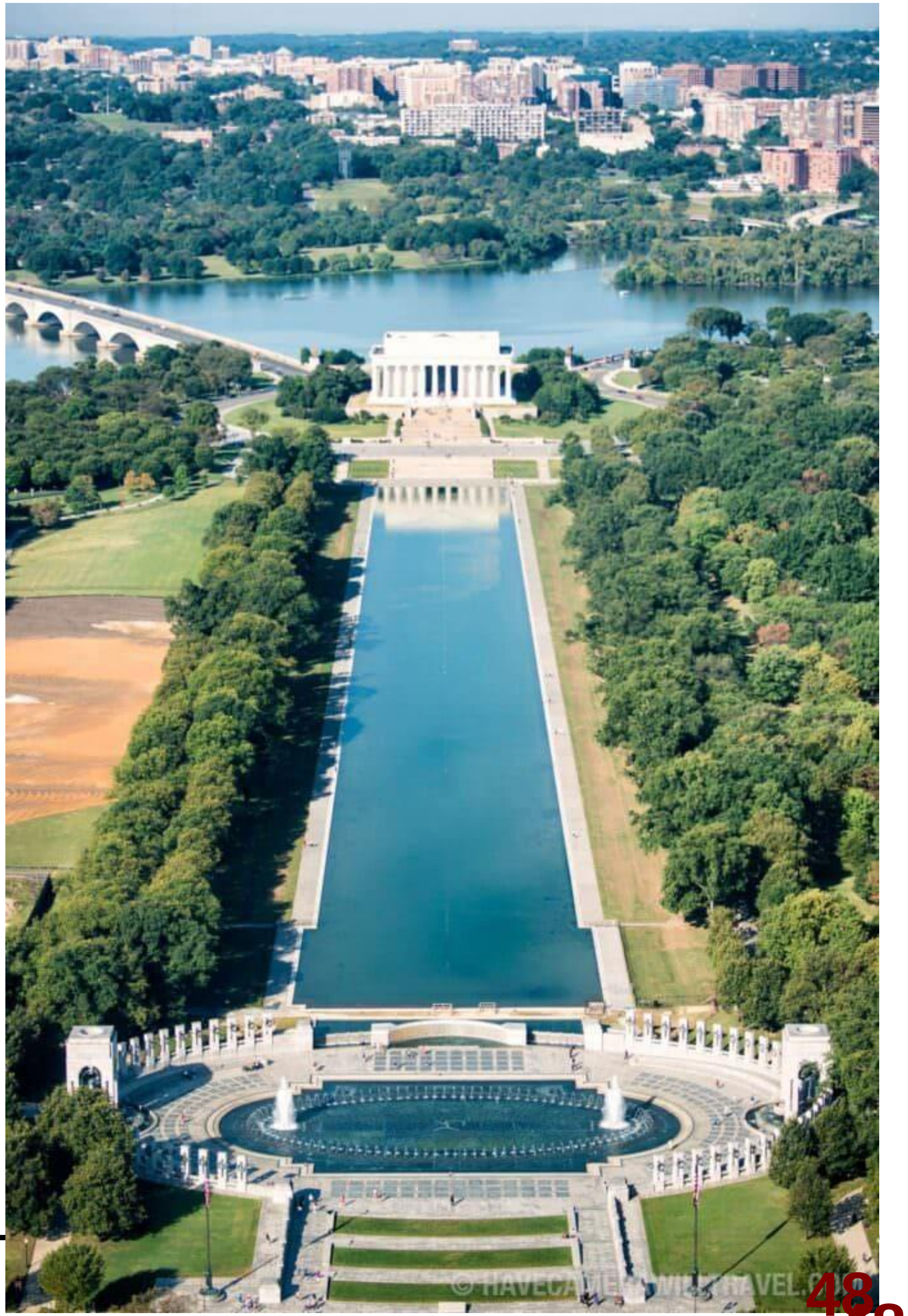
- Free-standing crushed rock pile 10 to 40 m high
- No horizontal forces against walls (Unlike tanks with liquids)
- Crushed rock capital costs: ~$0.10/kWh(t)



J. C. Willett, 2018, Minerals Yearbook, Stone, Crushed, USGS

Crushed Rock Heat Storage Is a Low-Cost But Physically Large System

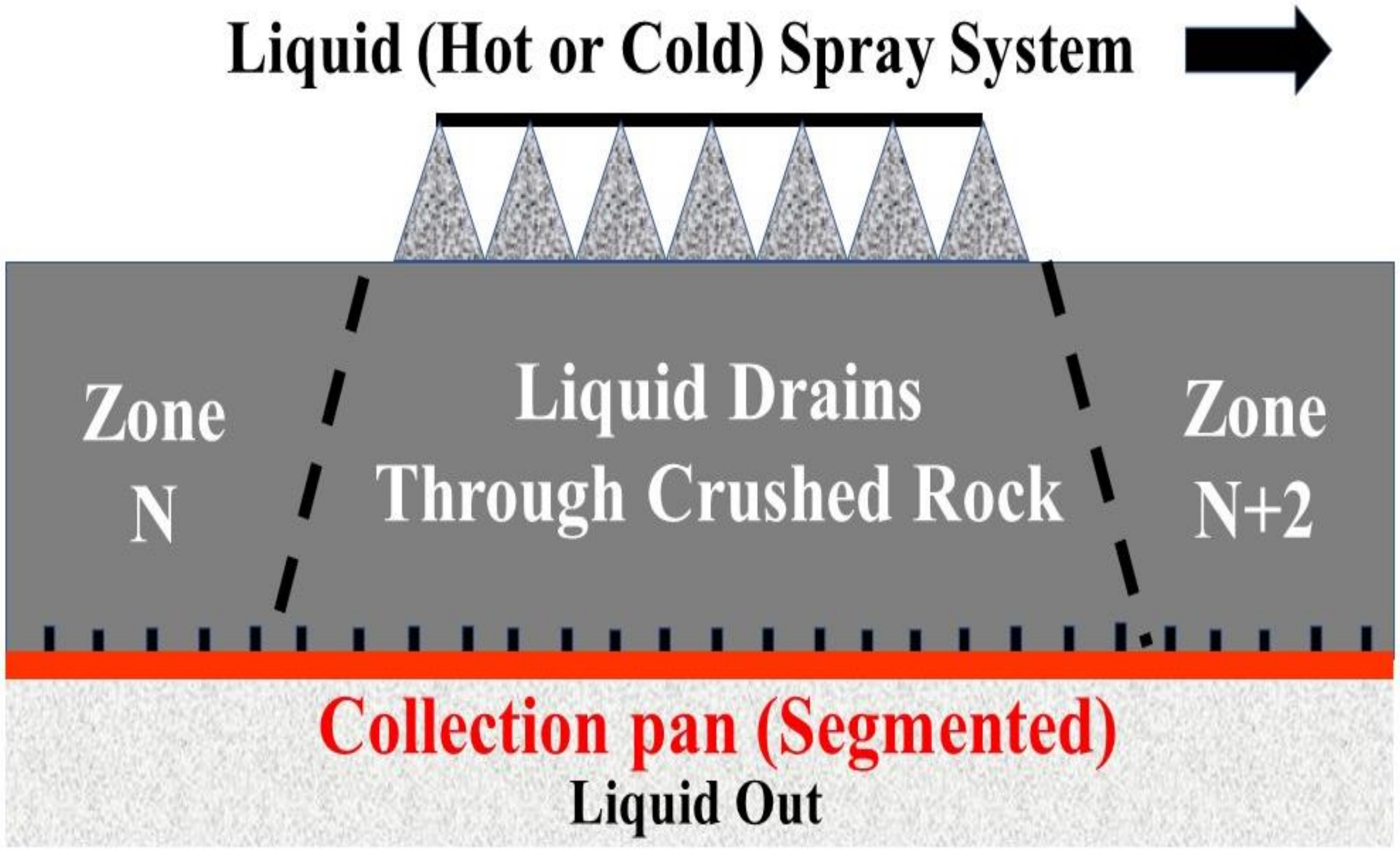
- Incremental capital cost goal is $2-4/ kWh of heat
- Lincoln Memorial Reflecting Pool in Washington D.C. is 51 meters by 618 meters
- ~60 GWh of heat storage



48

Transfer Heat Into and Out of Crushed-Rock with Heat-Transfer Oil (<400˚C) or Nitrate Salt

- Spray hot or cold fluid over rock with gravity flow. Trickles to collection pans at bottom
- Minimize heat transfer fluid inventory and cost, liquid moves heat, not heat storage

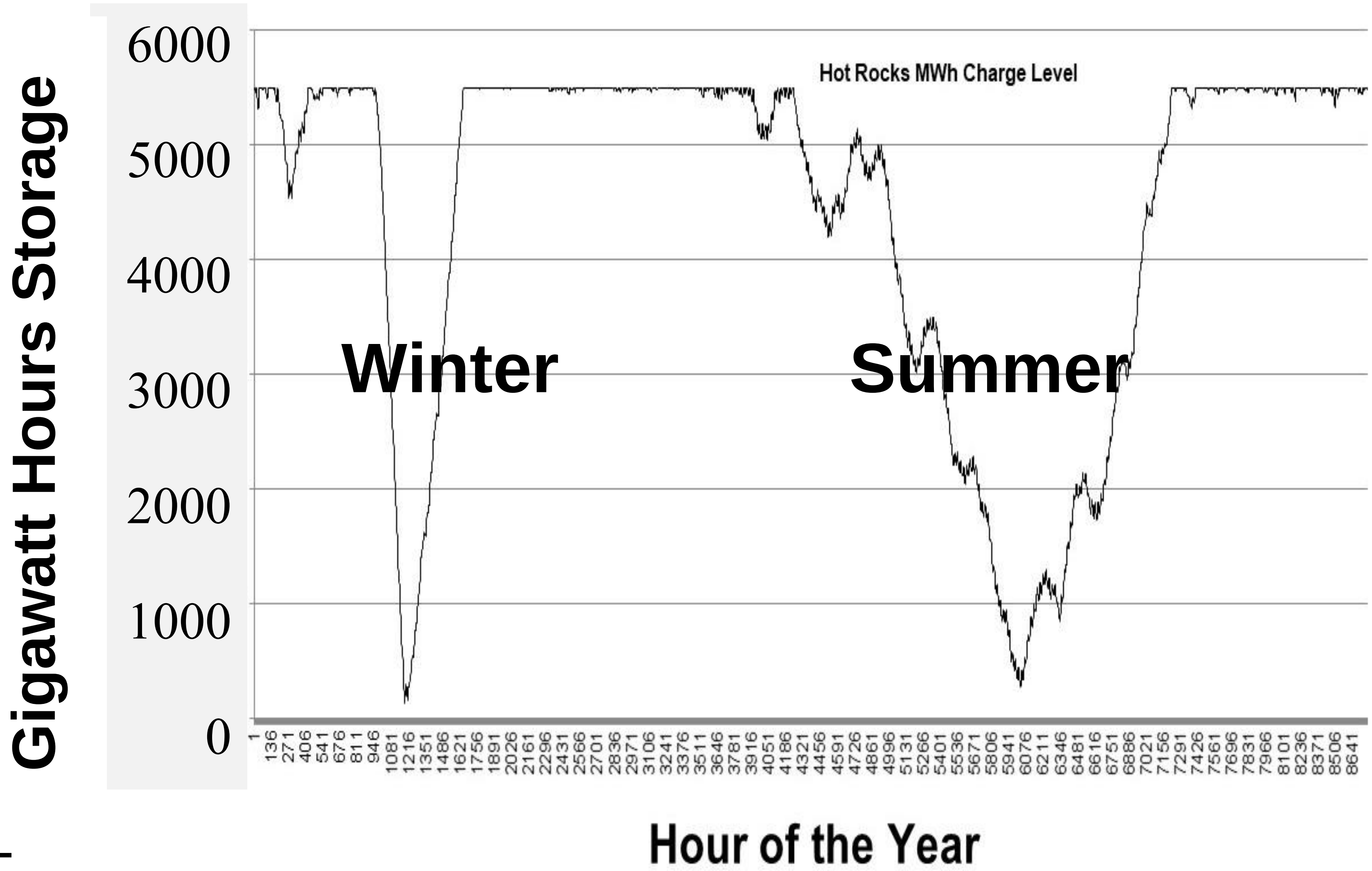


-

Similar to Heap Pile Leaching of Copper Ores

Nuclear Plus Low-Cost Storage Duplicates the Characteristics of Natural Gas Storage and Gas Turbine

- Continuous nuclear heat (natural gas) inputs
- Small daily variations of stored energy to power conversion system



Nuclear Air Brayton Combined Cycle (NACC) With Thermodynamic Topping Cycle

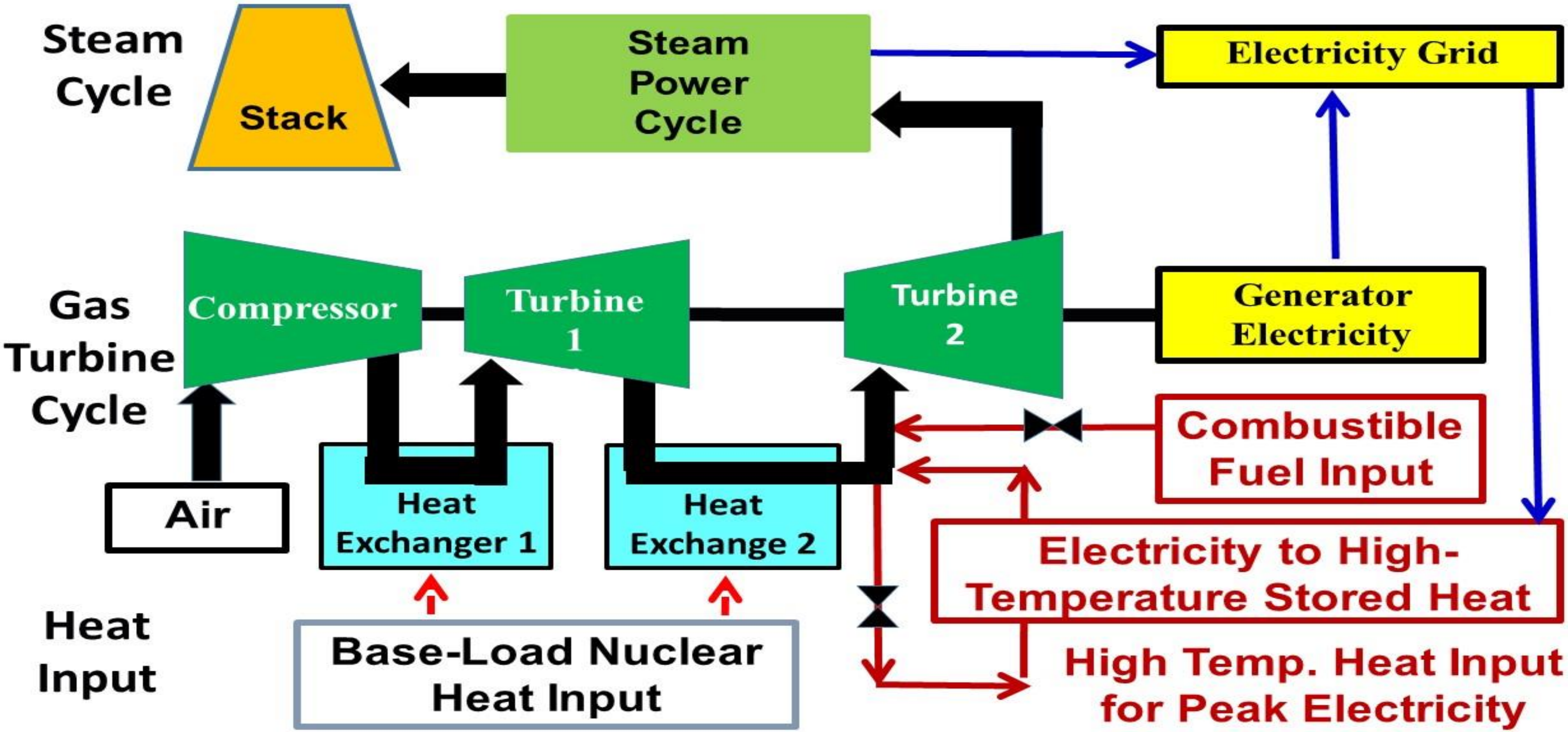
Thermal Storage Technologies for Electricity-to-Heat-to-Electricity Approaching Efficiency of Batteries

Early in Development

Nuclear Air Brayton Combined Cycle (NACC) With Thermodynamic Topping Cycle

- For advanced higher-temperature reactors (sodium, salt, helium)
- Built upon advancing gas turbine technology; Not viable 15 years ago. Replace natural-gas combined cycle plants
- Operates in two modes
  – Mode 1: Base-load with nuclear heat input and peak gas turbine temperature between 500 to 700˚C
  – Mode 2: Base-load nuclear heat input plus added heat input to raise peak gas turbine temperature to 1427˚C. Peak heating fuels:
    - Stored heat made from low price electricity
    - Hydrogen or biofuels

Base-load Nuclear, Daily Electricity Storage for Peak Power, Hydrogen or Biofuels for Long-Term Peak Power



Electrically Conductive Firebrick Enables Heating Firebrick to 1800˚C: Match Combustion Temp.

- Recently invented technology being commercialize by Electrified Thermal Solutions
- Converts low-cost firebrick into electric resistance heater
- Enables high-temperature heat storage

Converts Low-Price Electricity into very-high-Temperature Stored Heat for Day Storage (Like Batteries)

NACC Performance Parameters for Power Peaking Cycles (Many Power Cycle Designs)

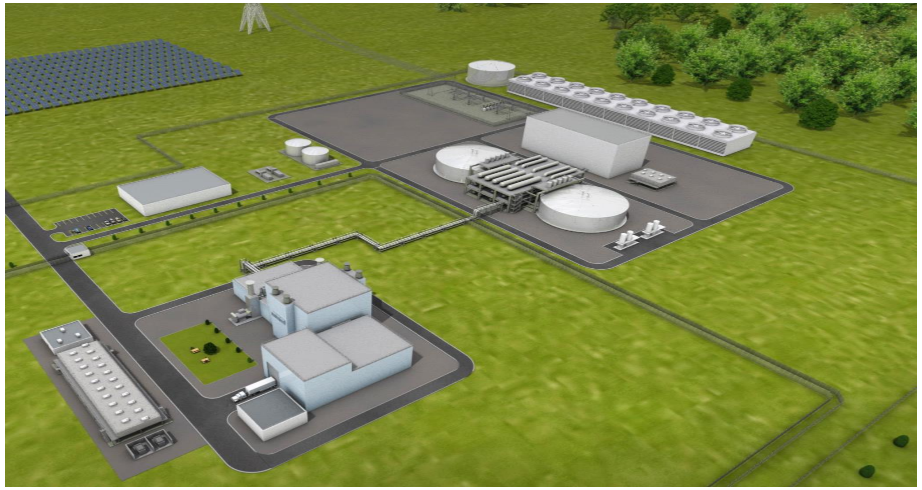
Base Efficiency	Peak Power Incremental Fuel to Electricity Efficiency	Combined Efficiency	Peak over Base Power Output
Sodium (Nominal Inlet Temperature 773 K (500˚C)			
32.8%	74.2%	60.4%	**5.7**
Salt (Nominal Inlet Temperature 973 K (700˚C)			
45.5%	75.0%	61.6%	**3.1**

Peak Gas Temperatures: 1700° K (1427° C)

"Electricity" Storage Short Times, H_2 or Biofuels Long Times

Conclusions

- Next 2 U.S. reactors are for heat markets (Dow Chemical) or include heat storage for dispatchable electricity (GE/TerraPower)
- Heat markets may become the largest use of nuclear energy
- Nuclear reactors with heat storage may replace the gas turbine (with underground natural gas storage) for dispatchable electricity
- Early in such a transition



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 (Electrified Thermal Solutions), 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 12 patents and published over 300 papers.

References: CRUSH: *Open Access

1. *C. W. Forsberg, "Separating Nuclear Reactors from the Power Block with Heat Storage to Improve Economics with Dispatchable Heat and Electricity", *Nuclear Technology*, August 2021.
2. *C. Forsberg, "Addressing the Low-Carbon Million Gigawatt-Hour Energy Storage Challenge", *The Electricity Journal*, 34 (10) 107042, December 2021. https://doi.org/10.1016/j.tej.2021.107042
3. C. W. Forsberg, "100-Gigawatt-Hour Crushed Rock Heat Storage for Variable Electricity and heat with base-load reactor operations," ICONE28-64632 , *Proceedings of the ASME 2021 International Conference on Nuclear Engineering*, ICONE 28, (August 4-6, 2021).
4. *A. S. Aljefri, *Technical and Economic Feasibility of Crushed Rock with Synthetic Oil Heat Storage Coupled to Light Water Reactors in the United Arab Emirates*, Master Thesis, Department of Nuclear Science and Engineering, Massachusetts Institute of Technology, (2021). https://dspace.mit.edu/bitstream/handle/1721.1/139910/Aljefri-aljefri-sm-nse-2021-thesis.pdf?sequence=1&isAllowed=y
5. *C. W. Forsberg and A.S. Aijefri, "100 Gigawatt Hour Crushed-Rock Heat Storage for CSP and Nuclear" SolarPaces 2020, Paper 8678, Sept. 29-Oct. 2, 2020. https://aip.scitation.org/doi/pdf/10.1063/5.0085684
6. C. W. Forsberg, "1000-MW CSP with 100-Gigawatt-Hour Crushed-Rock Heat Storage to Replace Dispatchable Fossil-Fuel Electricity", SolarPaces2021; Paper 7281, September 27-October 1, 2021
7. *W. M. Conlon and C. W. Forsberg, "Storage-coupled Nuclear Combined Cycle", AOJE-21-1033, *ASME Open Journal of Engineering*, 2022. https://asmedigitalcollection.asme.org/openengineering/article/doi/10.1115/1.4055277/1146236
8. C. W. Forsberg, "Oil and Nitrate-Salt Coolant Trade-Offs with Crushed-Rock Heat Storage and CSP", SolarPACES, Oct. 27-30, 2022.
9. C. W. Forsberg and G. Preston, "Long Duration Heat Storage Using Crushed Rock and Nuclear Heat: Impact on Grid Design", Transactions American Nuclear Society, November 2022.
10. *D. Bandyopadhyay and C. Forsberg, "Selecting Rock Types for Very-low-cost Crushed Rock Heat Storage Systems with Nitrate Salt Heat Transfer", *Journal of Energy Storage*, Vol. 61, 106664, May 2023. https://doi.org/10.1016/j.est.2023.106664
11. *C. W. Forsberg, "Low-cost Crushed Rock Heat Storage with Oil or Salt Heat Transfer", *Applied Energy,* 335, 120753, 2023. https://doi.org/10.1016/j.apenergy.2023.120753

References: Nuclear-Assisted Liquid Biofuels

Replacing All Crude Oil with Celluolsic Hydrocarbon Fuels (Gasoline, Diesel and Jet Fuel) using Massive External Heat and Hydrogen

1. C. W. Forsberg, “What is the Long-Term Demand for Liquid Hydrocarbon Fuels and Feedstocks?” *Applied Energy*, 341, 121104 (1 July 2023) https://doi.org/10.1016/j.apenergy.2023.121104
2. C. W. Forsberg and J. Shook, “Nuclear-Assisted Integrated Pulp, Paper and Biofuels Plants”, Transactions of the American Nuclear Society Meeting, Indianapolis, June 11-14, 2023.
3. C. W. Forsberg and B. Dale, “Can large integrated refineries replace all crude oil with cellulosic feedstocks for drop-in hydrocarbon biofuels?”, *Hydrocarbon Processing*, January 2023. Can large integrated refineries replace all crude oil with cellulosic feedstocks for drop-in hydrocarbon biofuels? (hydrocarbonprocessing.com)
4. C. W. Forsberg and B. Dale, *Can a Nuclear-Assisted Biofuels System Enable Liquid Biofuels as the Economic Low-carbon Replacement for All Liquid Fossil Fuels and Hydrocarbon Feedstocks and Enable Negative Carbon Emissions?*, Massachusetts Institute of Technology, MIT-NES-TR-023. April 2022. https://canes.mit.edu/download-a-report
5. C. W. Forsberg, C. W, B. E. Dale, D. S. Jones, T. Hossain, A.R.C. Morais and L. M. Wendt, “Replacing Liquid Fossil Fuels and Hydrocarbon Chemical Feedstocks with Liquid Biofuels from Large-Scale Nuclear Biorefineries”, *Applied Energy*, 298, 117525, 15 September 2021. Replacing liquid fossil fuels and hydrocarbon chemical feedstocks with liquid biofuels from large-scale nuclear biorefineries - ScienceDirect
6. C. Forsberg, “Addressing the Low-Carbon Million Gigawatt-Hour Energy Storage Challenge“, *The Electricity Journal*, December 2021. https://doi.org/10.1016/j.tej.2021.107042

REFERENCES: ELECTRICALLY CONDUCTIVE FIREBRICK

Startup Company *Electrified Thermal Solutions* Developing Technology

1. C. Forsberg and D. Stack, *Electrically Conductive Firebrick System*. U.S. Patent Application, Publication number US-2022-0132633-A1, File Date: Aug 31, 2021.
2. C. Forsberg, B. Dale and E. Ingersoll, "Nuclear Energy Drop-In Replacements for Gas Turbines, Natural Gas and Fossil Liquid Fuels", Applied Energy Symposium: MIT A+B, August 11-13, 2021 • Cambridge, USA. https://www.energy-proceedings.org/category/mitab2021/
3. C. Forsberg, D. Stack and P. McDaniel, "Nuclear Air-Brayton Combined Cycles Using Electrically-Heated Conductive Firebrick Heat Storage and Hydrogen for Peak Power", 28th International Conference on Nuclear Engineering, ICONE2021-64638, August 4-6, 2021.
4. D. Stack and C. Forsberg, "Combined Cycle Gas Turbines with Electrically-heated Thermal Energy Storage for Dispatchable Zero-Carbon Electricity," POWER2021-65529, Power 21 Power Conference A Legacy to Power the Future, American Society of Mechanical Engineers, Virtual Conference, July 20-22, 2021
5. C. W. Forsberg, P. J. McDaniel, and B. Zohuri, "Nuclear Air-Brayton Power Cycles with Thermodynamic Topping Cycles, Assured Peaking Capacity and Heat Storage for Variable Electricity and Heat," Nuclear Technology, 207 (4), 543-557, April 2021. https://doi.org/10.1080/00295450.2020.1785793
6. C. W. Forsberg et al. "Heat Storage Coupled to Generation IV Reactors for Variable Electricity from Base-Load Reactors," Workshop Proceedings, ANP-TR-185, Center for Advanced Nuclear Energy, Massachusetts Institute of Technology, INL/EXT-19-54909, Idaho National Laboratory (2019). https://osti.gov/biblio/1575201
7. Daniel C. Stack, Daniel Curtis, and Charles Forsberg, "Performance of Firebrick Resistance-Heated Energy Storage for Industrial Heat Applications and Round-Trip Electricity Storage", Applied Energy, 242, 782-796 (2019) https://doi.org/10.1016/j.apenergy.2019.03.100
8. Charles W. Forsberg (March 2019): Commentary: Nuclear Energy for Economic Variable Electricity: Replacing the Role of Fossil Fuels, Nuclear Technology, 205, iii-iv, DOI:10.1080/00295450.2018.1523623
9. C. Forsberg, D. C. Stack, D. Curtis, G. Haratyk, and N. A. Sepulveda, "Converting Excess Low-Priced Electricity into High-Temperature Stored Heat for Industry and High-Value Electricity Production", American Ceramic Society Bulletin, 97 (3) 2018.
10. C. W. Forsberg and P. F. Peterson, "Nuclear Combined Cycle Gas Turbines for Variable Electricity and Industrial Steam with Extended Firebrick Heat Storage", Trans. American Nuclear Society, Washington D.C., October 29-November 2, 2017.
11. C. Forsberg, D. Stack, D. Curtis, G. Haratyk, N. A. Sepulveda, "Converting Excess Low-Price Electricity into High-Temperature Stored Heat for Industry and High-Value Electricity Production," 30, 42-52, Electricity Journal, July 2017, doi.org/10.1016/j.tej.2017.06.009
12. Daniel C. Stack, Daniel Curtis, Richard Ibekwe, Charles Forsberg, "Conceptual Design and Market Assessment of Firebrick Resistance Heated Energy Storage (FIRES) – Avoiding Wind and Solar Electricity Price Collapse to Improve Nuclear, Wind, and Solar Economics", International Congress on Advanced Nuclear Power Plants (ICAPP 2016), Paper 16622, San Francisco, California, April 17-20, 2016.

The World Will Not Stop Using Liquid Hydrocarbons

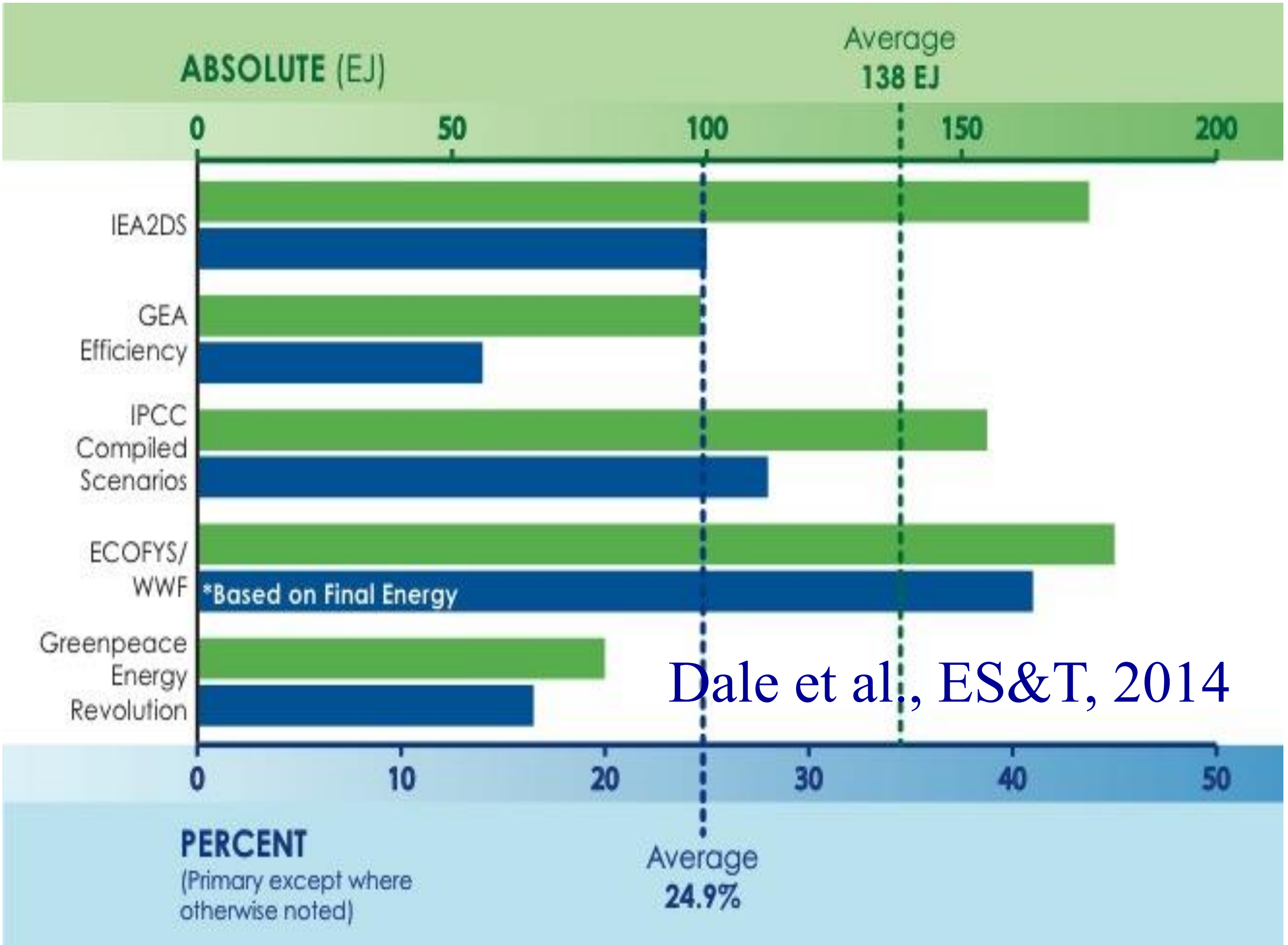
- Embedded by 150 years of technology development and infrastructure investments
- Multiple uses—not just energy!
  - Dense transportable energy source
  - Energy storage
  - Chemical feedstock
  - Chemical reducing agent
  - Enable high-temperature radiative heat transfer in industry

Product	U.S.: Millions of barrels per day
Finished motor gasoline	8.034
Distillate fuel oil (diesel fuel and heating oil)	3.776
Hydrocarbon gas liquids (HGLs)	3.197
Kerosene-type jet fuel	1.078
Still gas	0.611
Asphalt and road oil	0.342
Petrochemical feedstocks	0.286
Petroleum coke	0.260
Residual fuel oil	0.217
Miscellaneous products and other liquids	0.152
Lubricants	0.100
Special napthas	0.045
Aviation gasoline	0.011
Kerosene	0.008
Waxes	0.004
Total petroleum products	18.120

C. Forsberg, "What is the Demand for Low-Carbon Liquid Hydrocarbon Fuels and Feedstocks?" *Applied Energy Symposium: MIT* A+B, Cambridge, MA, APEN-MIT-2022_6226. July 5-8, 2022. https://www.energy-proceedings.org/category/mitab2022/

Global Biomass Sufficient to Replace All Crude Oil

- Biomass could provide a quarter of total global energy demand
- If convert to liquid hydrocarbons with massive external heat and hydrogen, can replace crude oil
- If external heat and H_2, hydrocarbon production not limited by biomass



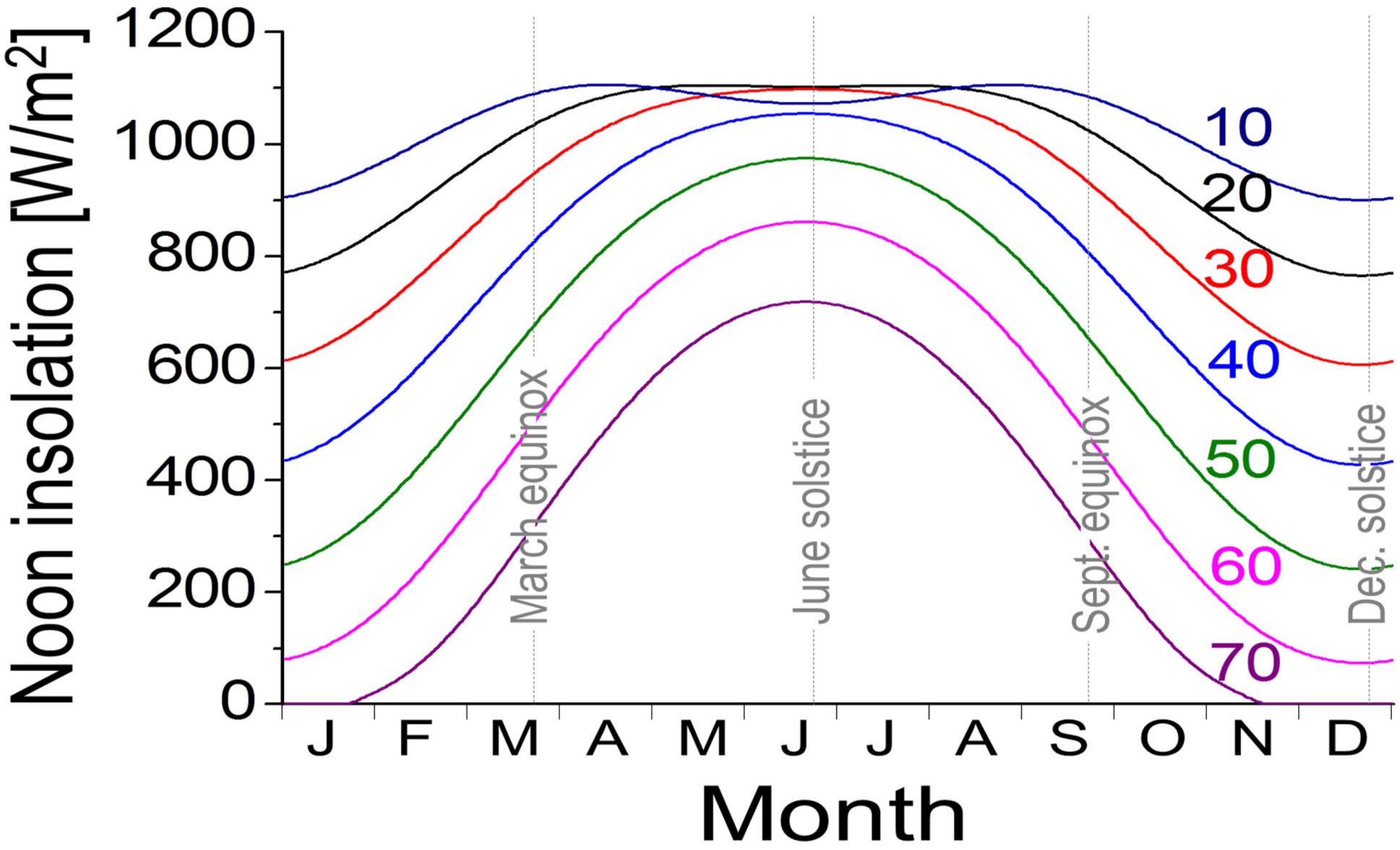
Dale et al., ES&T, 2014

Does Require Massive External Heat and Hydrogen Inputs

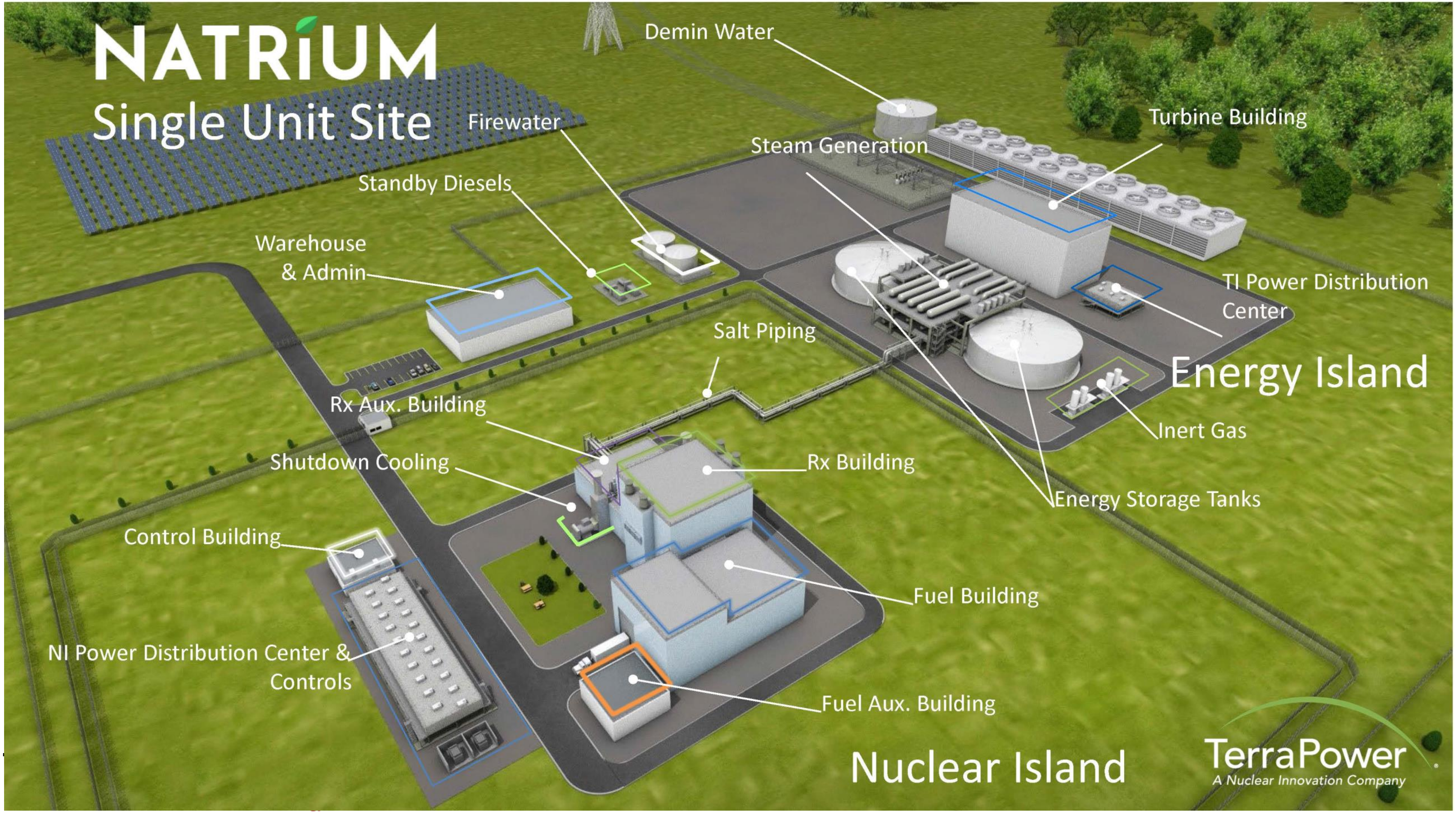
Climate and Energy Storage Are Driven By Solar & Latitude

Solar Flux Over a Year at Noon Versus Latitude

U.S. About 45° North

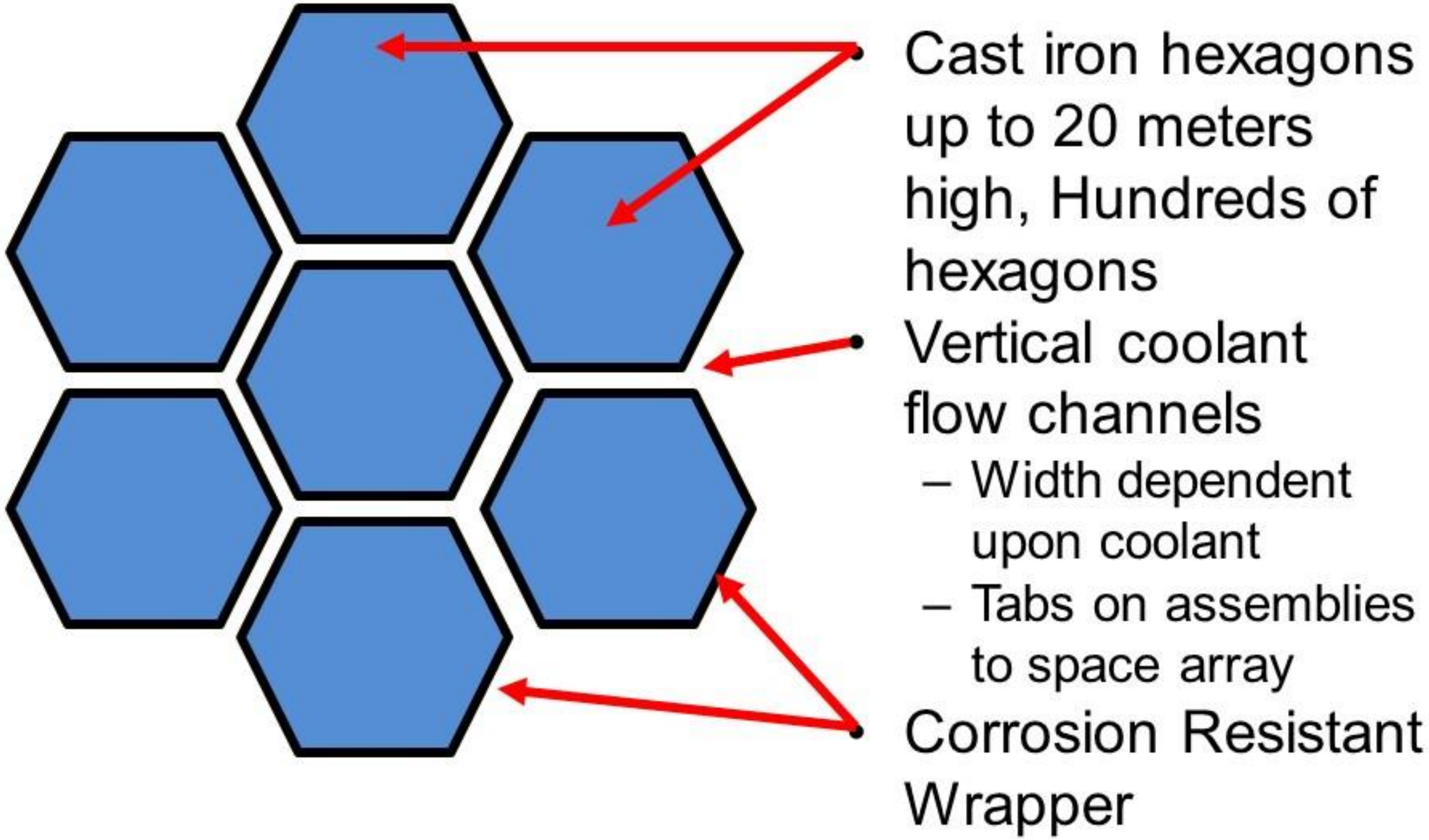


Published in: F. M. Mulder; *Journal of Renewable and Sustainable Energy* **6,** 033105 (2014),DOI: 10.1063/1.4874845;


NATRIUM
Single Unit Site
Demin Water
Firewater
Turbine Building
Steam Generation
Standby Diesels
Warehouse & Admin
TI Power Distribution Center
Salt Piping
Energy Island
Rx Aux. Building
Inert Gas
Shutdown Cooling
Rx Building
Energy Storage Tanks
Control Building
Fuel Building
NI Power Distribution Center & Controls
Fuel Aux. Building
Nuclear Island
TerraPower
A Nuclear Innovation Company

Cast Iron Storage for Any Coolant In Primary or Secondary Loop

- Tank filled with low-cost iron and small channels for low-pressure fluid (sodium, salt, etc.)
- Directly applicable to sodium-cooled CSP and sodium-cooled reactors where minimize sodium inventory
  - High cost of sodium
  - Fire hazard of sodium
- Limited by phase change of iron (about 800 C)

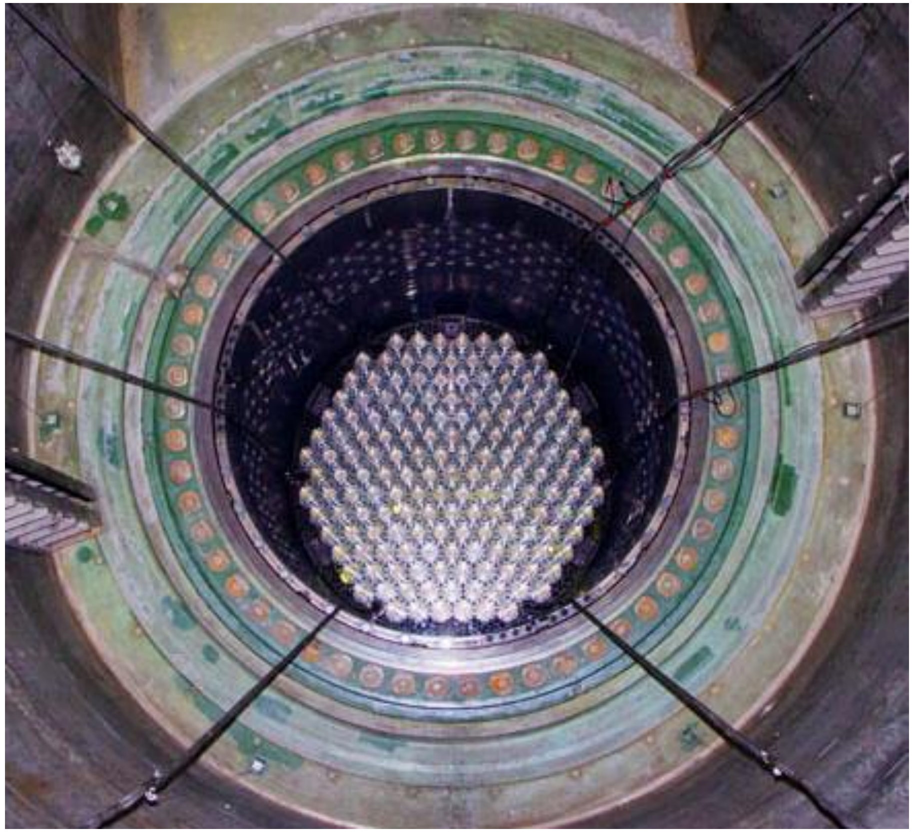


Sodium System Applications of Cast-Iron Storage

- Nuclear
  - Versatile Test Reactor project (INL)
  - Planned TerraPower sodium reactor (backup option to nitrate storage
  - Sodium fission batteries
- Concentrated Solar Power (CSP) tower
  - Proposed advanced CSP system using sodium coolant
  - Peak temperatures of 700°C

Cast Iron Storage In Tank Is Similar to Hexagonal Fuel Assemblies in Sodium and Russian Light Water Reactors

- We know how to design hexagonal structures in close-packed arrays
- Lots of practical experience with different coolants
- **In sodium reactors, design to minimize sodium inventory**



“Steam” Heat Storage

Steam Heat Transfer Fluid

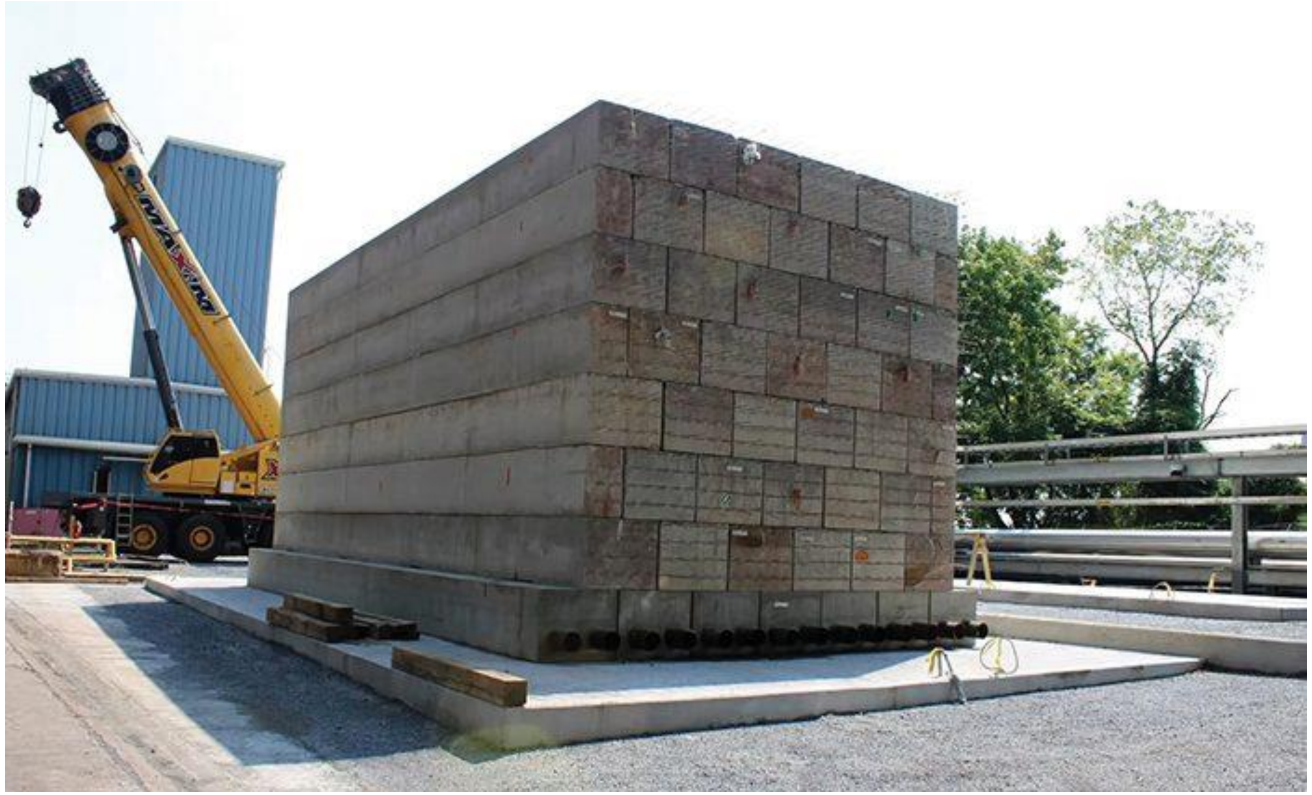
Steam Accumulators: Charlottenberg Power Station, Berlin

- Heat water in pressurized vessel with steam
- Release pressure and flashing of steam sent to turbine, most energy stored in the hot water
- Steam accumulators built 1929
  - >600 t steam
  - 50 MW_e (separate turbine)
  - 67 MWh
  - 16 tanks
  - Tank dimensions: 65’ h ×14’ d (20 m ×4.3 m)

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

Steam Concrete Heat Storage

- Pipes in concrete
- Steam heats concrete while condensing to water
- Recover heat by pumping water into pipes that is converted to steam
- 10 MWt pilot plant



EPRI and Storworks Power Pilot Plant

https://netl.doe.gov/sites/default/files/netl-file/21TPG_Hume_0.pdf

Electricity To Heat Storage

Replacing Fossil Fuels for High-Temperature Heat

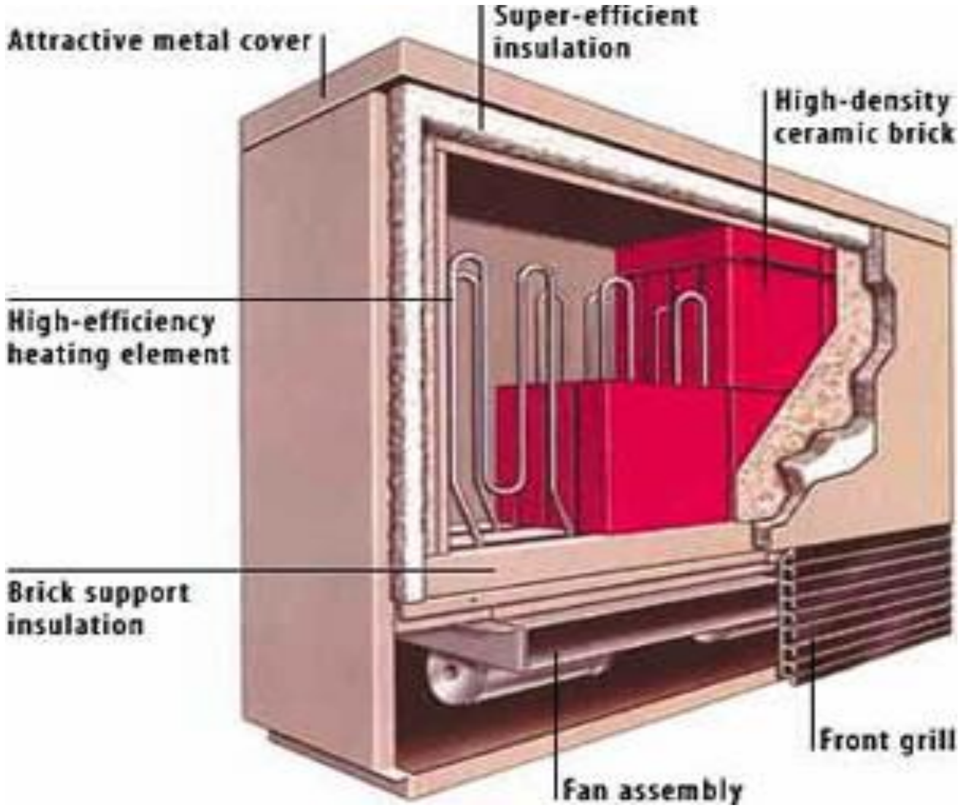
Current and Advanced Systems (1800 C)

Nuclear Air-Brayton Combined Cycles (NACC):

Advanced Power Cycle

Molten Salt Reactors Originally Designed for Nuclear-Powered Jet Aircraft: NACC Updated for Peak Electricity Production

Electricity to Heat Storage Systems Have Been Commercial for Many Decades: Heat out as Hot Air

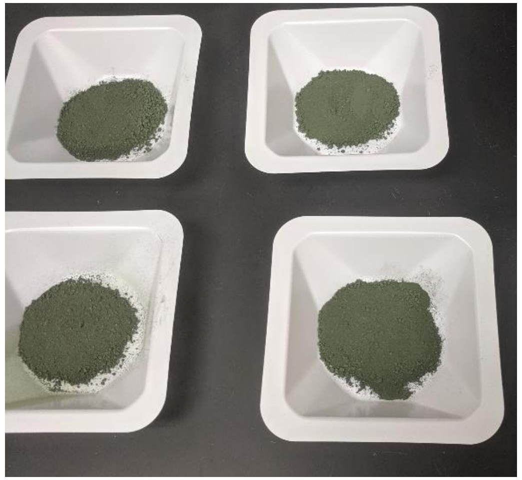


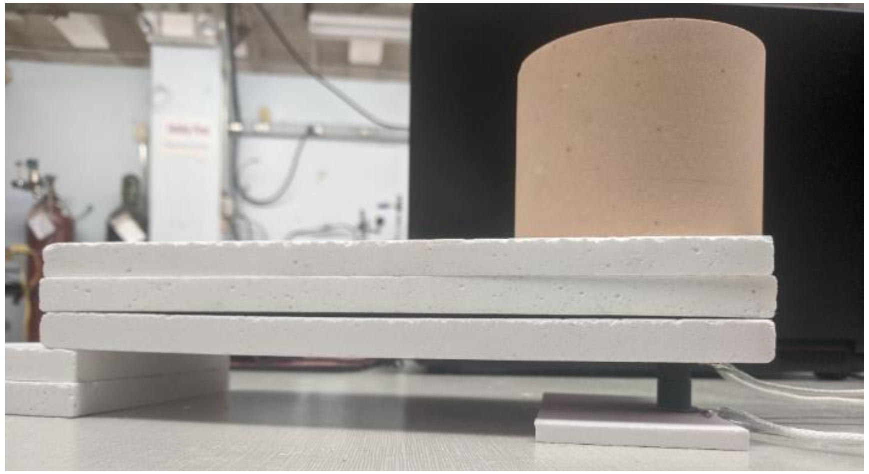
- From kilowatt hours to megawatt hours
- Large-scale use
  - Reduce peak electric demand (Europe)
  - Reduce local air pollution (China; MWhs)

"Toaster Wire" Plus Brick Heat Storage Temperature Limited By Resistance Heater Limits

We Developed an Electrically-Conductive Firebrick Enable Temperatures to 1800+˚C

- Only firebrick can withstand very high temperatures
- Cheap traditional firebricks are electrical insulators
- Doped firebrick to create conductive firebrick with required electrical properties
- Example: Dope chrome oxide with nickel oxide

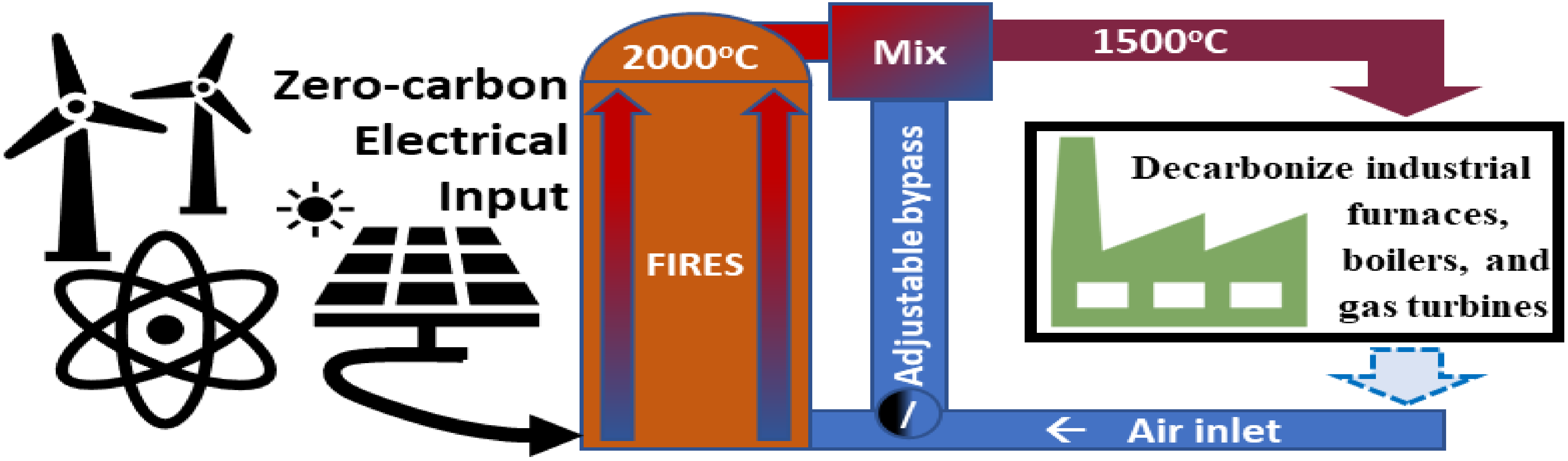




-

Startup Company: Electrified Thermal Solutions

Very high-temperature stored heat in ceramic mass to provide hot air to heating sector or power plants



Constant heat

Steam systems (<500°C): chemicals, pulp, paper, food, others

Gas systems (500-1600°C): glass, ceramics, cement, steel, others

Low-cost electrical storage

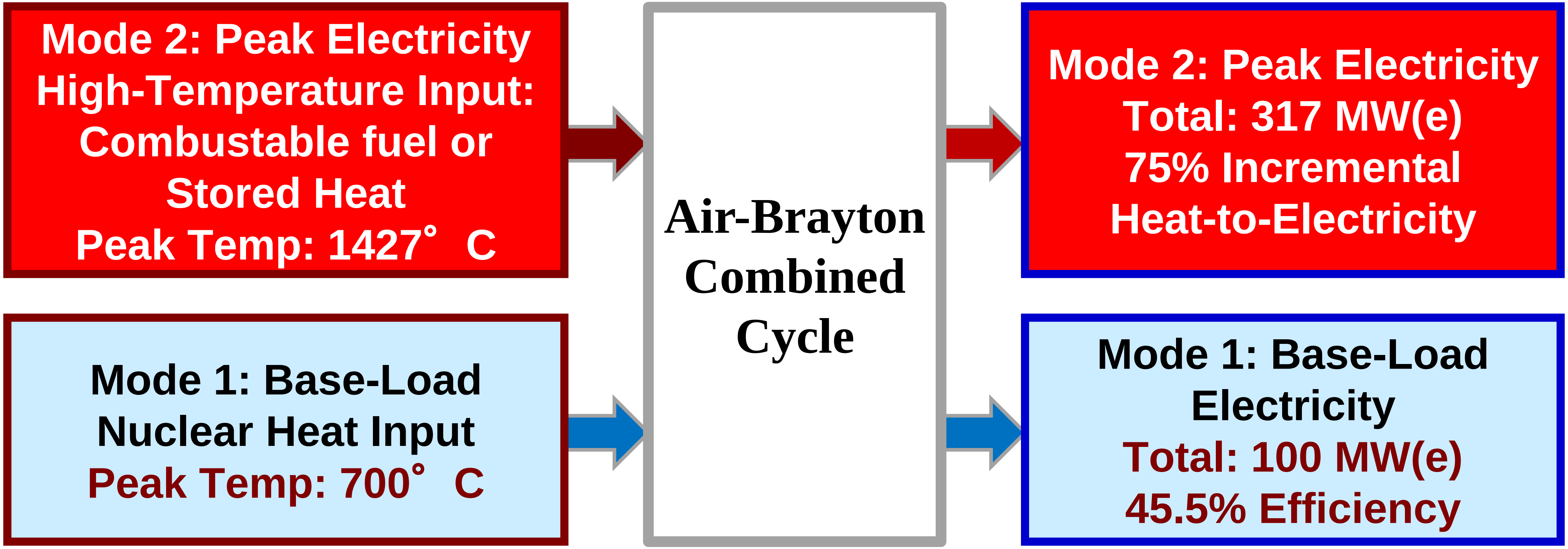
Steam power plants (35-45%)

Traditional gas turbine combined cycles (55-65%)

Nuclear-heated gas turbine with FIRES topping heat (65-75%)

Thermodynamic Topping Cycles Are Efficient

700˚C Air from Salt-Cooled Reactor Heat Exchangers



Overall Plant Efficiency In Peaking Mode: 61.6%