Technologies for an Economic Low-Carbon Nuclear Renewables Grid: The Case of Firebrick Resistance-Heated Energy Storage (FIRES)

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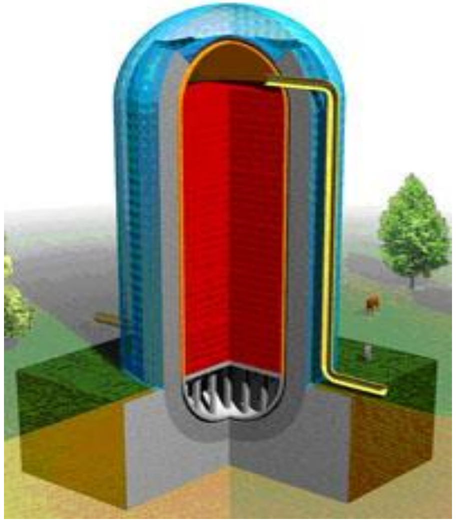

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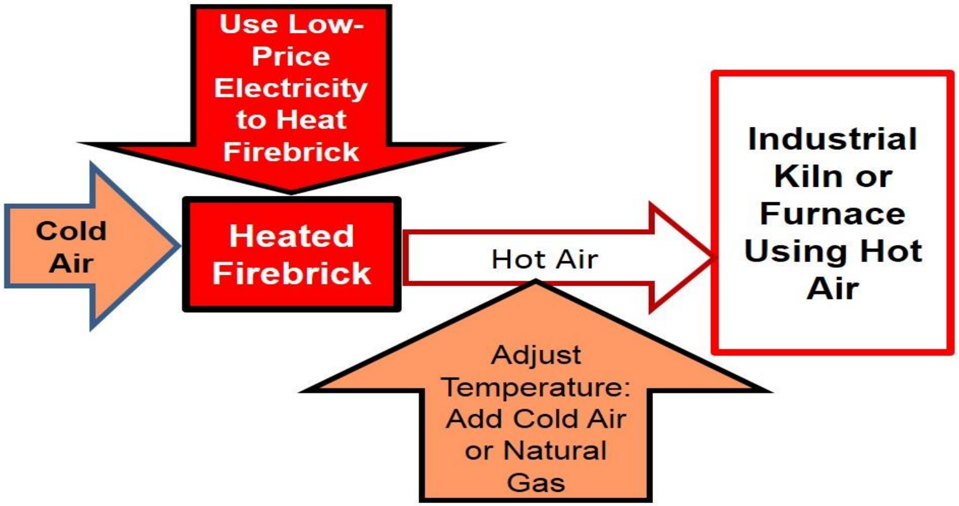
FIRES Converts Low-Price Electricity into Stored Heat for Multiple Applications

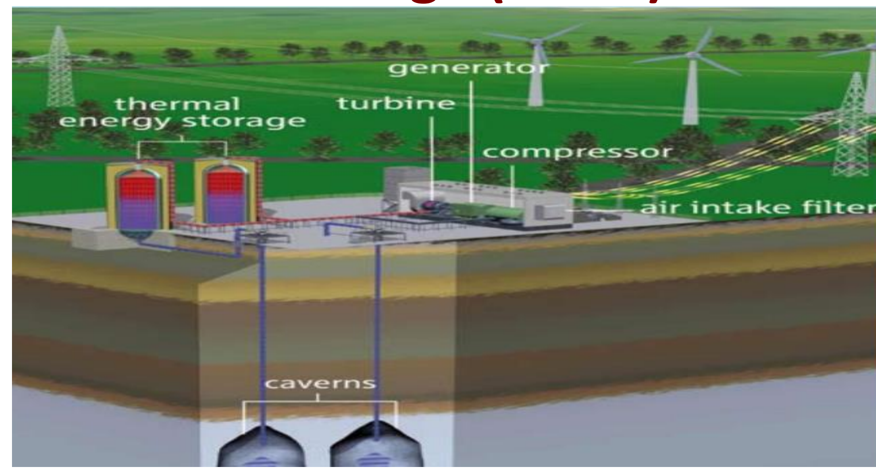
- Addition of renewables to grid causes electricity price collapse at times of high wind and solar
- Price of electricity drops below that of natural gas and coal per unit of heat
- FIRES converts low-price electricity into stored high-temperature heat for the industrial sector and gas turbines to replace natural gas and coal
- FIRES Increases revenue for capital-intensive low-operating-cost nuclear, wind, and solar

FIRES Is A Family of Technologies

FIRES with Industrial Furnaces

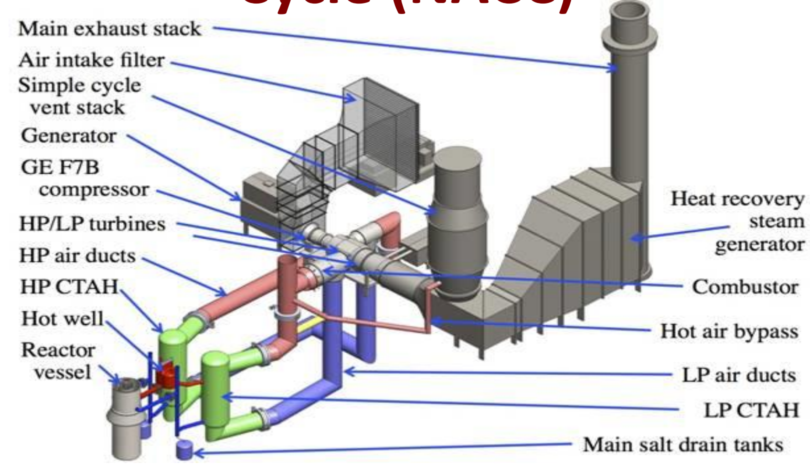


FIRES with Adiabatic Compressed Air Storage (ACAS)



FIRES with Natural Gas Combined Cycle (NGCC)

FIRES with Nuclear Air Combined Cycle (NACC)



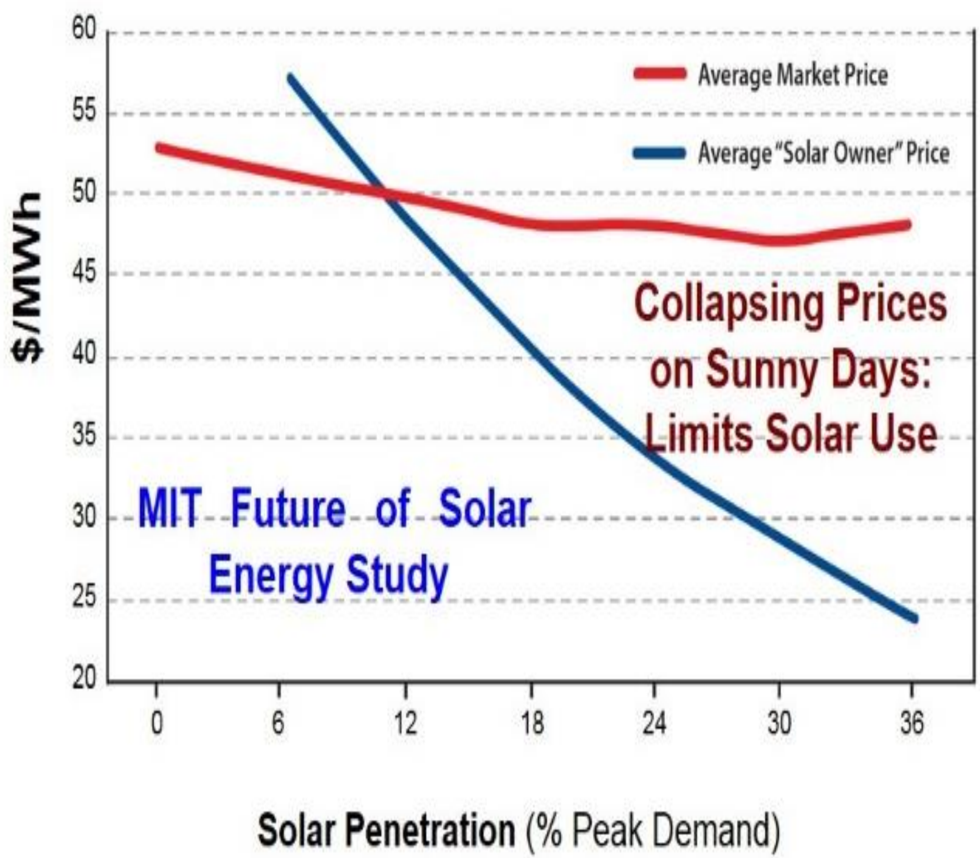
The Electricity Market

Solar and Wind Change Electricity Markets

Low-carbon Grid Requirements Change Electricity Markets

In Competitive Markets, Solar Revenue Collapses as Solar Output Increases

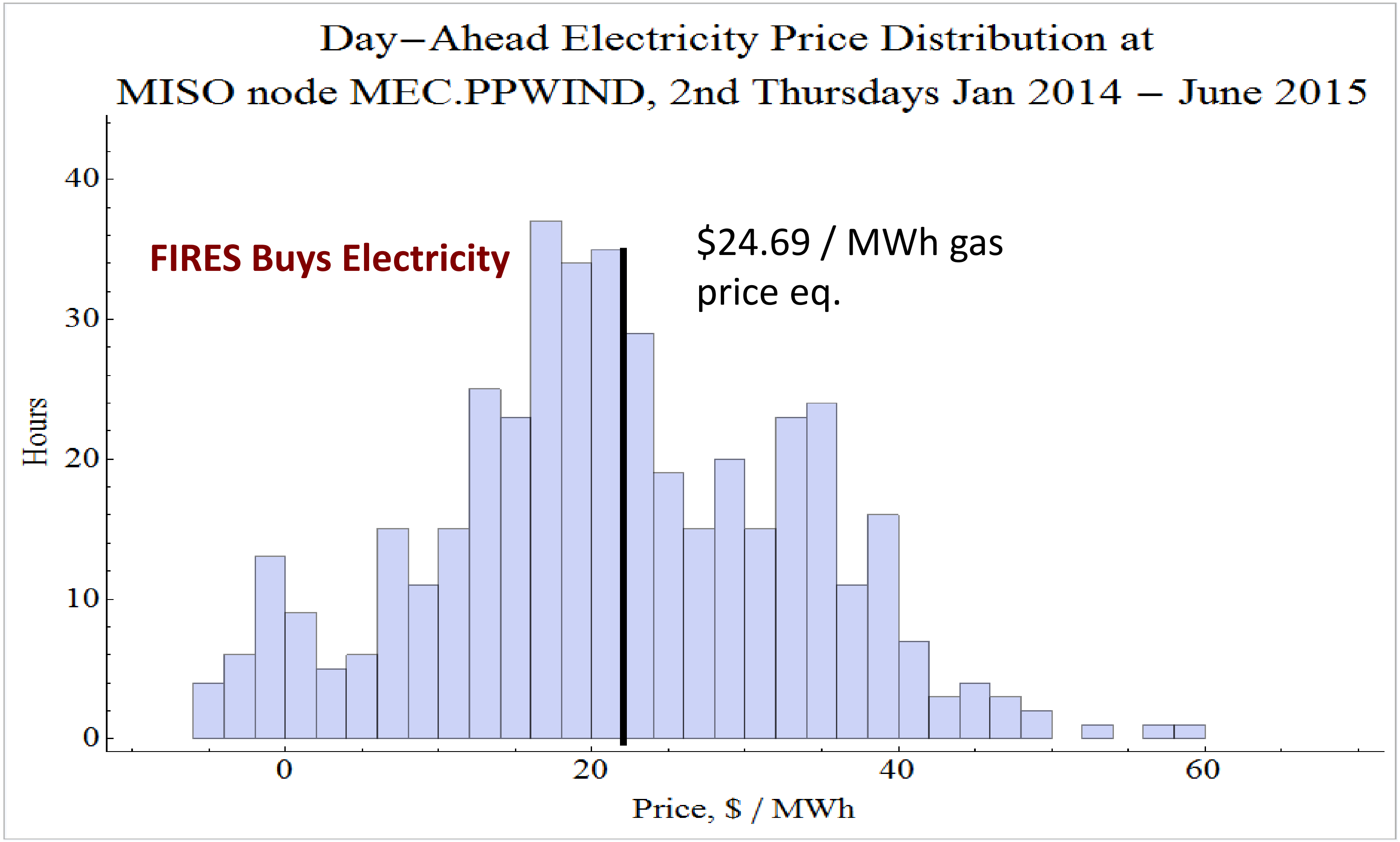
- Price collapse is a characteristic of large-scale use of low-operating-cost high-capital-cost technologies.
- Becomes significant when fraction of total electricity is
  - 10% solar
  - 20% wind
  - 70% nuclear
- Does not happen with fossil-fuel plants
- Price collapse limits use of low-carbon electric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



Same Effect If Large-Scale Use of Wind

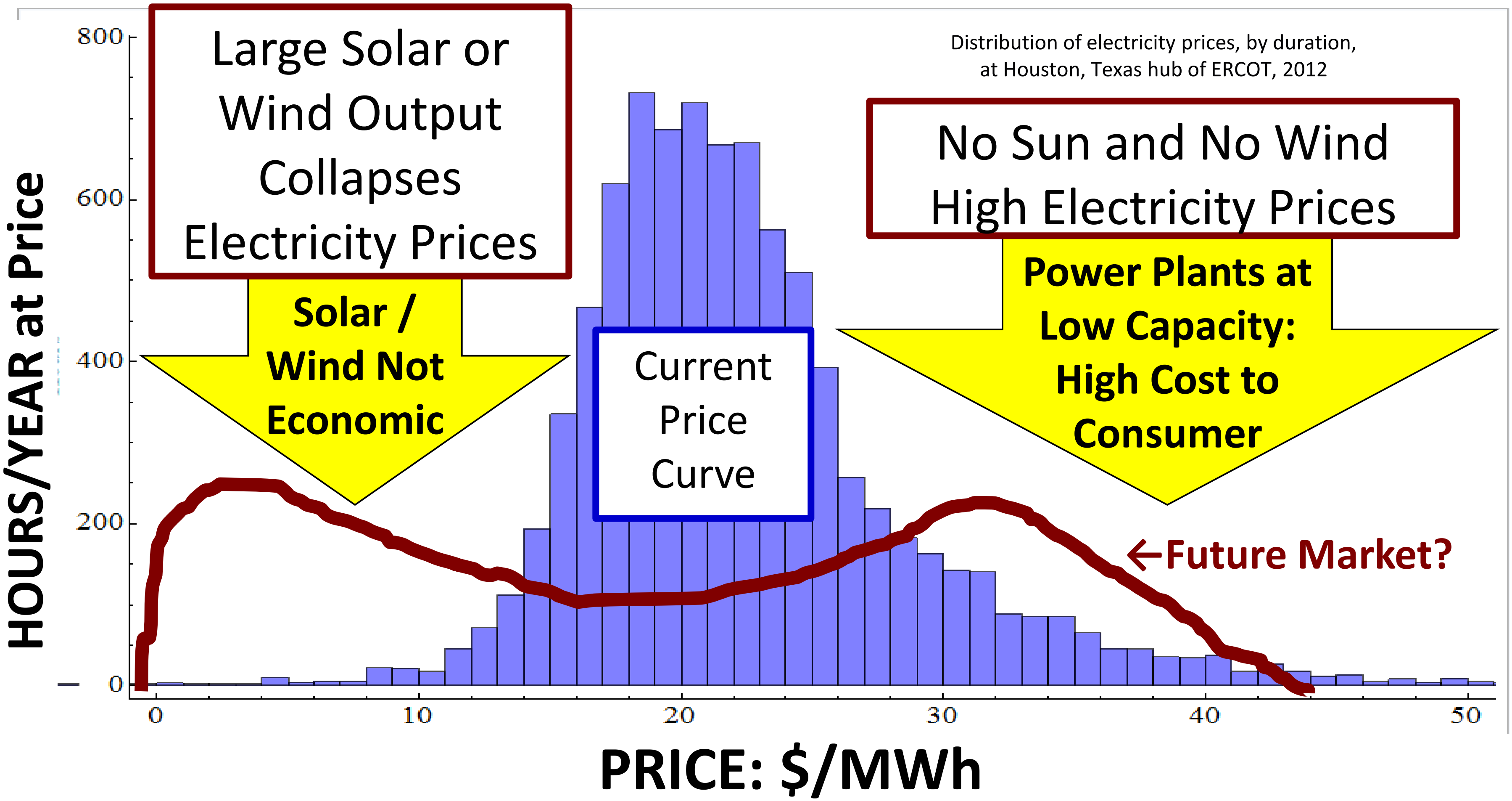
Price Collapse is Real: Iowa with Wind

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?

Implications of Electricity Market Price Collapse

- A consequence of going from low-capital-cost high-operating-cost fossil electricity generation to high-capital-cost low-operating-cost nuclear, wind, and solar system
- Price collapse limits use of nuclear, wind and solar
- This is the economic barrier to a low-carbon electric grid
- Need to find productive use for “excess” electricity to set a floor on electricity prices

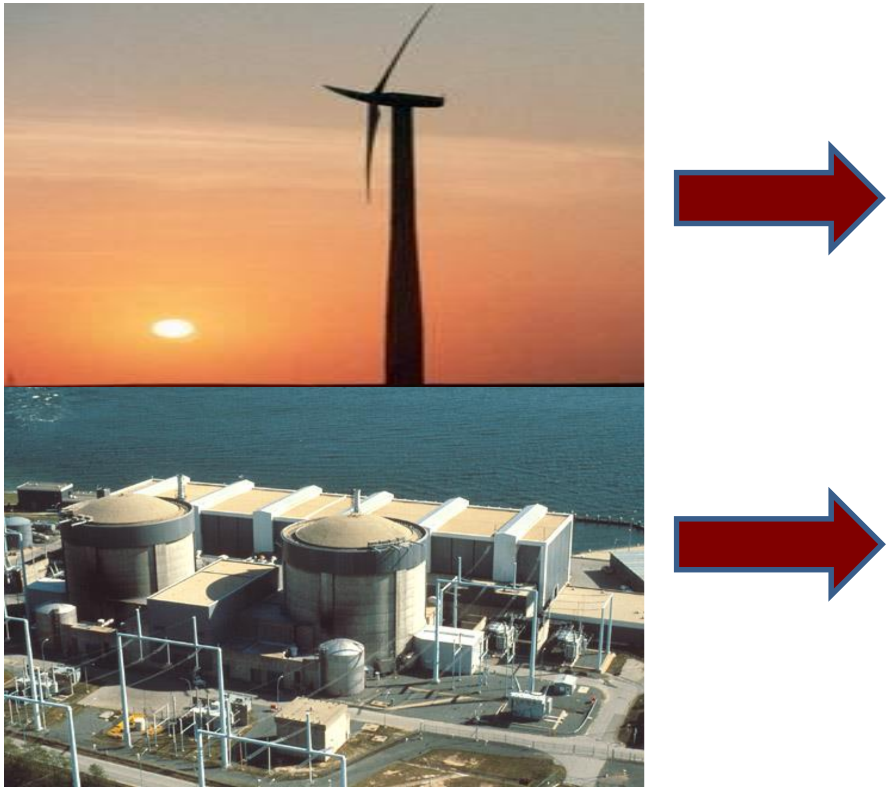
Strategy to Create a Low-Carbon Energy System

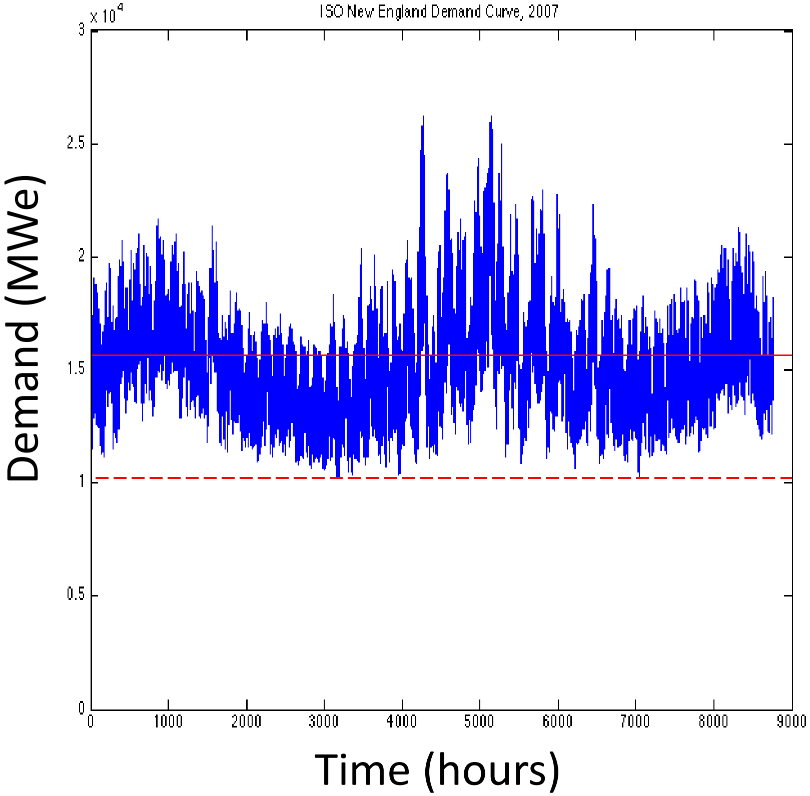
Ground Rules:

Full Utilization of High-Capital-Cost Low-Operating-Cost Nuclear, Wind, and Solar

Meet Variable Electricity Demand and Help Meet Industrial Energy Demand

Economics Requires Full Use of Capital-Intensive Low-Operating-Cost Nuclear and Renewable Generators

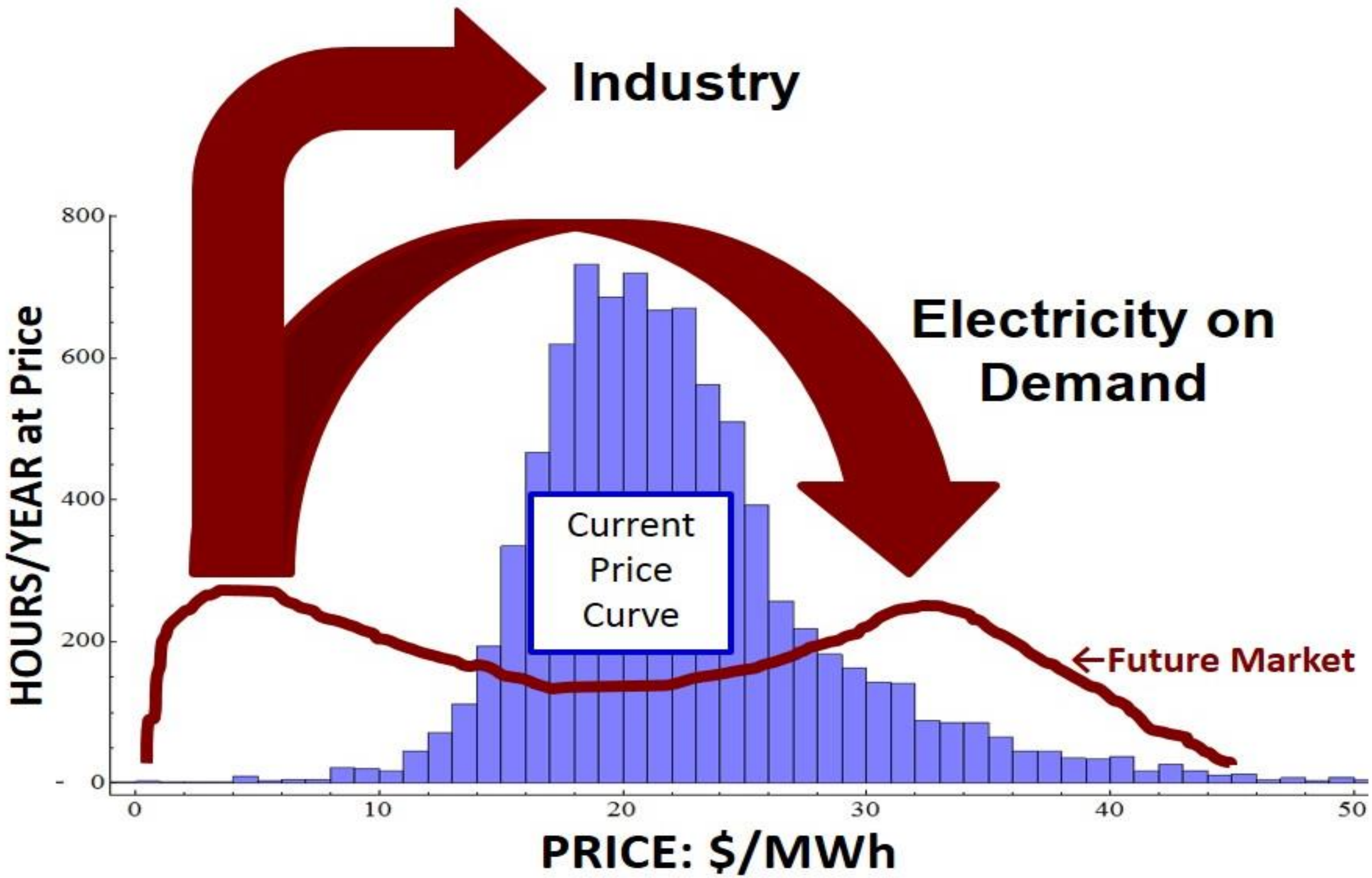




But No Combination of Nuclear & Renewables Output Matches Demand

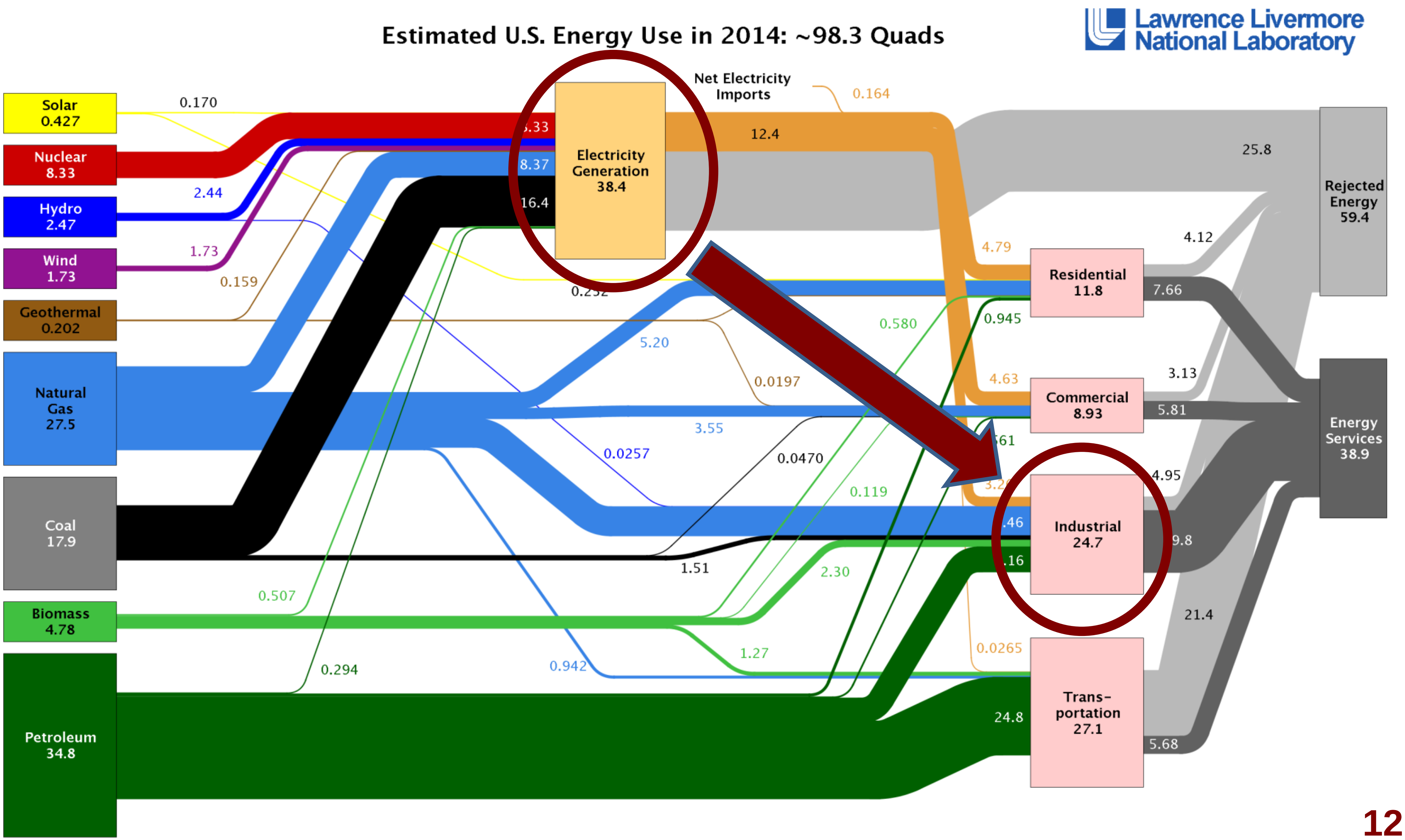
Two Strategies to Fully Utilize Solar, Wind and Nuclear—and Avoid Price Collapse

Excess Energy to Industry and Electricity-on-Demand



Only Industrial Sector Capable of Absorbing All Excess Energy from Electric Sector

Other Sectors Too Small or Absorb Energy for Limited Periods of Time



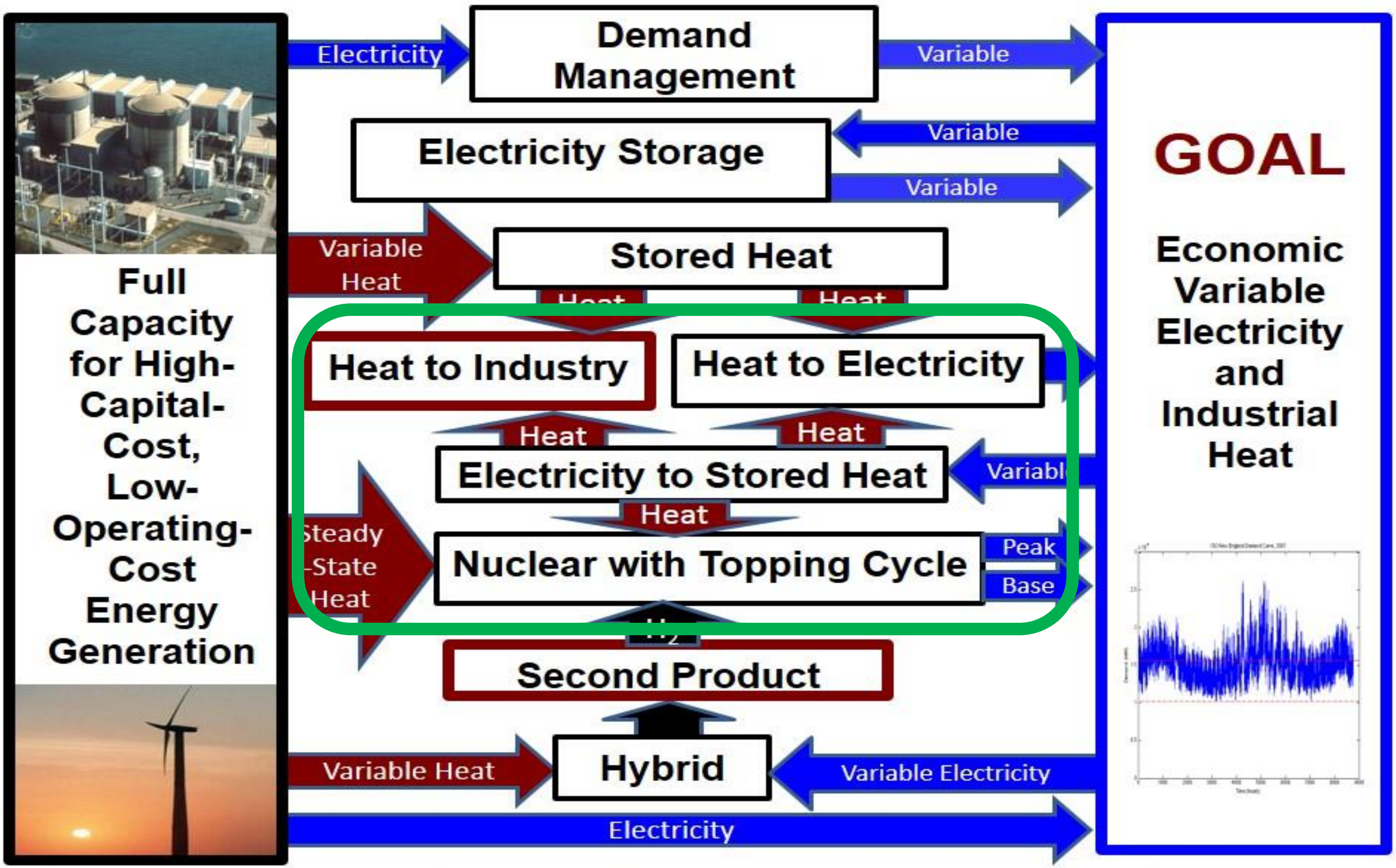
Options to Create Low-Carbon Energy System

Ground Rules:

Full Utilization of High-Capital-Cost Low-Operating-Cost Nuclear, Wind, and Solar

Meet Variable Electricity Demand and Help Meet Industrial Energy Demand

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-

Firebrick Resistance Heated Energy Storage (FIRES)

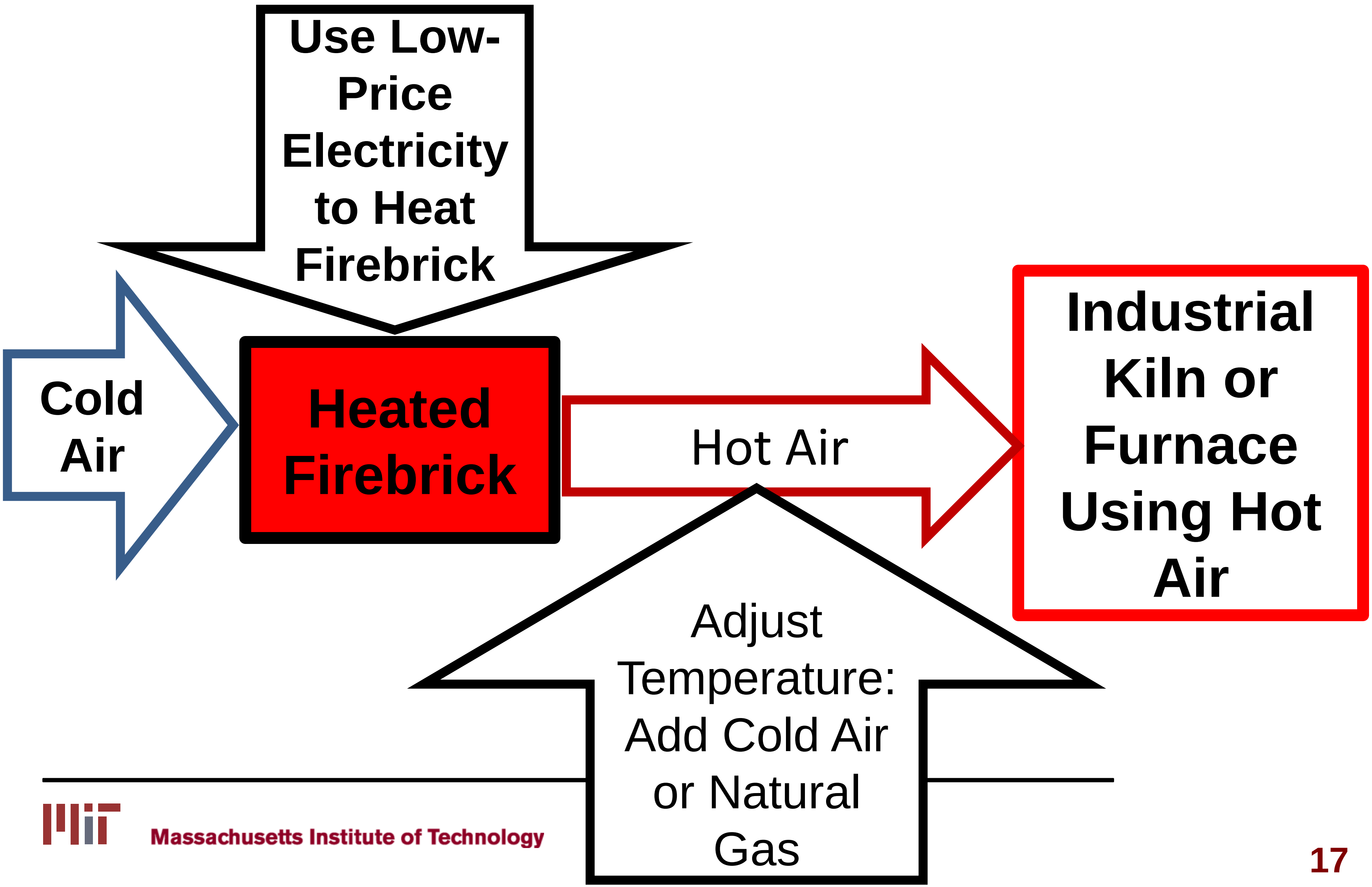
A Family of Technologies

Firebrick Resistance-Heated Energy Storage (FIRES)

- Buy electricity when electricity prices are less than natural gas
- Electrically heat firebrick to very high temperatures
- Use stored heat for several applications
  - Industrial heat
  - Peak electricity production using gas turbines

Option of Conductive Brick as Electric-Resistance Heater

Simplest Application: FIRES Stores Heat in Firebrick to Provide Hot Air to Industry



Previous Experience: Residential Heat Storage Units

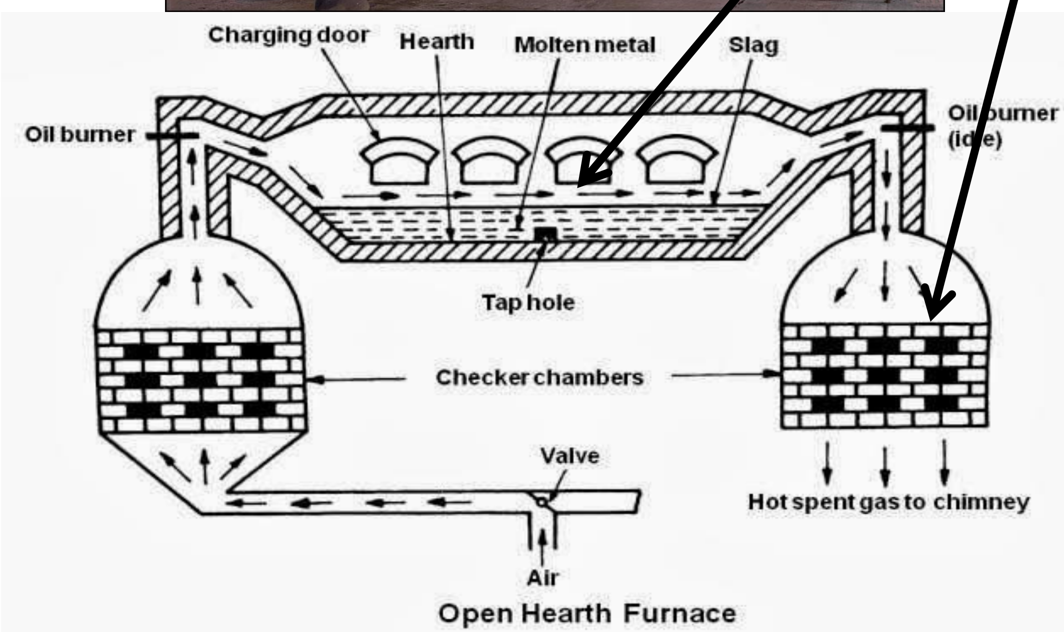
Steffes Heating Systems: home heat storage unit with resistance heaters

- Some utilities offer night-time electricity discounts for electrically heated homes
- Insulated 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**

FIRES Will Be Orders of Magnitude Larger and Operate at Higher Temperatures for Industrial Applications

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

Brick Heat Storage Without Electrical Heating



- 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

Firebrick Recuperator Under Construction for Glass Furnace

FIRES Requires Addition of Electrical Heaters

Industrial FIRES Design Goals

- Base Technology: Firebrick air recuperator with air channels (1910 open-hearth steel furnace technology)
- Use low-price electricity to heat up firebrick
  - Peak temperatures to ~1800°C
  - ~1000+C variation in cold to hot temperatures
  - Direct resistance heating using electrically conductive firebrick or heaters
- Incremental firebrick cost ~$1-2/kWh plus electrical heating, structure, and insulation (~0.75 MWh/m^3)
- **Cost goal: $5/kWh (thermal); 40 times less than batteries**

FIRES Can Go to Higher Temperatures Than Other Heat Storage Systems

- Most heat storage technologies require heat exchangers
  - Practical limits of heat exchangers ~700°C so peak storage temperatures limited to ~700°C
  - No way to reach high temperatures

- FIRES can go to 1800°C to enable supplying heat to high-temperature kilns and high-efficiency gas turbine cycles
  - Direct electrical heating of firebrick
  - Direct transfer of high-temperature heat to air, helium, or other gas

Short Estimated Payback Period

Iowa: Currently Best U.S. Case

- Payback period under one year for first user
  - Iowa wholesale electricity and natural gas prices
  - Industrial customer
  - Assume $5/kWh (thermal) capital costs
  - Not impact grid price structure
- Home heat storage costs ~$15/kWh(t) but incremental capacity is <$10/kWh(t) (retail)
  - Industrial system 100 to 1000 times large

Industrial FIRES Implications for the Electricity Grid

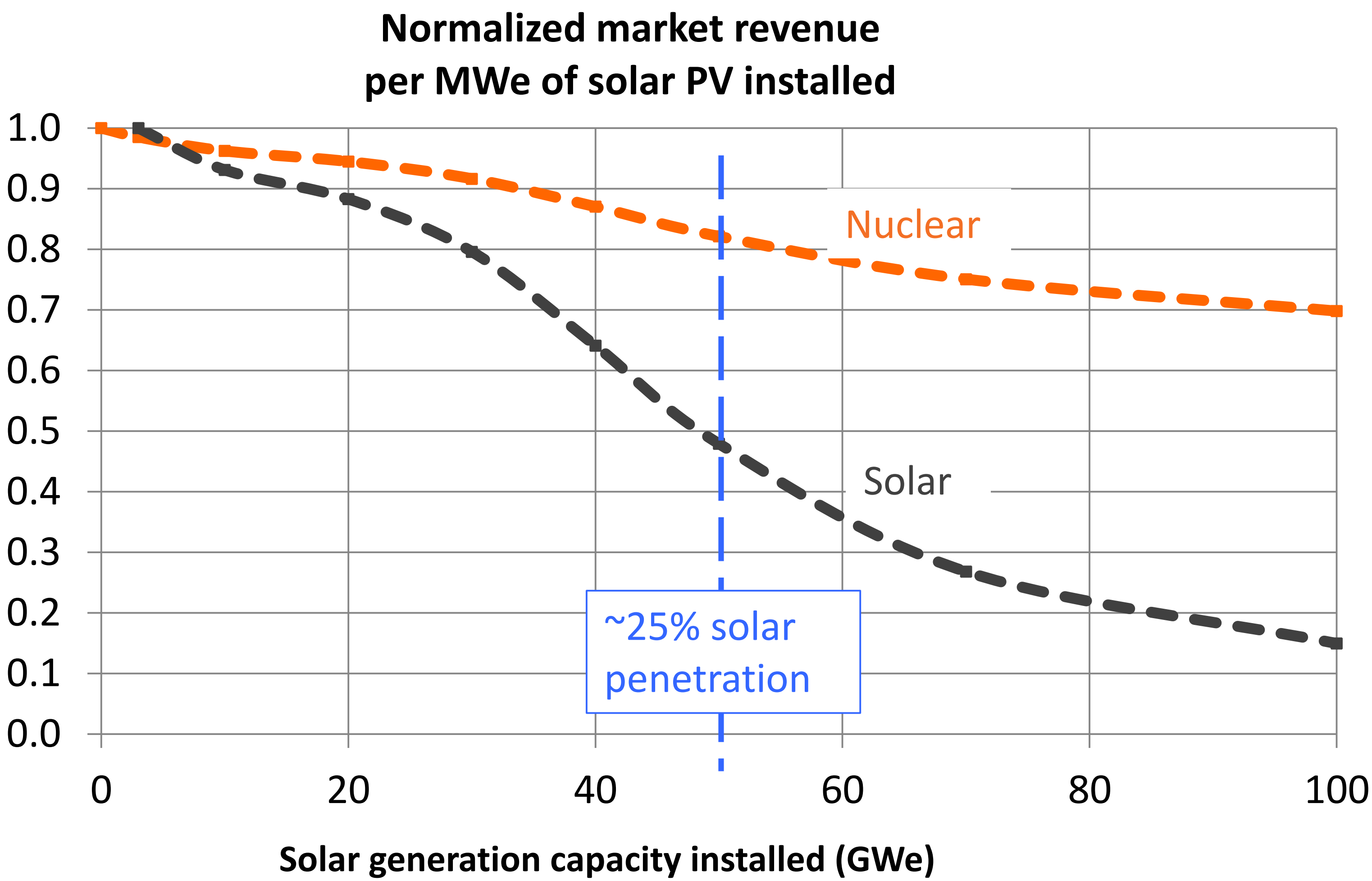
Enabling Technology for Low-Carbon Grid

Analysis Based on Existing Grid

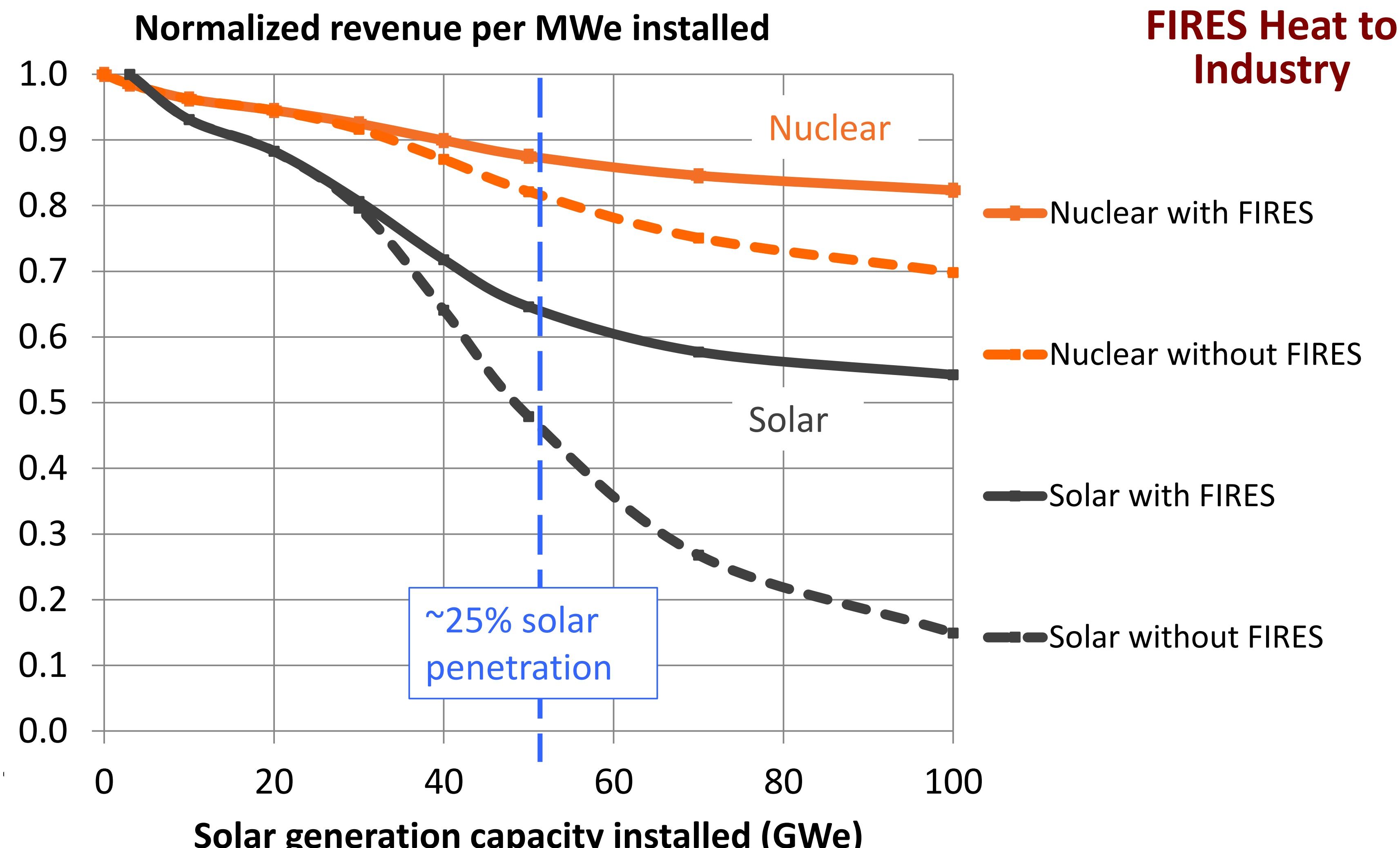
Geoffrey Haratyk

Large-scale Renewables Crash Electricity Prices: Limits Nuclear, Wind and Solar

Simulation of Deregulated Tokyo Grid (Assume half of nuclear Capacity Restarts)

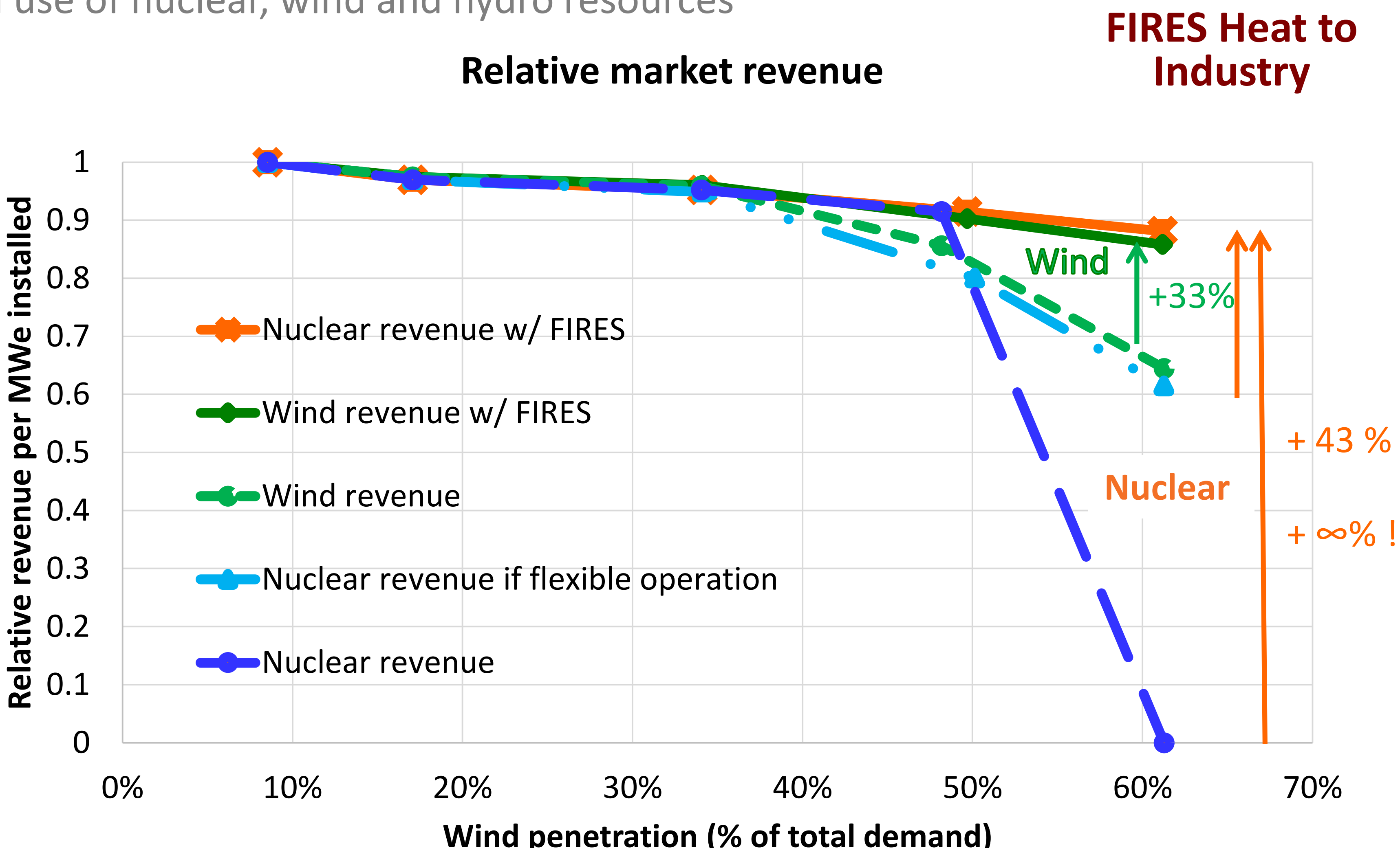


FIRES Limits Revenue Collapse for Nuclear and Solar in Japan



FIRES Limits Wind and Nuclear Revenue Collapse in Midwest U.S.

Full use of nuclear, wind and hydro resources



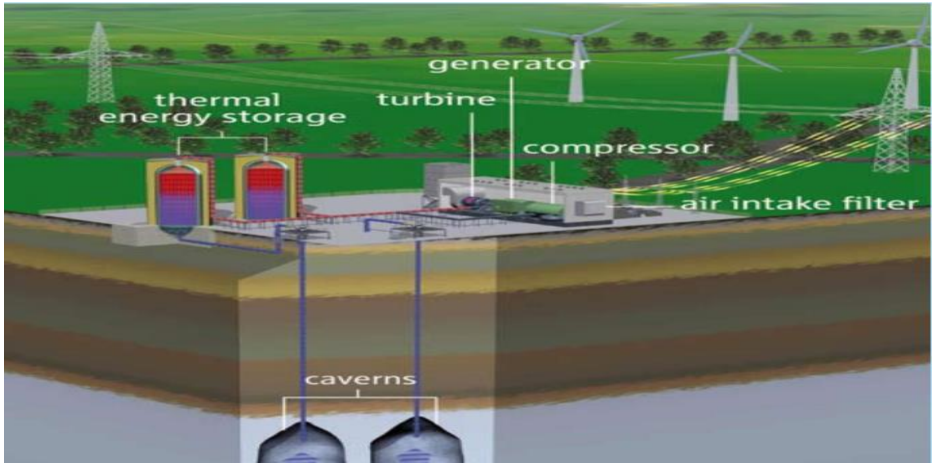
FIRES Coupled to High-Temperature Efficient Gas Turbines

Only FIRES Heat-Storage Technologies Can Deliver Heat at the High Temperatures Required by Gas Turbines

FIRES Gas-Turbine Applications

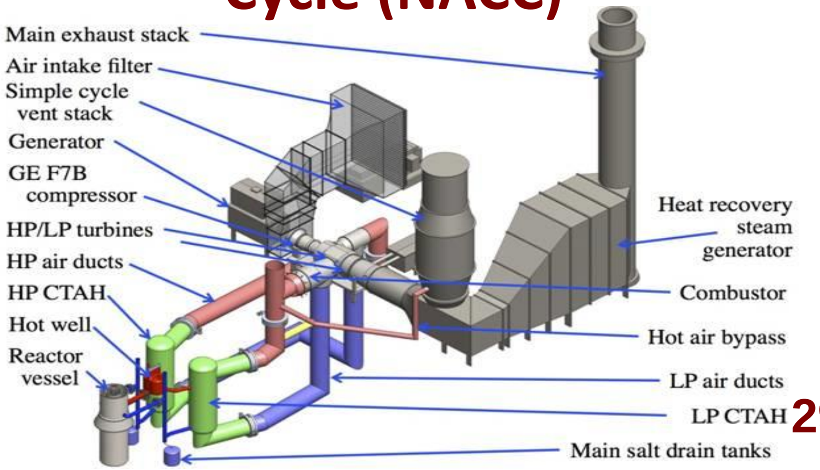
FIRES Operating at Gas-Turbine Pressures and Temperatures

FIRES with Adiabatic Compressed Air Storage (ACAS)



FIRES with Natural Gas Combined Cycle (NGCC)

FIRES with Nuclear Air Combined Cycle (NACC)



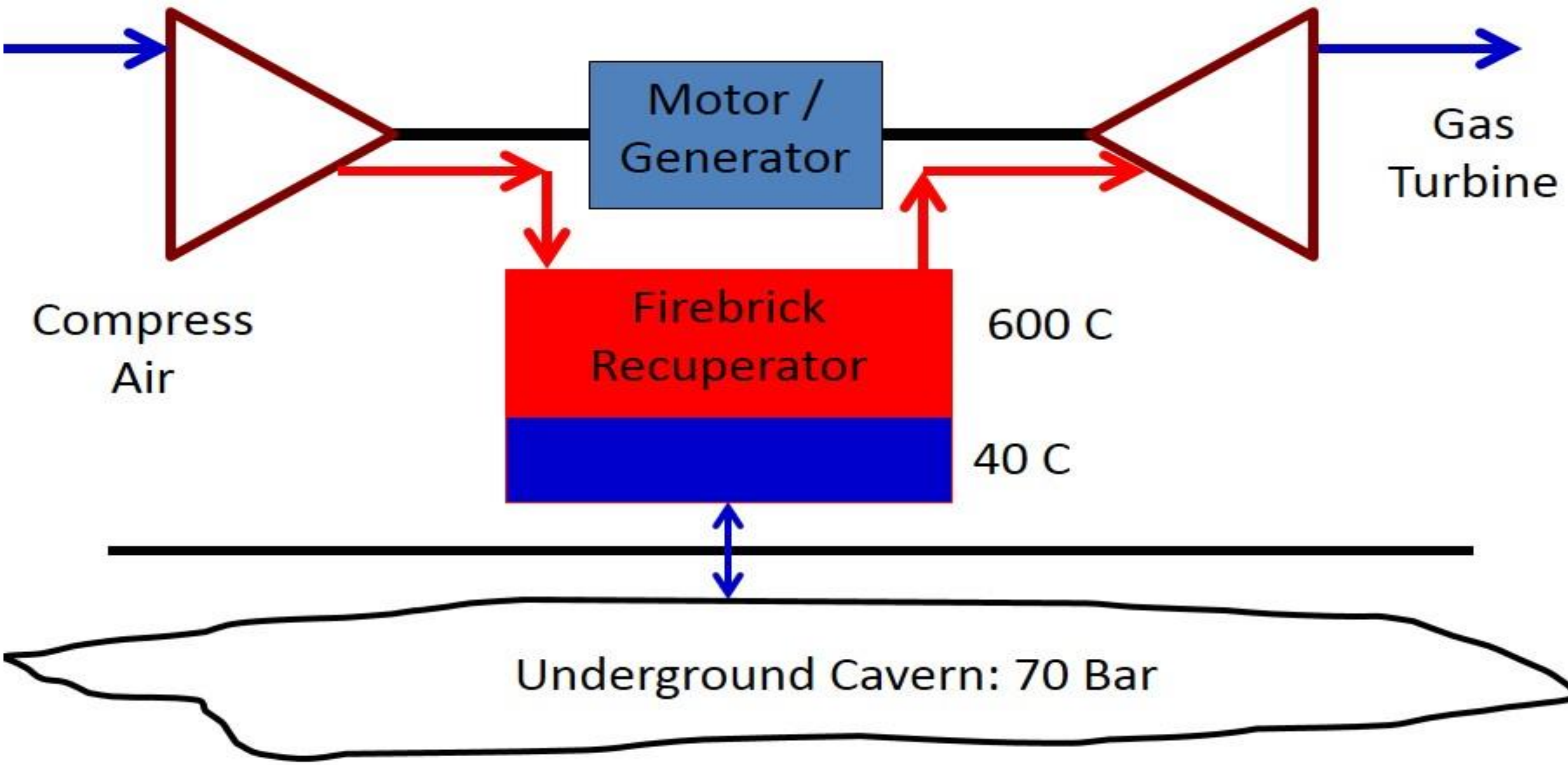
FIRES Coupled to Adiabatic Compressed Air Storage (ACAS)

Electricity Storage

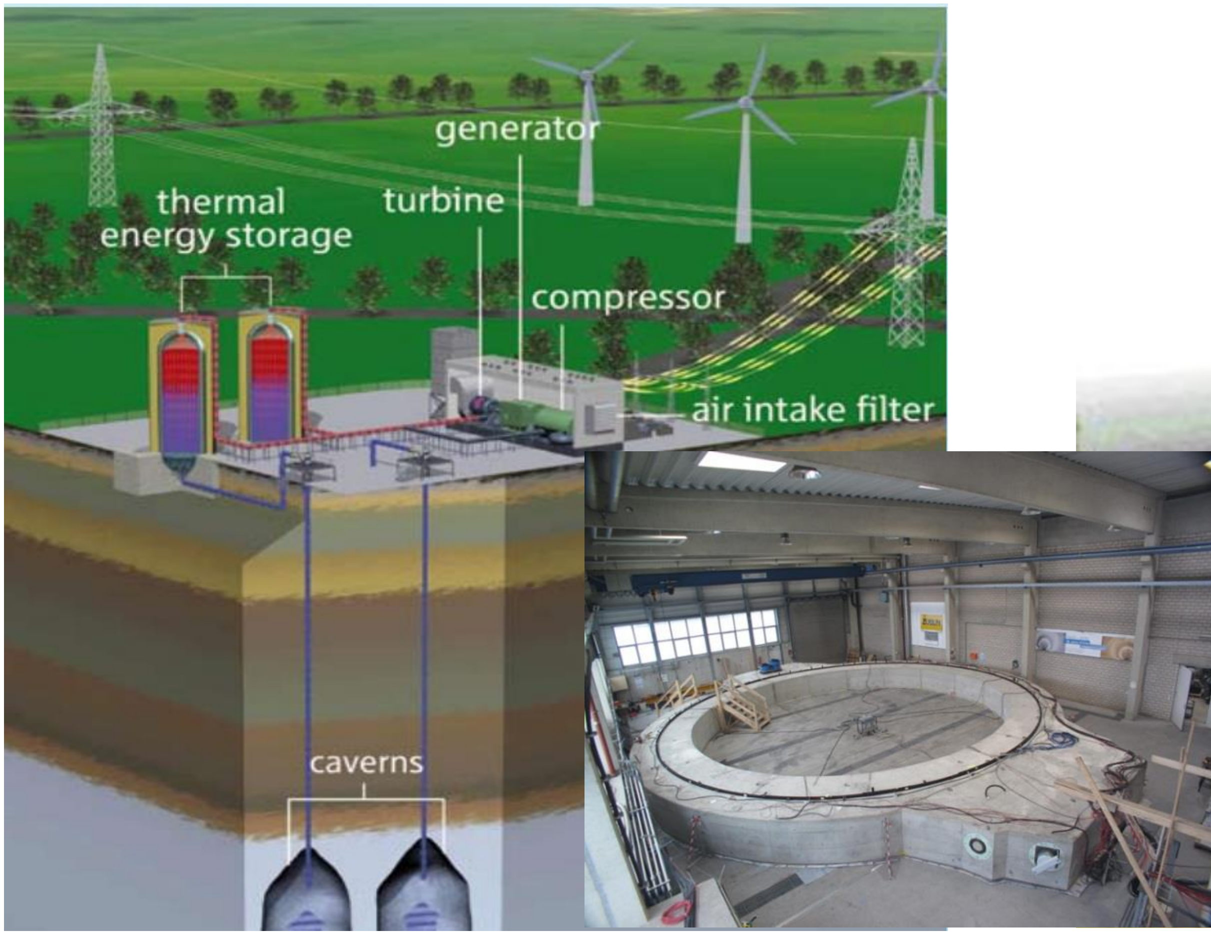
GE/RWE Adele Project
Option to Add FIRES

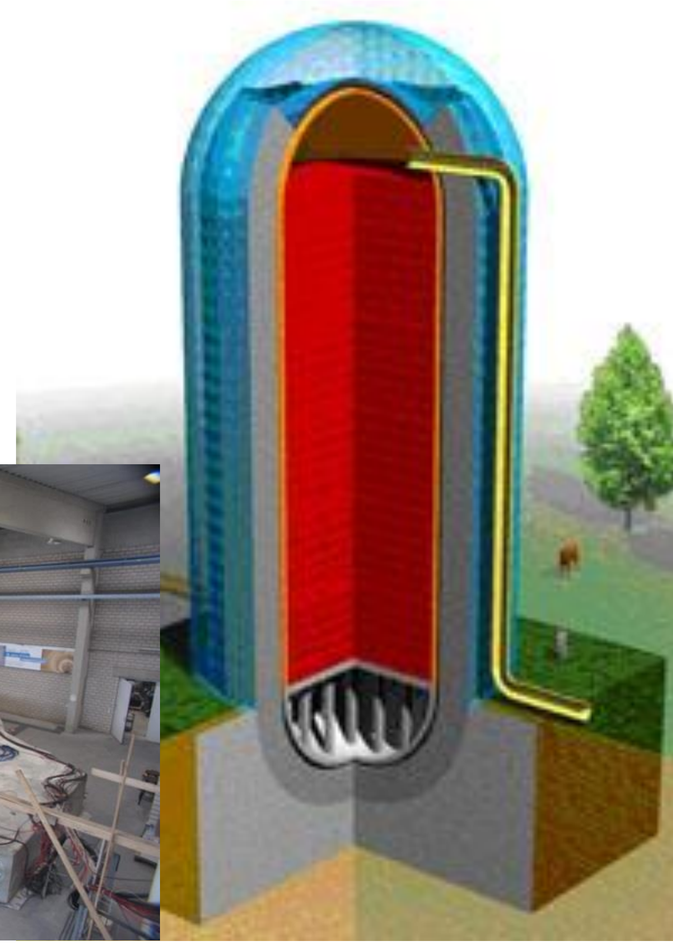
General Electric Adiabatic Compressed Air Storage (ACAS) System

Demo Next Several Years in Germany



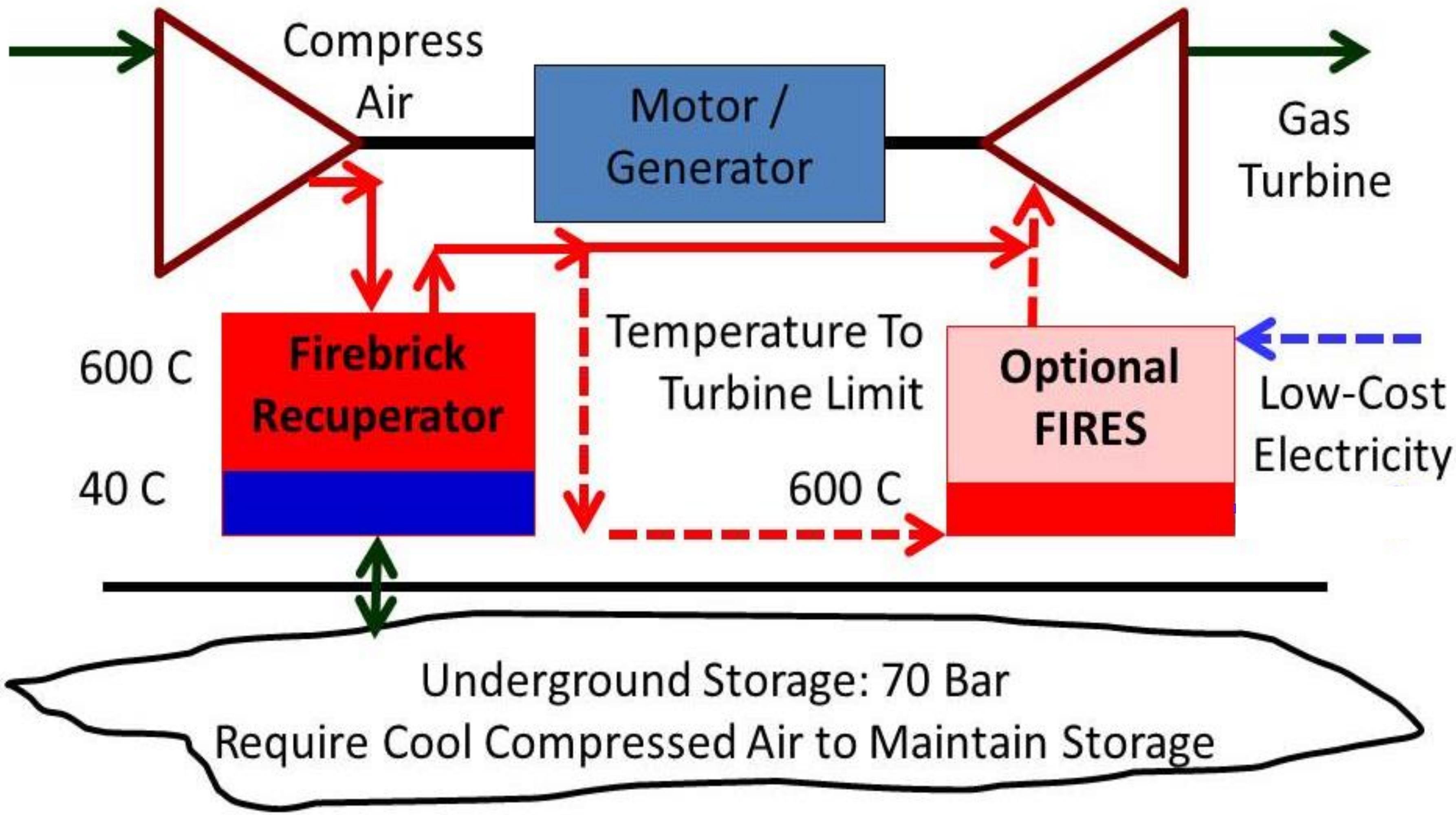
ACAS without FIRES Being Developed by General Electric and RWE (German Utility)





GE Integrating Brick Recuperator (No Electric Heat) into a Large Gas Turbine System

Adiabatic Compressed Air Storage (ACAS) with FIRES for Electricity Storage



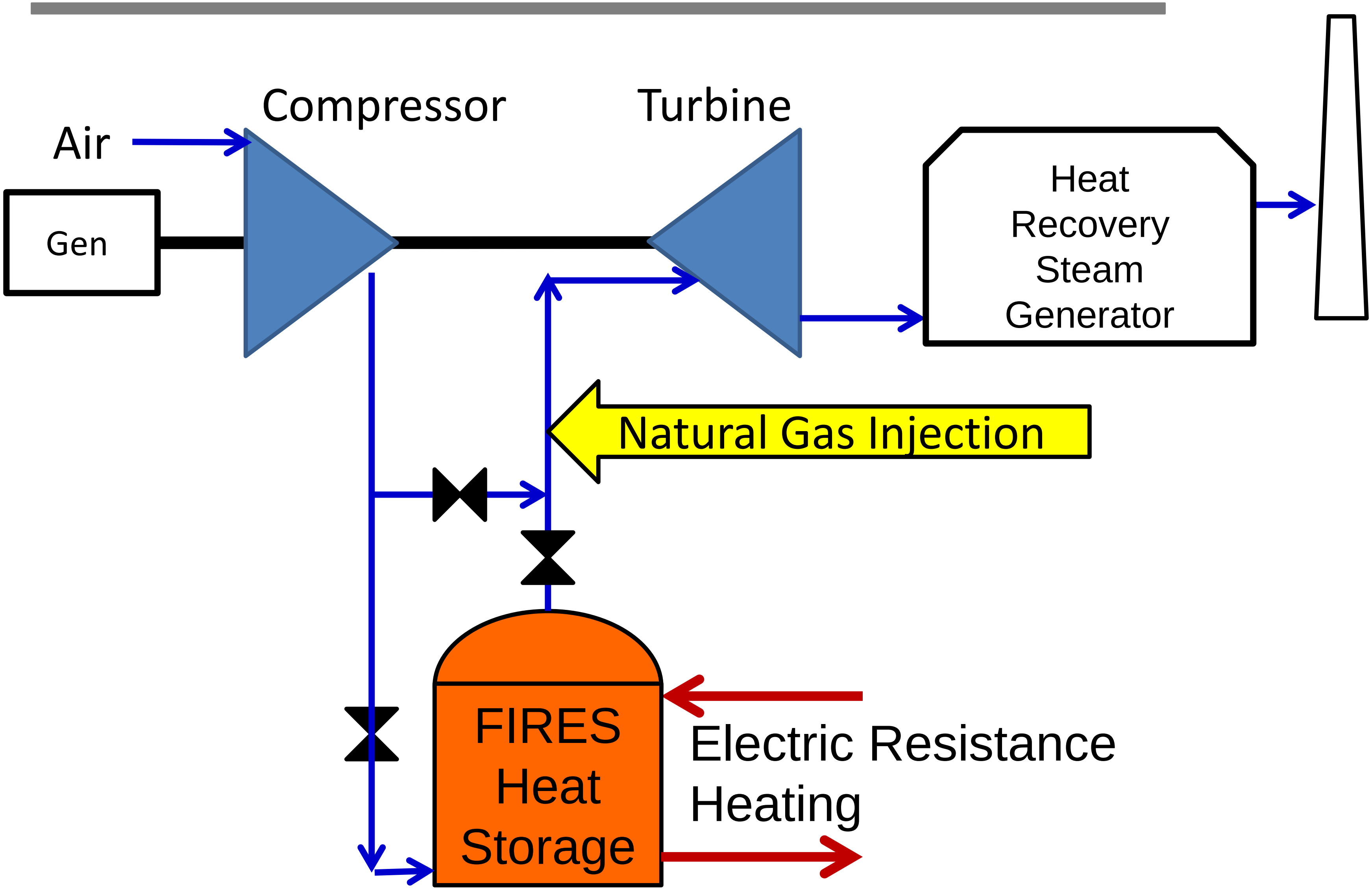
FIRES Coupled with Natural Gas Combined Cycle Turbine (NGCC)

Partial Replacement of Natural Gas or Oil in NGCC to Produce Electricity

Potentially Competitive in Locations with High Fossil Fuel Prices and Lower Renewable Costs (Islands Such as Hawaii)

Gas Turbine with FIRES Heat Storage

Integration of FIRES into Natural Gas Turbine



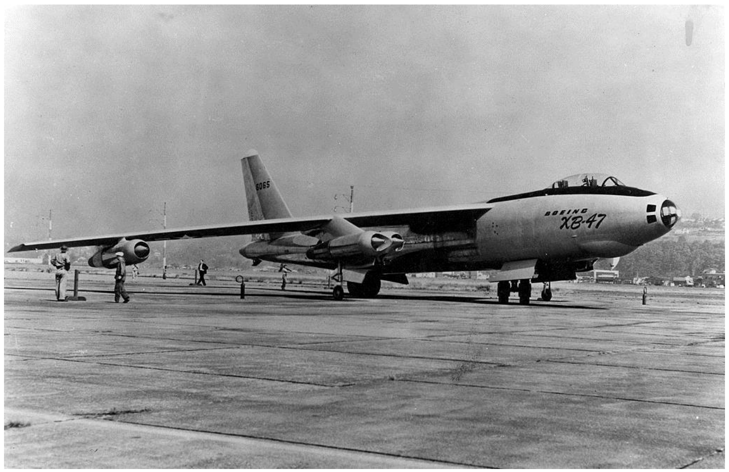
FIRES Coupled to Nuclear Air-Brayton Combined Cycle (NACC)

Base-Load Nuclear Power with Variable Electricity to the Grid

Couples with High-Temperature Salt-Cooled Reactors (600 to 700C)

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

Salt Coolants Designed to Couple Reactors to Jet Engines



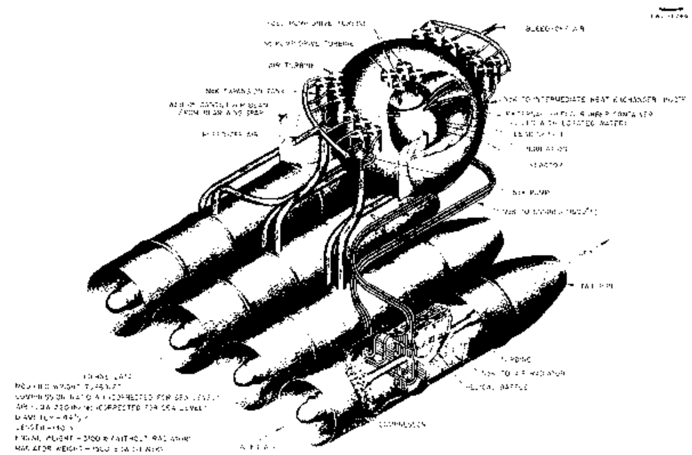


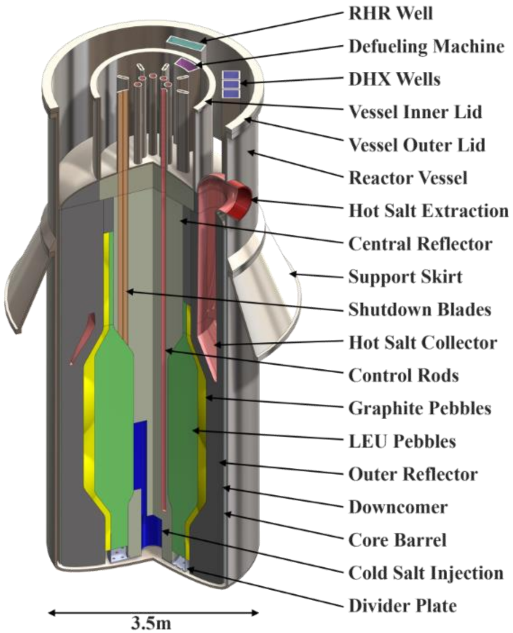
Fig. 4.33. Aircraft Power Plant (200 Megawatt).

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

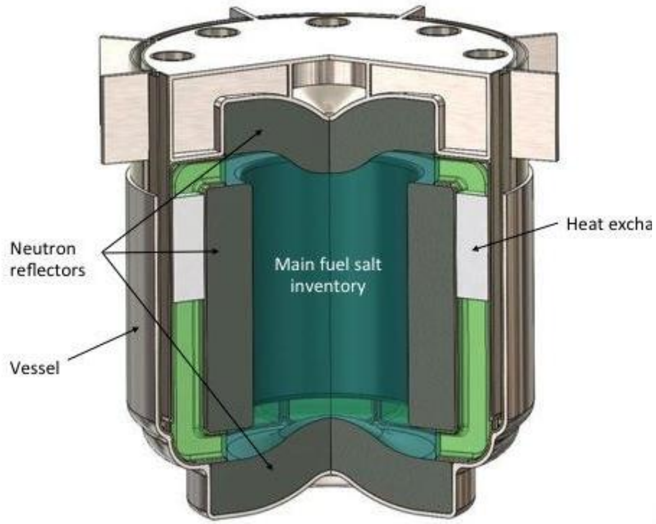
Coupling Reactors to Gas-Turbines is Transformational

NACC Power Cycle Requires Delivery of Heat Between 600 and 700°C

Three Salt-Cooled Concepts With That Capability

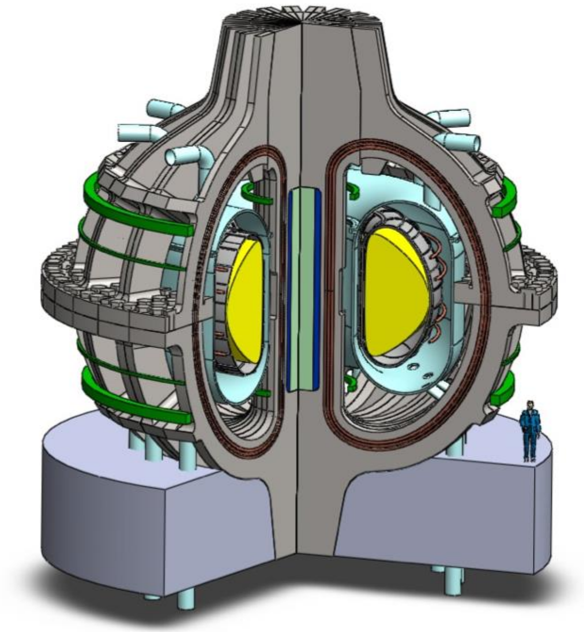


Fluoride Salt-Cooled High-Temperature Reactor (FHR)



Molten Salt Reactor (MSR)

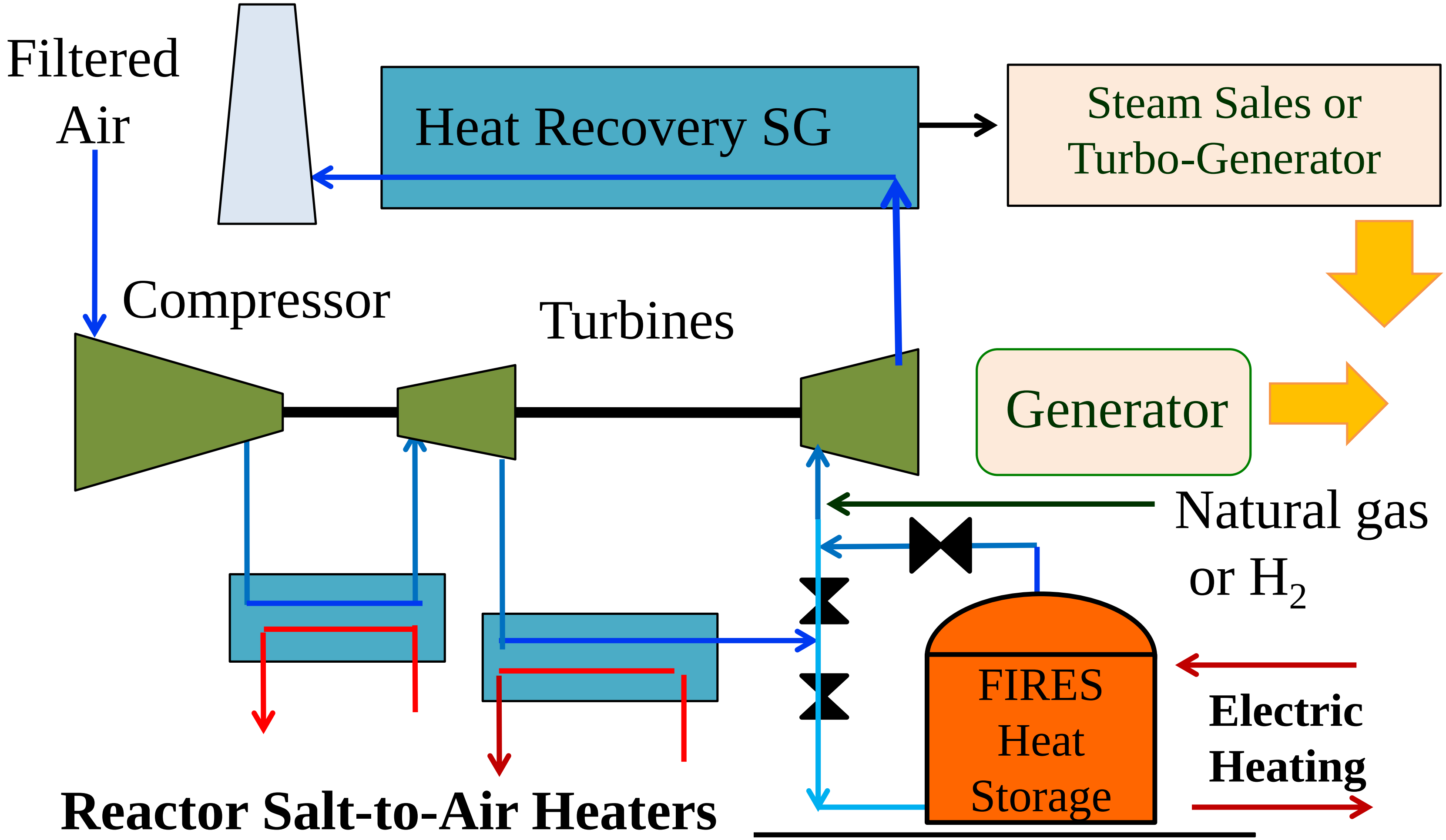
Terrapower Design



Salt-Cooled Fusion

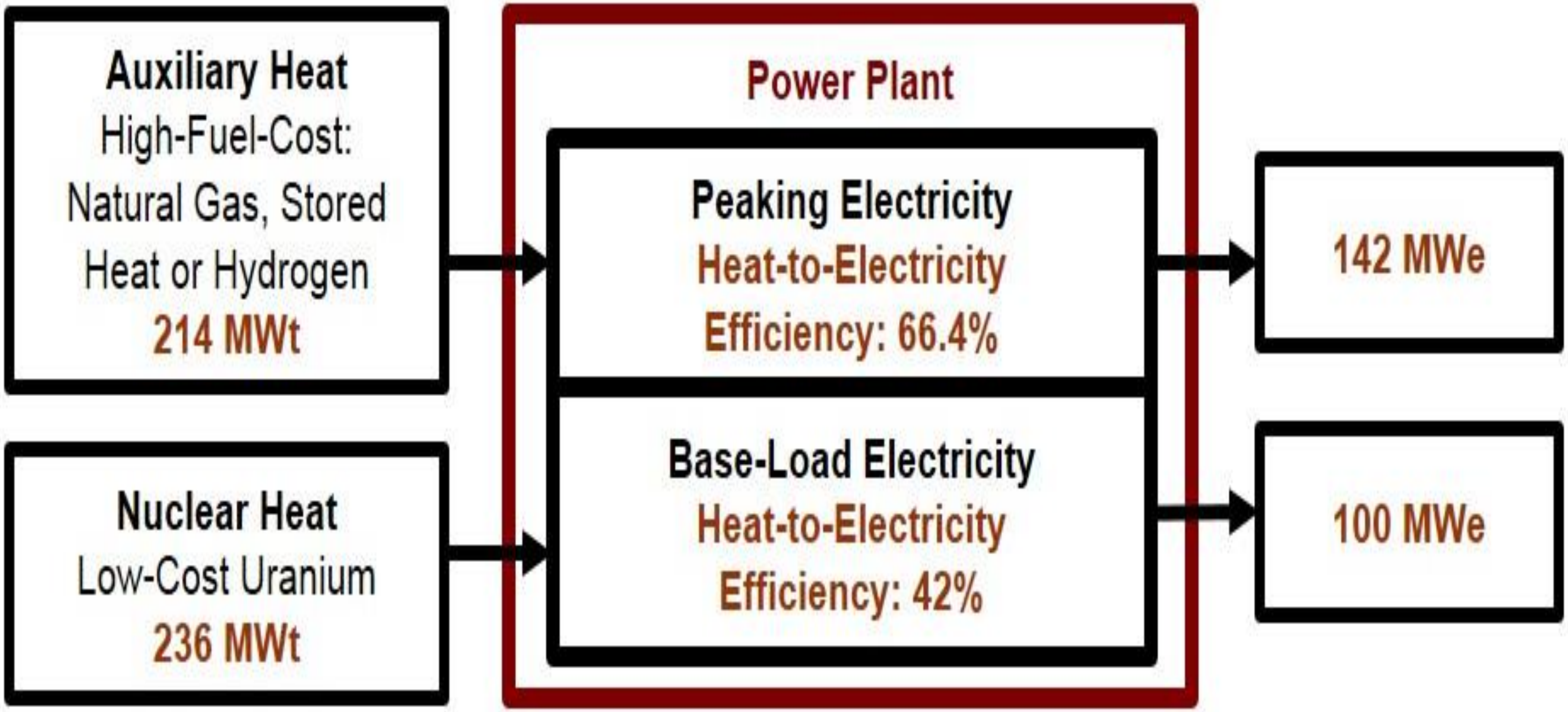
NACC Power System With FIRES

Modified Natural-Gas-Fired Power Cycle



NACC Has a Classical Thermodynamic Topping Cycle for Peak Electricity

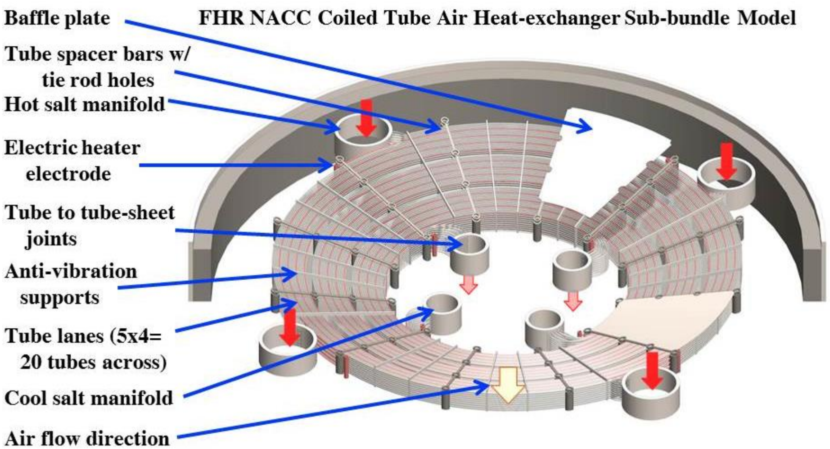
Efficiency of Topping Cycle Greater than Base-Load Cycle



Peaking Incremental Heat-To-Electricity Efficiency (66.4%) Exceeds Stand-Alone Combined Cycle Natural Gas Plant (60%)

Gas Turbine Temperature Limits Make Possible High-Efficiency Topping Cycles

- Bottoming cycle limited by temperature limits of heat exchanger materials
  - 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

Revenue Using 2012 Texas and California Hourly Electricity Prices

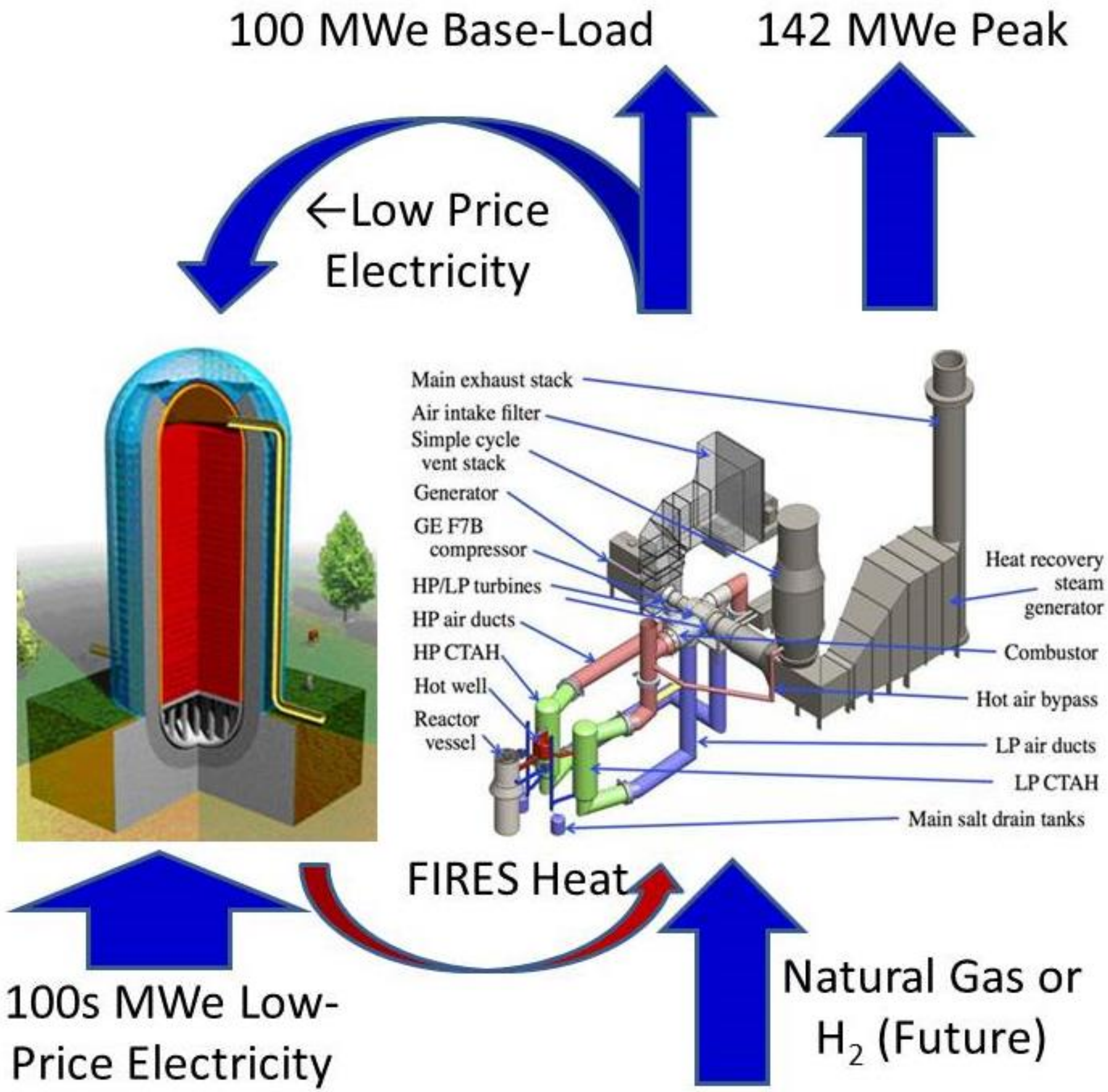
After Subtracting Cost of Natural Gas, No FIRES

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 Because Higher Efficiency in Converting Natural Gas to Electricity (66.4%) versus 60% for Stand-Alone Natural Gas Plant

Variable Zero-Carbon Electricity

Base-Load Reactor with FIRES and Nuclear Air-Brayton Cycle Buys and Sells Electricity to Grid



Power Generation and Electricity Storage

FHR/NACC/FIRES Observations

- Most efficient incremental heat-to-electricity system
  - If burning natural gas, first “natural gas” plant dispatched
  - If FIRES, buy electricity whenever below natural gas price or if no natural gas, below peak price after accounting for round-trip efficiency.
  - If future use of hydrogen for peak electricity, this is the most efficient method to convert hydrogen to electricity
- Because gas turbines have large economics of scale, incremental capital cost of peaking power less than stand-alone natural gas plant

In a Zero-Carbon World, NACC Could 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 the cost of the FIRES pre-stressed 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 electricity to hydrogen to electricity generating system**

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 and 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

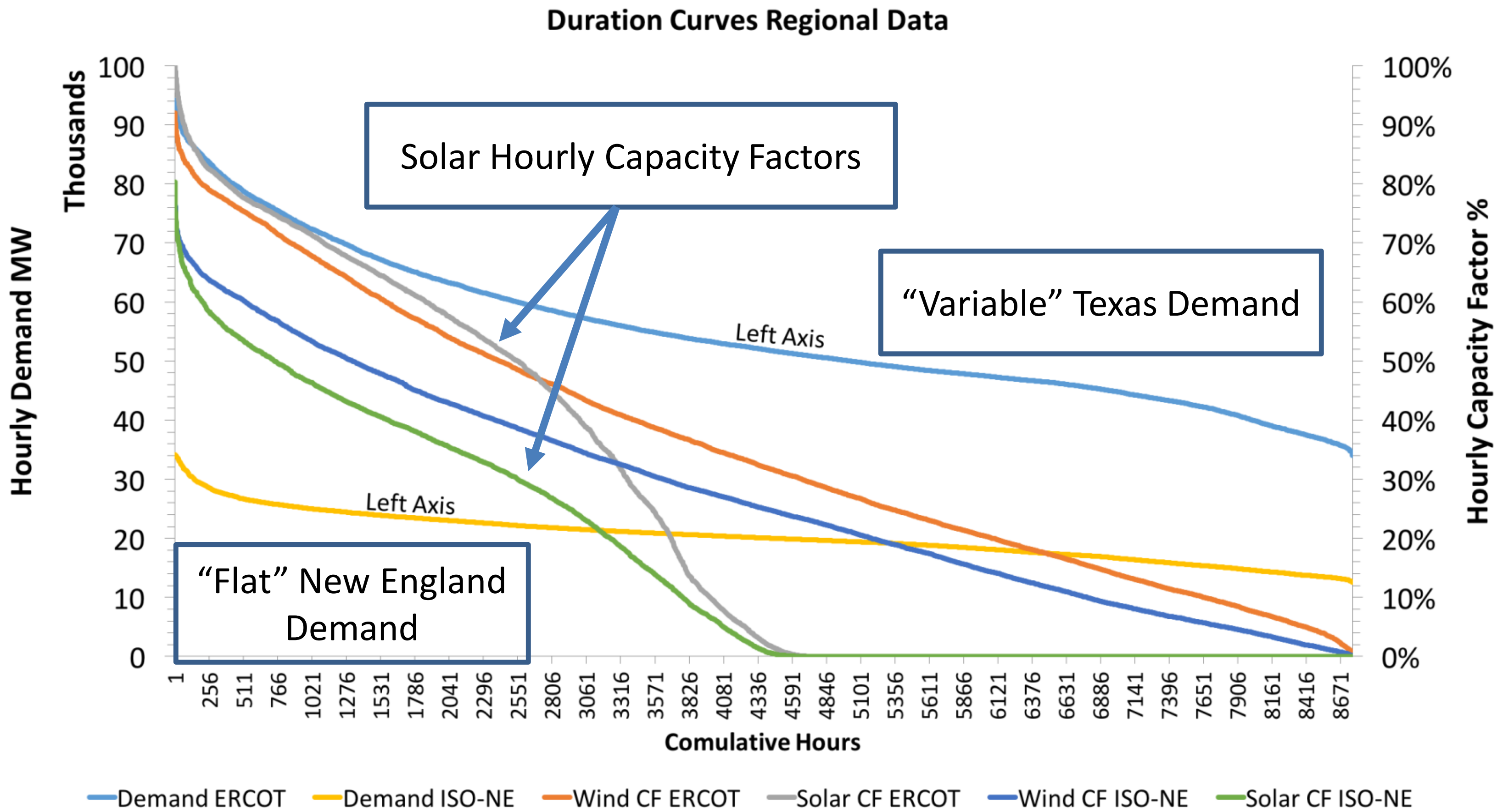
Each Technology Has Different Economic / Performance Characteristics

- Combined cycle gas turbine (natural gas)
- Open cycle gas turbine (natural gas)
- Nuclear (LWR, SFR, etc.)
- 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 and FIRES)*

***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.**

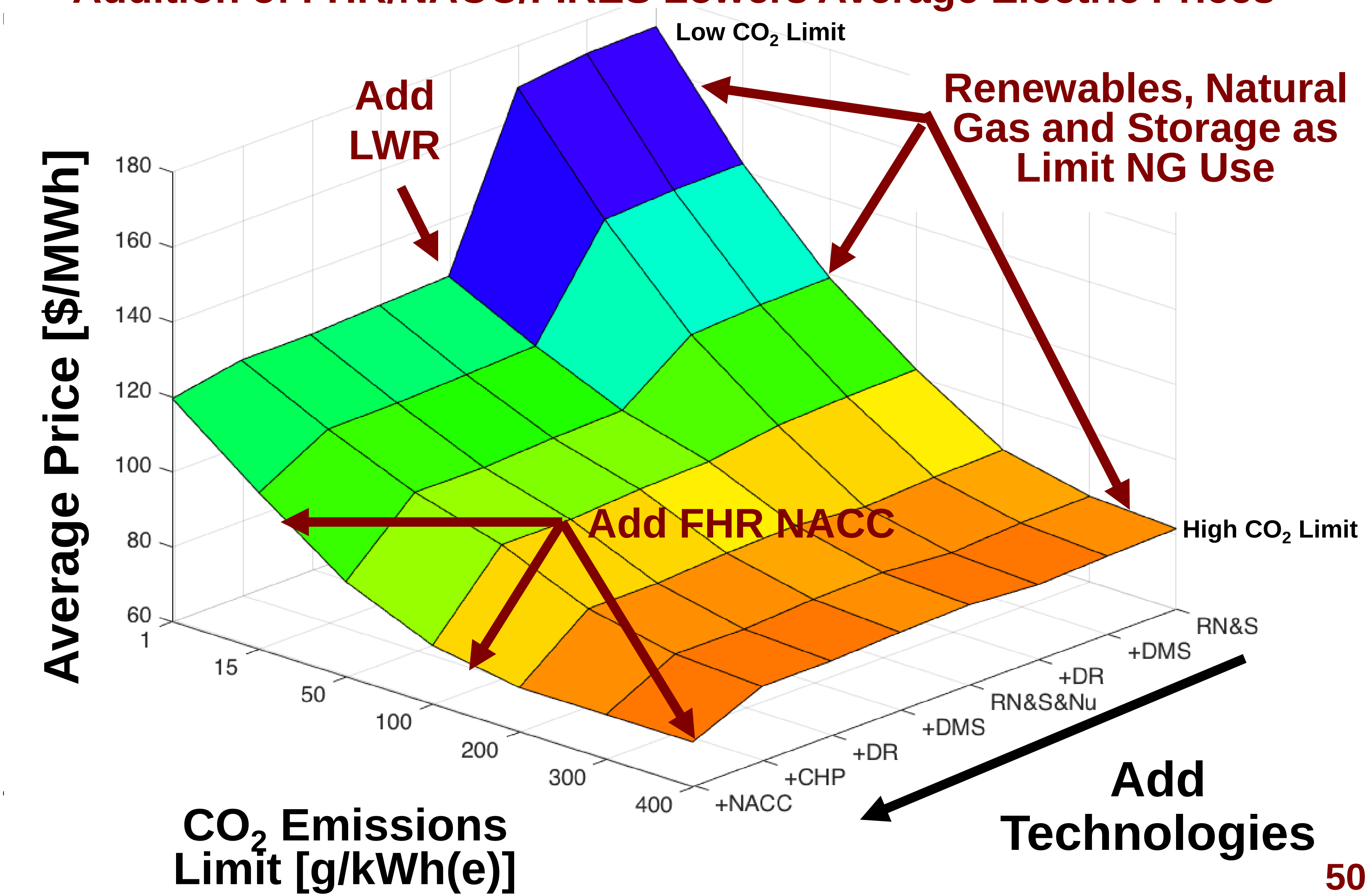
Results are Grid Dependent

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

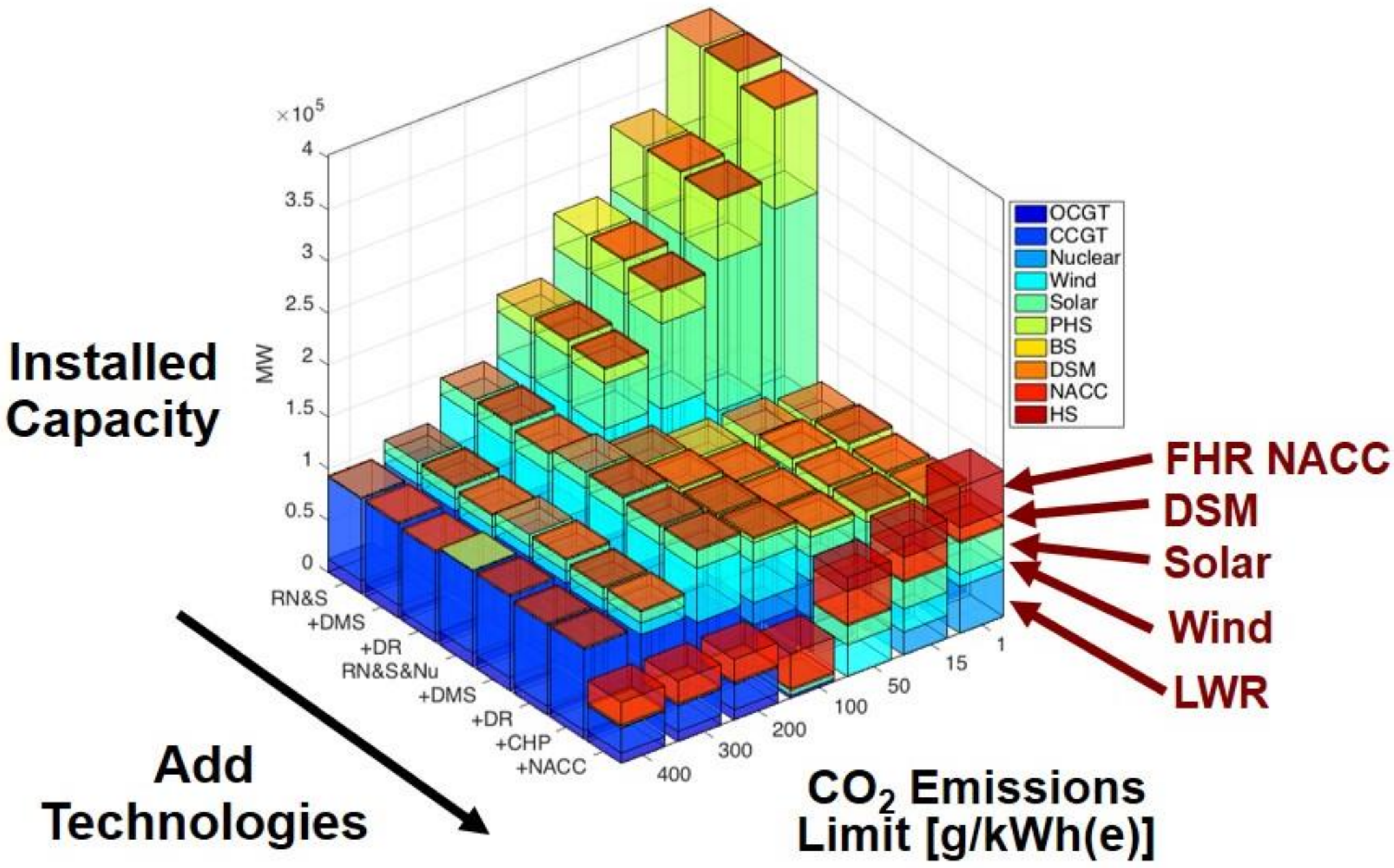


Key to Technology Options on 3-Dimensional Plots

- 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
  - +DMS: Demand Management
  - +DR: Demand Reduction
  - +CHP: FIRES (Industrial and other applications)
  - +NACC: FHR with NACC and FIRES

2050 Texas Installed Capacity Versus Added Technologies and CO_2 Limits

Technology Choices Change with CO_2 Limits and Added Technologies

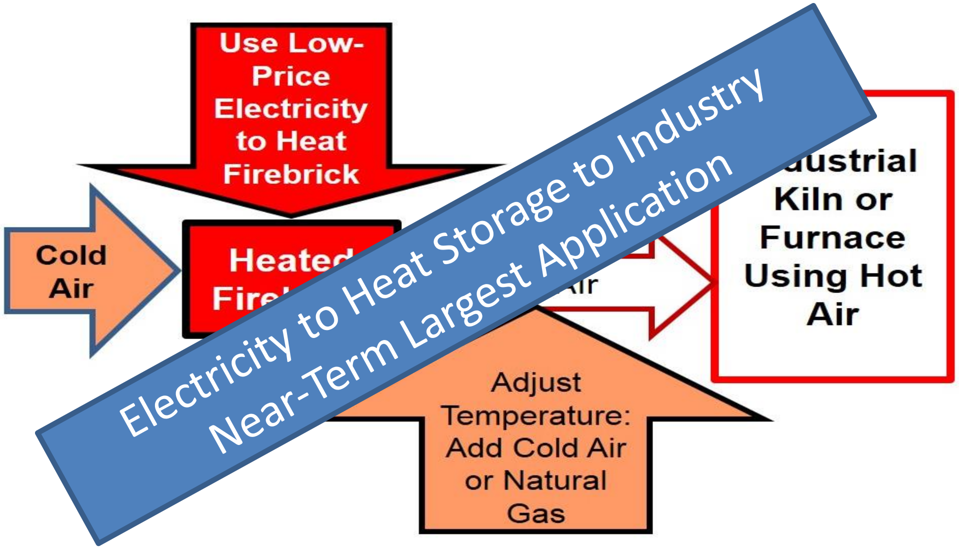


Conclusions

- Addition of renewables to grid causes electricity price collapse at times of high wind and solar
- Price collapse limits use of nuclear, wind and solar
- FIRES enables a low-carbon grid by stopping price collapse with low-price electricity to heat storage for industry and gas turbines (Peak electricity)
- Changes in electricity markets or a goal of a low-carbon grid create the incentive to develop advanced reactors with NACC and FIRES

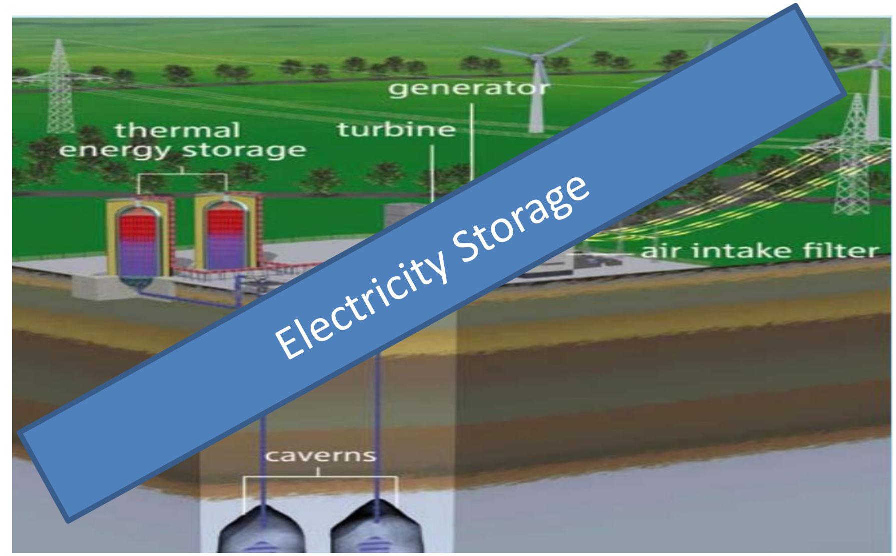
Questions?

FIRES with Industrial Furnaces



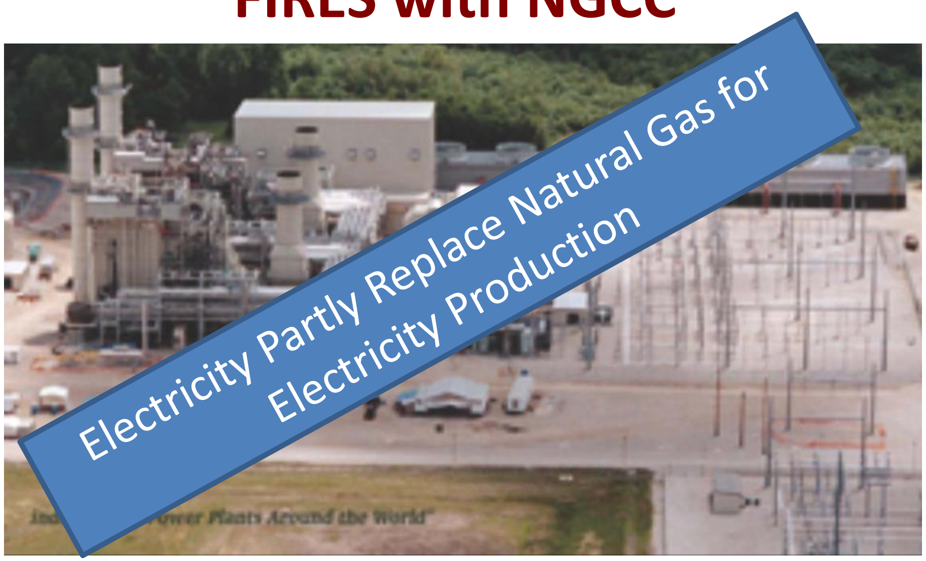
Electricity to Heat Storage to Industry
Near-Term Largest Application

FIRES with ACAS



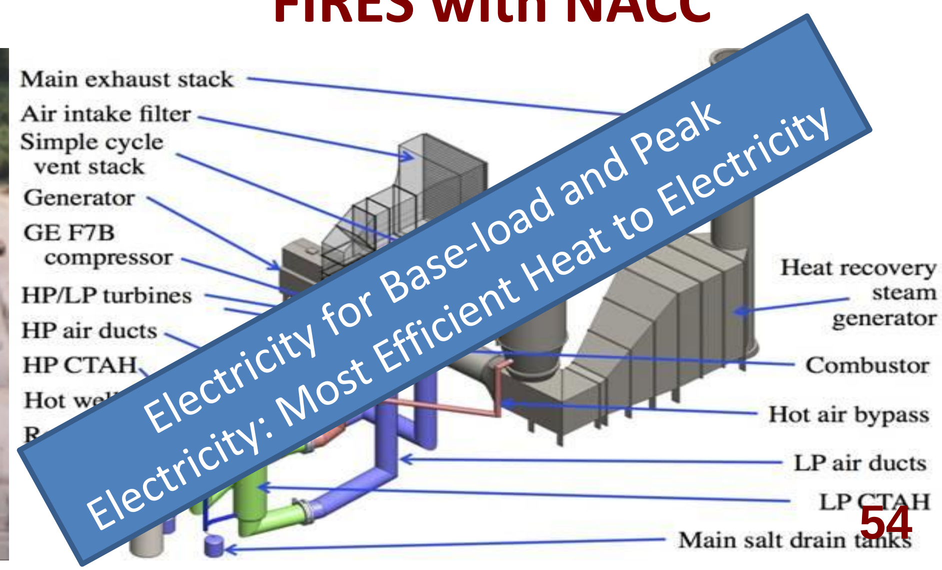
Electricity Storage

FIRES with NGCC



Electricity Partly Replace Natural Gas for Electricity Production

FIRES with NACC



Electricity for Base-load and Peak
Electricity: Most Efficient Heat to Electricity

Technologies for an Economic Low-Carbon Nuclear Renewables Grid: The Case of Firebrick Resistance-Heated Energy Storage

The addition of large quantities of solar or wind to the grid causes electricity price collapse at times of large solar or wind input. For example, wind farms in parts of Iowa have resulted in wholesale electricity prices less than natural gas for over half the year. Electricity price collapse hurts the economics of wind, solar and nuclear and is a major barrier to a low-carbon grid. One potential solution is Firebrick Resistance Heated Energy Storage (FIRES). FIRES stops price collapse by buying cheap electricity (below the price of natural gas) when available and heats firebrick to high temperatures using electric resistance heaters. Cold air is sent through the hot firebrick to produce hot air that substitutes for air heated by natural gas in industrial furnaces and plants that produce peak electricity. FIRES sets a minimum price for electricity. It is a low-cost heat-storage technology that productively converts excess low-price electricity into stored heat for industry and peak power to improve nuclear, wind and solar economics in a low-carbon grid. It can have dramatic favorable impacts on the economics of nuclear, wind, and solar if large quantities of wind and solar are built.

Biography: Charles Forsberg

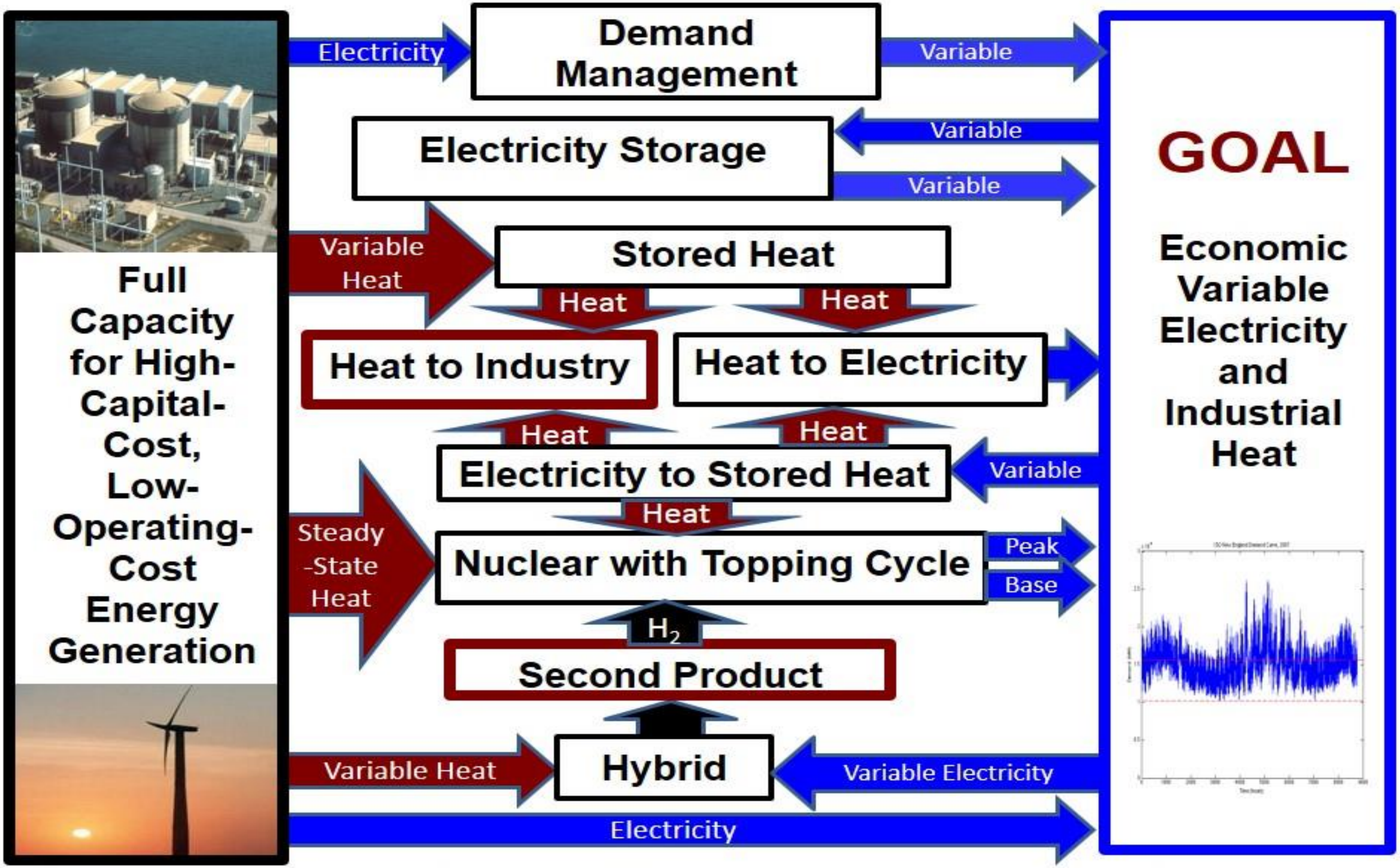
Dr. Charles Forsberg is the Director and principle investigator of the High-Temperature Salt-Cooled Reactor Project and University Lead for the Idaho National Laboratory Institute for Nuclear Energy and Science (INEST) Nuclear Hybrid Energy Systems program. He is one of several co-principle investigators 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.

Options to Match Electricity Production with Demand

Most Involve Heat That Couples to Nuclear Power
Most Dump Excess Energy to Industrial Sector

Option	Notes
Demand Management: Moves Electricity Demand in Time	
Electricity Storage: Electricity → Storage Media → Electricity	Work Storage
Electricity → **Heat Storage** → Industry or Peak Power	FIRES and Other Technologies
Heat → **Heat Storage** → Industry or Peak Power	Nuclear and Solar Thermal Input
Hybrid: **Heat** → Second Product + Variable Electricity	Nuclear and Solar Thermal Input
Nuclear Topping Cycle Base-load: Heat → Electricity + Steam (Optional) Peak: Electricity → Heat Storage → Electricity	Nuclear and Solar Thermal Input

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

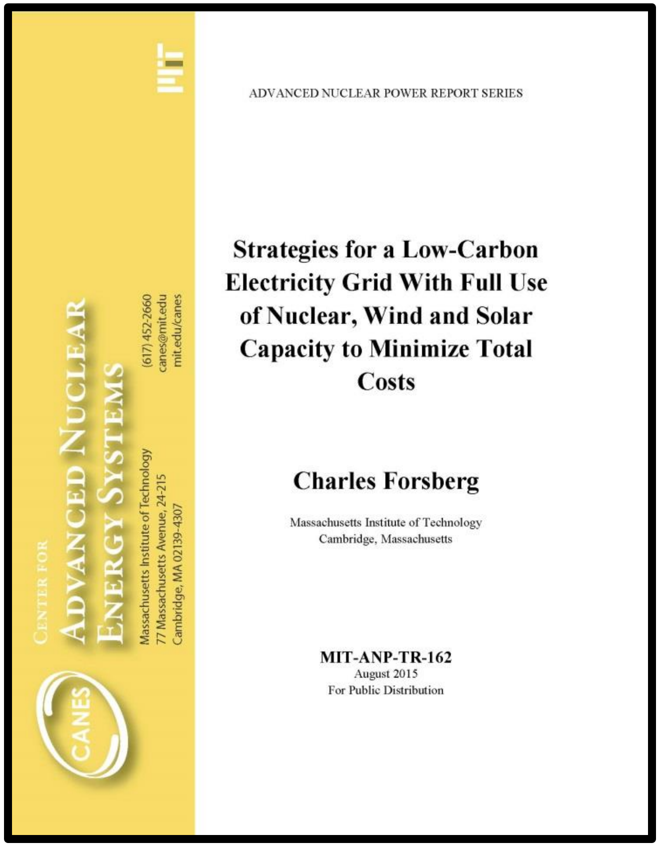


C. Forsberg, Strategies for a Low-Carbon Electricity Grid With Full Use of Nuclear, Wind and Solar Capacity to Minimize Total Costs, MIT-ANP-TR-162, August 2015; http://mitei.mit.edu/publications/reports-studies/strategies-low-carbon-electricity-grid-full-use-nuclear-wind-and-solar-

Options to Match Electricity Production with Demand

Operate Nuclear, Wind and Solar at Full Capacity

- Demand Management
- Electricity Storage
- Electricity to Heat Storage for Industry or Peak Electricity
- Heat to Storage to Industry or Peak Electricity
- Hybrid Energy Systems: Heat to Electricity and Second Product
- Nuclear Energy with Topping Cycle (NUTOP)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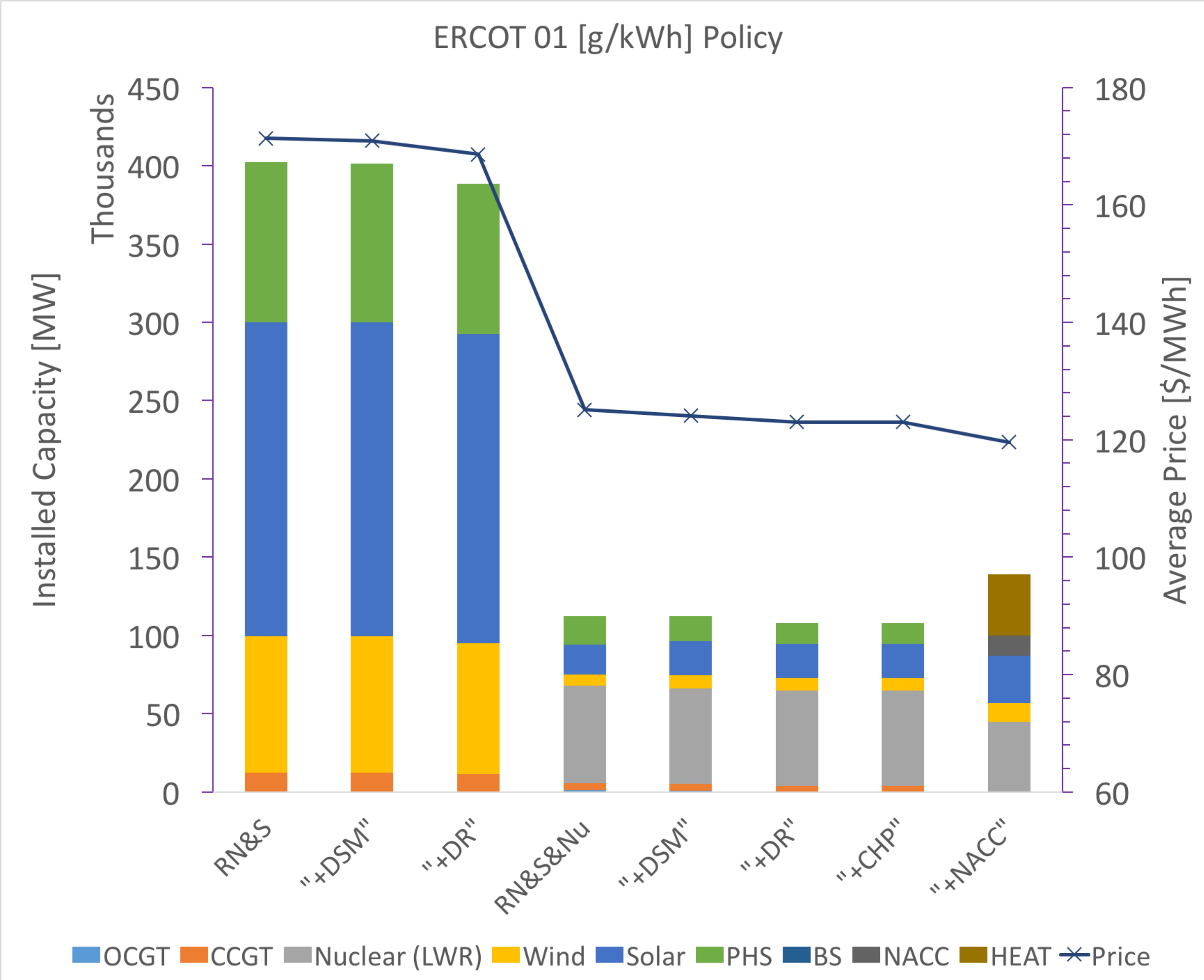
Strategies for a Low-Carbon Electricity Grid With Full Use of Nuclear, Wind and Solar Capacity to Minimize Total Costs

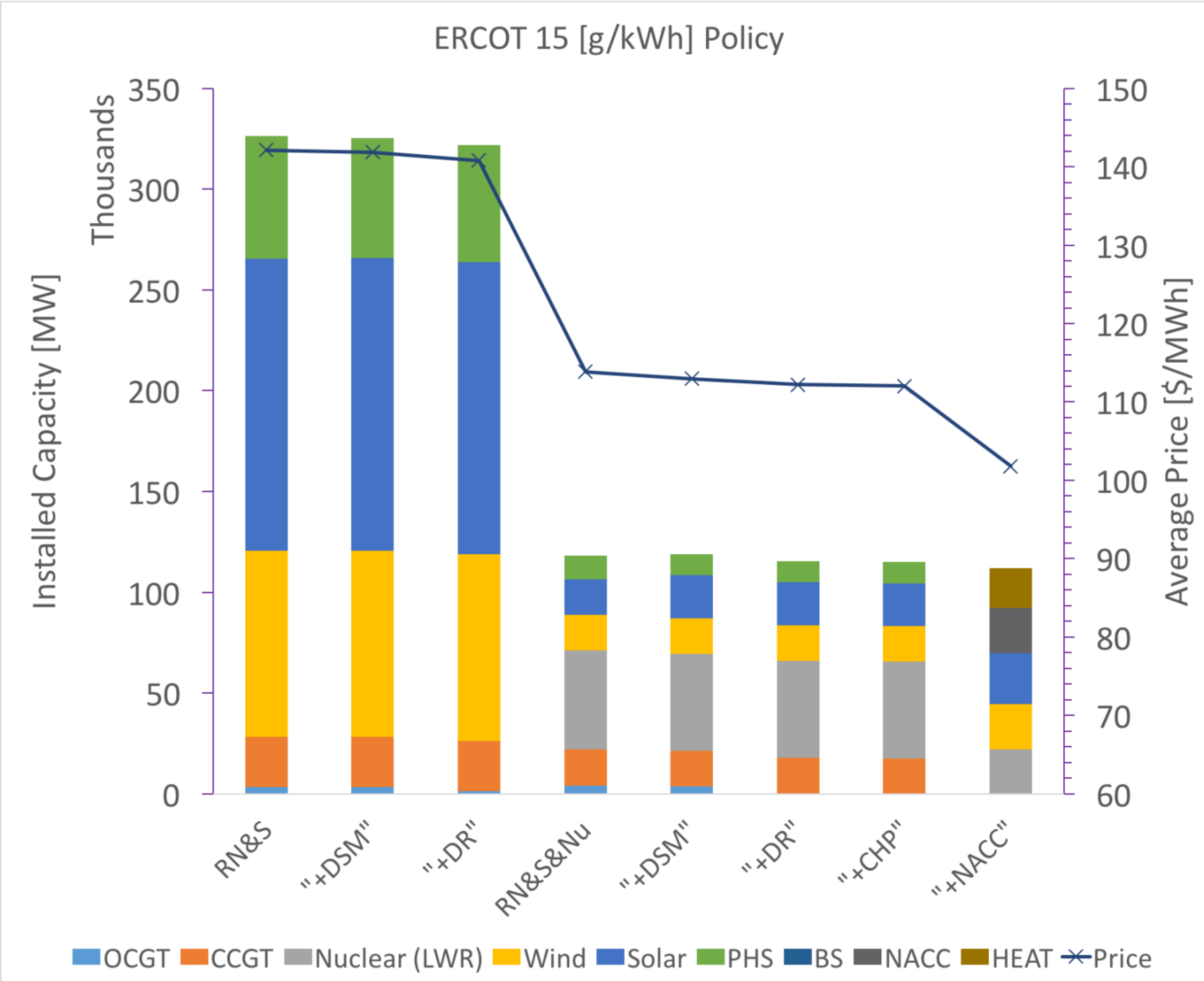
Charles Forsberg

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-


ERCOT 01 [g/kWh] Policy
Thousands
Installed Capacity [MW]
450
400
350
300
250
200
150
100
50
0
Average Price [$/MWh]
180
160
140
120
100
80
60
RN&S
"+DSM"
"+DR"
RN&S&Nu
"+DSM"
"+DR"
"+CHP"
"+NACC"
OCGT
CCGT
Nuclear (LWR)
Wind
Solar
PHS
BS
NACC
HEAT
Price


ERCOT 15 [g/kWh] Policy
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Average Price [$/MWh]
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200
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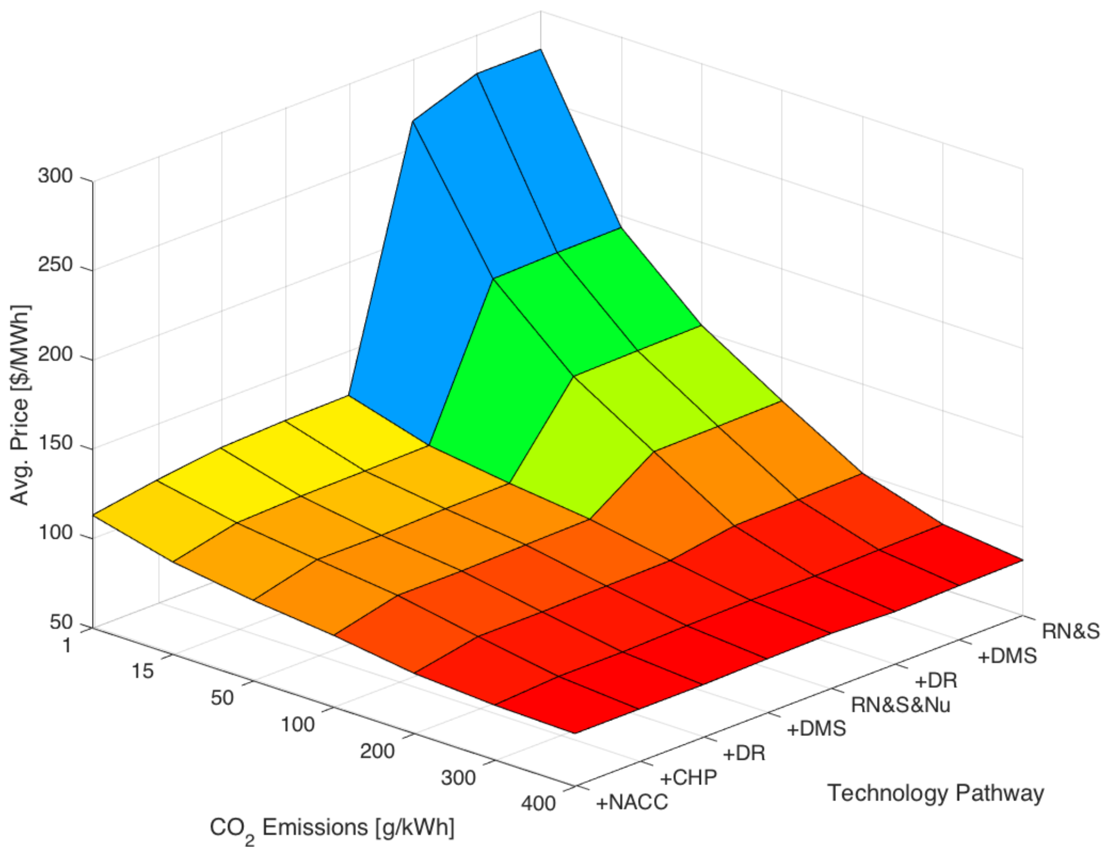
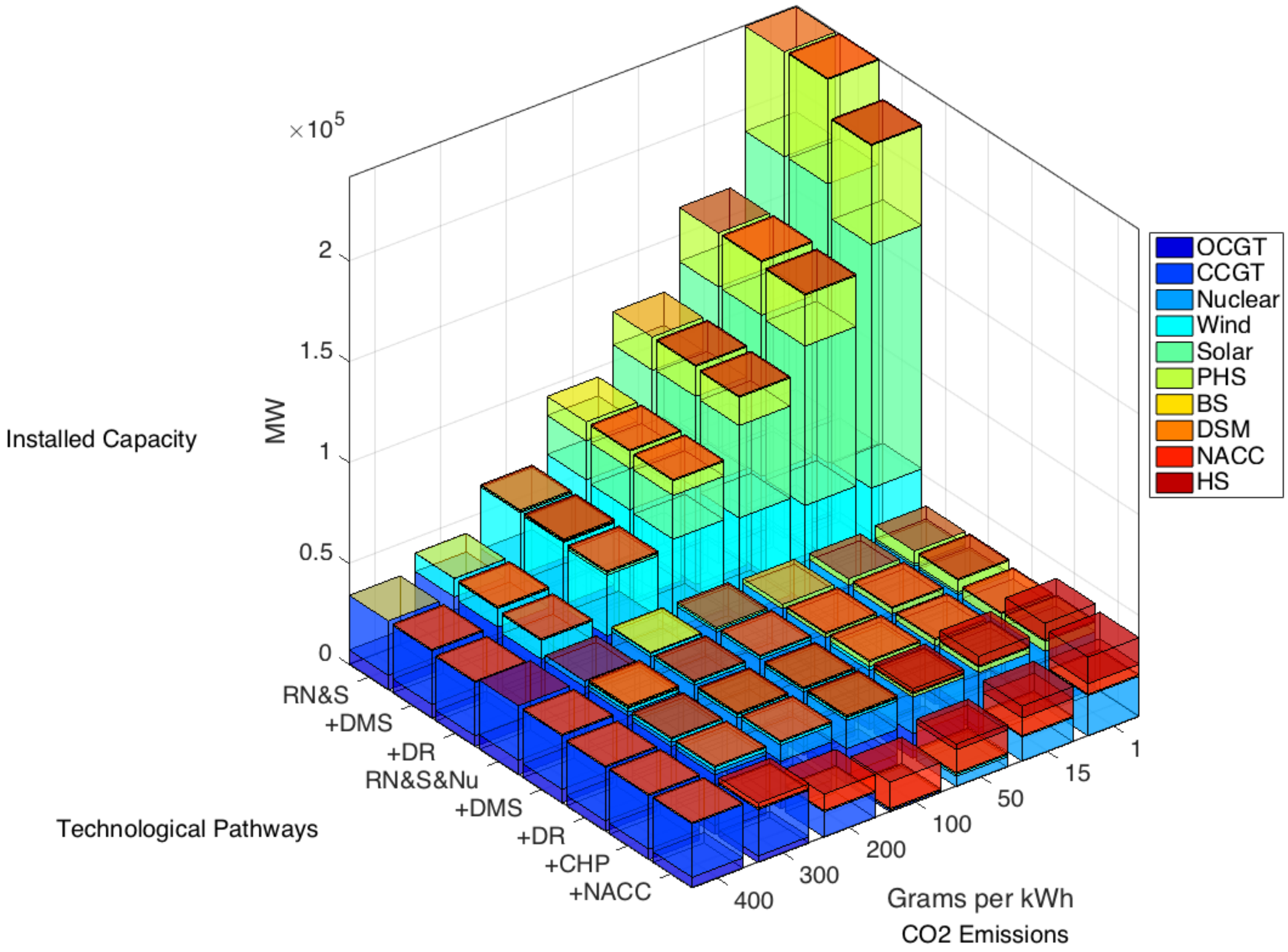
"+DSM"
"+DR"
"+CHP"
"+NACC"
OCGT
CCGT
Nuclear (LWR)
Wind
Solar
PHS
BS
NACC
HEAT
Price

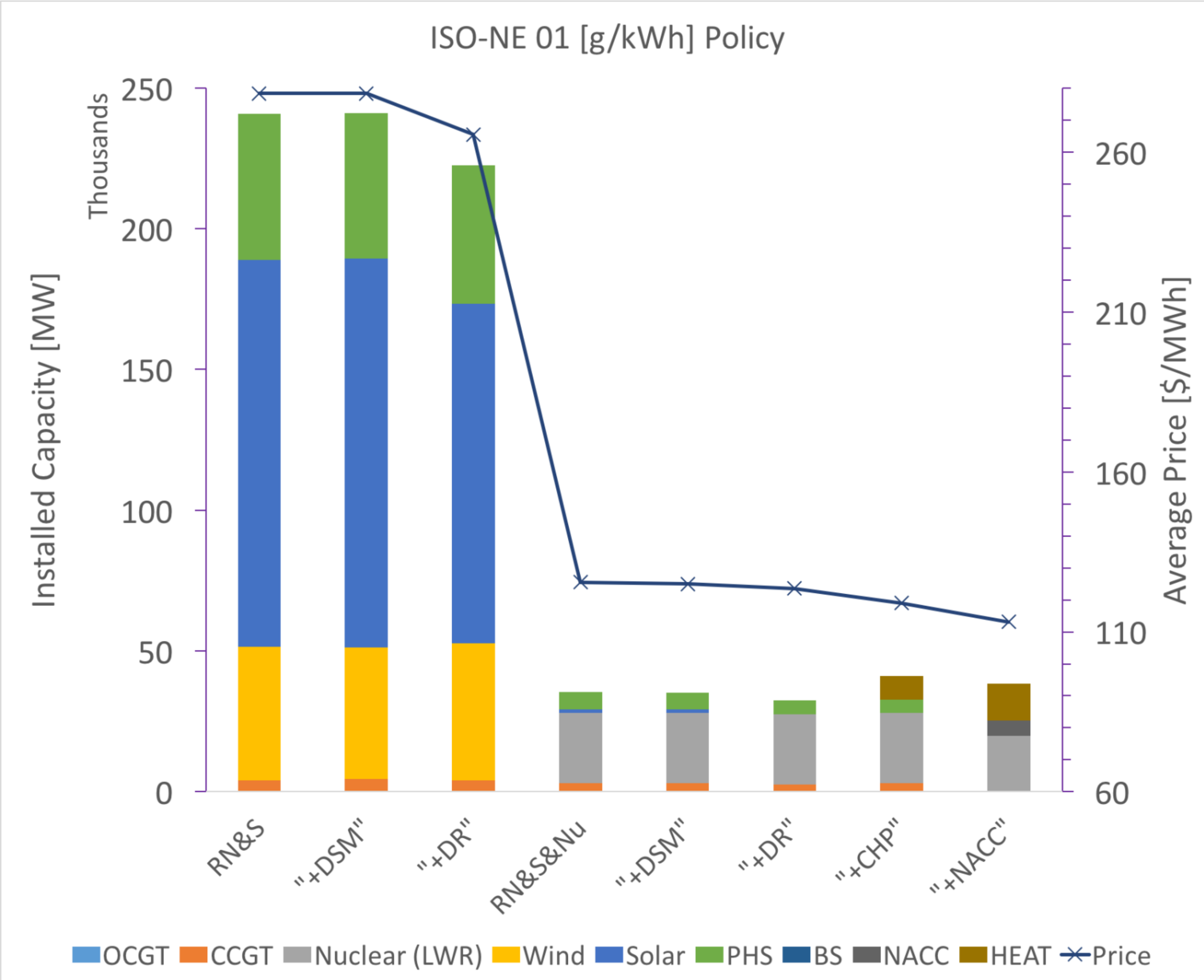
2050 Minimum-Cost New England Grid Versus Added Technologies and CO_2 Limits

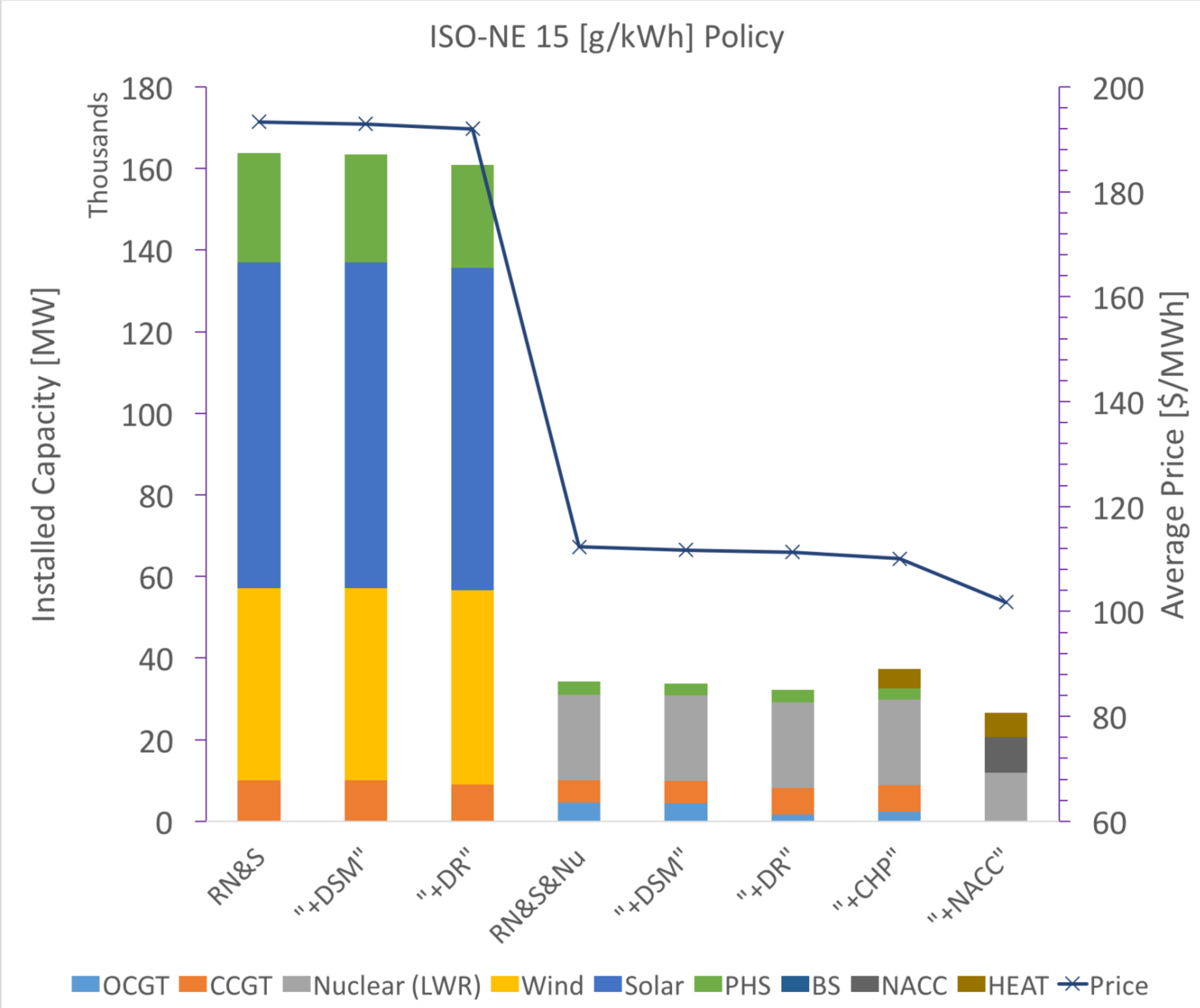


2050 New England Installed Capacity Versus Added Technologies and CO_2 Limits

Technology Choices Change with CO_2 Limits and Added Technologies




ISO-NE 01 [g/kWh] Policy
Thousands
Installed Capacity [MW]
250
200
150
100
50
0
Average Price [$/MWh]
260
210
160
110
60
RN&S
"+DSM"
"+DR"
RN&S&Nu
"+DSM"
"+DR"
"+CHP"
"+NACC"
OCGT
CCGT
Nuclear (LWR)
Wind
Solar
PHS
BS
NACC
HEAT
Price



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Texas Case with Renewables, Natural Gas, and Storage with 400g/kWh(e) Allowable Releases