Fluoride-Salt-Cooled High-Temperature Reactor with Nuclear Air-Brayton Combined Cycle and Firebrick Resistance Heated Energy Storage

Competing with Stand-Alone Natural Gas and Enabling a Zero-Carbon Energy World

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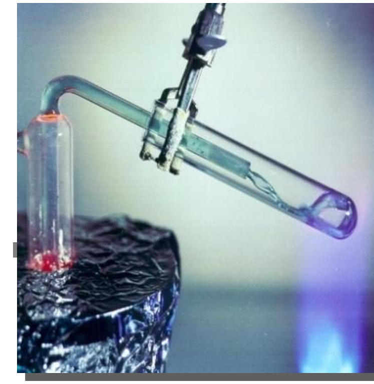
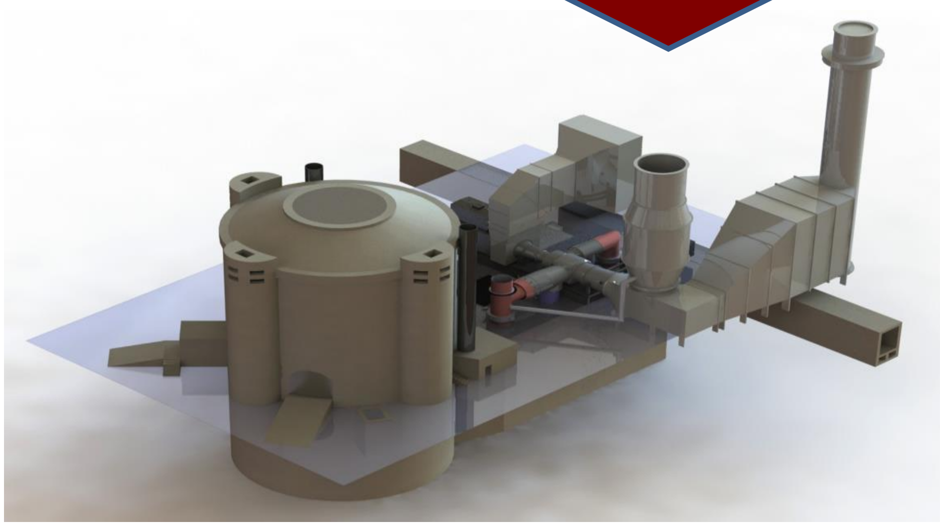
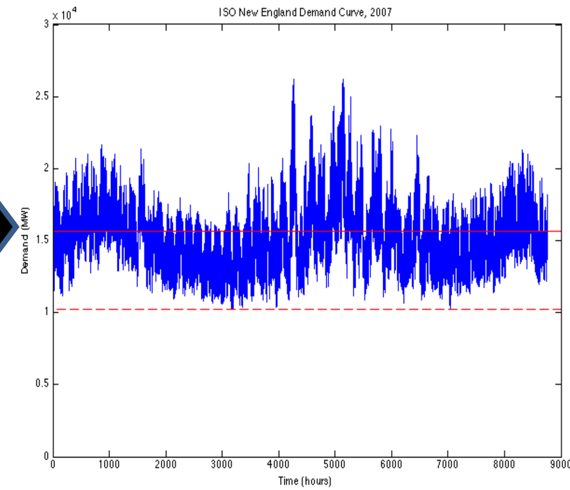
Summary

Fluoride-Salt-Cooled High Temperature Reactor (FHR) with Nuclear Air-Brayton Combined Cycle (NACC)



Stored Heat and/or Natural Gas



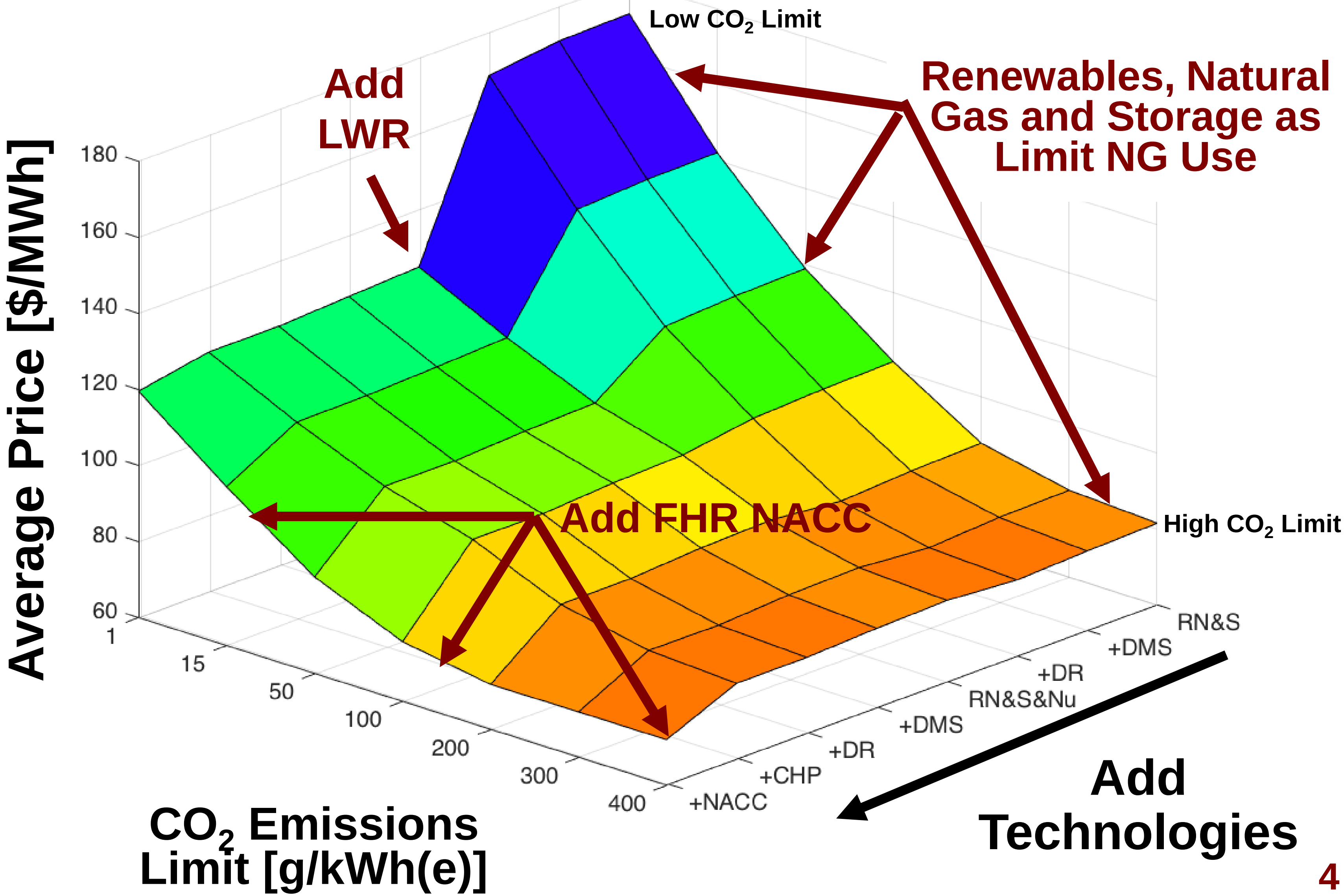


Base-Load Reactor | **Gas Turbine** | **Variable Electricity And Steam**

- **50 to100% Greater Revenue than Base-Load Plant**
- **Enable Zero-Carbon Energy System when Coupled to Heat Storage**
- **Safety Strategy to Assure Fuel Integrity in All Accidents**

The Different Capabilities of an FHR with NACC and FIRES May Enable Lower-Cost Electricity

2050 Minimum-Cost Texas Grid Vs Added Technologies and CO_2 Limits



Energy Requirements for a Low-Carbon Economy

Market Defines Reactor Strategy

Understand 2030 Market

Base-load Electricity, Variable Electricity, Heat to Industry

↓

Power Conversion System to Meet Market Requirements

Nuclear Air Brayton Combined Cycle (NACC) with Firebrick-Resistance Heated Energy Storage (FIRES)

↓

Reactor: Salt-Cooled

Going from Fossil-Fuel to Low-Carbon Electricity Changes Electricity Markets

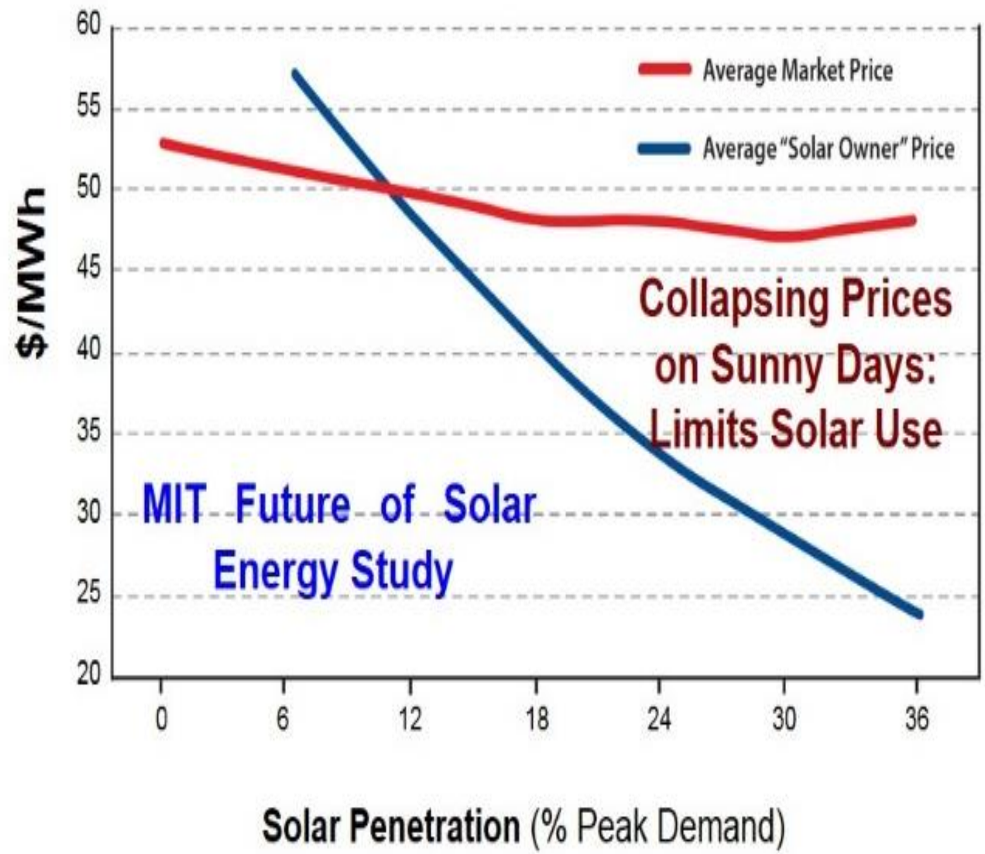
Fossil Fuel Electricity
Low Capital Cost
High Operating Cost

Low-Carbon Electricity
High Capital Cost
Low Operating Cost

Low-Carbon Electricity is Only Economic If Operate Capital-Intensive Plants at Full Capacity

In Competitive Markets, Solar Revenue Collapses as Solar Output Increases

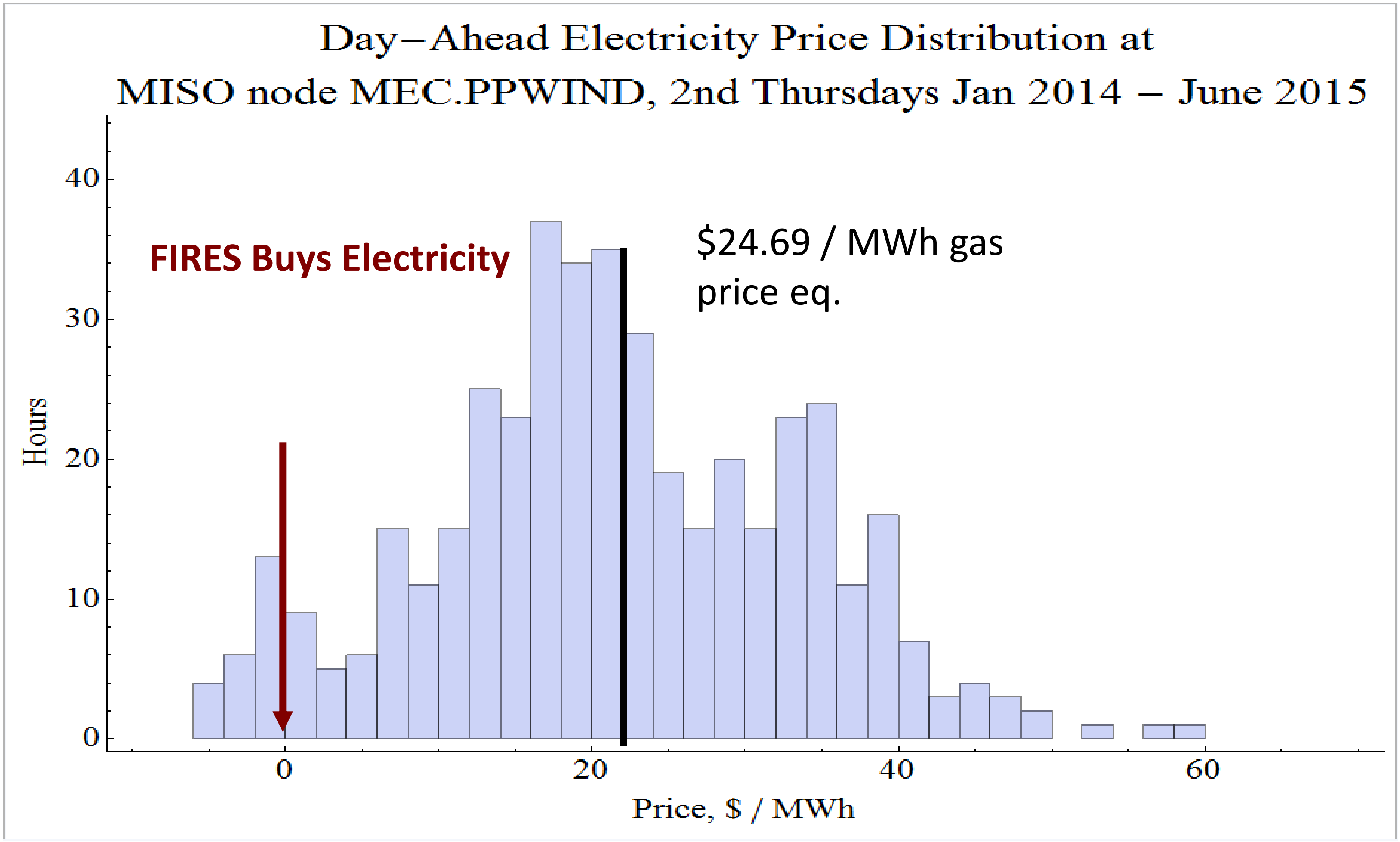
- Price collapse is a characteristic of large-scale use of low-operating-cost high-capital-cost technologies.
- Becomes significant when fraction of total electricity is
  - 10% solar
  - 20% wind
  - 70% nuclear
- Does not happen with fossil-fuel plants



Same Effect If Large-Scale Use of Wind

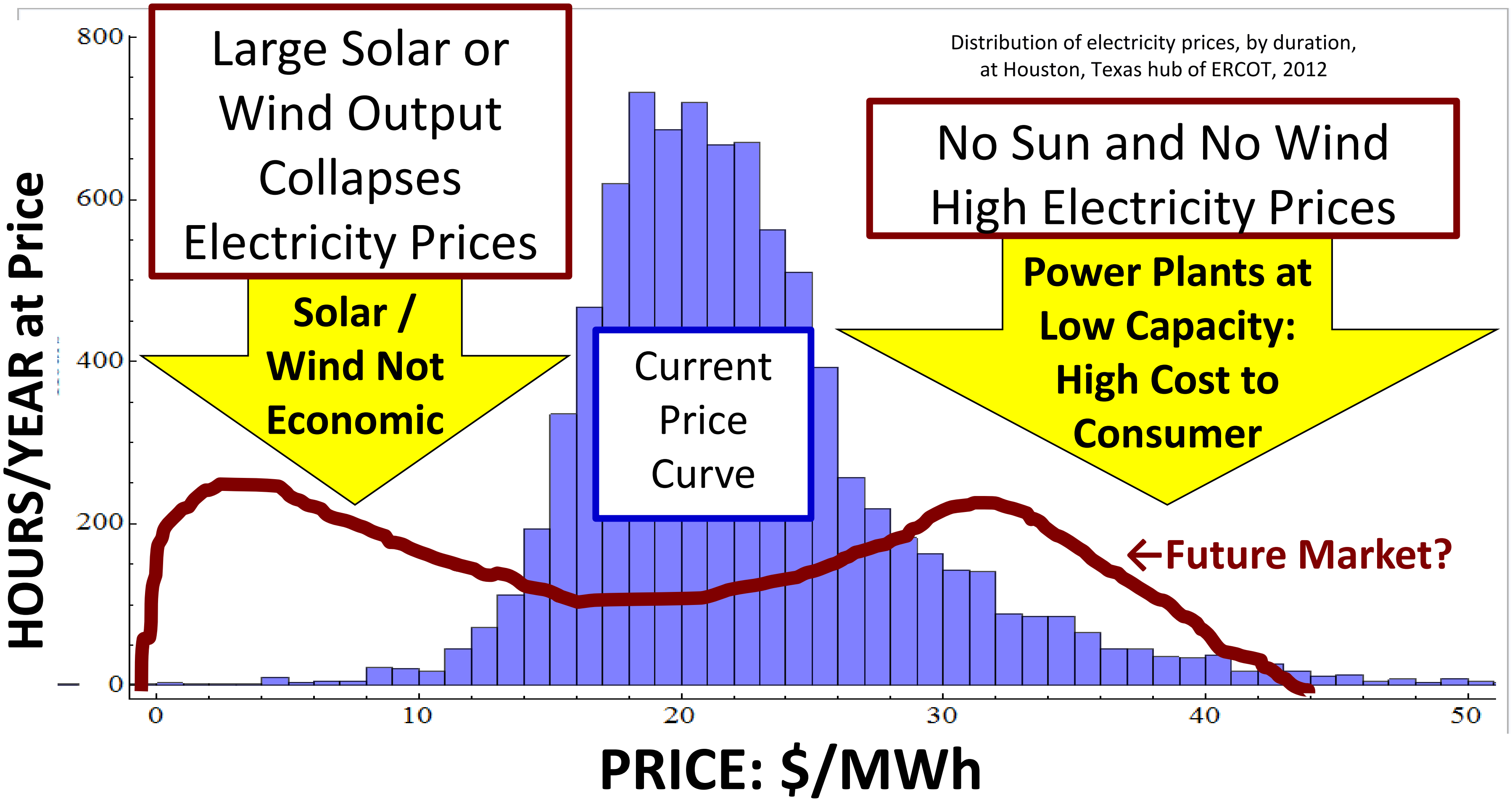
Price Collapse is Real: Iowa and Wind

Half the Time Electricity is less than Natural Gas



How Can We Use Cheap Electricity Delivered On Irregular Schedule?

Low-Carbon Nuclear-Renewable Grid Changes Electricity Price Structure

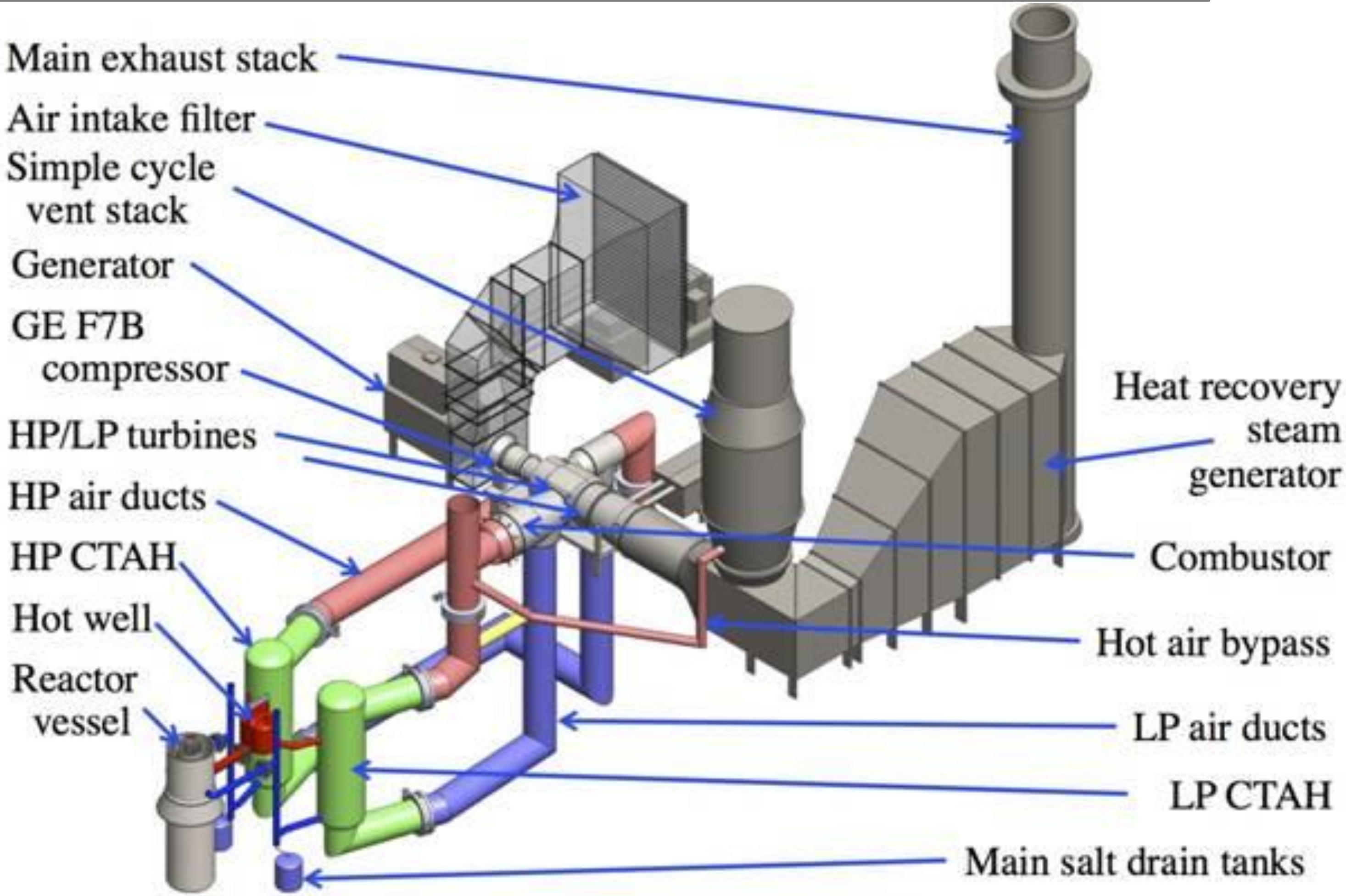


How Do We Create an Economically Viable Low-Carbon Electricity Grid?

Require Rethinking Coupled Reactor and Power System to Meet New Electricity Grid Requirements

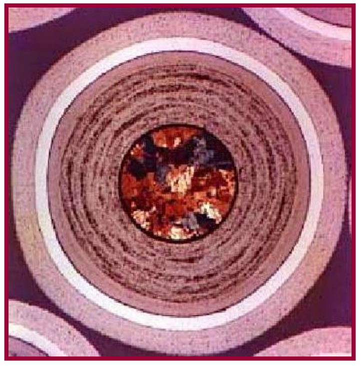
Fluoride-Salt-Cooled High-Temperature Reactor (FHR)
Nuclear Air-Brayton Combined Cycle (NACC)
Firebrick Resistance Heated Energy Storage (FIRES)

FHR: Salt-Cooled Reactor Coupled to Nuclear Air-Brayton Combined Cycle (NACC)

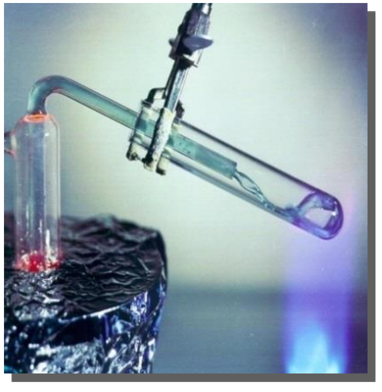


Power Cycle Similar to Natural-Gas Combined Cycle Plant

FHR Combines Existing Technologies



Fuel: High-Temperature Coated-Particle Fuel Developed for High-Temperature Gas-Cooled Reactors (HTGRs): Added details Appendix A

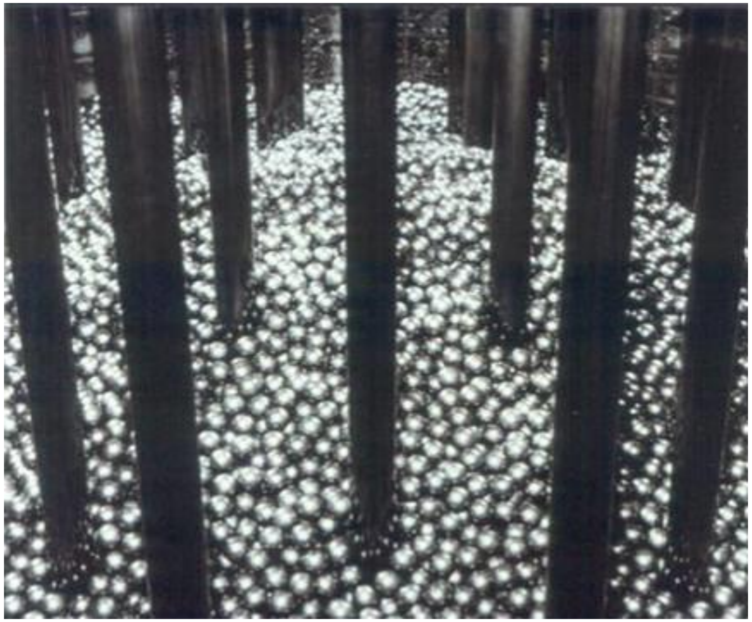


Coolant: High-Temperature, Low-Pressure Liquid-Salt Coolant developed for the 1950s Aircraft Nuclear Propulsion Program: Added Details Appendix B

Power Cycle: Modified Natural-Gas Air Brayton Power Cycle with General Electric 7FB Compressor: Added Details Appendix C

Fuel is the Graphite-Matrix Coated Particle Fuel Used in High-Temperature Gas-cooled Reactors

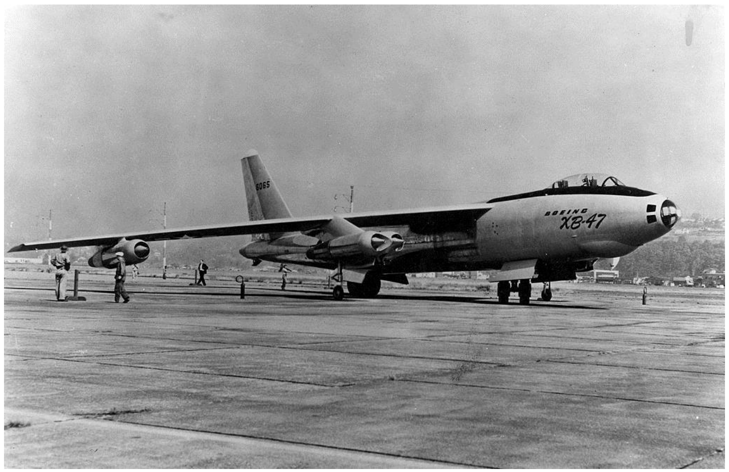
- Coated particle fuel used in high-temperature reactors
  - Failure temperatures ~1750°C
  - Initial development in the 1970s
- Multiple HTGRs built
  - U.S.: Two reactors
  - Today
    - One test reactor in Japan
    - One test reactor in China
    - Two power reactors under construction in China
- U.S. NGNP program improved performance in the last decade



Helium-Cooled Pebble Bed Reactor Core

In the 1950s the U.S. Launched the Aircraft Nuclear Propulsion Program

Salt Coolants Designed to Couple Reactors to Jet Engines



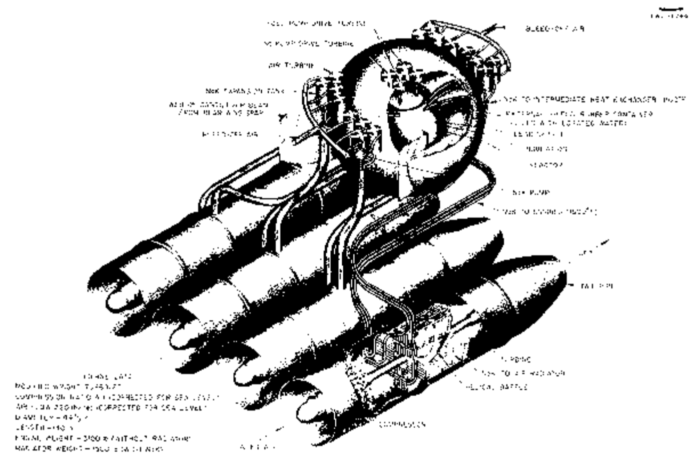


Fig. 4.33. Aircraft Power Plant (200 Megawatt).

It Has Taken 50 Years for Utility Gas Turbine Technology to Mature Sufficiently to Enable Coupling with a Reactor

Goal: Jet Bomber to Bomb Moscow (Cold War)

Significant Development of Salt Coolants

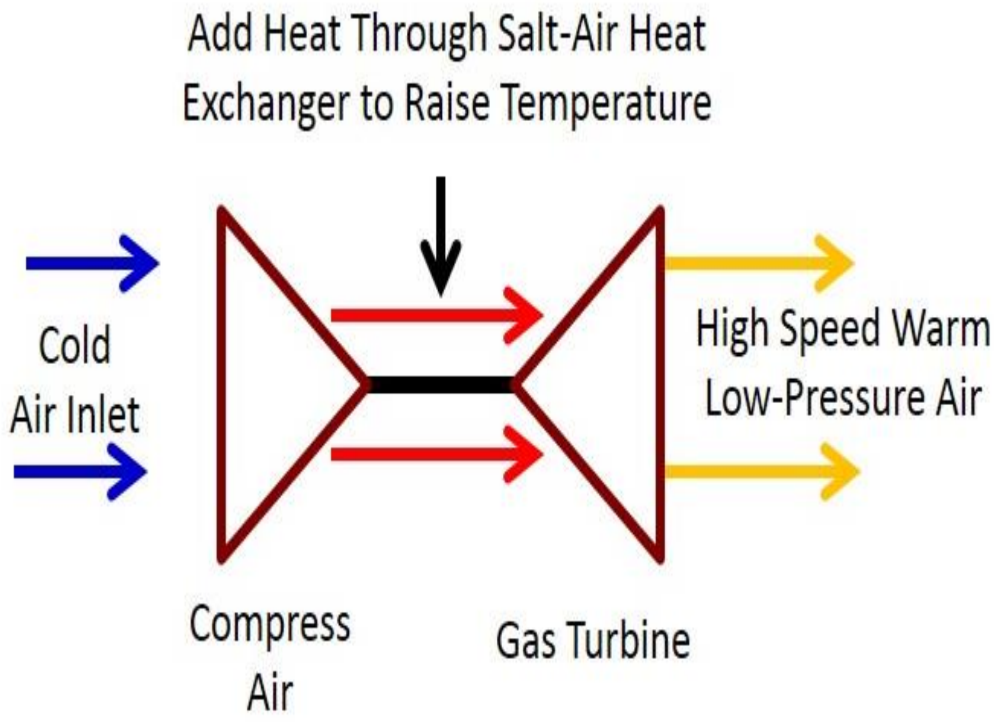
- Two reactors built
  - Aircraft Reactor Experiment (ARE)
  - Molten Salt Reactor Experiment (MSRE)
    - 8 MWt; Operated late 1960s
- Fuel dissolved in salt (not solid fuel)
  - Needed low weight (high power density) reactor for aircraft jet engine
  - ARE military reactor
  - MSRE explored concept for civilian reactor use
- Created the technological basis for liquid salt coolants
- Boiling points >1400°C
- **FHR Uses clean salt coolants (no fuel dissolved in salt)**

Molten Salt Reactor Experiment (MSRE)

Added Information: Appendix B

Salt Coolants Originally Developed To Meet Jet Engine Requirements

- Front-end air compressor raises air temperatures to several hundred degrees C.
- Heat input must be at higher temperatures
- <u>Salt coolants designed to match jet engine requirements</u>; deliver heat in the 600 to 700°C range



Turbine Powers Air Compressor

Performance Limited By Temperature Limits of Salt-Air Heat Exchanger—Below Gas Turbine Limits

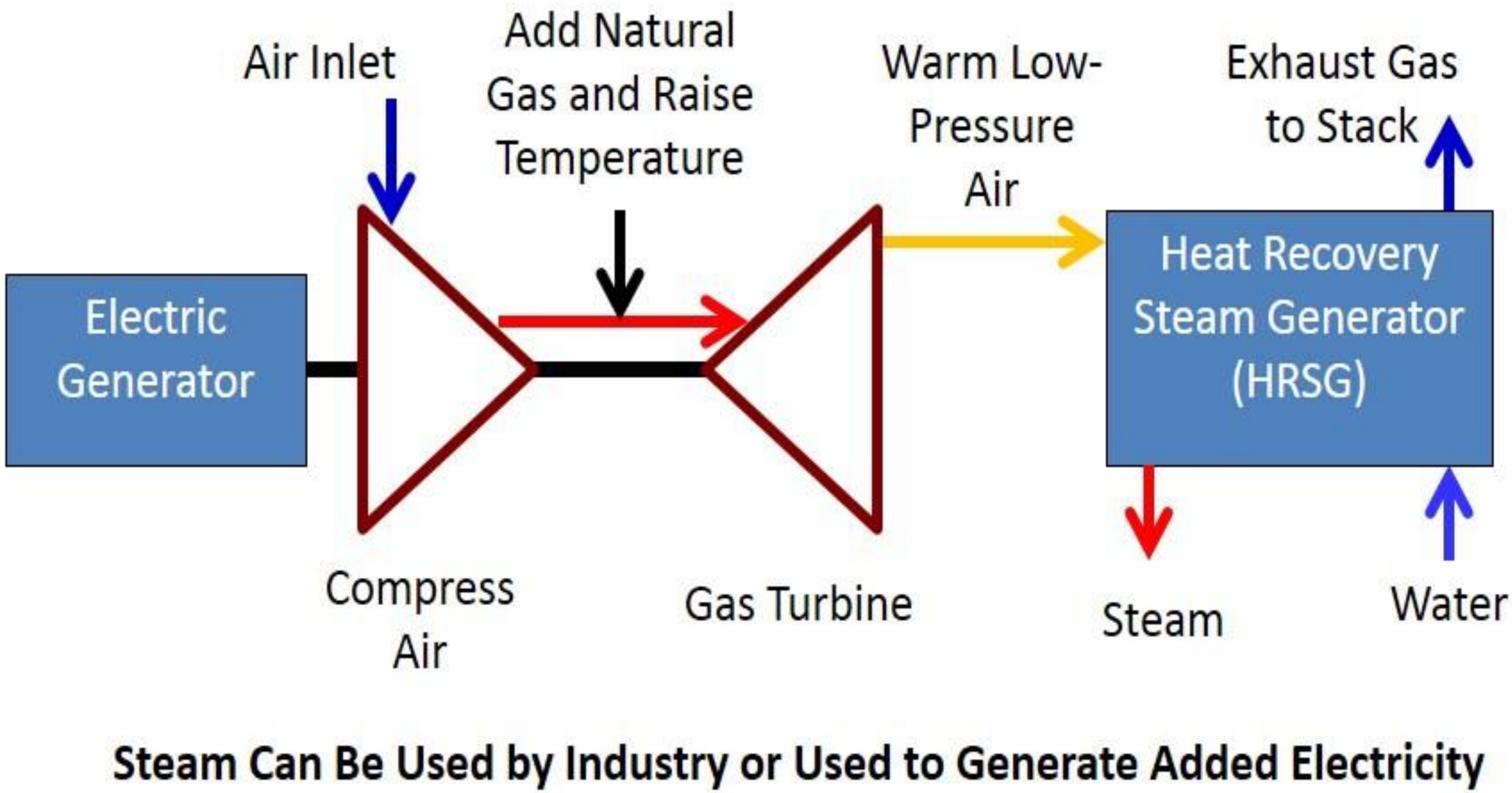
Power Cycle: There Has Been a Revolution in Natural-Gas Combined Cycle Gas Turbines

- Most efficient heat-to-electricity technology: 60%
- Reduced cooling water demand
- Produces
  - Electricity
  - Steam for added electricity or industry
- Used by utilities and industry

Result of 50 Years of Jet Engine Development

Natural-Gas Combined Cycle Plant

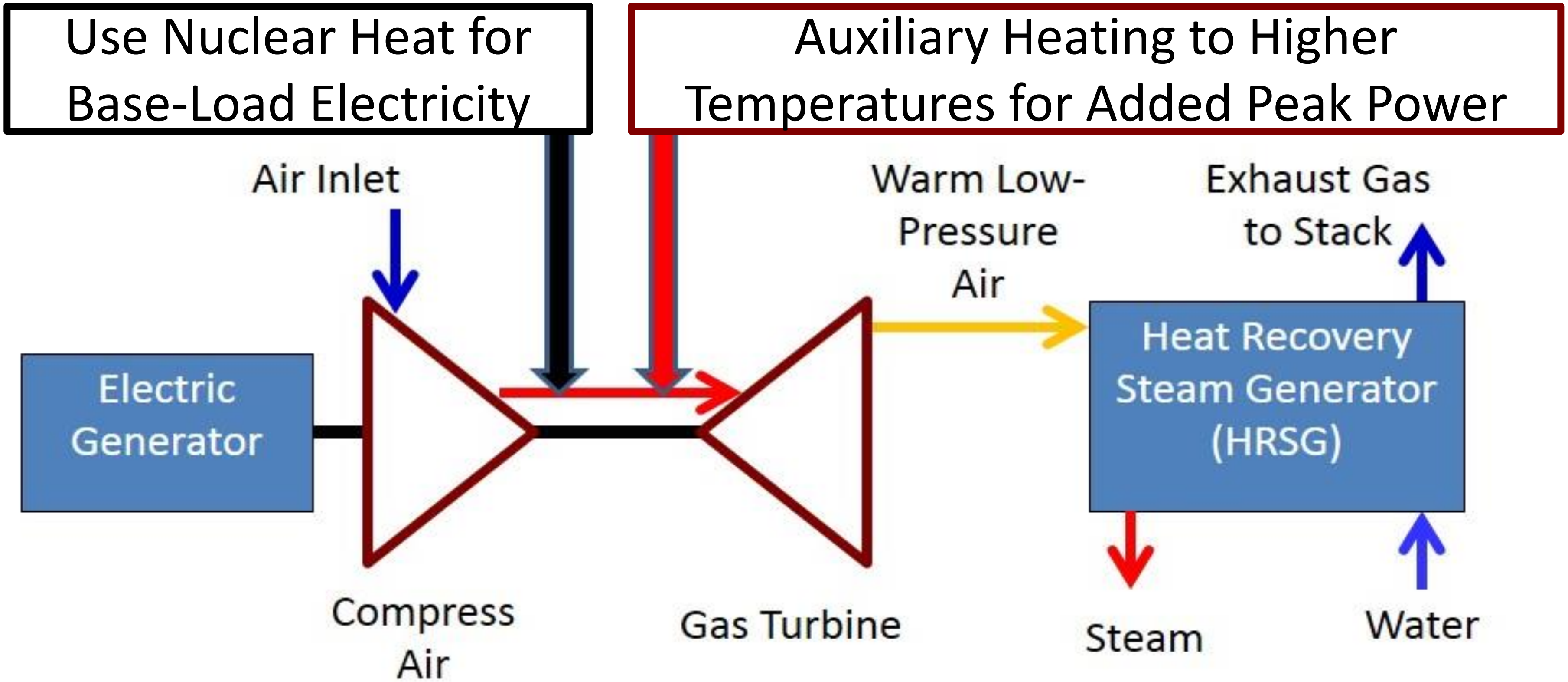
Simplified Schematic



Meets Electricity Grid and Industrial Needs (Steam)
But Large Carbon Dioxide Emissions

Nuclear Air-Brayton Combined Cycle (NACC) is a Modified Natural-Gas Combined Cycle

Natural Gas Fired Combined Cycle: Peak Temperatures to ~1400°C
Beyond Reactor Heat Exchanger Temperature Limits

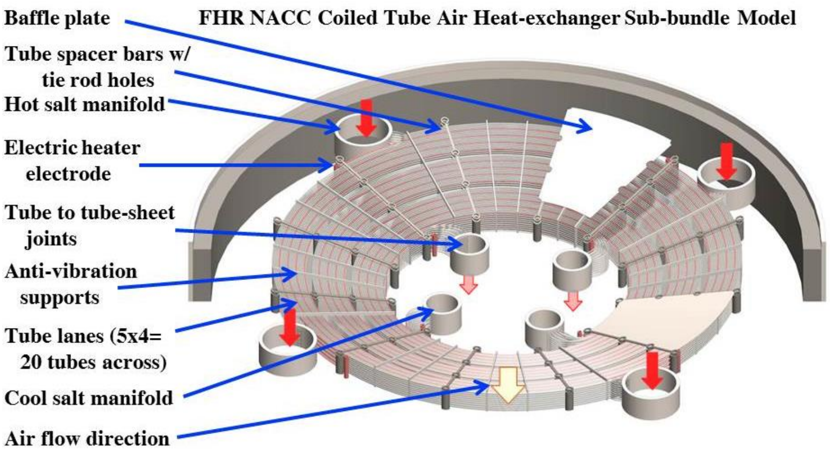


Auxiliary Heat: Natural Gas, Hydrogen, or Stored Heat

Simplified Schematic of Power Cycle

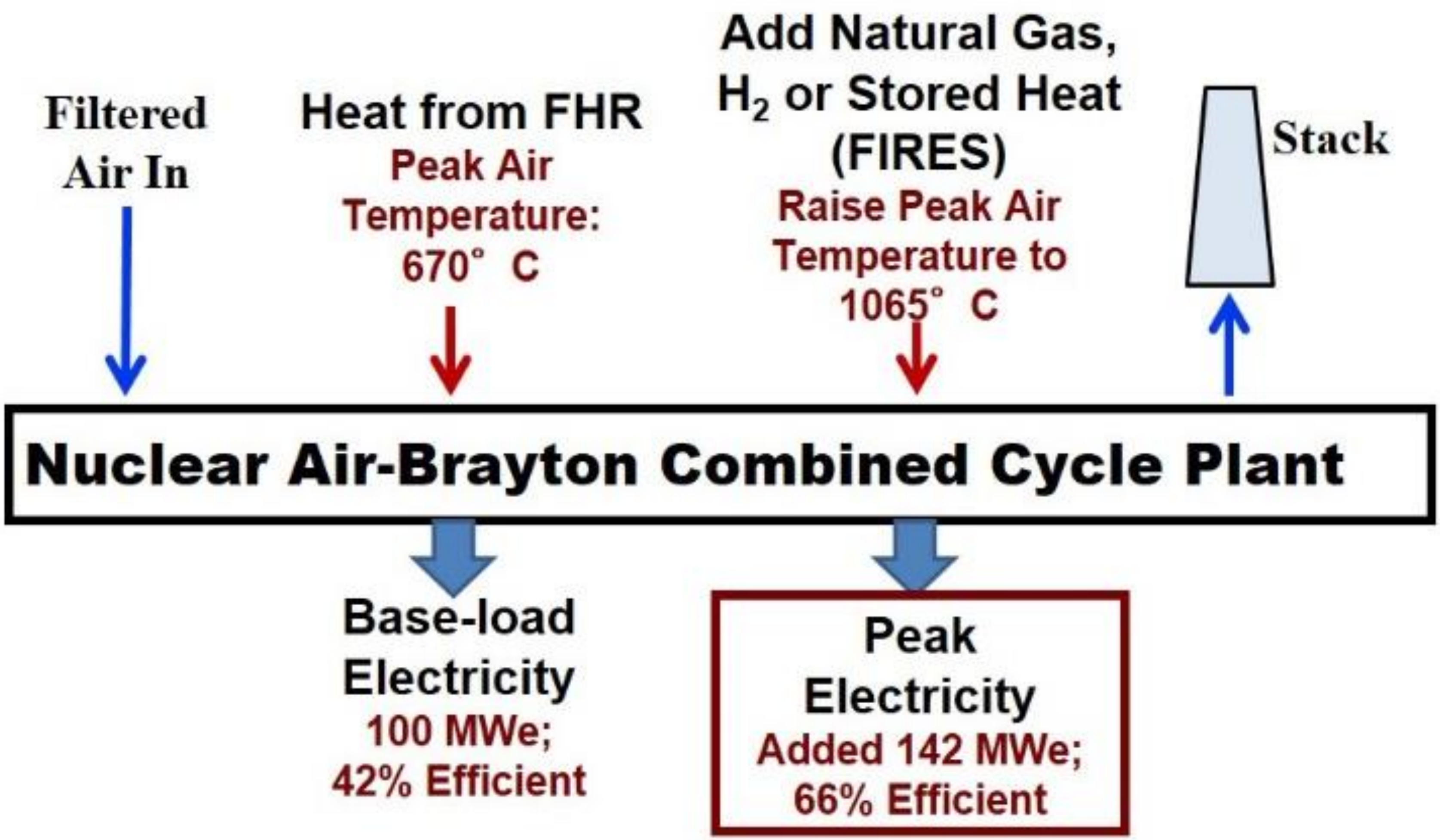
High Gas-Turbine Temperature Limits Make Possible High-Efficiency Topping Cycles

- Indirect cycles (including nuclear) limited by heat exchanger materials temperature limits
  - Typically near 700C
  - Transferring heat through metal
- Topping cycle limited by much-higher gas-turbine-blade peak temperature
  - Hot gas inlet approaching 1600C in advanced industrial gas turbines
  - Blade temperatures far below gas temperatures with internally-cooled turbine blades with ceramic external coatings
  - Direct heating by natural gas flame or firebrick heating (next section)



Coupling Reactors to Gas-Turbines is Transformational

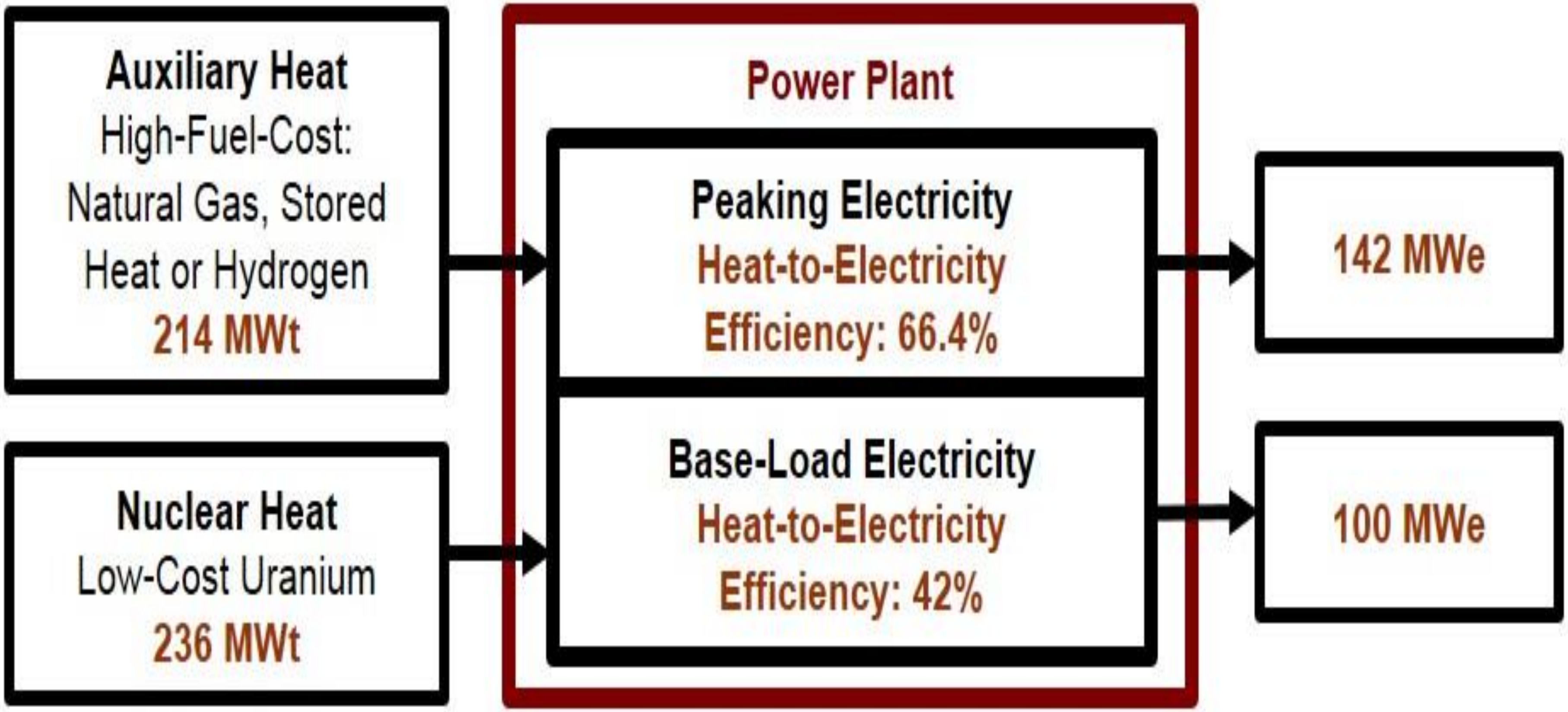
NACC for Variable Electricity Output



Topping Cycle: 66% Efficient for added Heat-to-Electricity: Stand-Alone Natural Gas Plants 60% Efficient

NACC Has a Classical Thermodynamic Topping Cycle for Peak Electricity

Efficiency of Topping Cycle Greater than Base-Load Cycle

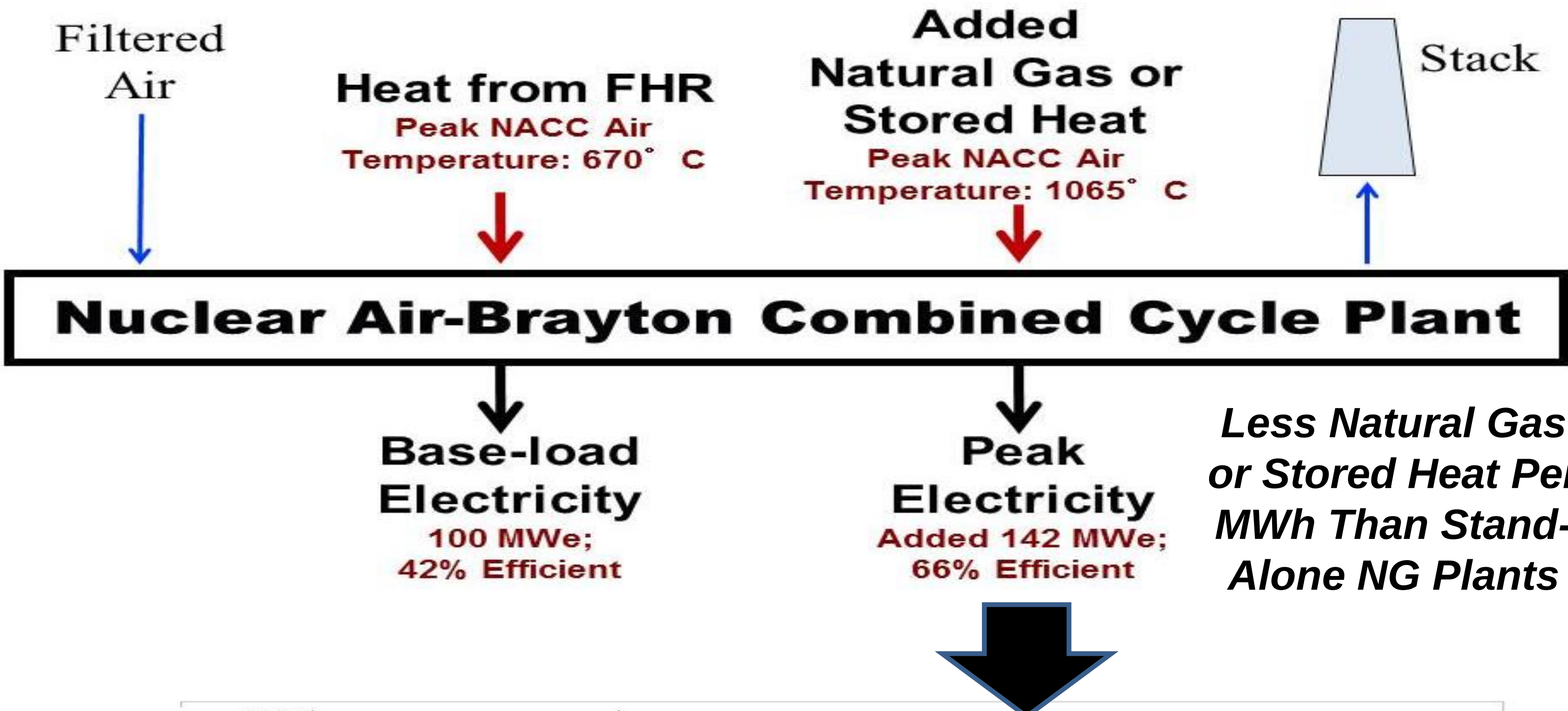


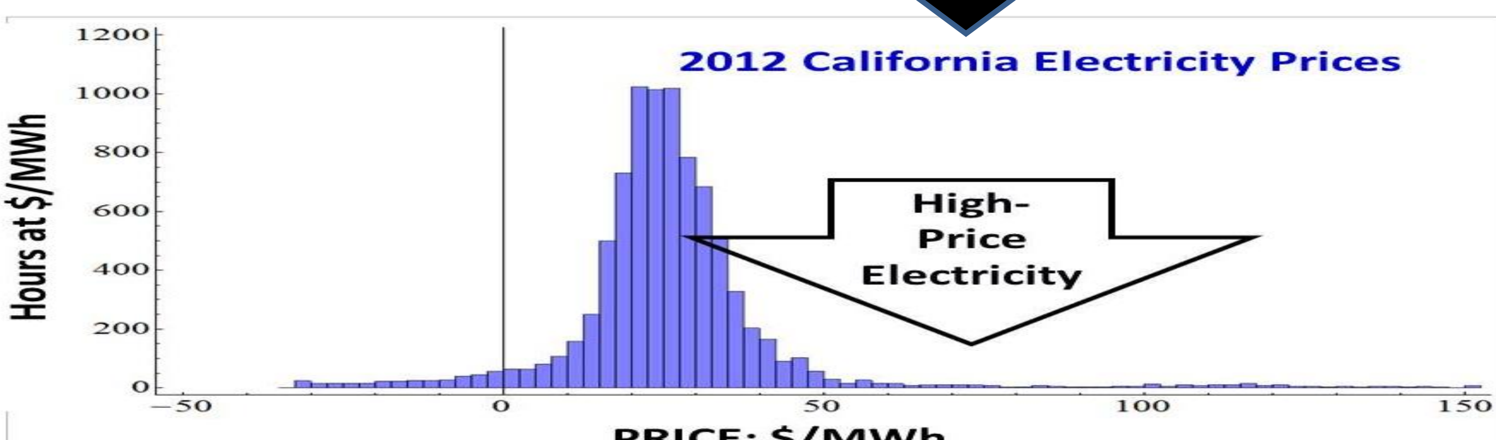
Topping Cycles are Not New: Indian Point I PWR Had Oil-Fired Super Heater (Topping Cycle)

Characteristics of FHR with NACC and Topping Cycle

- Baseload (100 MWe: Example case)
  - Nuclear heat only
  - Cheap uranium fuel
  - 42% efficiency.
- Peak Power (Added 142 MWe)
  - Auxiliary heat from natural gas, stored heat or hydrogen in the future
  - Expensive fuels relative to uranium
  - 66% incremental heat to electricity efficiency
  - **Topping cycle more efficient than stand-alone natural gas combined cycle plant (60%)**

FHR with NACC Produces More Electricity When Prices Are High and a Need for More Electricity





FHR Revenue Using 2012 Texas and California Hourly Electricity Prices

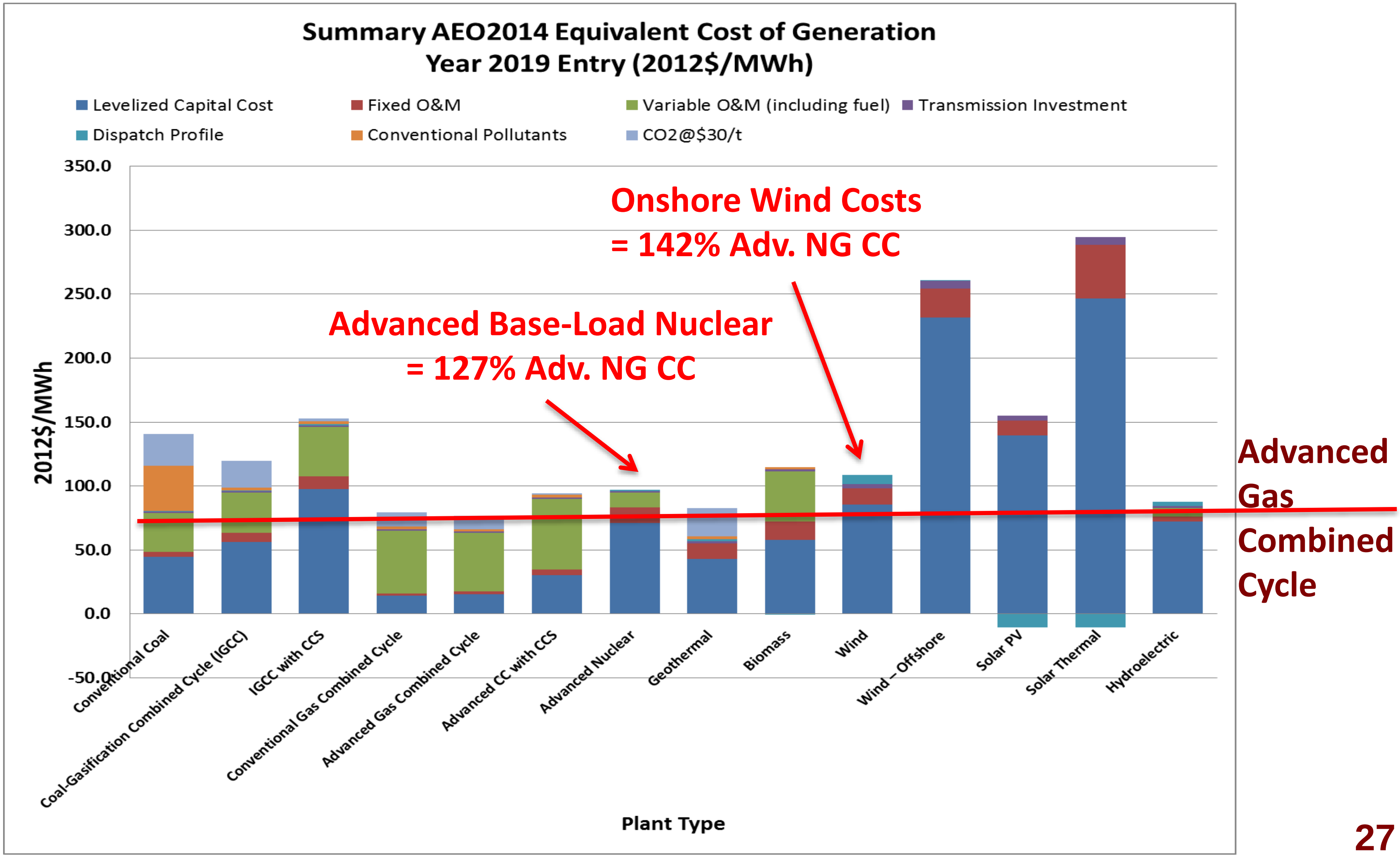
After Subtracting Cost of Natural Gas, No FIRES

Grid→ Operating Modes	Texas Percent (%)	California Percent (%)
Base-Load Electricity	100	100
Base With Peak (NG)	142	167

Increased Nuclear Plant Revenue Producing Peak Power with Natural Gas—More Efficient than Stand-Alone Natural Gas Plants

Potentially Credible Scenarios where FHR with NACC Takes Out Stand-Alone NG Plants

50 to 100% More Revenue than Advanced Base-Load Nuclear



Potential Economic Competitive System Based on Two Characteristics

- Increase Revenue by Coupling to NACC & FIRES
  - Meets new market needs
  - Economics improves with advances in gas turbines
- Potential for lower capital costs (But less certain)
  - High-temperature for higher base-load efficiency
  - Reasonable power densities in the reactor core
  - Low pressure primary system
  - Characteristics that improve safety to potentially lower costs
    - Low-pressure containment
    - High-temperature fuel with failure >1600°C

Energy Storage

Firebrick Resistance Heated Energy Storage (FIRES)

Heat Storage is Cheaper than Work Storage (Batteries, Pumped Hydro, etc.)

FHR Peak Electricity Using Firebrick Resistance-Heated Energy Storage (FIRES)

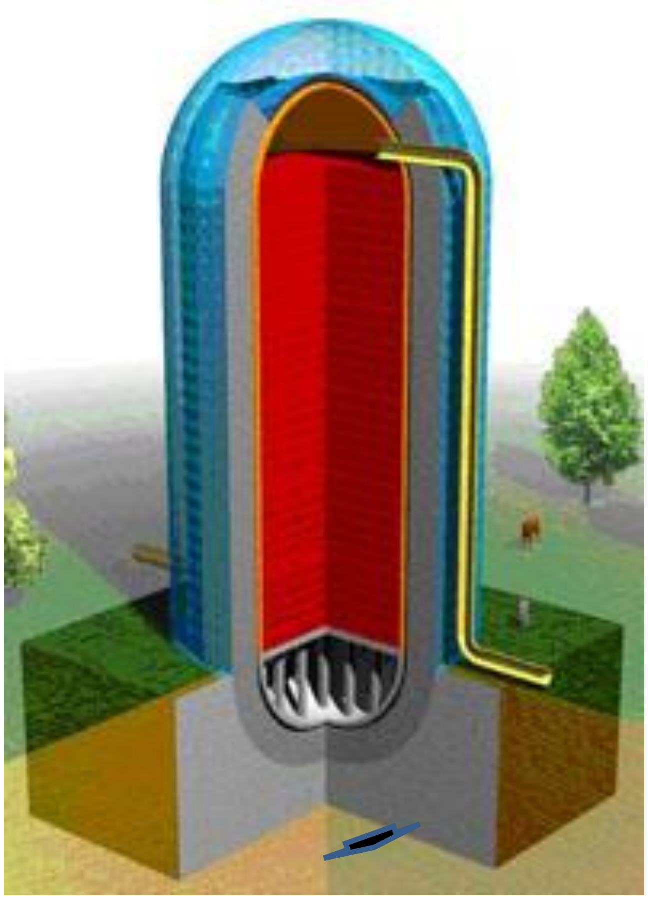
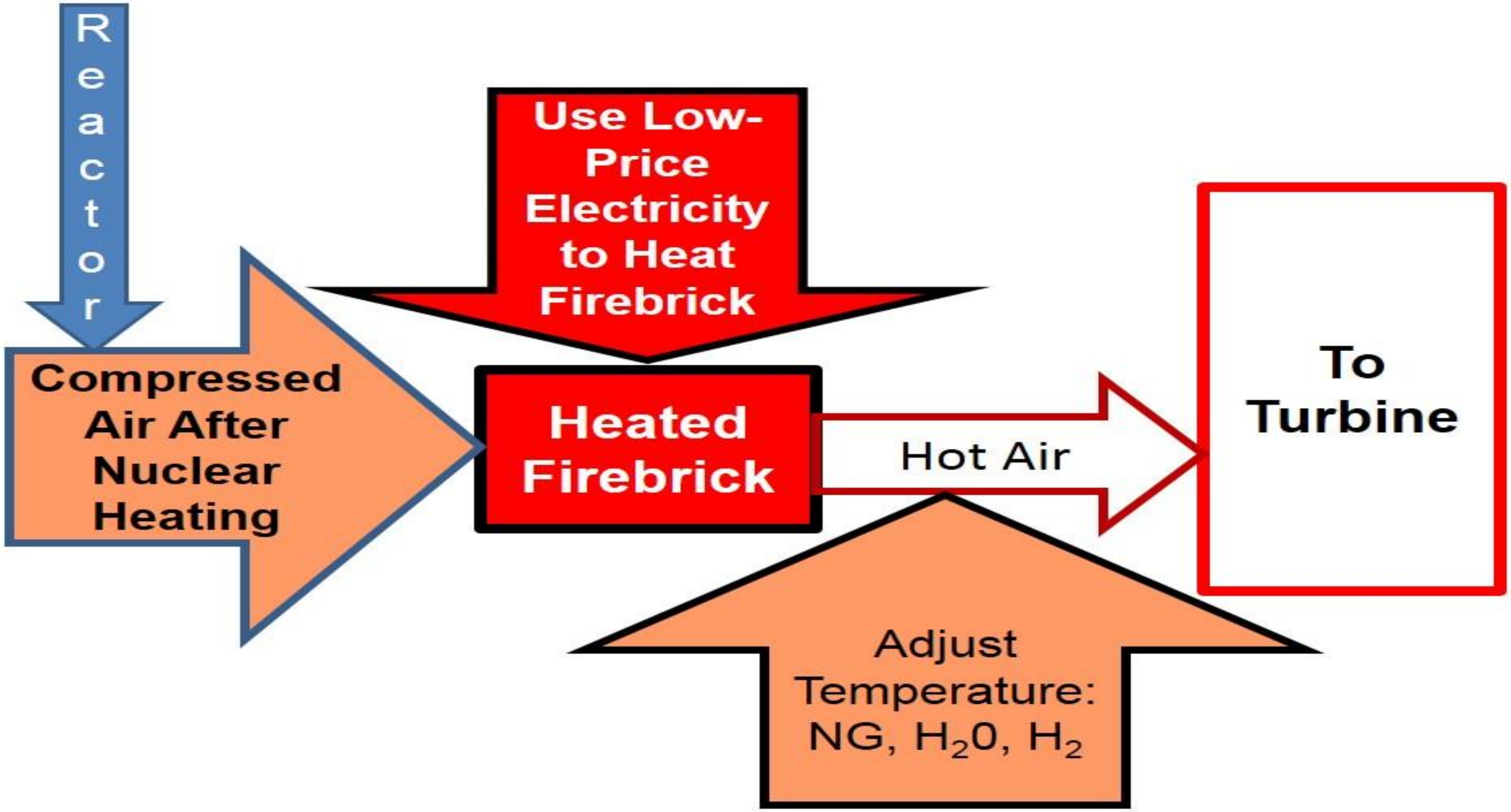


Figure courtesy of General Electric Adele Adiabatic Compressed Air Storage Project that is Integrating Firebrick Heat Storage with Gas Turbine

- Firebrick electrically heated when low electricity prices; less than price of natural gas (excess wind/solar electricity generation)
  - Electricity from FHR
  - Electricity from grid
- **Use hot firebrick as substitute for natural gas peak electricity**
- Reasonable round-trip efficiency
  - 100% electricity to heat
  - 66+% heat-to-electricity efficiency (peak power)
- **Lower cost storage than hydro pump-storage, batteries, etc.**

FIRES Is an "Electric" Storage Device Inside FHR with NACC

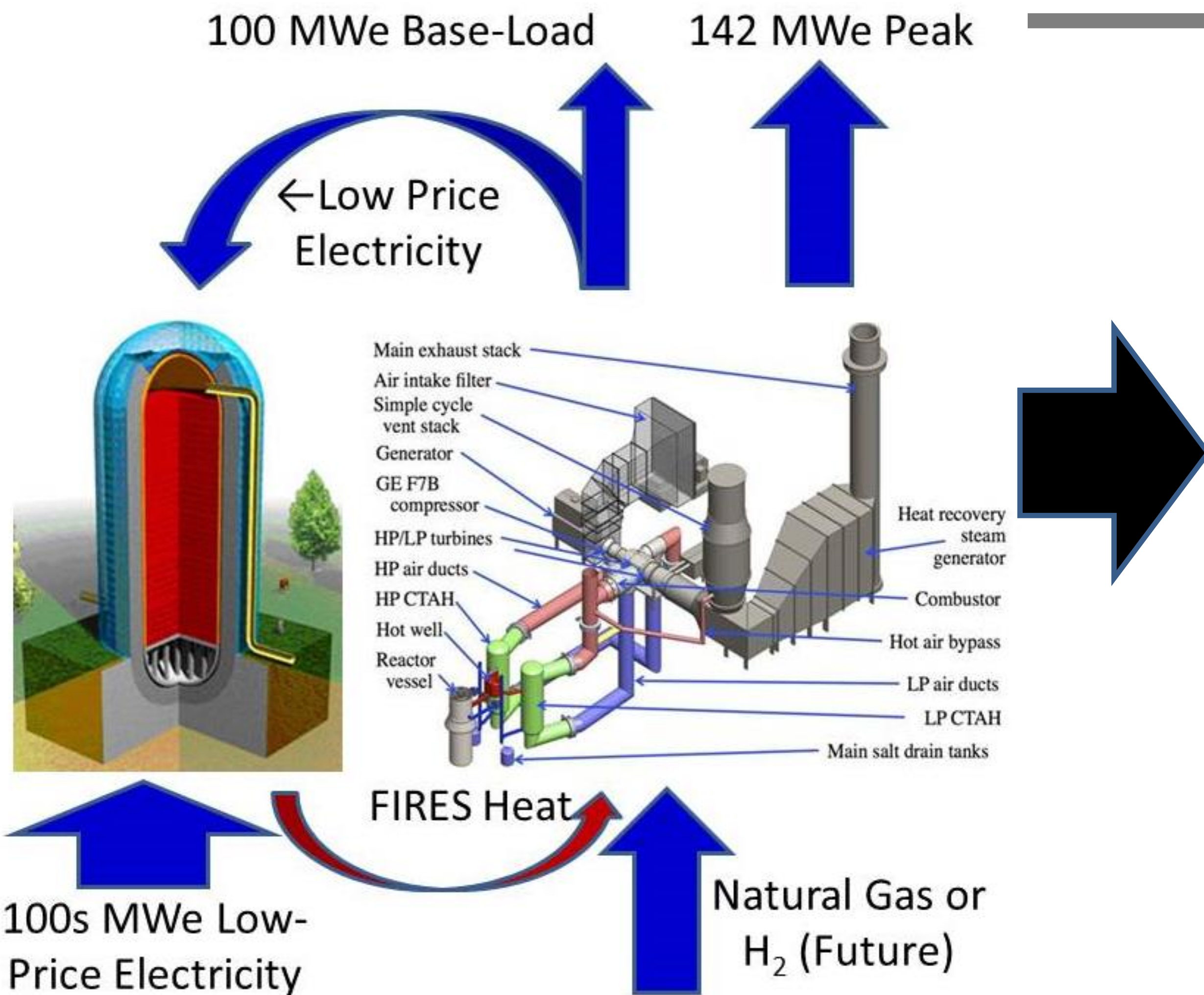
Electricity to Heat to Electricity

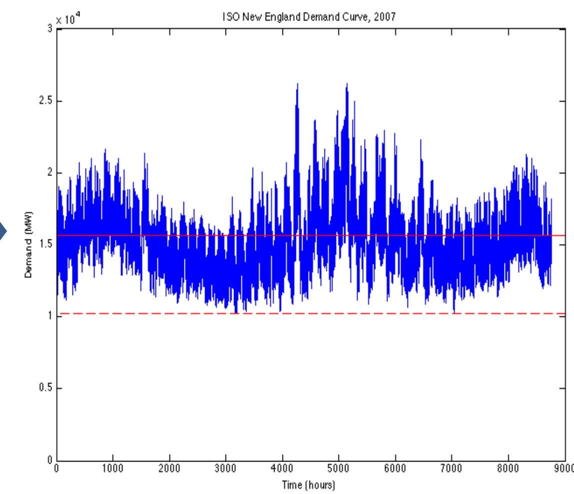


Economically Viable Because of High Efficiency in Converting Stored Heat to Peak Electricity

FHR and Power System

Base-load Electricity, Peak Electricity, Heat Storage

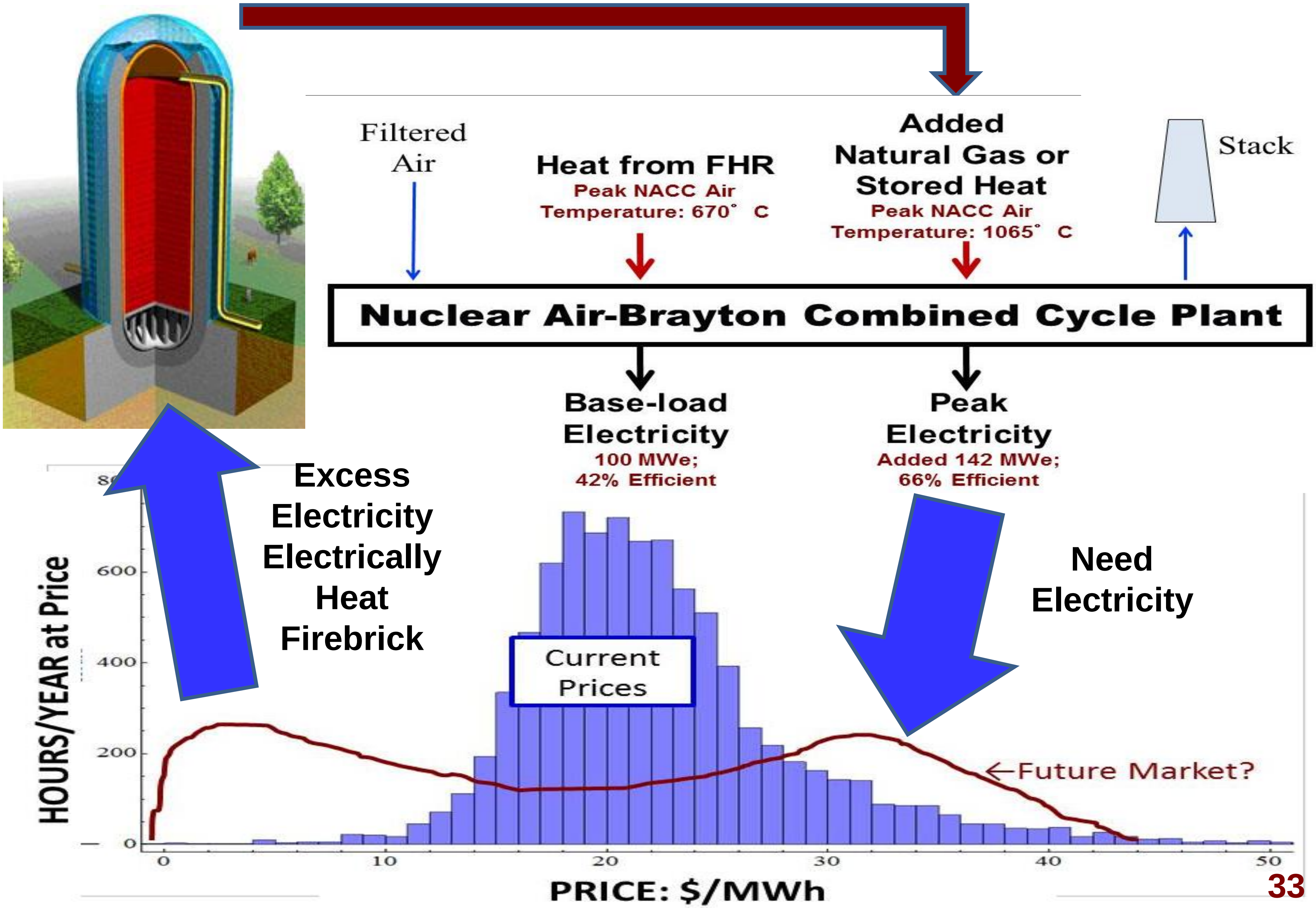




Base-Load Reactor, NACC and FIRES

Variable Electricity And Steam

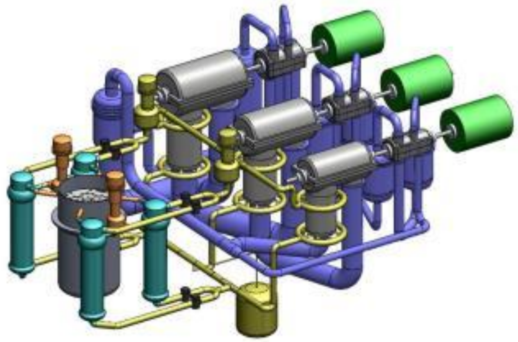
FHR/NACC/FIRES May Replace Grid Storage



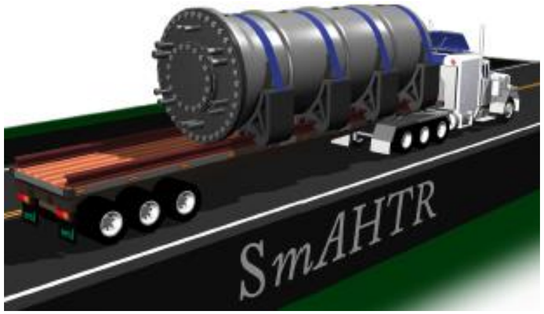
Salt-Cooled Reactor Options

Several Different Conceptual Designs of FHRs are Being Developed

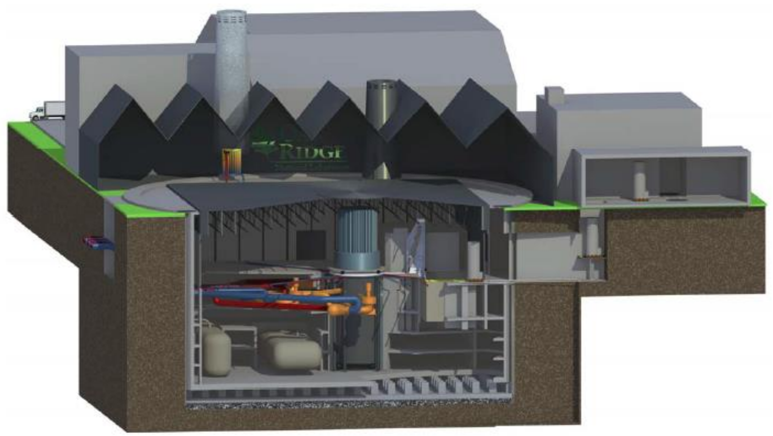
2008: 900 MWt: PB-FHR



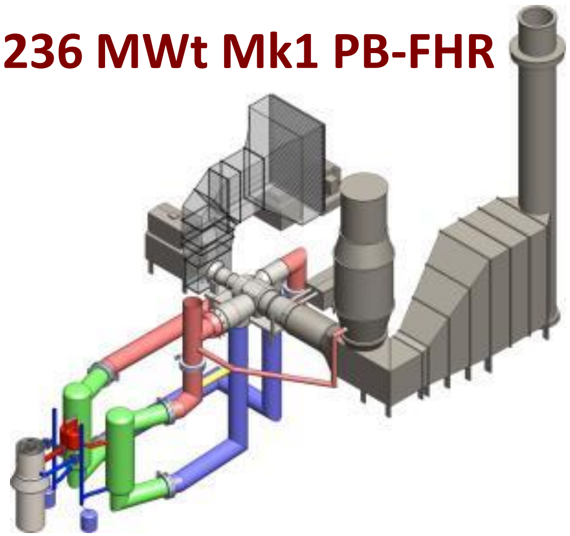
2010: 125 MWt SmAHTR



2012: 3600 MWt



2014: 236 MWt Mk1 PB-FHR

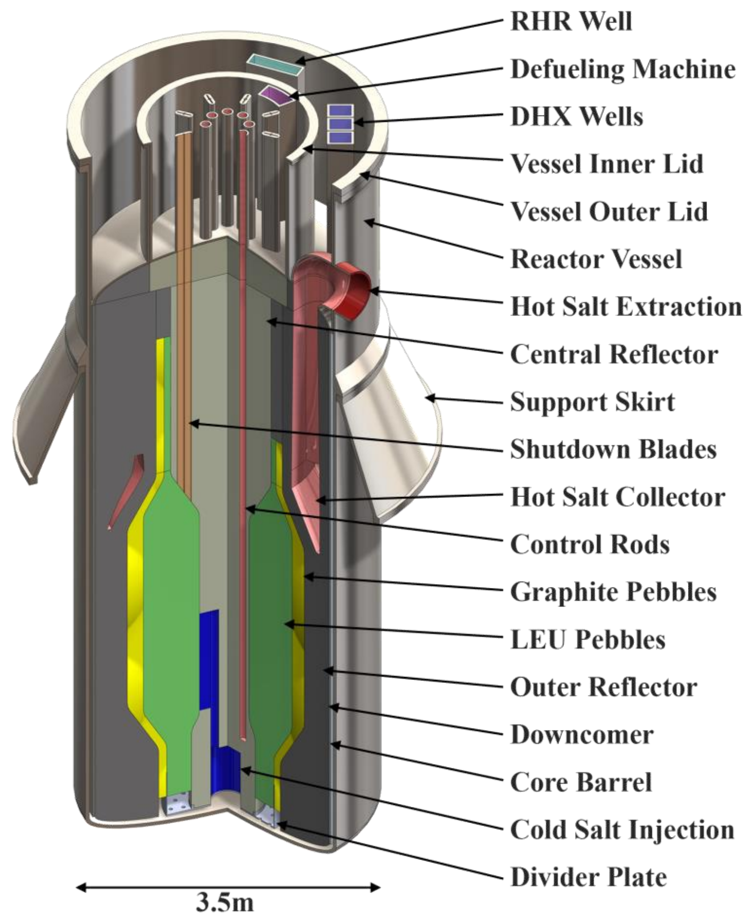


The FHR Is a Family of Reactors

- Many different designs but common features are the fuel and the clean liquid salt coolant
  - Fuel can be in many geometric forms
  - Alternative salt coolant options
  - Reactor designs from 50 to 3000 MWt
- Our baseline concept is a pebble bed FHR
  - MIT, Berkeley, Wisconsin base case
  - China plans to build a 10 MWt pebble-bed FHR
  - China is building several commercial helium-cooled pebble bed reactors
- Specific PB-FHR
  - 100 MWe baseload
  - 142 MWe peak power
  - 242 Total power when base and peak electricity production

Pebble-Bed FHR Reactor Built on Helium-Cooled Pebble Bed Reactor Technology

- Most developed design
- Similar to helium-cooled pebble bed reactor but some important differences
  - Power density 4 to 10 times higher (liquids are better than gases for cooling)
  - Low pressure rather than high pressure
  - On-line refueling
- Liquid cooling potentially results in better economics (higher power density and low pressure)

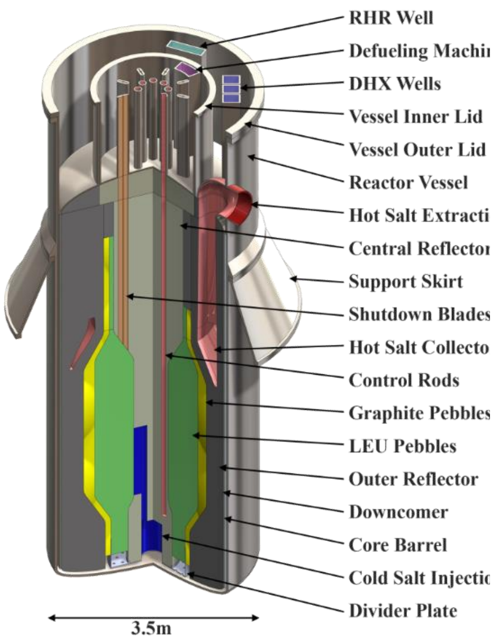


Status of FHR Today

- Concept a decade old
  - Until 15 years ago, the gas turbines were not good enough for economic concept
  - U.S. High-temperature Gas-cooled Reactor (HTGR) program developed much better fuel in the last decade
- United States
  - New concept with growing R&D
  - One of three concepts being considered for new DOE demonstration reactor
- China
  - Examined our program, launched effort
  - Goal: 10 MWt test reactor by 2020

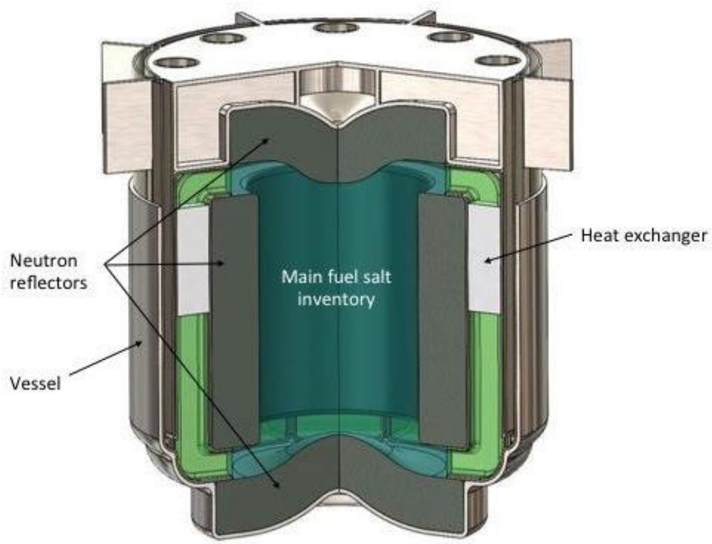
Three Classes of Salt-Cooled Reactors Can Couple to NACC Power Cycle

Requires Delivery of Heat Between 600 and 700°C



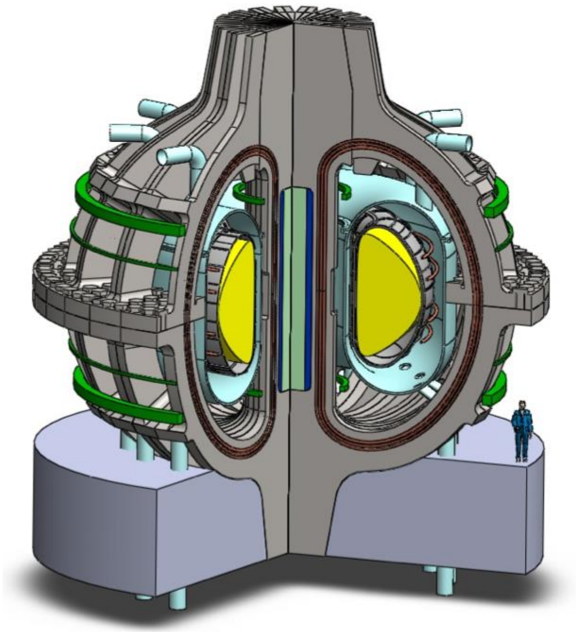
FHR

Pebble Bed



Molten Salt Reactor (MSR)

Terrapower Design



Salt-Cooled Fusion

Status of Alternative Reactor Options

- FHR Near-Term Option (~2030 if push)
  - Solid fuel and clean liquid coolant: Experience base
  - Demonstrated HTGR fuel
- Molten Salt Reactor (Midterm)
  - FHR gets one half-way to a MSR
  - Fuel dissolved in salt—added complications
  - Many groups working on concept (Terrapower, Southern)
- Fusion
  - Superconductor breakthroughs in fusion may make fusion feasible
  - New designs may require salt cooling

The U.S. Has a Competitive Advantage If It Choses to Develop the FHR

- Concept originated in the U.S.
- World leader in gas turbine technology
- World leader in high-temperature materials
- World leader in High-temperature Coated-Particle Fuel
  - Developed for High-temperature Gas-cooled Reactors (HTGRs)
  - Same basic fuel used for the FHR

Preliminary Grid Analysis

Maximizing Social Welfare by Minimizing Cost of Electricity with a Low-Carbon Constraint

Long-Term Impact of FHR/NACC/FIRES Deployment on Electricity Prices

Nestor Sepulveda, Charles Forsberg, Richard Lester

Grid Analysis Assumptions/Methodology-1

- Greenfield 2050 generating mix with 1% yearly growth from 2015 to 2050
- Real hourly data for demand and wind/solar capacity factors
- No deployment capacity constraints (Land, etc.)
- Model solves for optimal investment and operation considering
  - Unit commitment, startup, shutdown, and startup costs
  - Ramp rates for up and down between consecutive hours
  - Up and down efficiencies for storage charge and discharge
  - Minimum stable output and maximum output
- Cost assumptions
  - IEA and NEA 2015 report on cost generation
  - FIRES: $15//kwh
  - FHR cost per kWe identical to LWR plus adjustment for peaking gas turbine capability

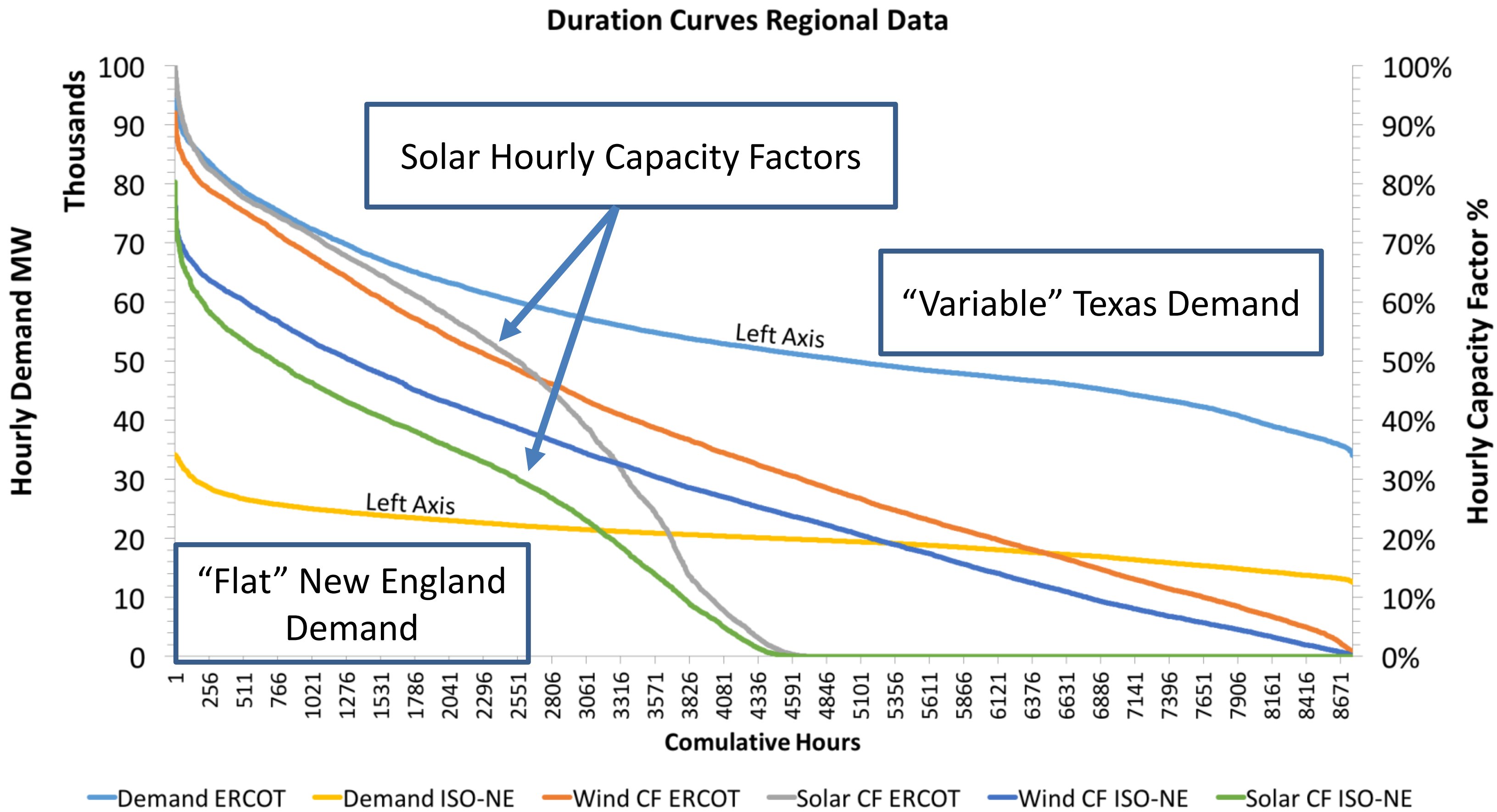
Grid Analysis: Technologies Available

- Combined cycle gas turbine (natural gas)
- Open cycle gas turbine (natural gas)
- Nuclear (LWR, traditional)
- Solar (PV)
- Wind (on shore)
- Pumped hydro
- Batteries
- Demand-side Management (shift load in time)
- Demand response (Curtail load)
- Heat Storage (FIRES)
- Advanced Nuclear (FHR with NACC)*

***FHR with NACC and FIRES can operate on nuclear with peaking using stored heat or natural gas depending upon economics and allowable CO_2 emissions. In terms of capacity, treated as buying base-load but has peaking capacity that comes with that base load—does not fit any of the usual categories.**

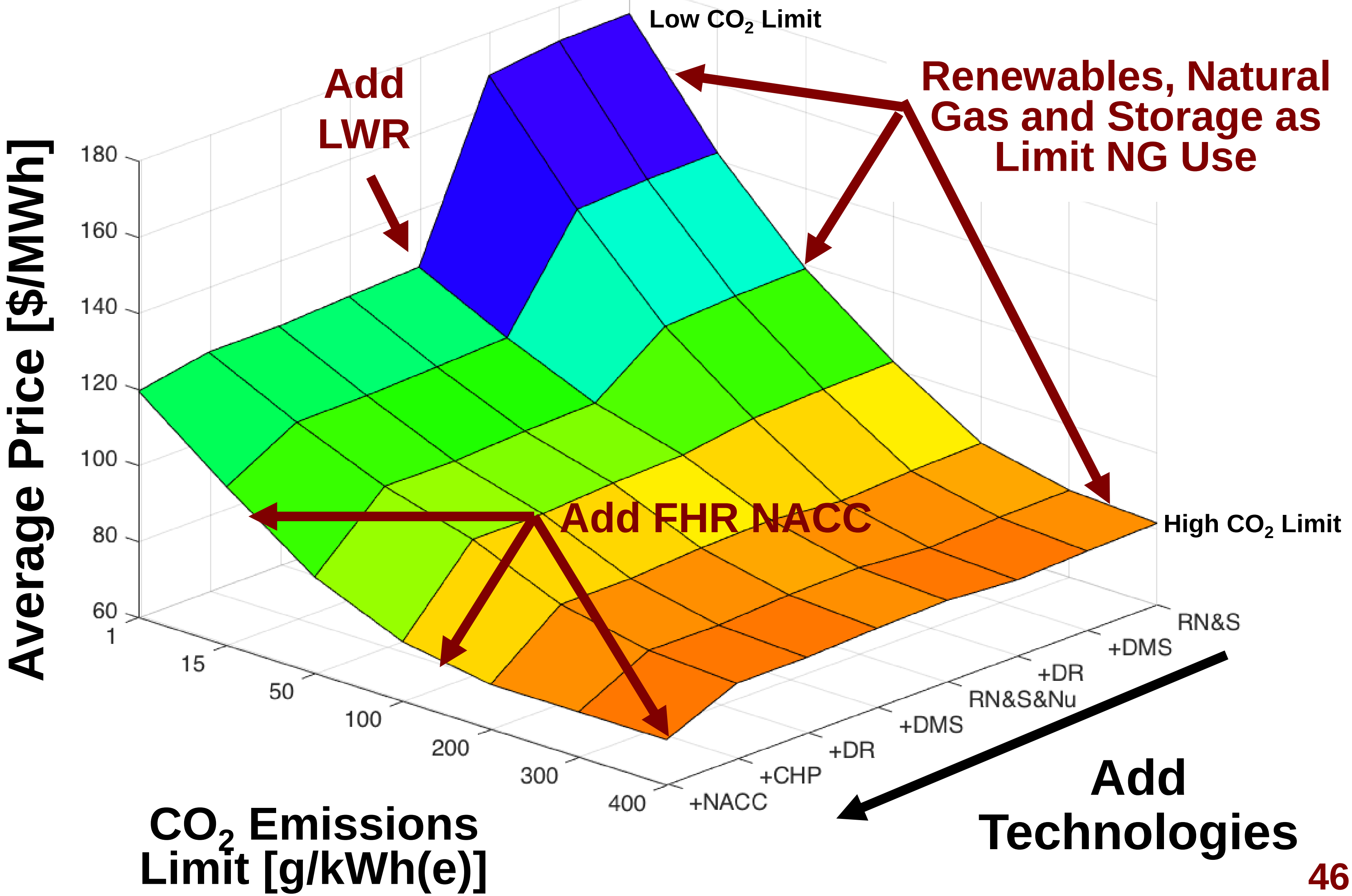
Results are Grid Dependent

Texas and New England ISO (Grids)



2050 Minimum-Cost Texas Grid Versus Added Technologies and CO_2 Limits

Addition of FHR/NACC/FIRES Lowers Average Electric Prices



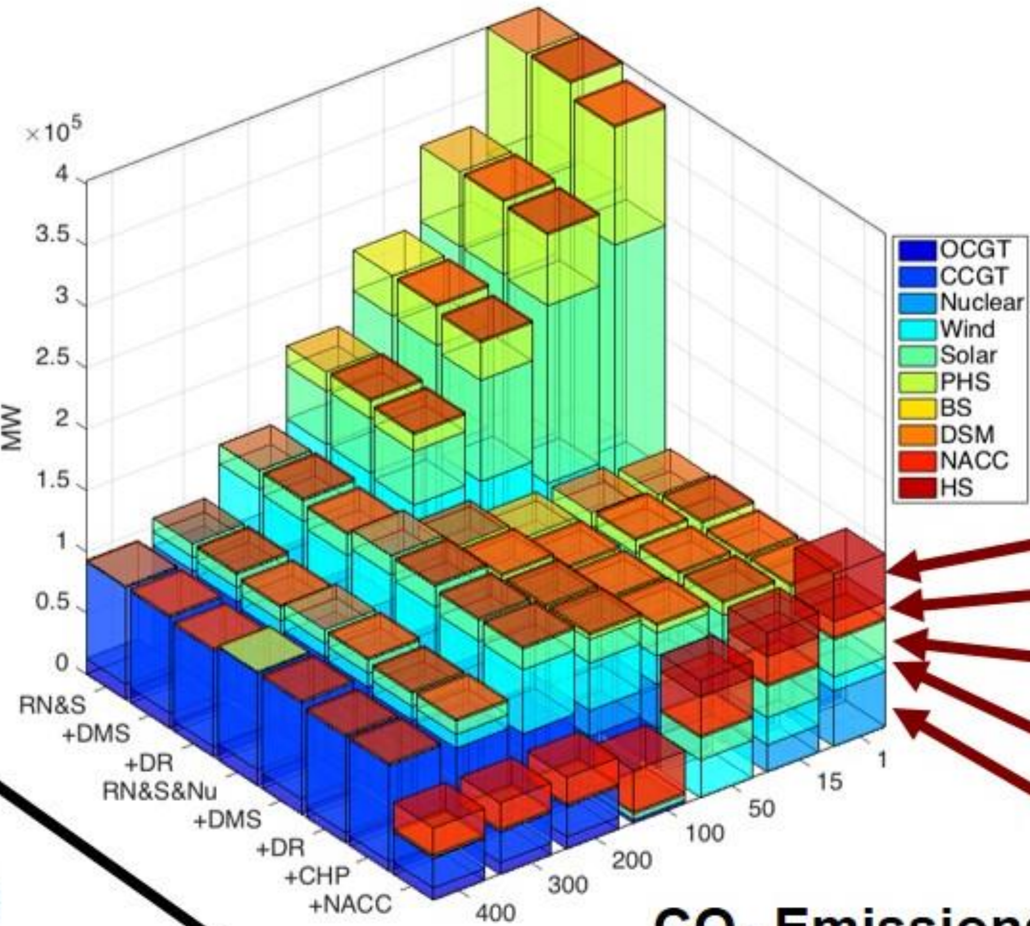
Key to Technology Options on 3-Dimensional Plots (Next Viewgraph)

- First set of combinations considers
  - RN&S: Renewables, Natural Gas and Storage
  - +DMS: Demand Management
  - +DR: Demand Reduction
- Second set of combinations considers
  - RN&S&Nu: Renewables, Natural Gas, Storage and Nuclear (Traditional)
  - +DMS: Demand Management
  - +DR: Demand Reduction
  - +CHP: FIRES (Industrial and other applications)
  - +NACC: FHR with NACC and FIRES (Base-load reactor where the plant buys or sells electricity depending upon market conditions)

2050 Texas Installed Capacity Versus Added Technologies and CO_2 Limits

Technology Choices Change with CO_2 Limits and Added Technologies

Installed Capacity



FHR NACC

DSM

Solar

Wind

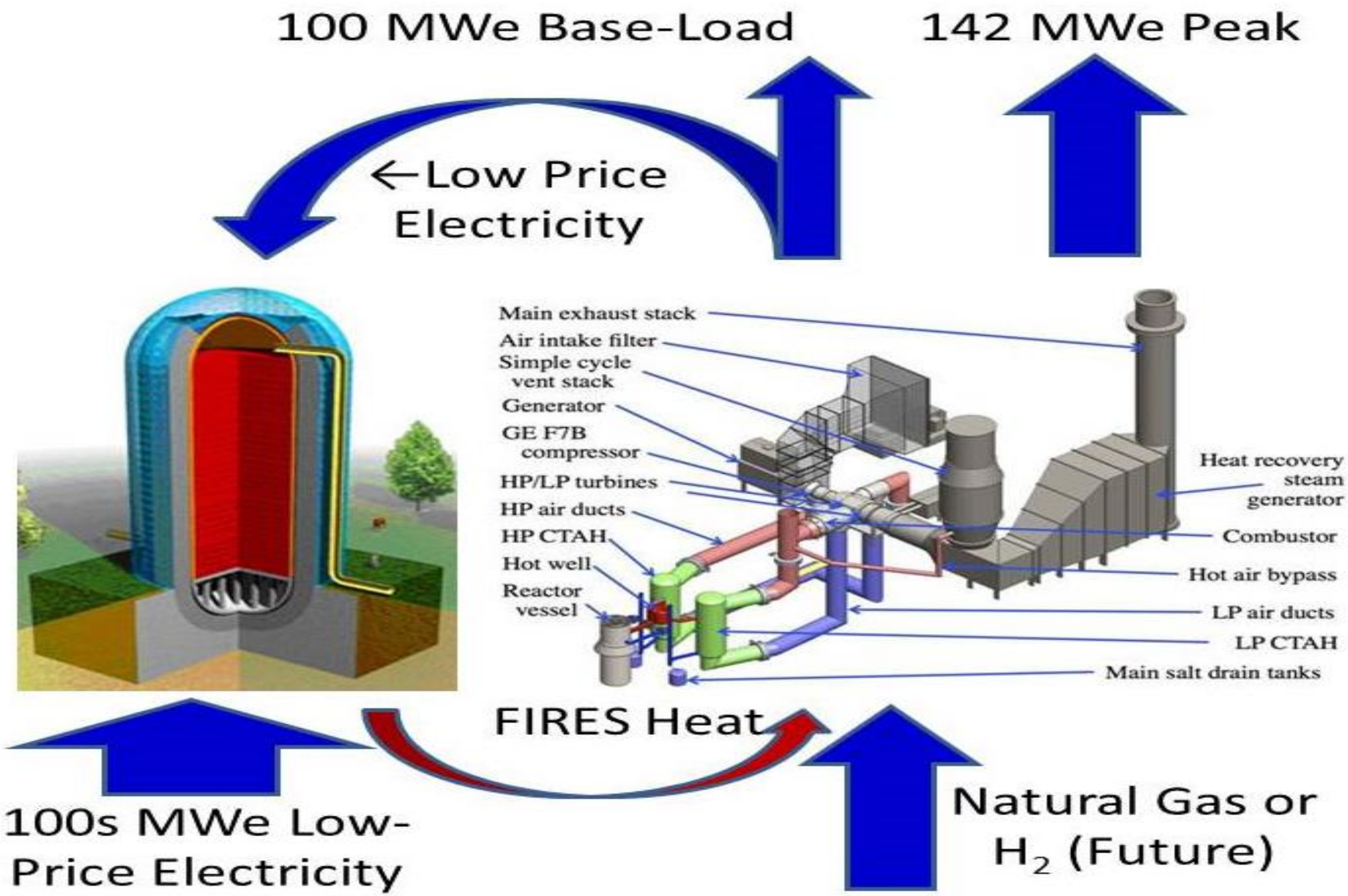
LWR

Add Technologies

CO_2 Emissions Limit [g/kWh(e)]

Salt-Cooled Reactors with NACC and FIRES Create a New Class of Reactors to Meet Different Market Needs

LWRs and FHRs/NACC/FIRES May Co-exist (Last Slide) in the Same Market

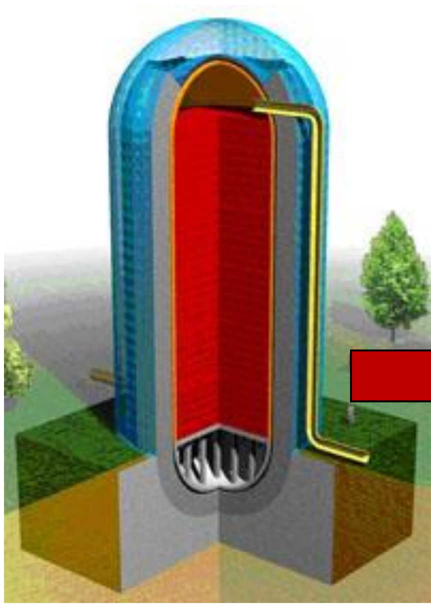


Conclusions

- No FHR has been built. It is a new concept enabled by advances in:
  - Combined cycle gas turbines (not viable 20 years ago)
  - High-temperature fuels developed for gas-cooled high-temperature reactors
- Reactor + Gas Turbine + FIRES enables
  - Increased revenue relative to base-load nuclear reactors
  - Enabling technology for zero-carbon electricity grid
  - Opens new markets for nuclear power because of <u>functionally different capabilities</u>
- High-temperature fuel + high-temperature coolant enables no major fuel failures (no major radionuclide releases) in major accidents
- Significant development required

Questions

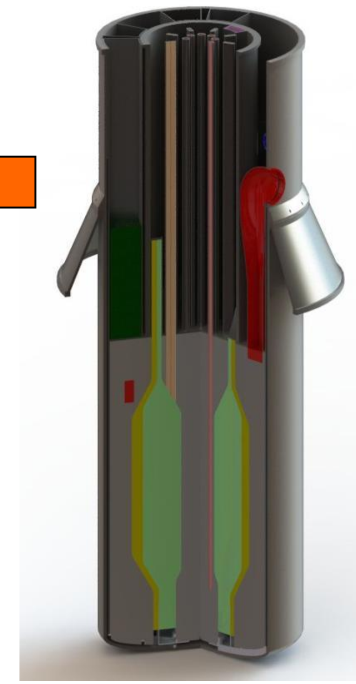
FIRES
Stored Heat

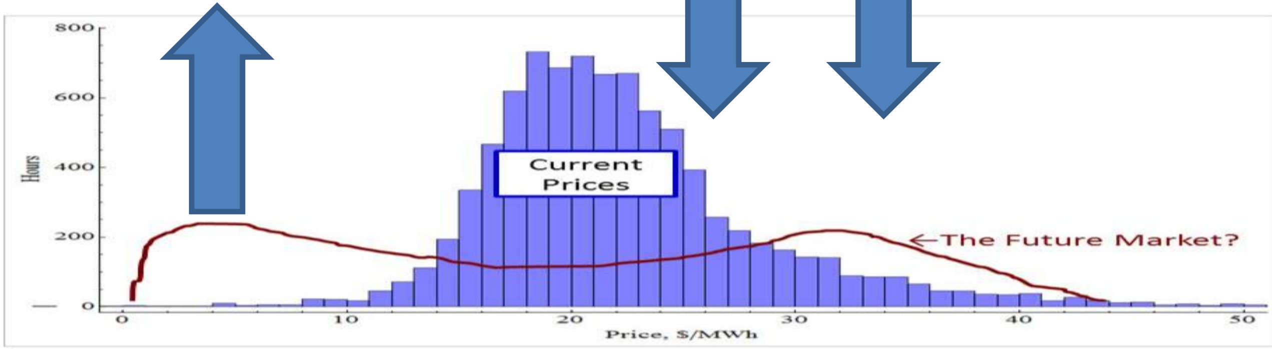


Combustible Fuel

Gas Turbine(NACC)

FHR
Constant High-Temperature Heat: 600-700°C





Biography: Charles Forsberg

Dr. Charles Forsberg is the Director and principle investigator of the High-Temperature Salt-Cooled Reactor Project and University Lead for the Idaho National Laboratory Institute for Nuclear Energy and Science (INEST) Nuclear Hybrid Energy Systems program. He is one of several co-principle investigators for the Concentrated Solar Power on Demand (CSPonD) project. He earlier was the Executive Director of the MIT Nuclear Fuel Cycle Study. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory. He is a Fellow of the American Nuclear Society, 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 hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design on salt-cooled reactors and the 2014 Seaborg Award. 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 has published over 200 papers.

Abstract: FHR with NACC and FIRES

The Fluoride-salt-cooled High-Temperature Reactor (FHR) with a Nuclear Air-Brayton Combined Cycle (NACC) and Firebrick Resistance Heated Energy Storage (FIRES) is a new reactor concept. It is designed to (1) increase revenue relative to base-load nuclear power plants by 50 to 100% (California and Texas markets) and compete with stand-alone natural gas plants, (2) enable a zero-carbon nuclear-renewable electricity grid by addressing the challenges of price collapse at times of high solar / wind input and providing electricity at times of low solar / wind input—with steam to industry, and (3) eliminate the potential for major fuel failures in severe accidents.

With the reactor operating at base-load, the plant can (1) deliver base-load electricity to the grid with a thermal efficiency of 42%, (2) deliver peak electricity to the grid using auxiliary natural gas or stored heat at times of high electricity prices with an incremental thermal efficiency of 66%--far exceeding the best stand-along natural gas plants, or (3) buy electricity and store as heat when electricity prices are below that of natural gas for peak power production at a later time. The system may provide grid electricity storage to replace pumped hydro storage, batteries, and other devices. These different capabilities create a new class of reactor technologies to meet different market needs. This implies that in some markets traditional nuclear (LWRs) and FHR coexisting because they meet different market needs because of their different functional capabilities.

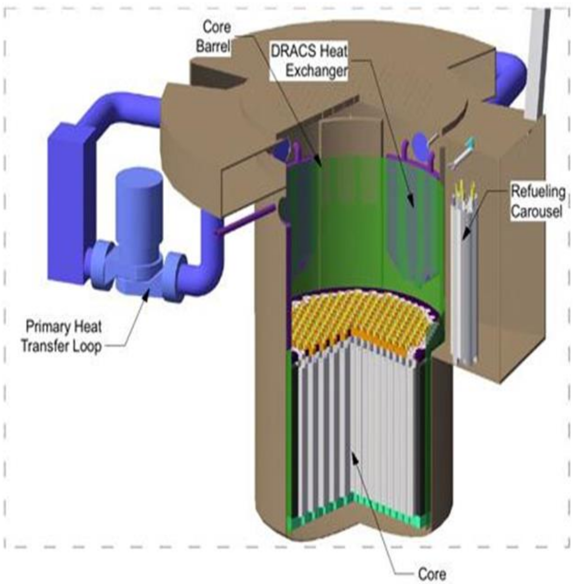
These capabilities are a consequences of (1) coupling the FHR (high-temperature gas-cooled reactor fuel and liquid salt coolant) to a gas turbine, (2) advances in gas turbine technology, and (3) advances in high-temperature fuels. MIT leads a university consortium with the University of California at Berkeley and the University of Wisconsin to develop the reactor. The Chinese Academy of Science plans to start up a 10 MWt test reactor by 2020. As a new reactor concept there are significant uncertainties and major development work is required. The four major FHR with NACC and FIRES project reports can be downloaded at: http://web.mit.edu/nse/people/research/forsberg.html. Added information at http://fhr.nuc.berkeley.edu/

Appendix A

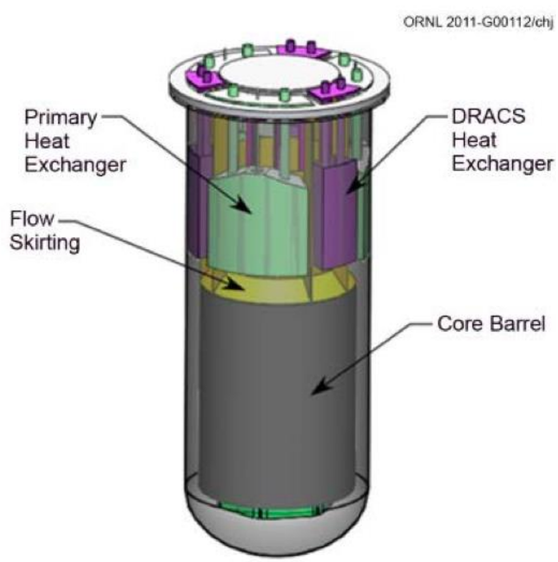
FHR Designs and Fuel

Several Different Conceptual Designs of FHRs are Being Developed

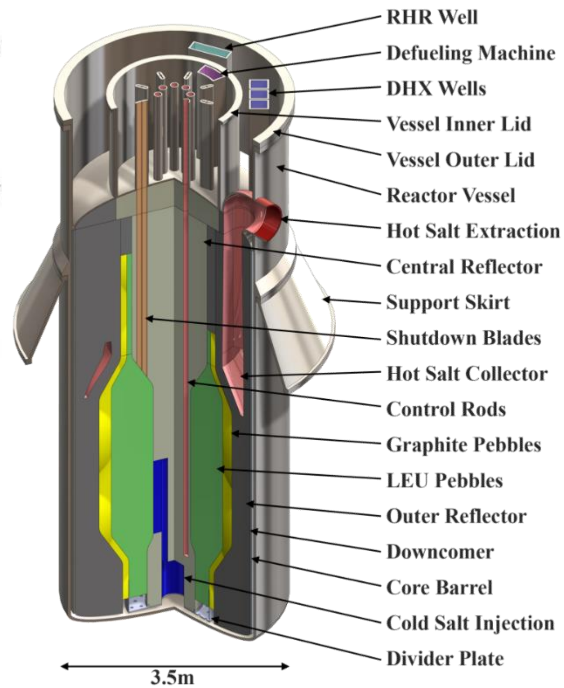
2012 3600 MWt
ORNL



2010 125 MWt
SmAHTR

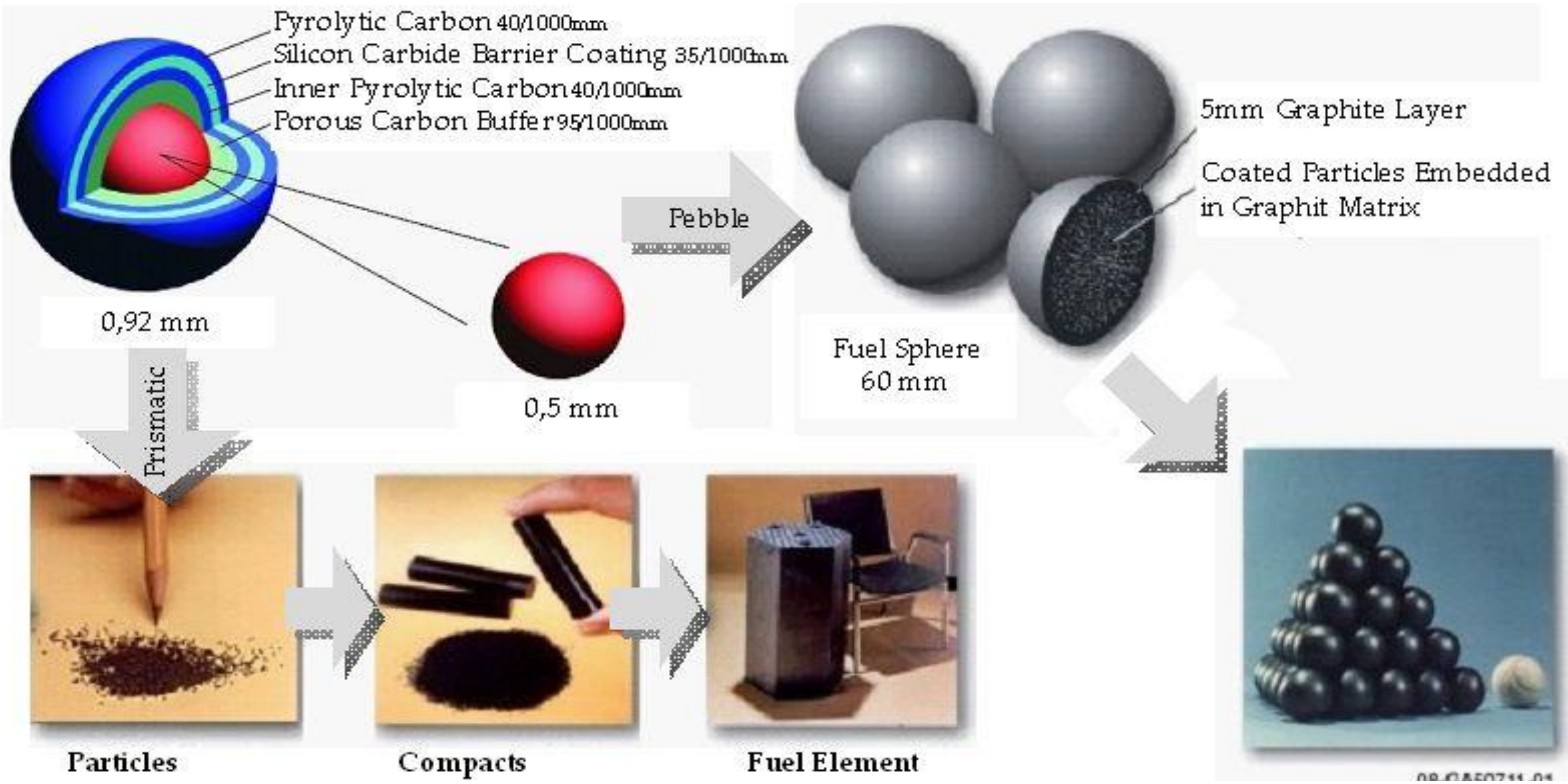


2014 236 MWt
Mk1 PB-FHR



FHR Uses HTGR Graphite-Matrix Coated-Particle Fuel

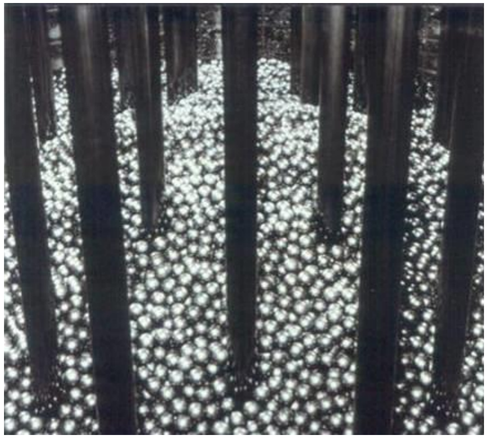
Several Alternative Fuel Geometries; Same Fuel as NGNP



Failure Temperatures > 1650° C

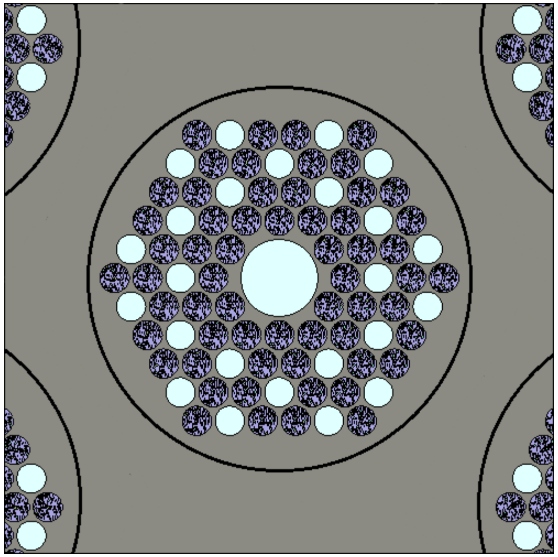
Many Geometrical Fuel Options

All Are Graphite-Matrix Coated-Particle Fuels



Pebble Bed

Fuel Plates in Hex Configuration

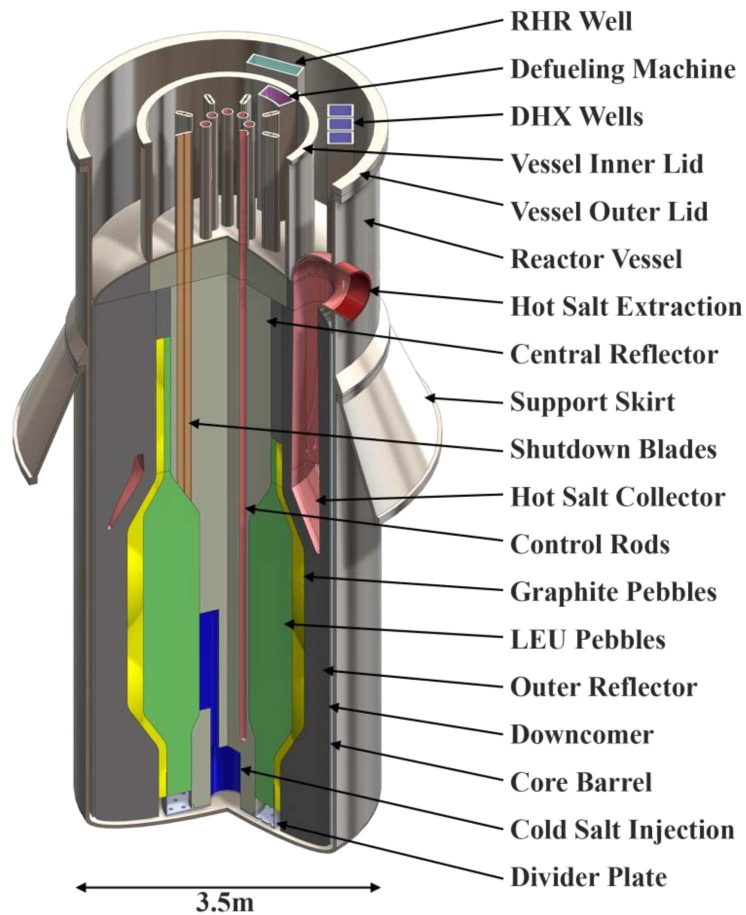


Fuel Inside Radial Moderator (FIRM)

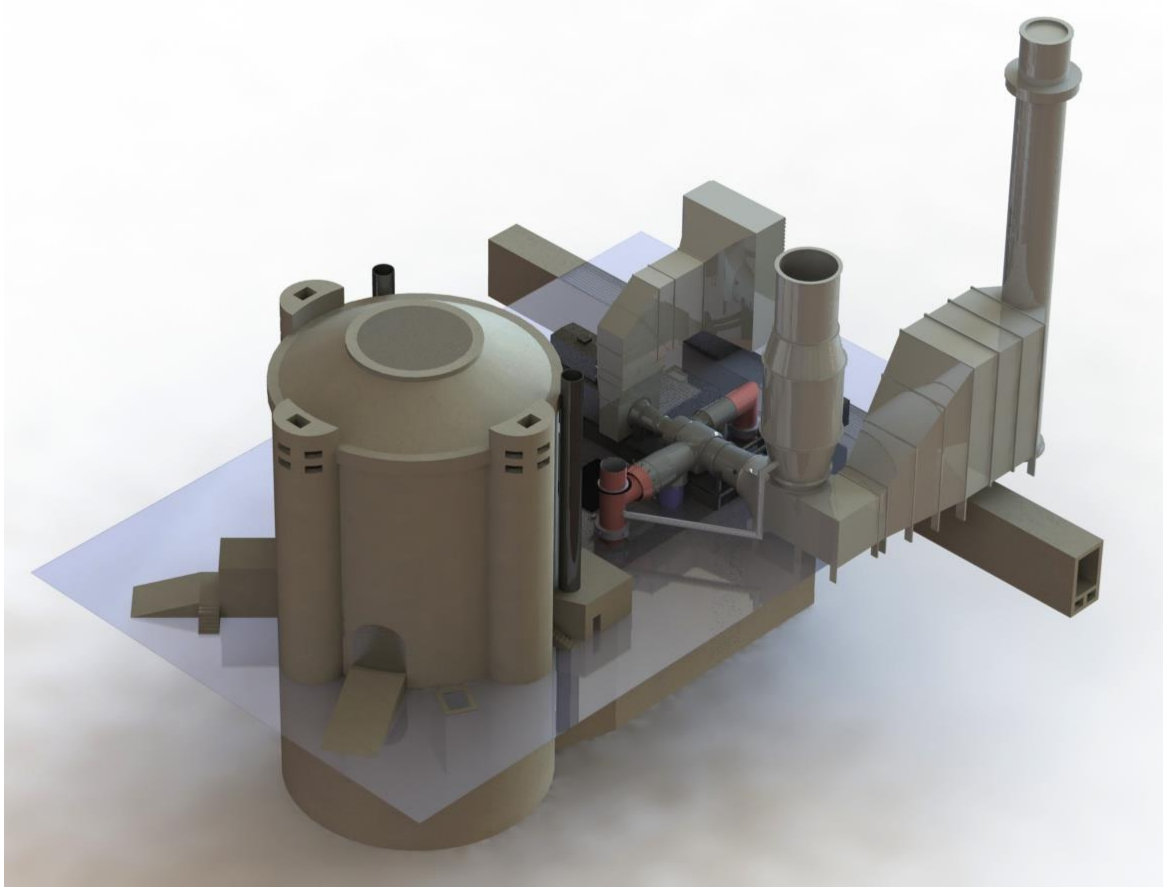
- Pebble bed: Base-Case: Current technology
- Plate Fuel: Existing materials, New Design
- Fuel in Radial Moderator: Variant of HTGR Prismatic Block Fuel

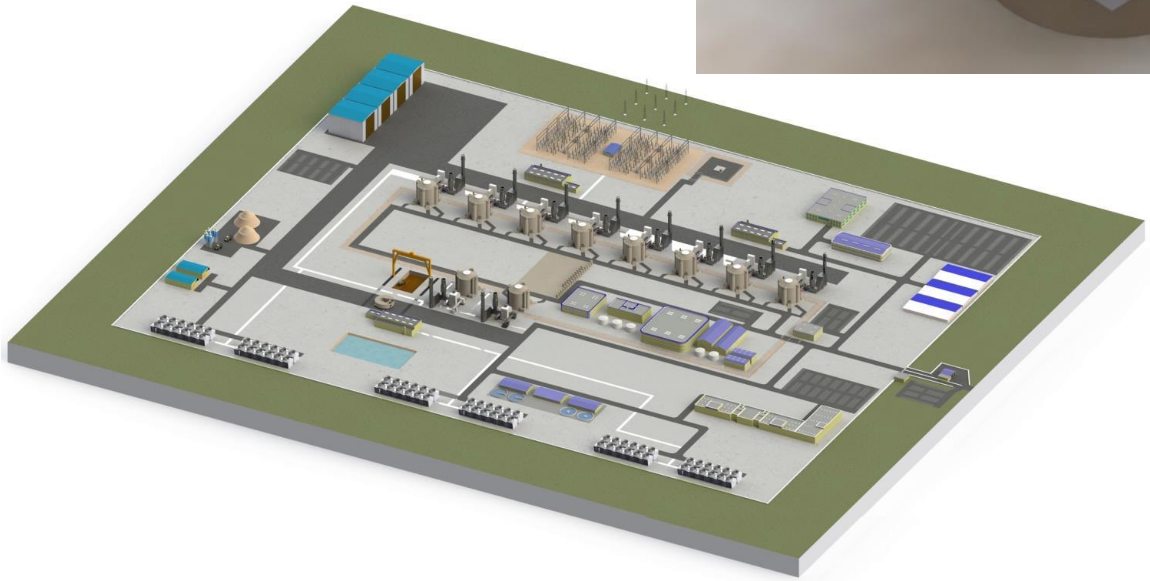
Pebble-Bed FHR Reactor Built on Helium-Cooled Pebble-Bed Reactor Technology

- Most developed design
- Similar to helium-cooled pebble bed reactors
  - FHR power density 4 to 10 times higher because liquids are better coolants than gases
  - On-line refueling (but pebbles float in salt so pebbles out top



FHR Plant and Site Design



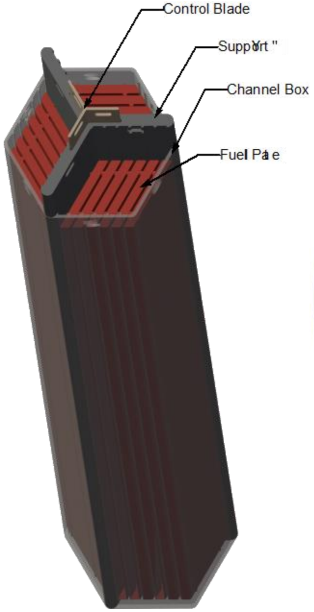


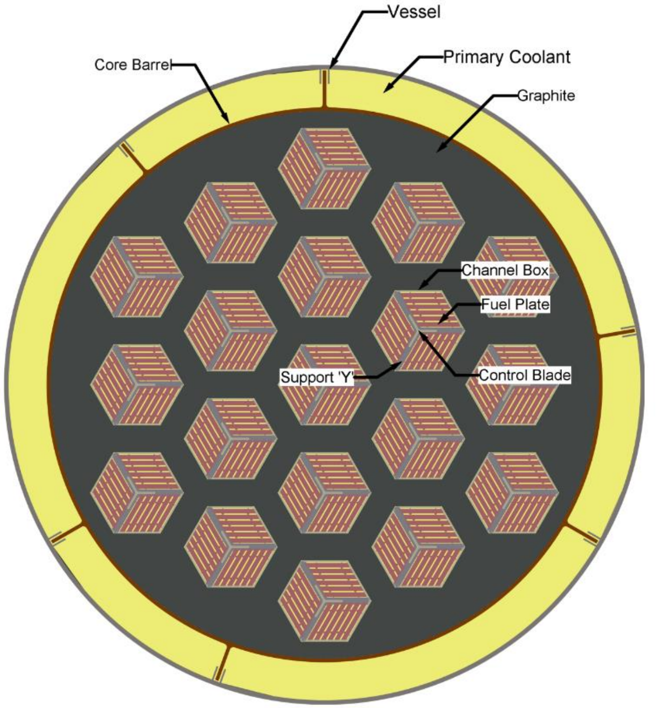
Notional 12-unit Mk1 station

1200 MWe base load; 2900 MWe peak

Plate-Type FHR Reactor Has a Traditional-Geometry Fuel Assembly

- Fuel assembly similar to traditional reactors
- New fuel assembly design
  - Carbon-carbon plates
  - Coated-particle fuel in carbon as a layer on the plates



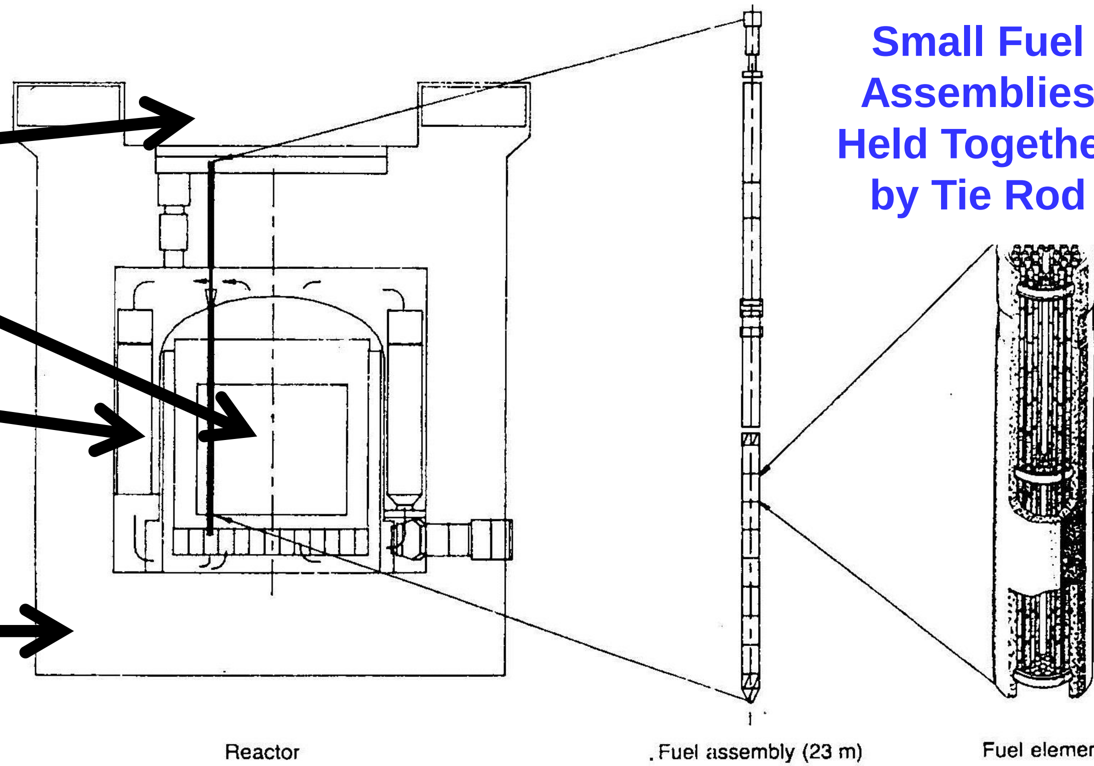


*D. Ilas, D. E. Holcomb, and J. C. Gehin, "SmAHTR-CTC Neutronic Design", PHYSOR 2014, Kyoto, Japan, Sep 28-Oct 3, 2014

FIRM FHR: HTGR Prismatic Fuel and British Advanced Gas-Cooled High-Temperature Reactor (AGR)

Use AGR Core, External Fuel Geometry and Refueling Designs

- Refueling Floor
- Graphite Core
- Boiler
- Pre-Stress Concrete Reactor Vessel

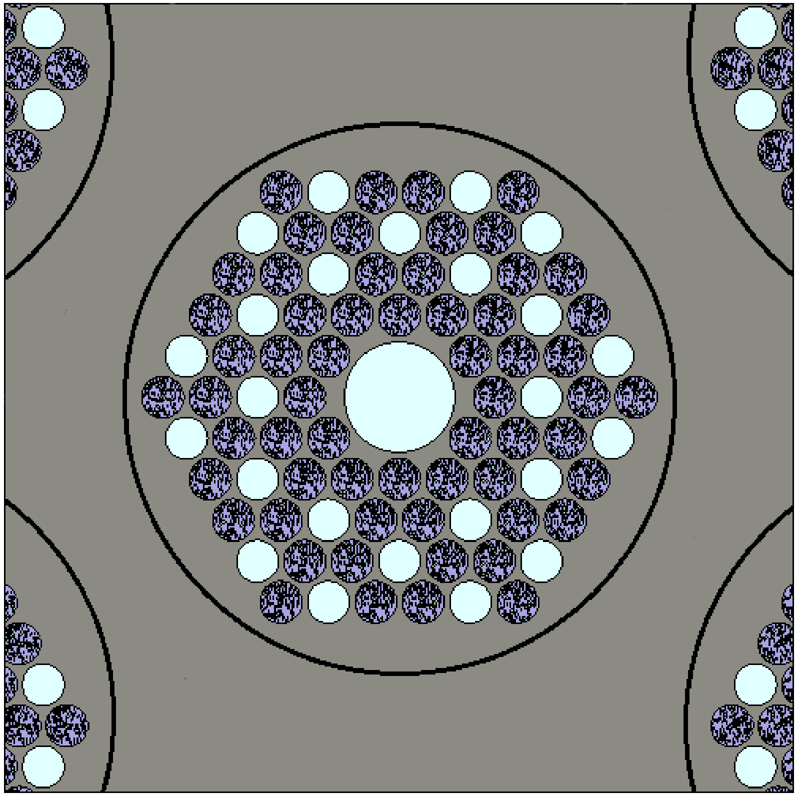


Small Fuel Assemblies Held Together by Tie Rod

Design Above: 14 AGRs Operating (2-Reactor Plants)
Graphite Moderated, Carbon- Dioxide Cooled, Metal-Clad Pin Fuel

Fuel Inside Radial Moderator (FIRM) Assembly Design

- Surround fuel and coolant channels with solid graphite region
  - 54 fuel channels
  - 24 coolant channels
  - Central hole for handling and materials irradiations
- Introduces spatial resonance self-shielding:
  - Enhances resonance escape probability
  - Significantly increases fuel burnup



Fuel Design is Variant of Proven Ft. St. Vrain Gas-Cooled High-Temperature Reactor Fuel

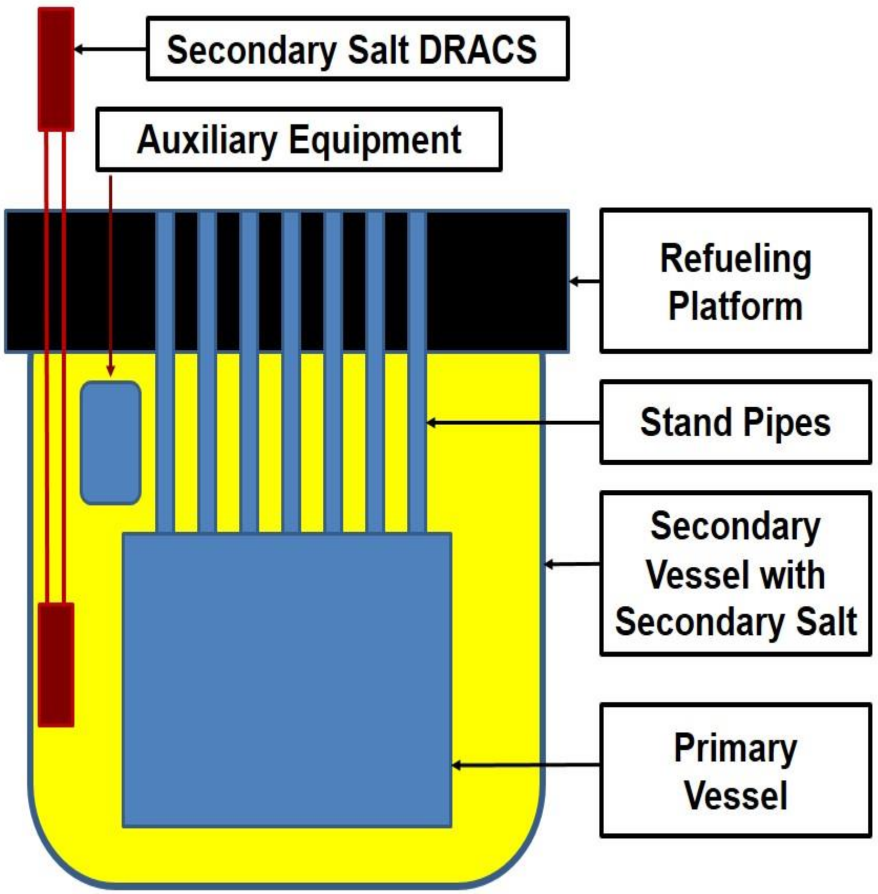
Similar FHR and AGR FIRM Fuel Geometry →Similar Core Designs

- Similar refueling (AGR 650°C versus 700°C peak FHR coolant temperatures)
- Similar in-core graphite inspection / maintenance
- Similar instrumentation
- Similar control rod systems
- 50-year AGR operational experience base to build upon

But FHR is Low-Pressure with Liquid Cooling so Much Smaller Machine and Couples to NACC

AGR "Like" FHR Creates New Reactor System Design Options

- Refueling same as AGR, direct vertical pull of fuel assemblies
- Primary coolant tank surrounded by secondary salt tank
  - Low-cost secondary salt
  - Secondary vessel decay heat sink
  - Radiation shielding
  - Low-stress primary reactor vessel



Advanced Fuel Option: Work at General Atomics and Elsewhere May Enable FHR Pin-Type Fuel Assemblies

- Lower fuel fabrication costs
- Lower enrichments with higher fuel loading
- Longer fuel cycle and higher burnup (less waste)
- Work in progress—being developed as part of LWR accident tolerant fuel program

Appendix B

FHR Liquid Salts

Base Case Salt is $^{7}Li_2BeF_4$ (Flibe)

There Are Alternative Coolant Salts

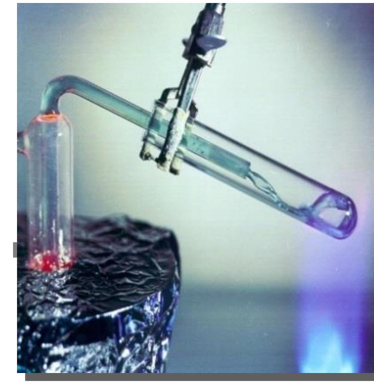
Coolant	T_{melt} (°C)	T_{boil} (°C)	ρ (kg/m^3)	ρC_p (kJ/m^3 °C)
$^{7}Li_2BeF_4$ (Flibe)	**459**	**1430**	**1940**	**4670**
59.5 NaF-40.5 ZrF_4	500	1290	3140	3670
26 ^{7}LiF-37 NaF-37 ZrF_4	436		2790	3500
51^{7} LiF-49 ZrF_4	509		3090	3750
Water (7.5 MPa)	0	290	732	4040

Salt compositions are shown in mole percent. Salt properties at 700ºC and 1 atm. Sodium-zirconium fluoride salt conductivity is estimated—not measured. Pressurized water data are shown at 290°C for comparison.

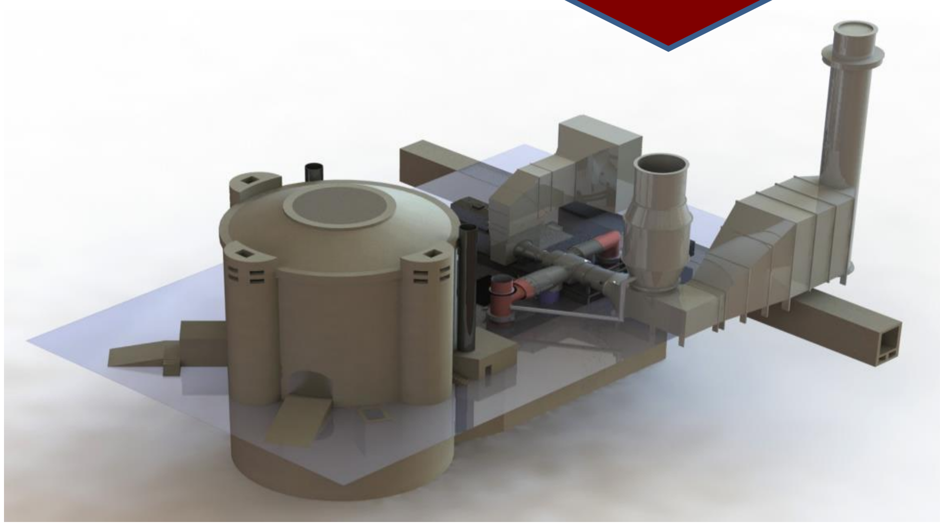
Appendix C

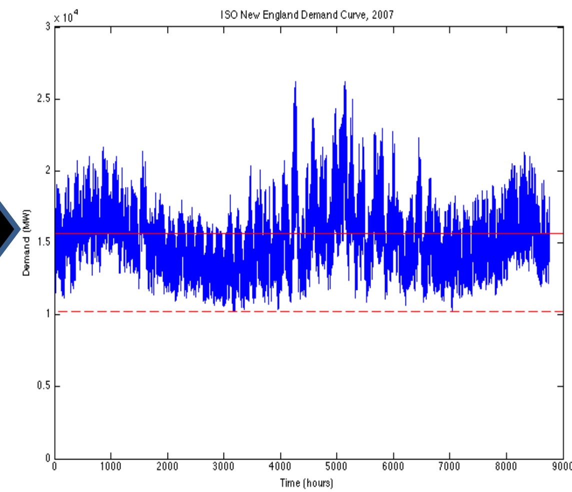
Power Cycle and Economics

Fluoride-Salt-Cooled High Temperature Reactor (FHR) with Nuclear Air-Brayton Combined Cycle (NACC)



Stored Heat and/or Natural Gas





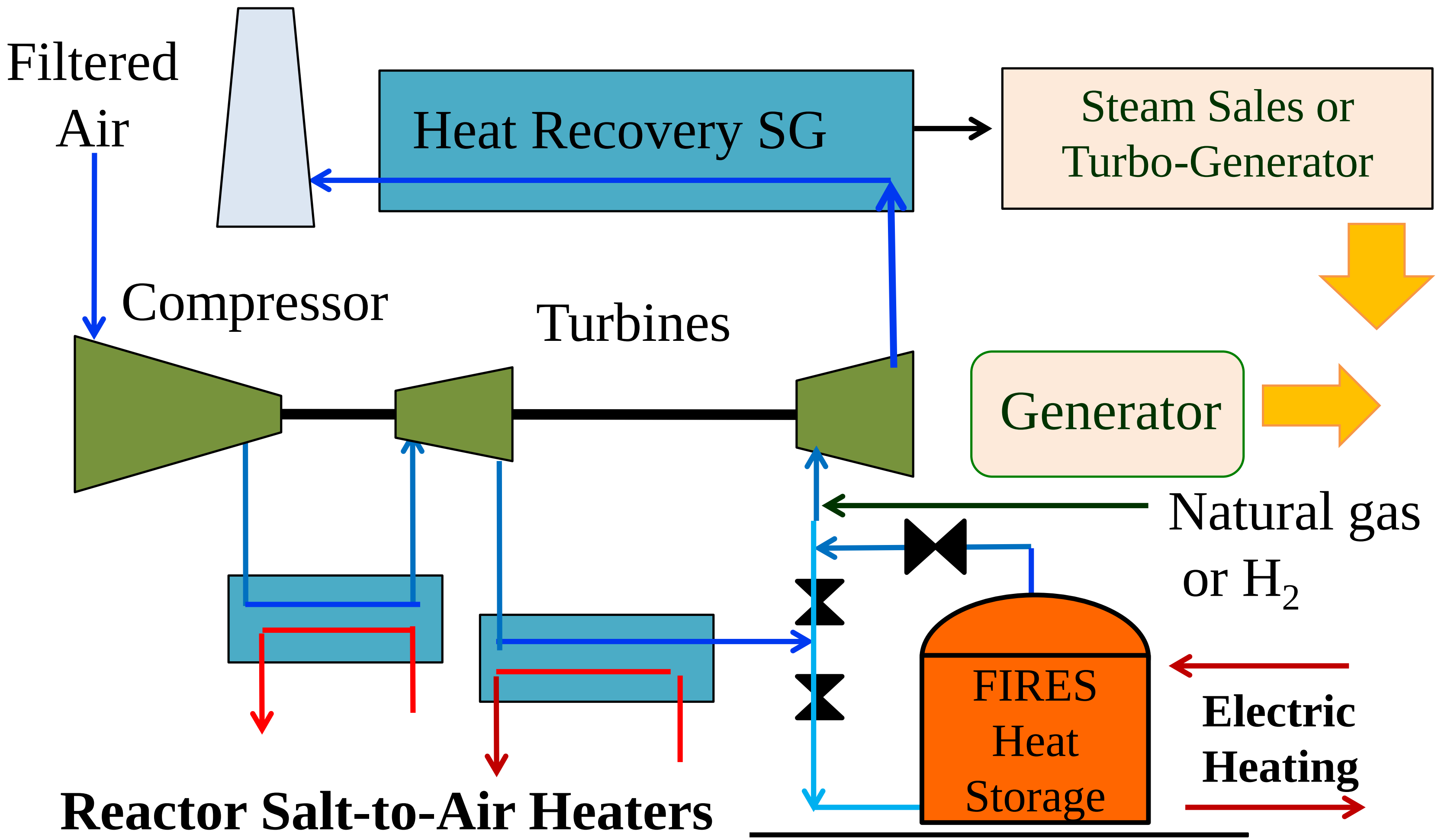
Base-Load Reactor | **Gas Turbine**

Variable Electricity, Steam and Hot Air

Enabled by Advances in Natural Gas Combined Cycle Plants and High-Temperature Reactor Fuels

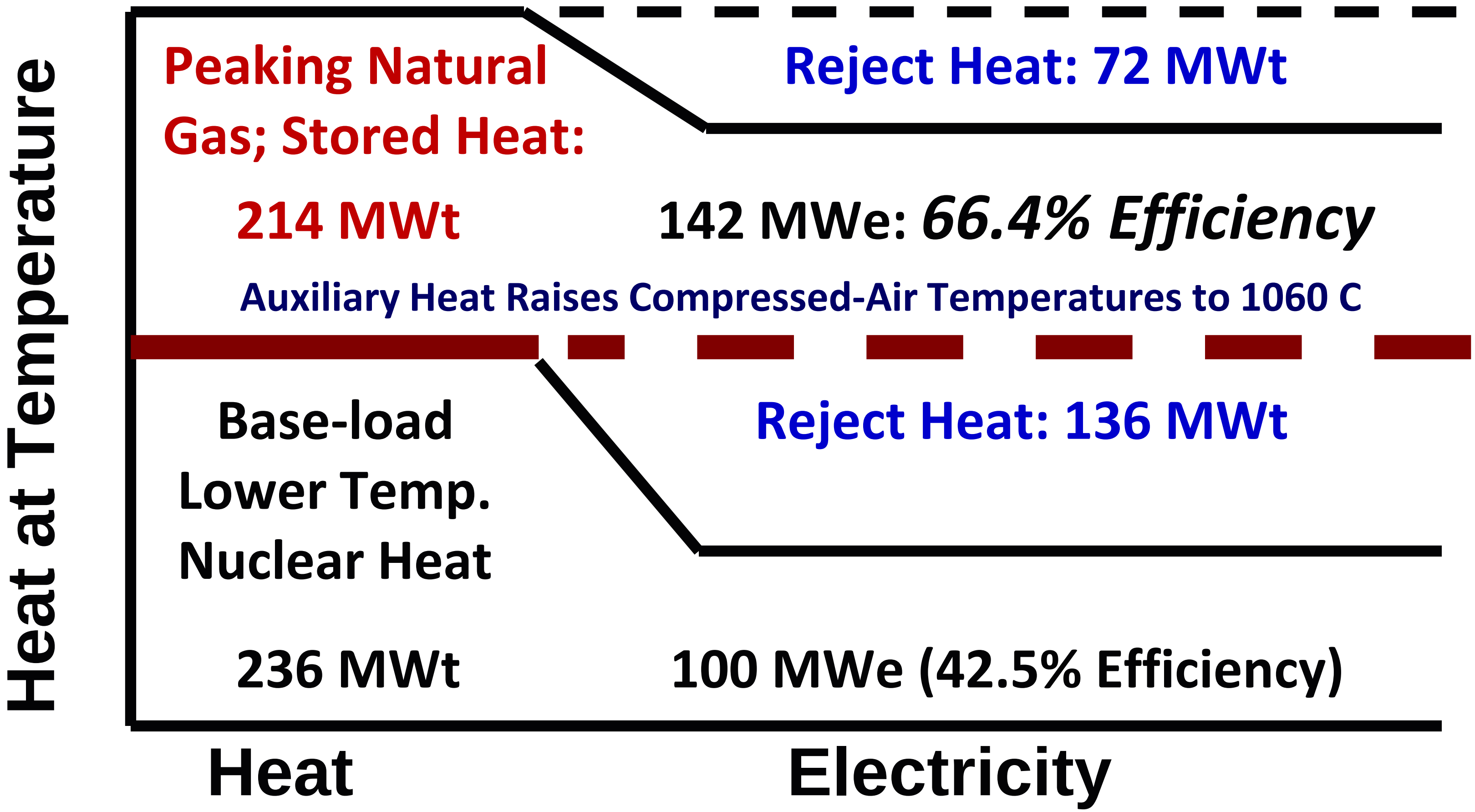
NACC Power System

Modified Natural-Gas-Fired Power Cycle



66% Peak Heat-To-Electricity Efficiency Better Alternatives

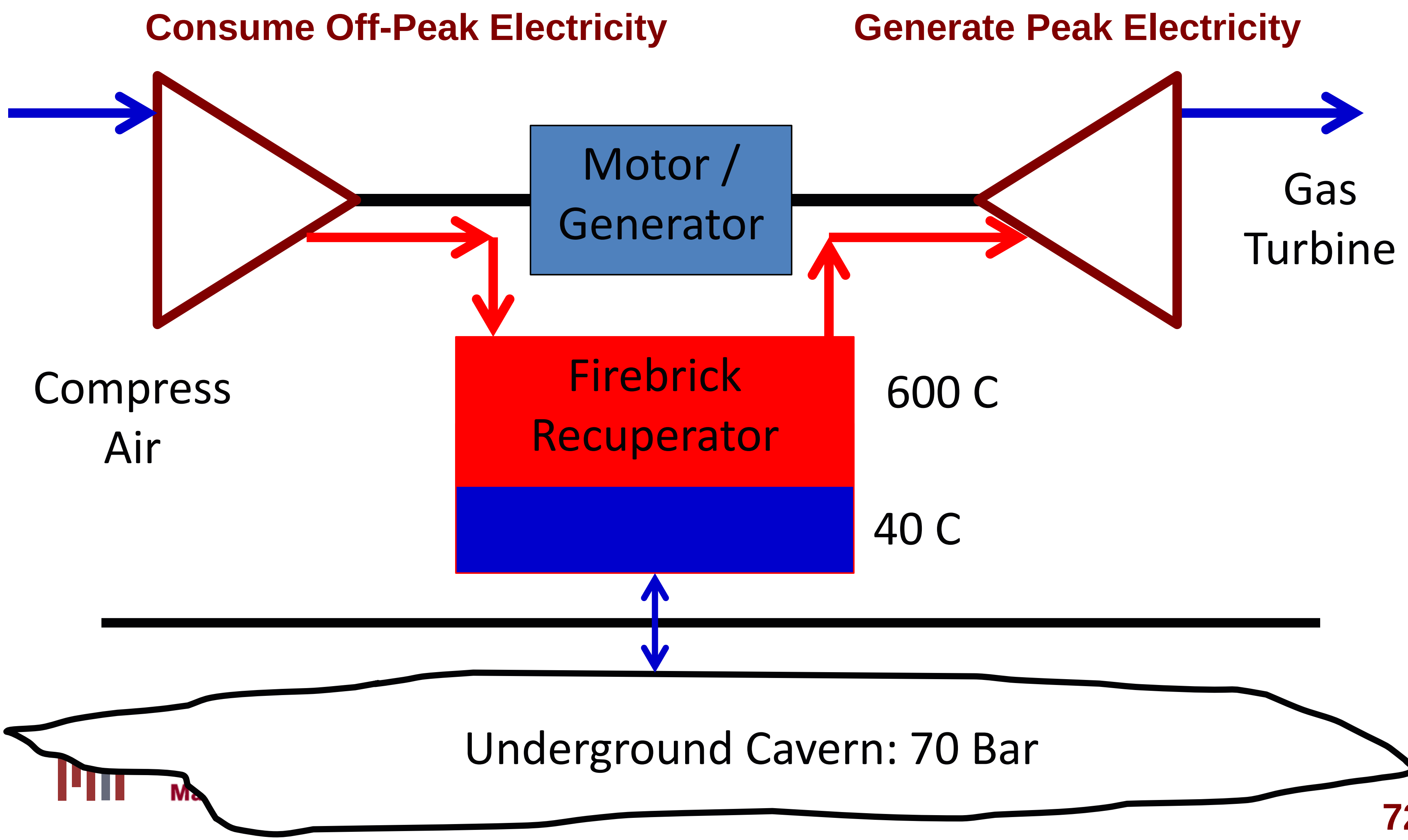
Natural-Gas Combined Cycle Gas Turbine: 60%



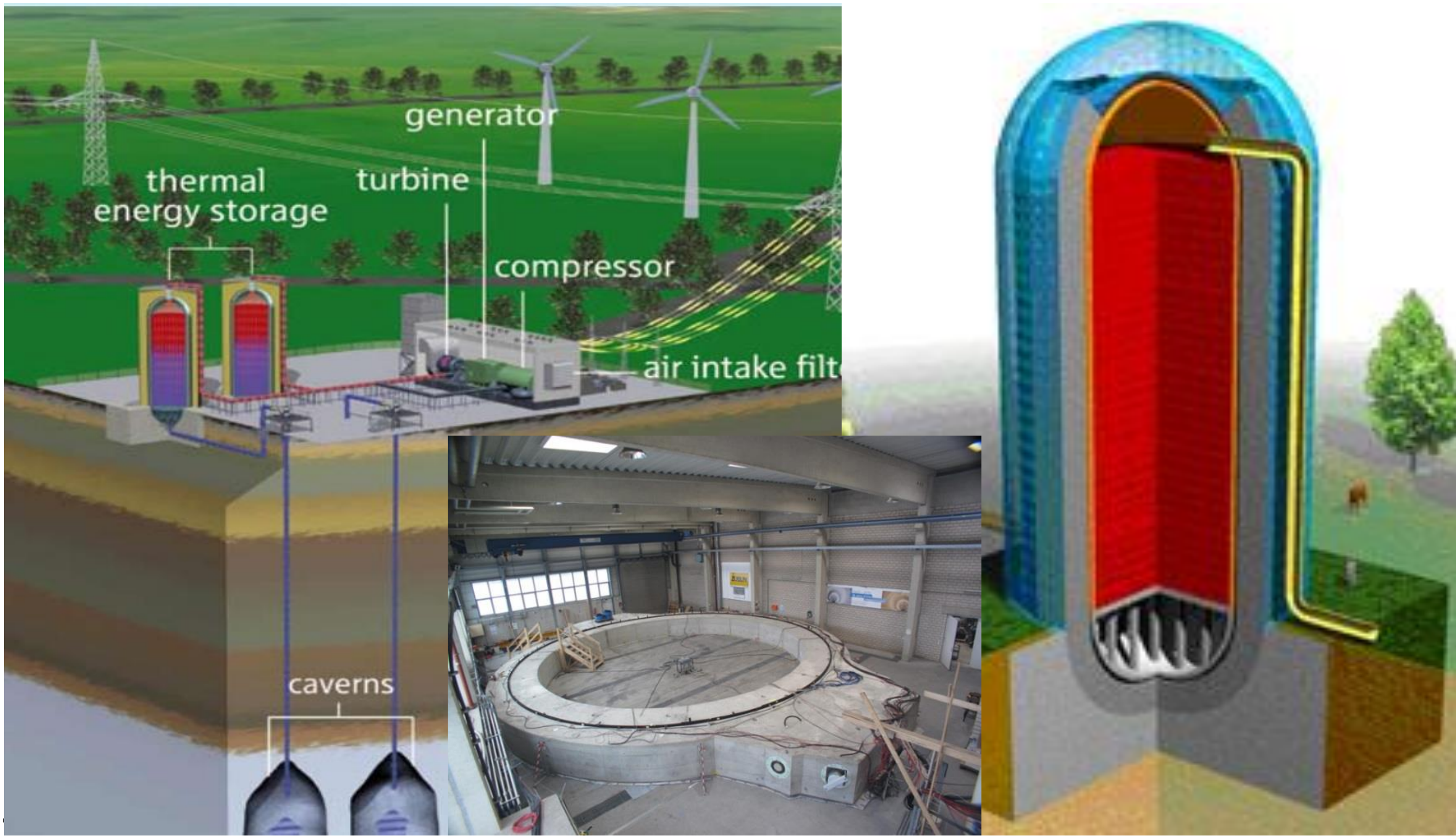
C. Andreades et. al, "Reheat-Air Brayton Combined Cycle Power Conversion Design and Performance under Normal Ambient Conditions," *J. of Engineering for Gas Turbines and Power*, **136**, June 2014

FIRES Technology Partly Being Developed by GE

Gas-Turbine Firebrick Heat Storage Is Being Developed by General Electric/RWE for Adiabatic Compressed Air Storage Systems



FIRES Builds Upon GE/RWE Adiabatic Compressed Air Storage Integration of Firebrick Heat Storage with Gas Turbines

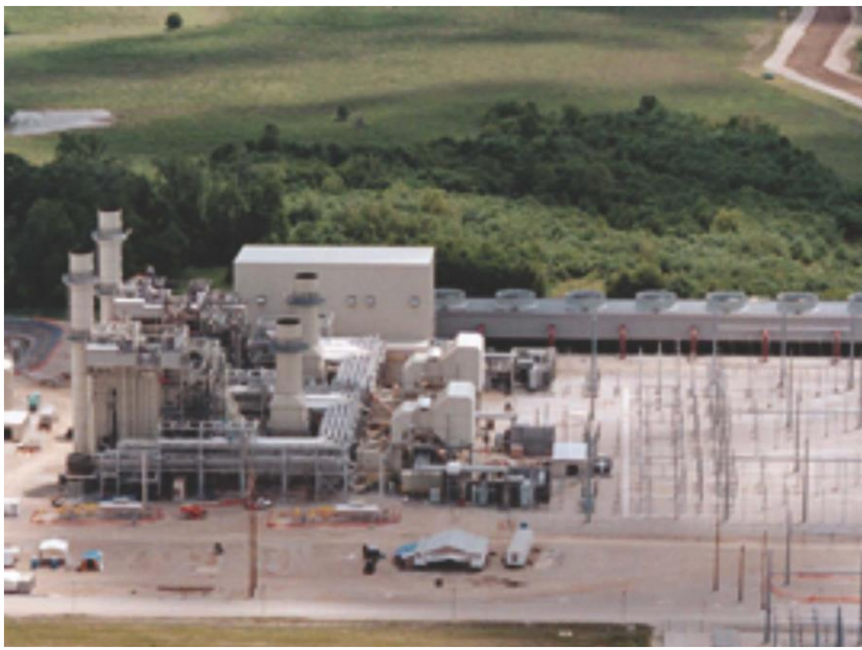


Differences between Adele and FIRES. FIRES lower pressure, higher temperature and electric heating

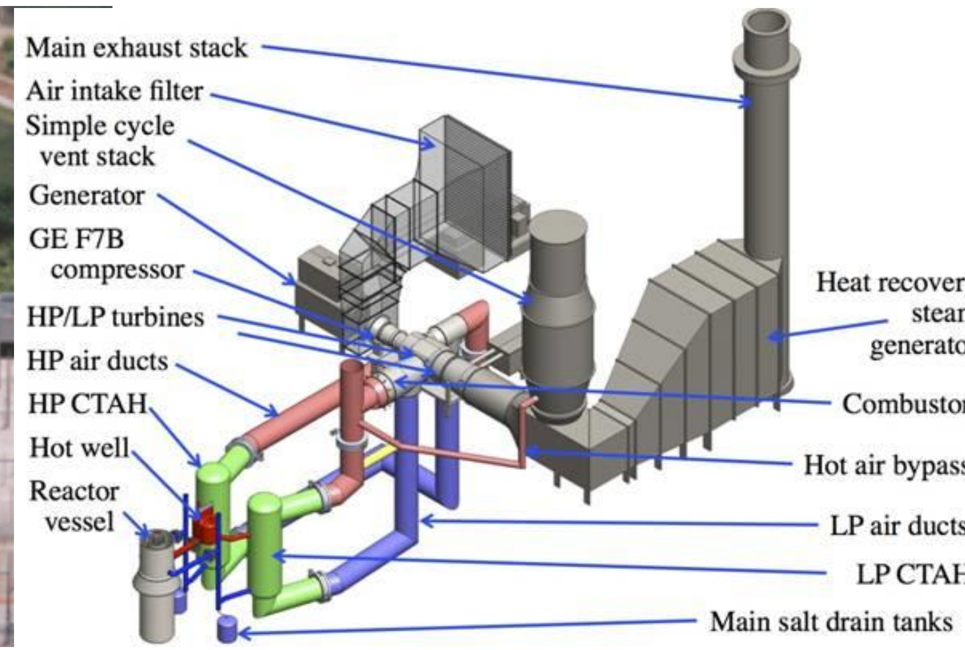
Gas-Turbine Combined-Cycle Plants Have Low Water Consumption

FHR with NACC: 40% Water Consumption of Water-Cooled Reactor

- Gas turbine cycle heat rejection to air
- Steam cycle heat rejection to cooling towers



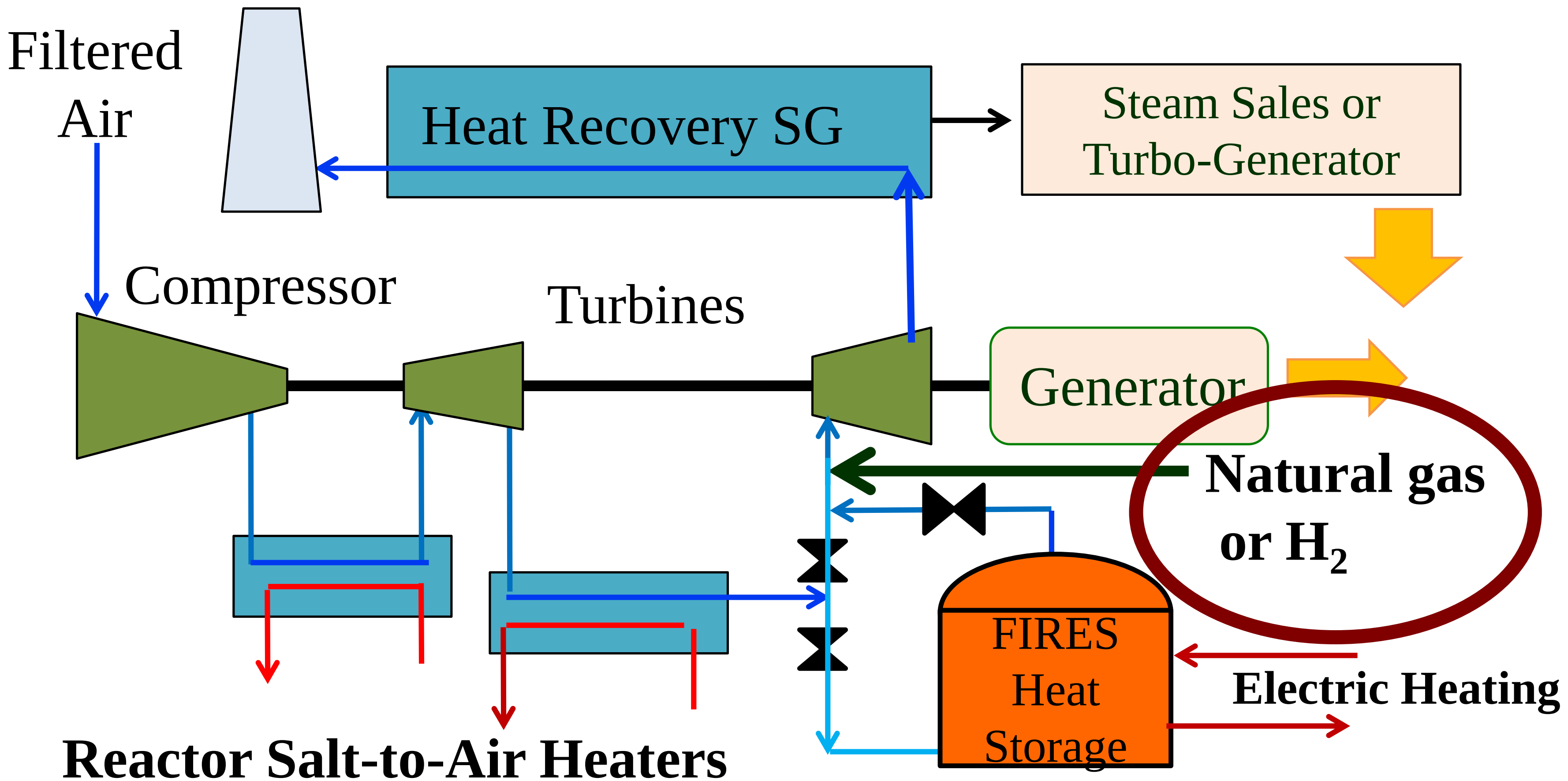
Sugar Creek Natural Gas Combined-Cycle Plant



FHR with Nuclear Air Combined-Cycle Plant

Power Response: Tens of Milliseconds

Time from Gas Injection to First Turbine Blade



Fast Response Because Peak Electricity Above Base Load Running Plant and Temperatures Above Auto-ignition of Fuel

In a Zero-Carbon World, NACC Would Use FIRES and Hydrogen for Peak Power

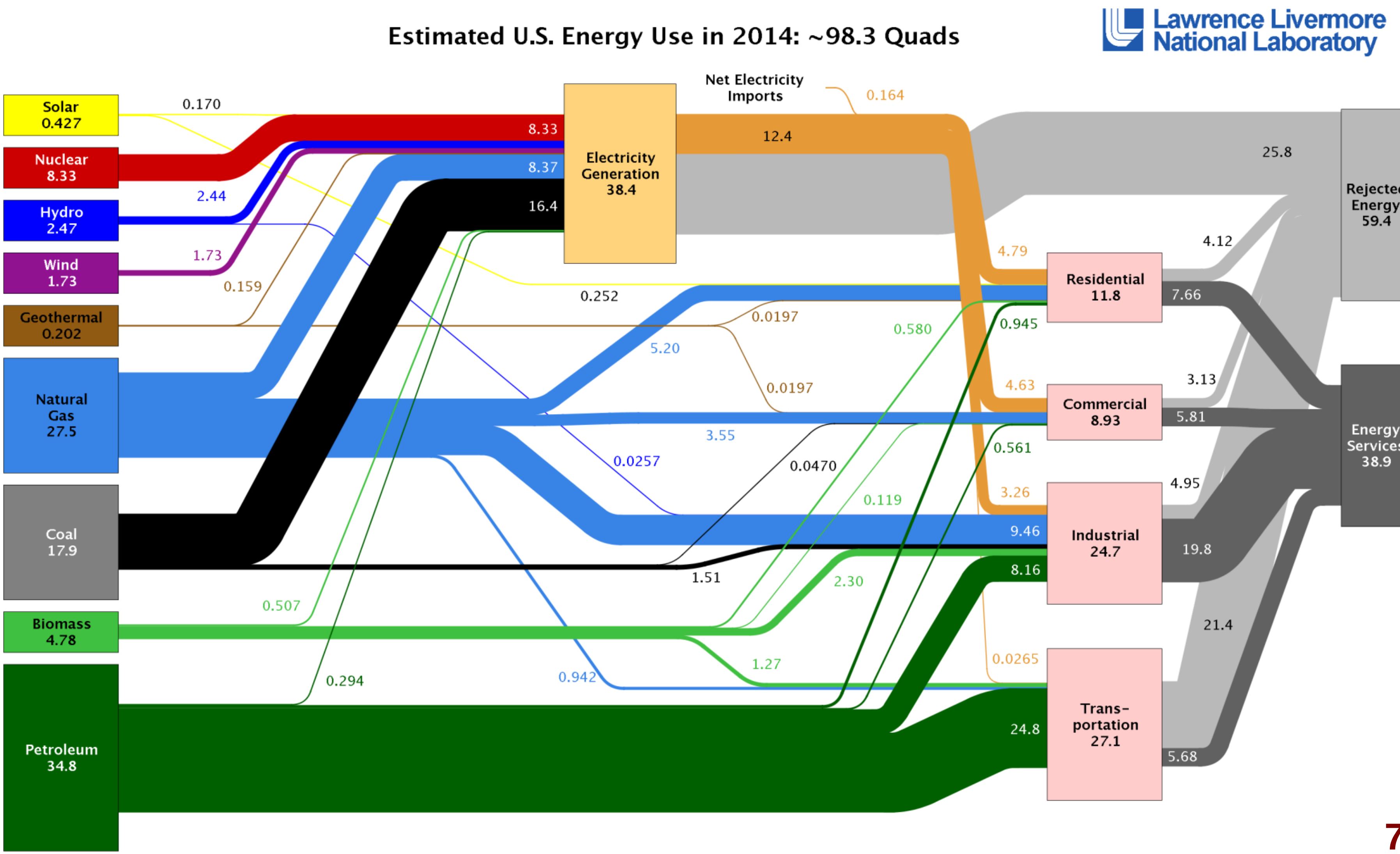
- FIRES Energy Storage
  - With 66% (future 70%) electricity-to-heat-to-electricity, it is potentially competitive with other storage options
  - FIRES is cheap storage for a day but expensive long-term energy storage because cost of FIRES prestress concrete vessel holding the firebrick
- Hydrogen Energy Storage
  - Energy storage efficiency with any system (electricity-to hydrogen-to-electricity) is less than 50%--inefficient
  - Underground hydrogen storage (a commercial technology) is cheap—same as natural gas storage
  - Hydrogen preferred for seasonal storage
  - **FHR with NACC is the most efficient hydrogen-to-electricity generating system**

Other Observations on NACC

- The grid requires X amount of generating capacity to meet demand
  - Capacity can be in NACC or stand-alone gas plant
  - If in NACC, peaking cycle capability at very high efficiency versus stand-alone natural gas plants
- Gas turbine technology advancing rapidly
  - Most R&D on power cycles is to improve gas turbines
  - Very hard for competing technologies to become competitive
  - Improvements in gas turbines directly improve FHR with NACC

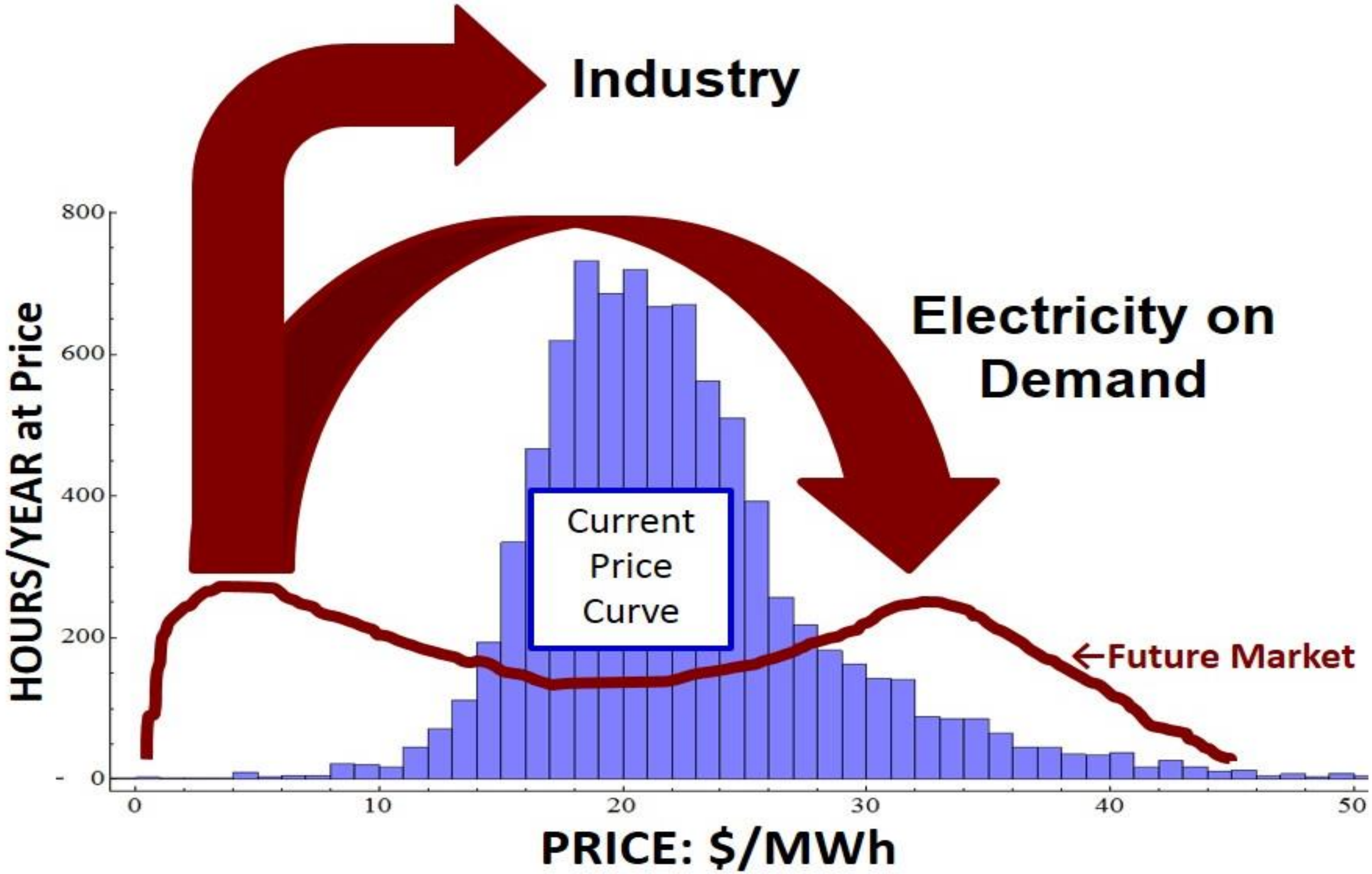
Energy Systems Must Address All Markets

Large Sectors are Electricity, Industry, and Transportation

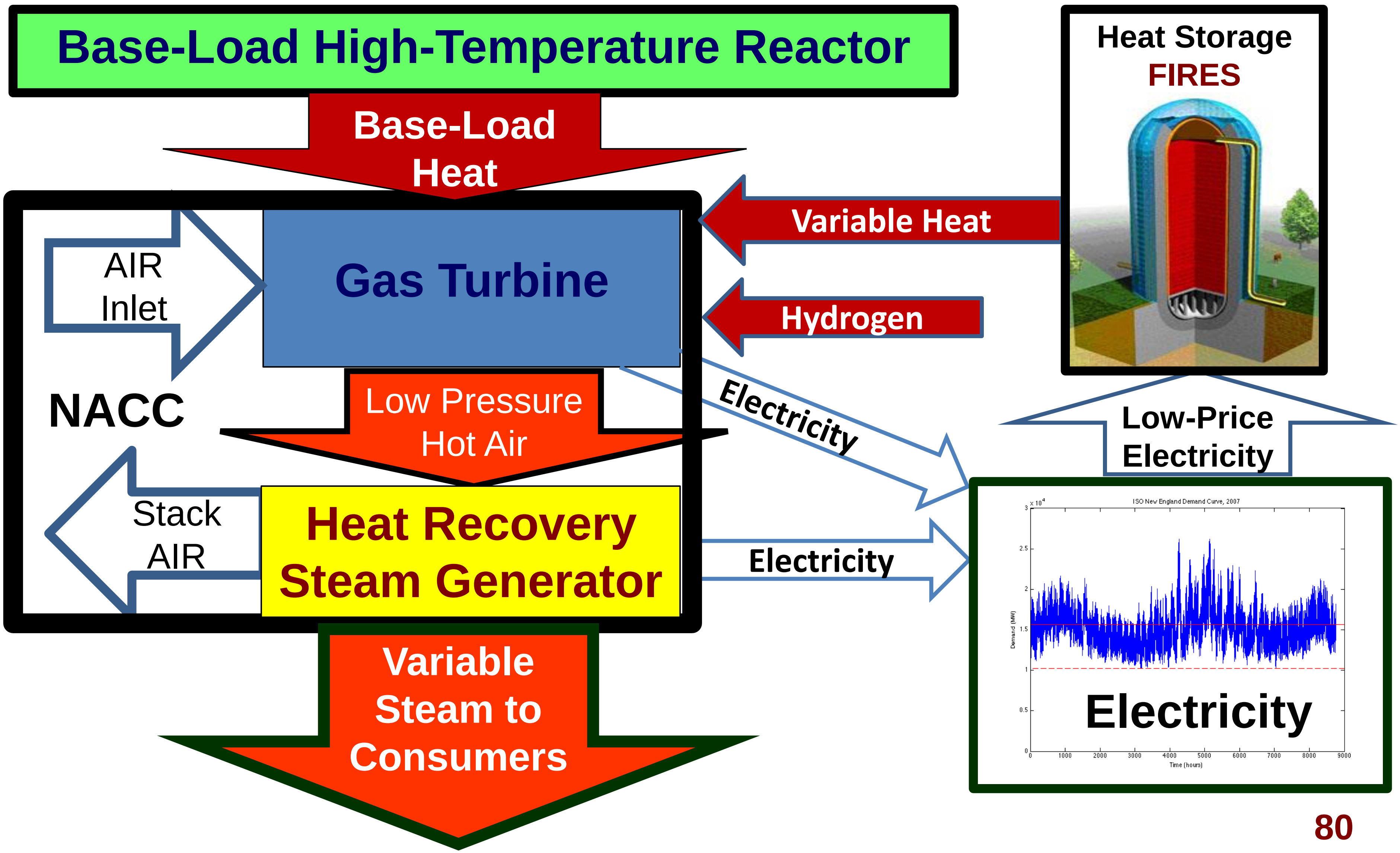


Two Strategies to Fully Utilize Solar, Wind and Nuclear—and Avoid Price Collapse

Excess Energy to Industry and Electricity-on-Demand

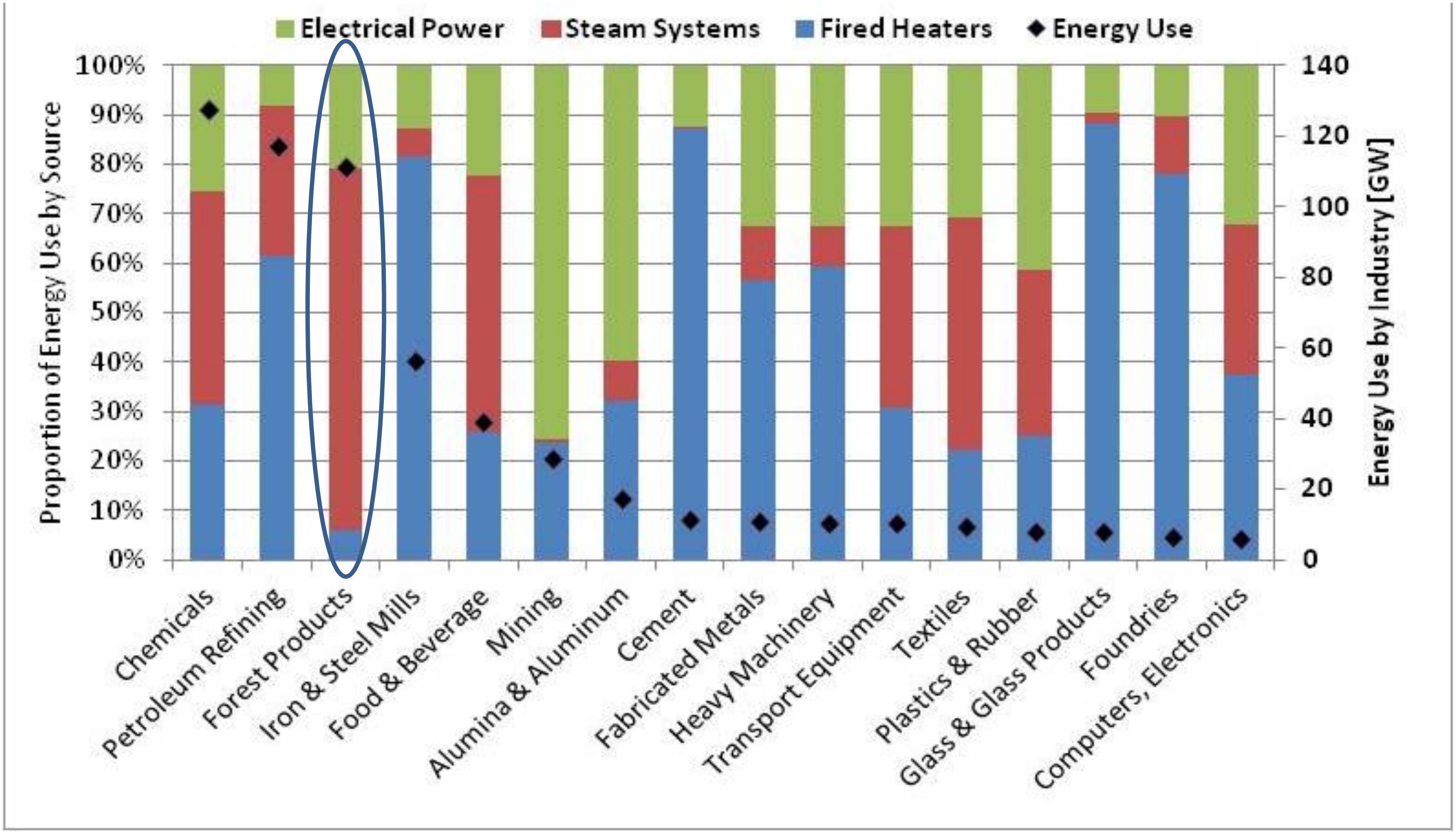


NACC With FIRES Enables Base-Load Nuclear with Variable Electricity and Steam to Industry



Must Consider Industrial Energy Needs

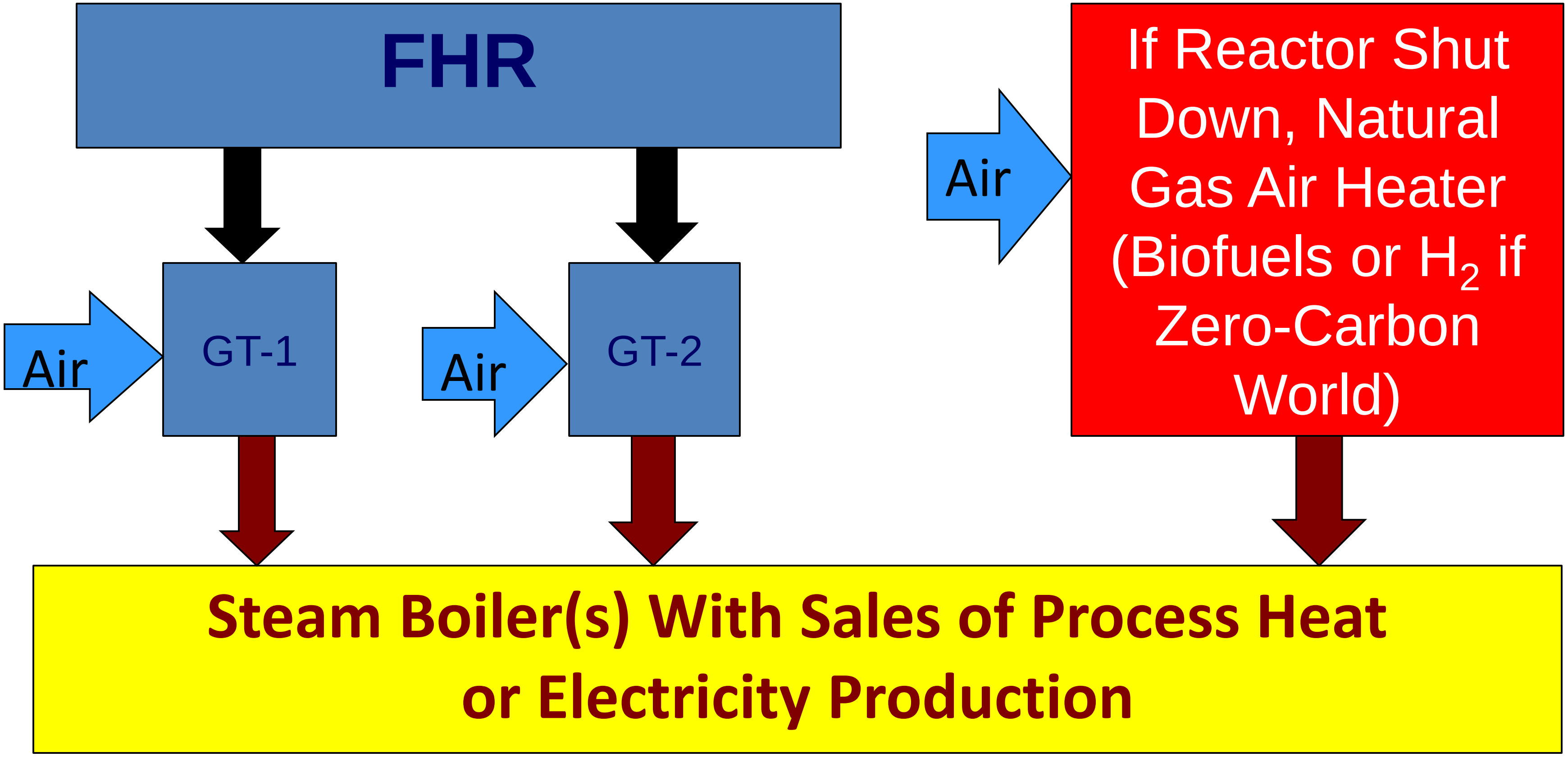
Industry Has Large Steam (Red) and Heat Demands (Blue)



Biofuels Production Similar to Forest Products

Air Brayton Power Cycle Enables Reliable Steam Supply for Industry

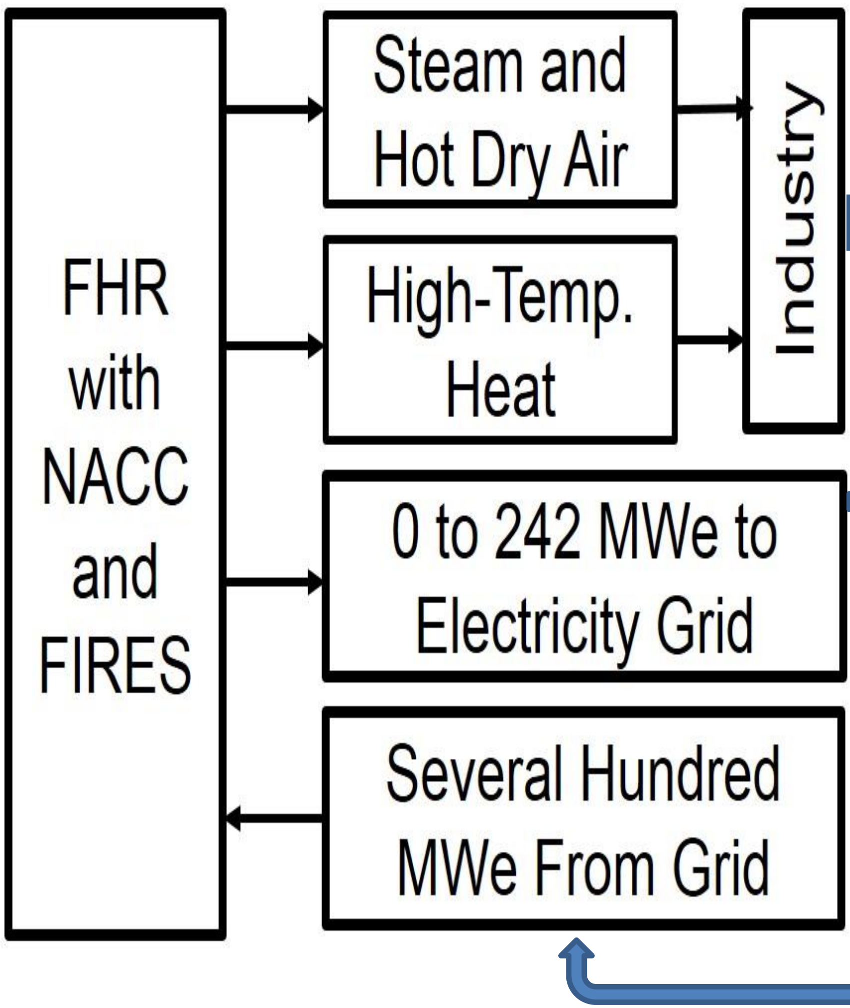
Similar to Power Systems in Chemical Plants



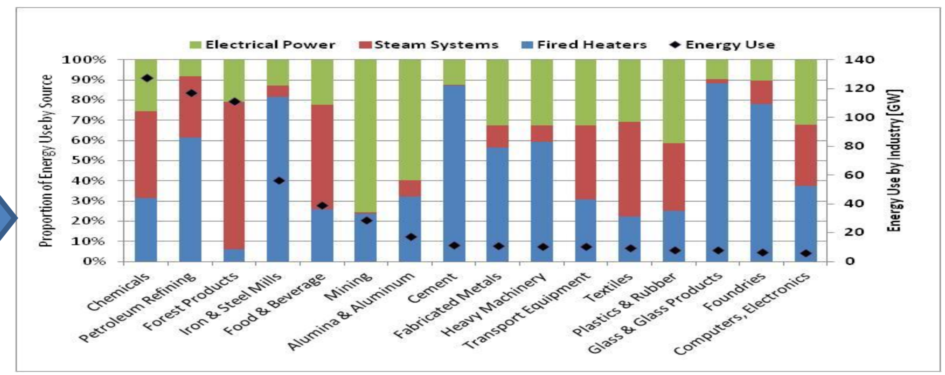
Eliminates Historic Nuclear Process Heat Problem: What if the Nuclear Reactor Shuts Down?

Base-Load FHR Integrates the Electricity Grid with Industry for a Low-Carbon Economy

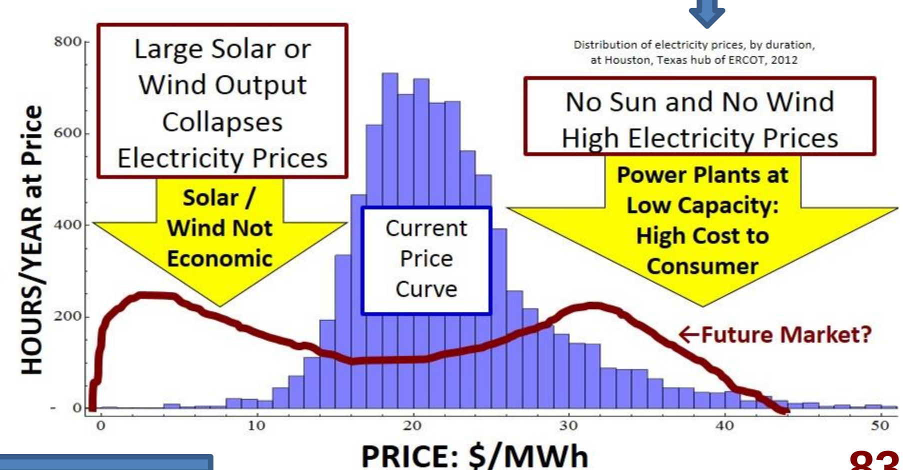
FHR with NACC



Industrial Energy Demand

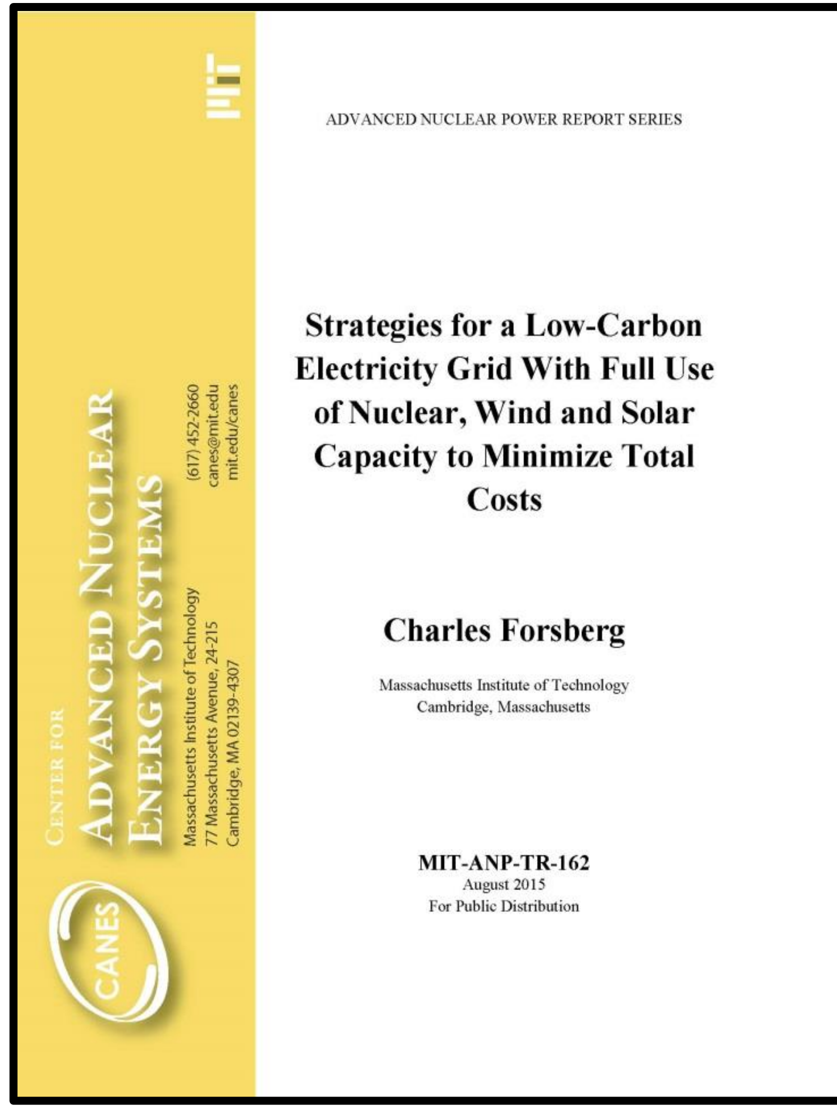


Electricity Grid



Appendix D

Options to Integrate Nuclear and Renewables



ADVANCED NUCLEAR POWER REPORT SERIES

Strategies for a Low-Carbon Electricity Grid With Full Use of Nuclear, Wind and Solar Capacity to Minimize Total Costs

Charles Forsberg

Massachusetts Institute of Technology
Cambridge, Massachusetts

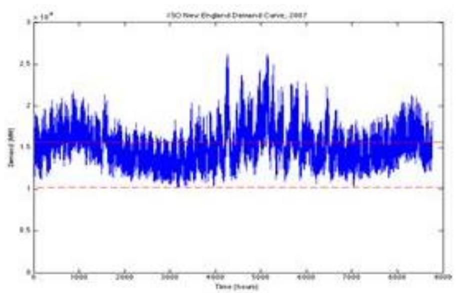
MIT-ANP-TR-162
August 2015
For Public Distribution

http://mitei.mit.edu/publications/reports-studies/strategies-low-carbon-electricity-grid-full-use-nuclear-wind-and-solar-

Goals Define Strategies

GOAL

Economic Low-Carbon Electricity that Meets Variable Electricity Demand

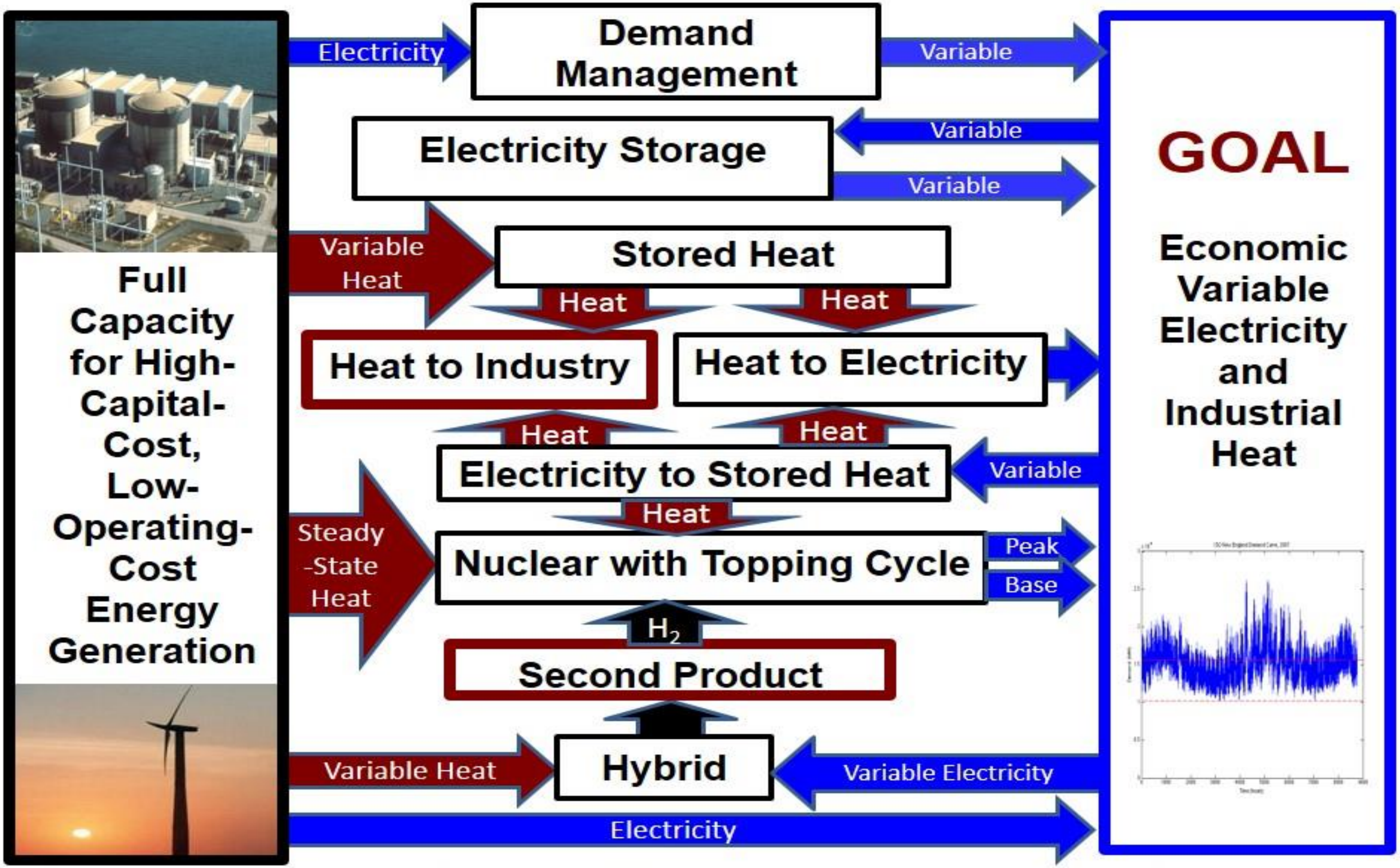


How?

STRATEGY

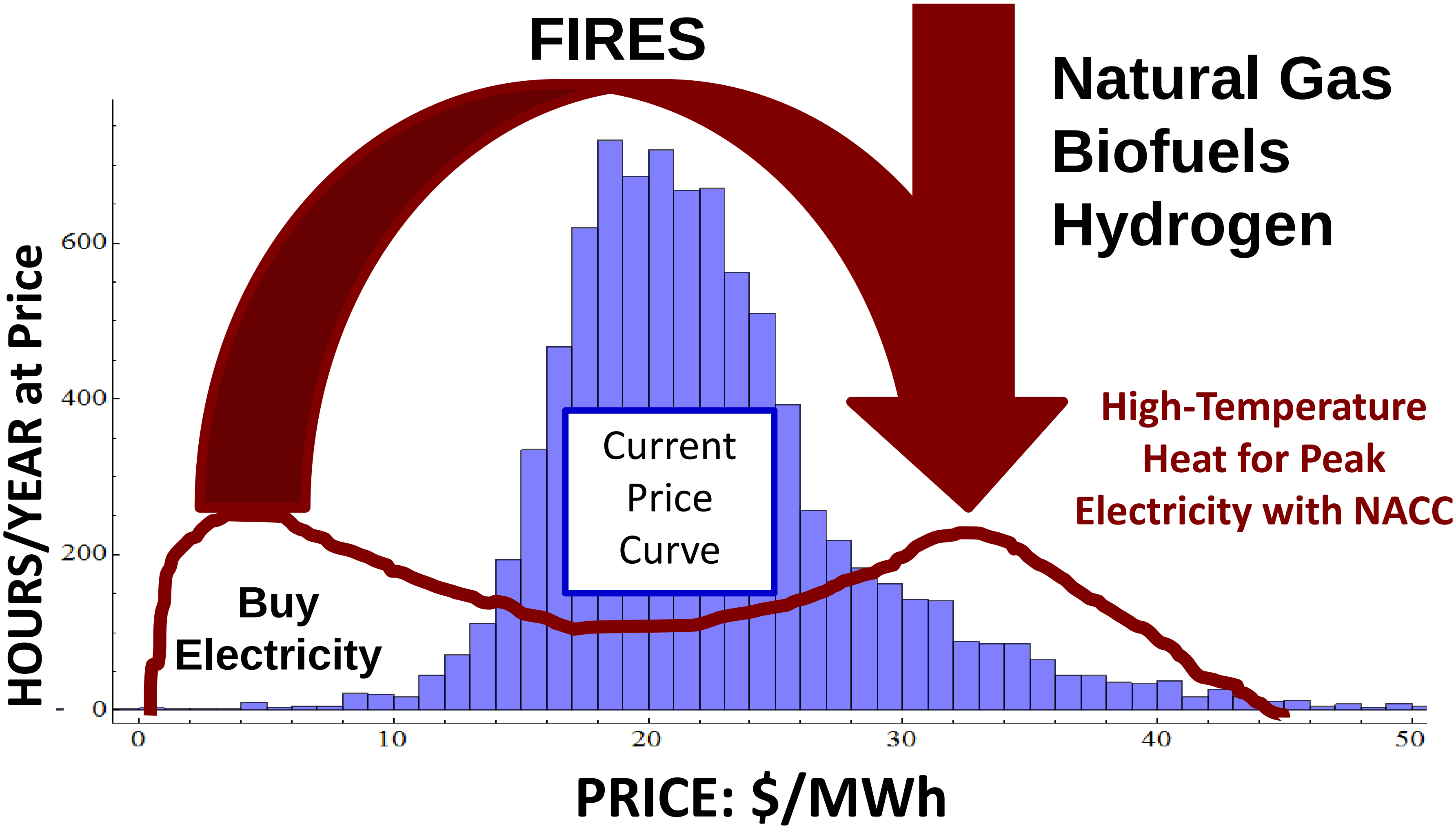
Maximize Output (Full Load) of Low-Carbon, High-Capital-Cost, Low-Operating-Cost Electricity Generation

Options to Meet Variable Electricity Demand In a Low-Carbon Electricity Grid



C. Forsberg, Strategies for a Low-Carbon Electricity Grid With Full Use of Nuclear, Wind and Solar Capacity to Minimize Total Costs, MIT-ANP-TR-162, August 2015; http://mitei.mit.edu/publications/reports-studies/strategies-low-carbon-electricity-grid-full-use-nuclear-wind-and-solar-

NACC with FIRES Economics Improves As Solar and Wind Collapse Electricity Prices



FHR Helps Solar and Wind By Slowing Price Collapse

Electricity Dispatched Based on Marginal Production Costs