Zero-Carbon Nuclear-Renewable Futures

Energy Storage, Hybrid Energy Systems and Alternative Nuclear Systems

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Developing a Strategy to a Zero-Carbon World

A Primer

Work in Progress…….

Outline

- The Low-Carbon Energy Challenge
- The Electricity Market—Excess Capacity in a Zero-Carbon World
- Options for Efficient Use of Capital-Intensive Electricity Generating Sources
  - Energy Storage Systems
  - Hybrid Systems
  - Change Characteristics of Nuclear Energy
- Conclusions

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NREL/TP-6A20-62778

Integrated Nuclear-Renewable Energy Systems: Foundational Workshop Report

Shannon Bragg-Sitton and Richard Boardman
Idaho National Laboratory (INL)

Mark Ruth and Owen Zinaman
National Renewable Energy Laboratory (NREL)

With Contributions From
Charles Forsberg
Massachusetts Institute of Technology (MIT)
and
John Collins
Idaho National Laboratory (INL)

August 2014

The INL is a U.S. Department of Energy National Laboratory
operated by Battelle Energy Alliance

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

The Low-Carbon Energy Challenge

Understanding What a Low-Carbon World Implies for Nuclear and Renewables

Charles Forsberg and Mike Golay, “Challenges for a Zero-Carbon Nuclear Renewable Energy Futures,” *2014 American Nuclear Society Annual Meeting*,, Reno, Nevada, June, 2014

For a Half-Million Years Man Has Met Variable Energy Demands by Putting More Carbon on the Fire

Wood Cooking Fire

Natural-Gas Turbine

Only the Technology Has Changed

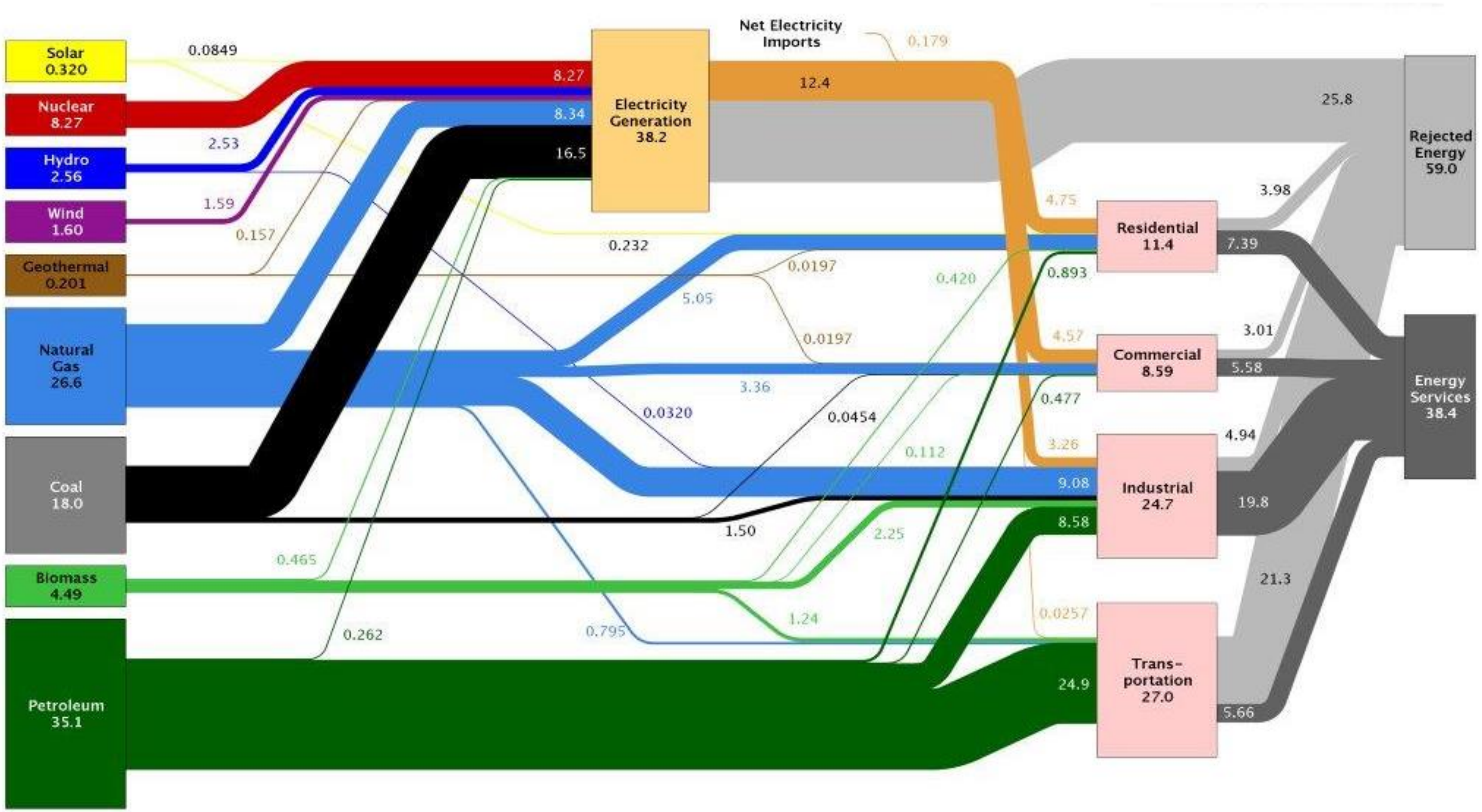
Man Will Transition Off Fire In This Century

Control Climate Change or Fossil Resource Depletion

First Half or Second Half of the Century

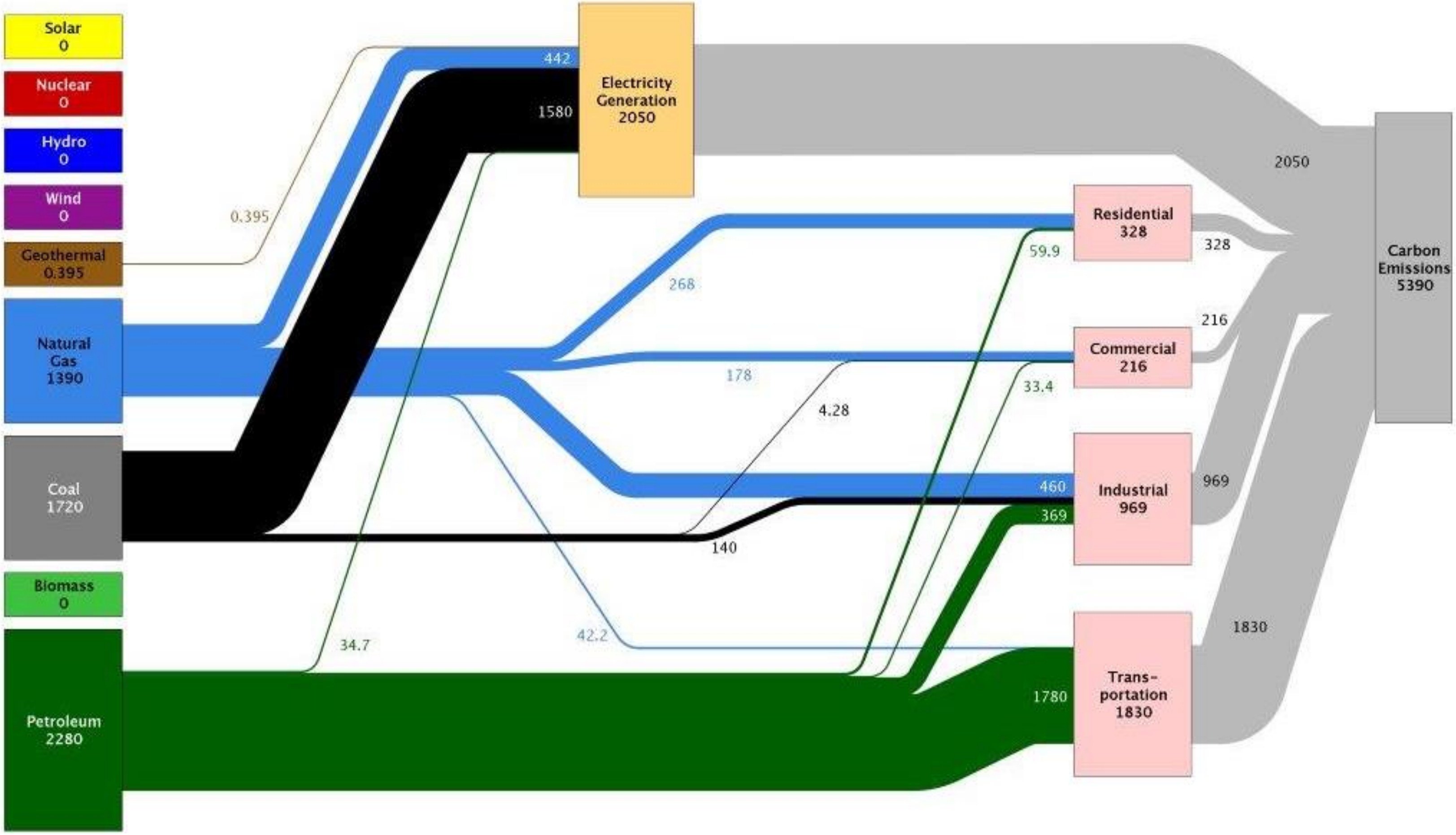
Electricity and Transportation Are The Primary Energy Demands

Fossil Fuels are the Primary Energy Source



Estimated U.S. Energy Use in 2013: ~97.4 Quads (LLNL)

Electricity and Transportation Are The Primary CO_2 Emissions



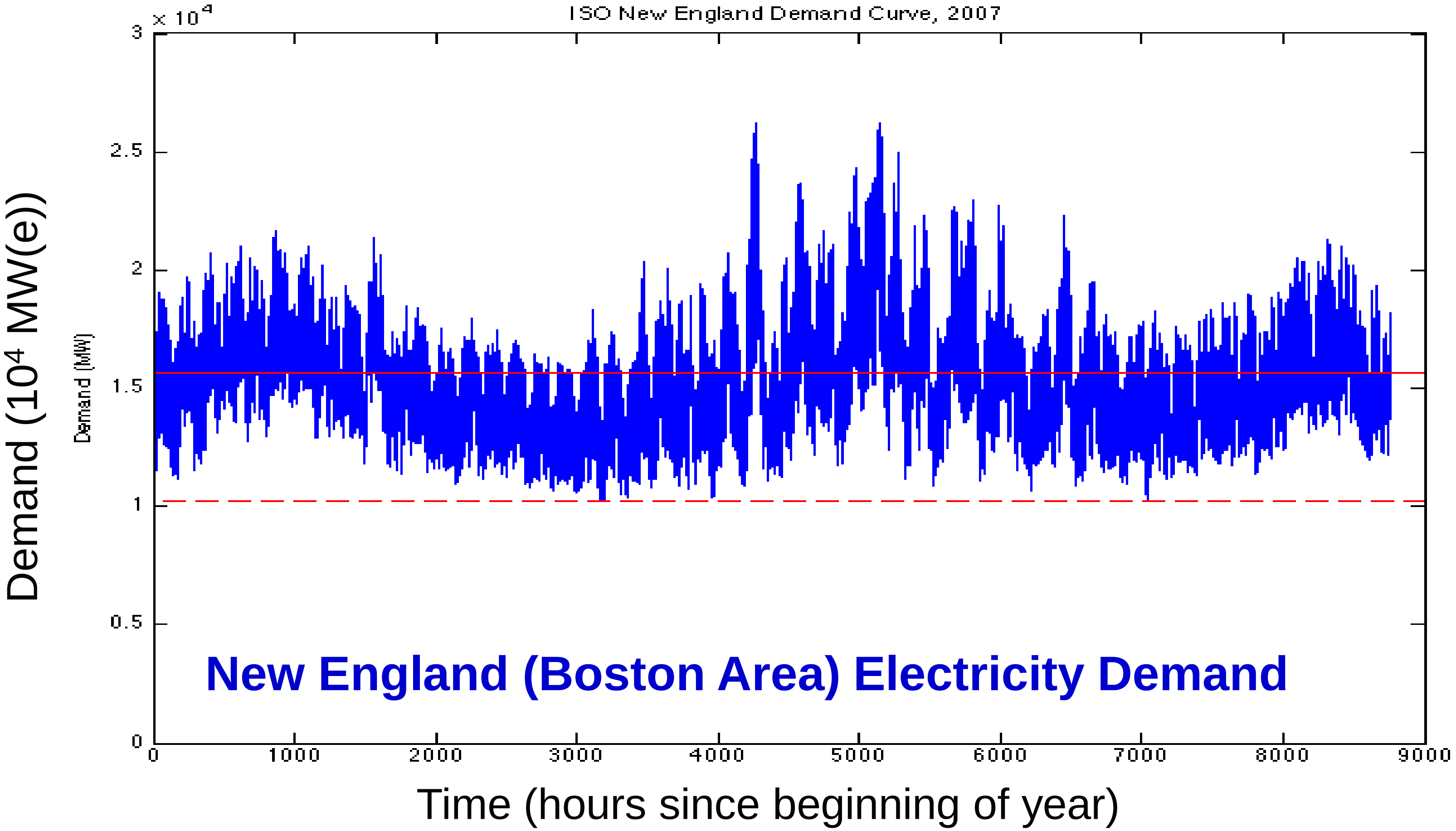
Estimated U.S. CO_2 Emissions 2013: ~5.4 Billion Tons (LLNL)

The Electricity Market

Zero-Carbon Electricity Grid Changes the Market

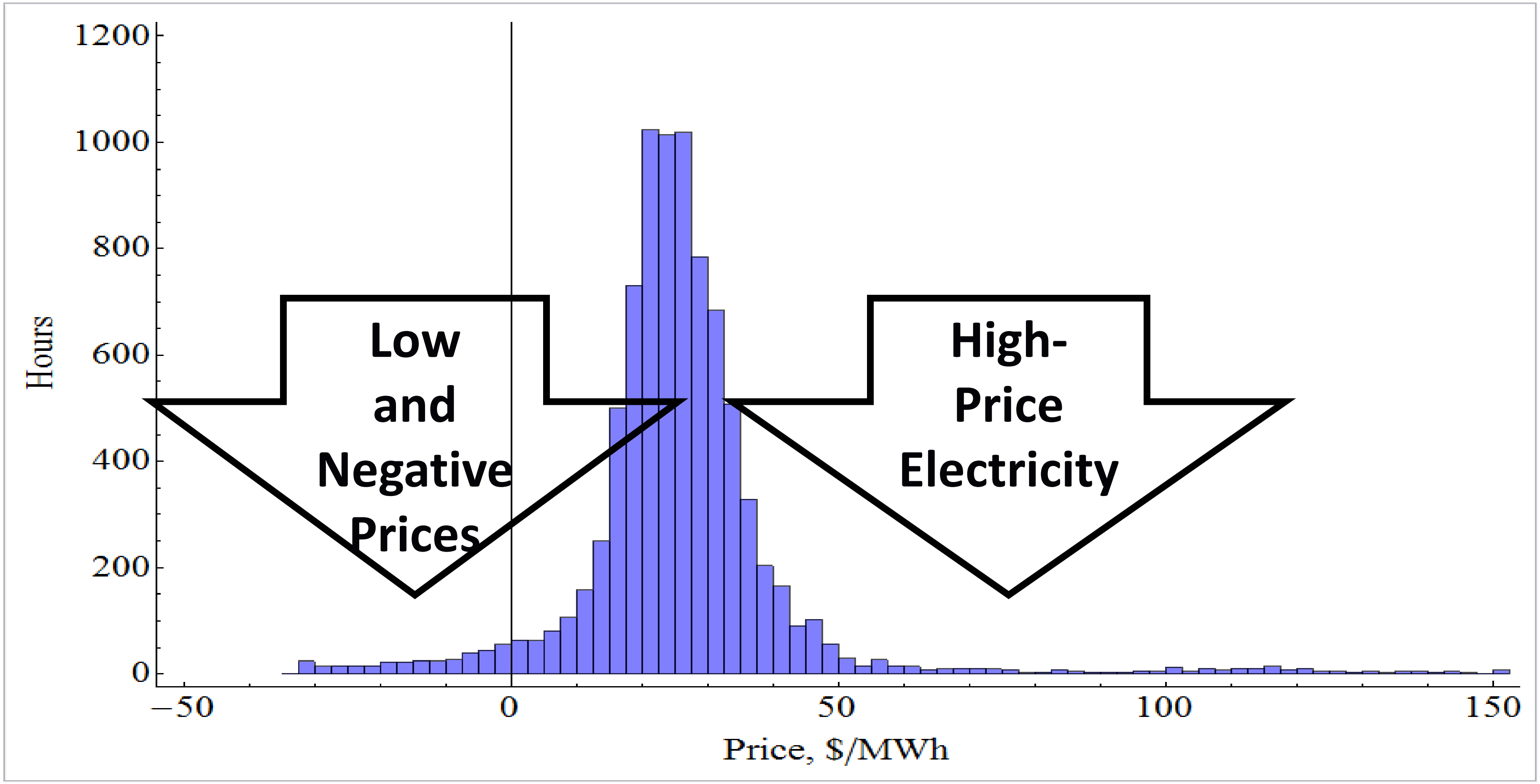
Electricity Demand Varies With Time

No Combination of Nuclear and Renewables Matches Electricity Demand



In a Free Market Electricity Prices Vary

The General Shape of Price Curve Reflects Fossil Electricity Generation



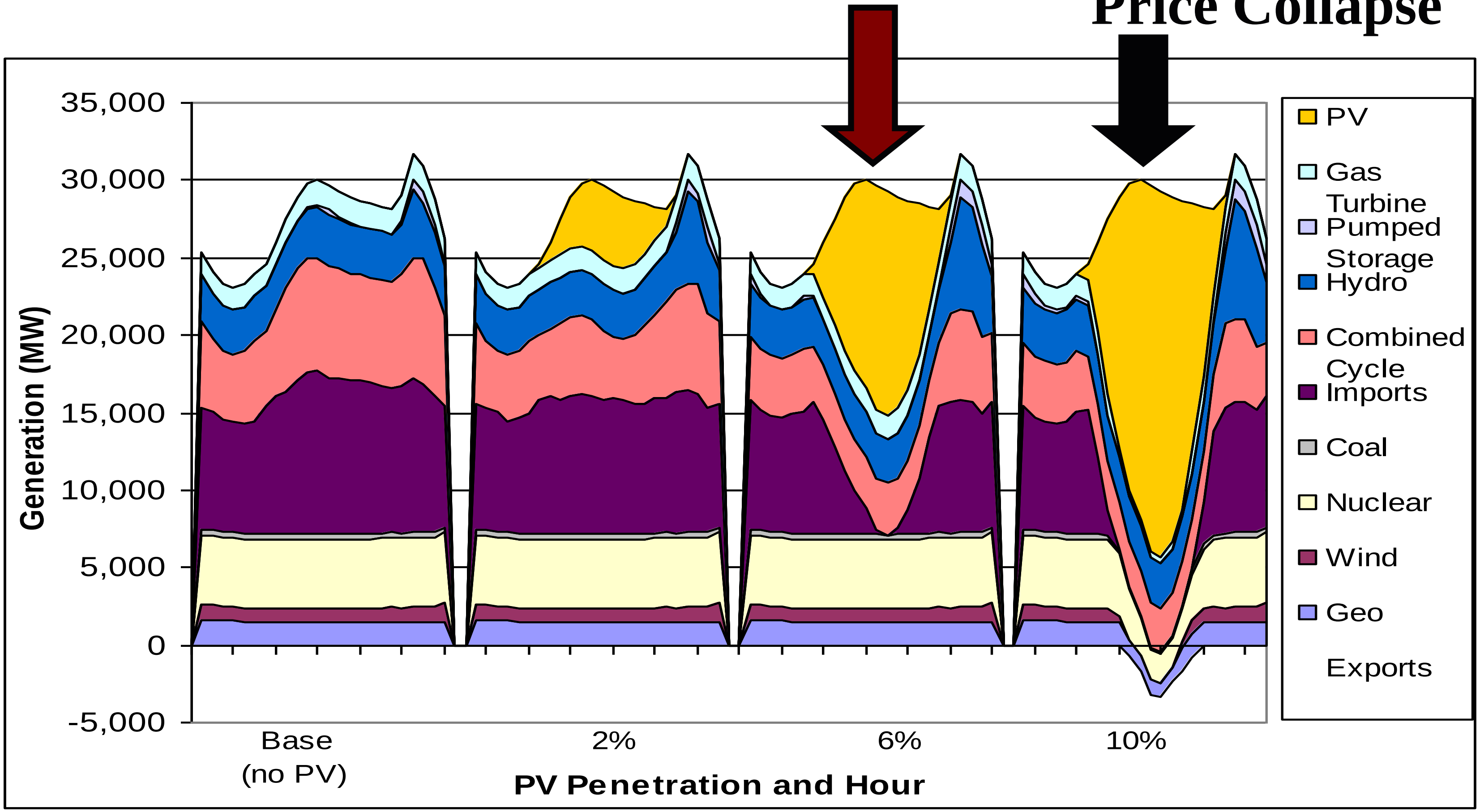
Massachusetts Institute of Technology

2012 California Electricity Prices

Adding Solar and Wind Changes Electricity Prices & Price Structure

Unstable Electrical Grid

Excess Electricity with Price Collapse



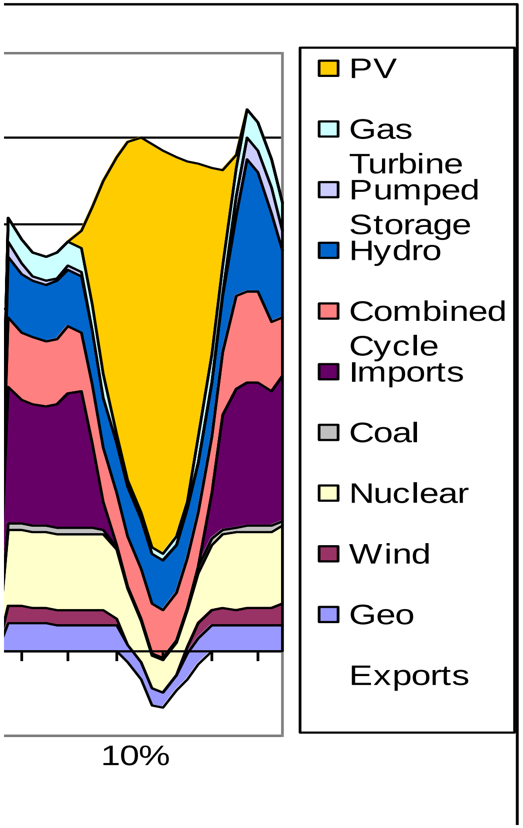
California Daily Spring Electricity Demand and Production with Different Levels of Annual Photovoltaic Electricity Generation

Notes on California Solar Production

- Far left figure shows mix of electricity generating units supplying power on a spring day in California. The figures to the right shows the impact on grid of adding PV capacity assuming it is dispatched first—low operating cost.
- Percent PV for each case is the average yearly fraction of the electricity provided by PV. The % of power from PV is much higher in late June in the middle of the day and is zero at night. Initially PV helps the grid because PV input roughly matches peak load. Problems first show up on spring days as shown herein when significant PV and low electricity load.
- With 6% PV, wild swings in power supply during spring with major problems for the grid. By 10% PV on low-electricity-demand days PV provides most of the power in the middle of many spring days.
- In a free market PV producers with zero production costs will accept any price above zero. As PV grows, revenue to PV begins to collapse in the middle of the day as electricity prices collapse. Collapsing revenue limits PV new build. Large-scale PV also hurts the base-load electricity market while increasing market for peak power when no sun. In the U.S. that variable demand is getting filled with gas turbines. Similar effects at other times with large wind input. This is one of the reasons why in some cases one has increased greenhouse gas emissions with increased use of renewables.
- The revenue problem with renewables is similar to selling tomatoes in August when all the home-grown tomatoes turn red and the price collapses to near zero
- The other part of the story is the need for backup power when low wind or solar. For example, in Texas only 8% of the wind capacity can be assigned as dispatchable. That implies in Texas for every 1000 MW of wind, need 920 MW of backup capacity for when the wind does not blow—almost a full backup of wind. In the Midwest grid, only 13.3% of the wind capacity can be assigned as dispatchable. Consequently, with today’s technologies large scale renewables implies large-scale fossil fuel useage

In a Free Market, Revenue Collapse for Solar (CA) at ~10% Total Electricity

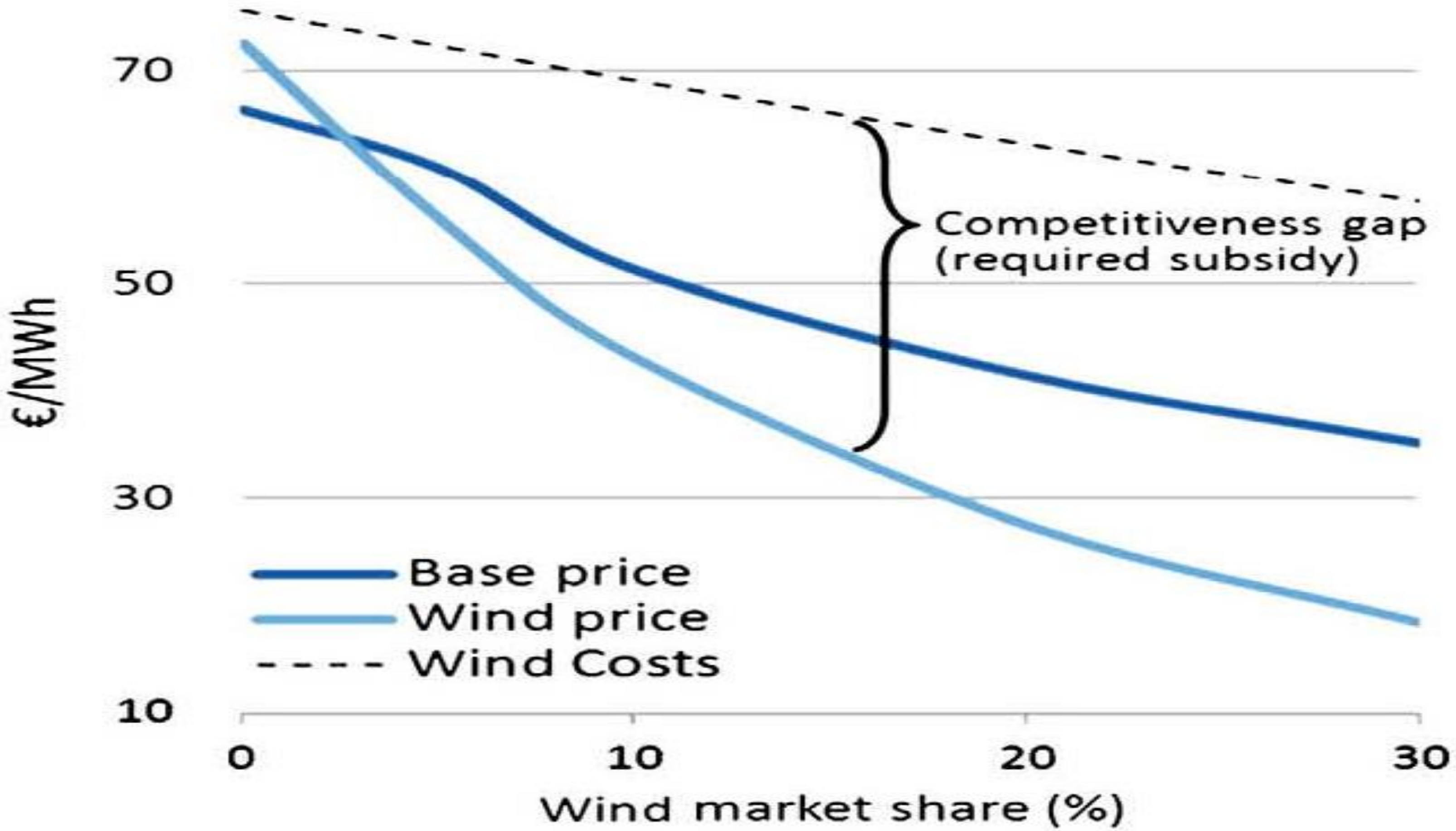
- Each solar owner sells whenever electricity prices above zero
- When solar approaches total demand, price to near zero
- Less total revenue for each solar addition



Solar Electricity like Tomatoes in August when Tomatoes Turn Red—Perishable Crop so Price Collapse

European Electricity Prices Versus Wind

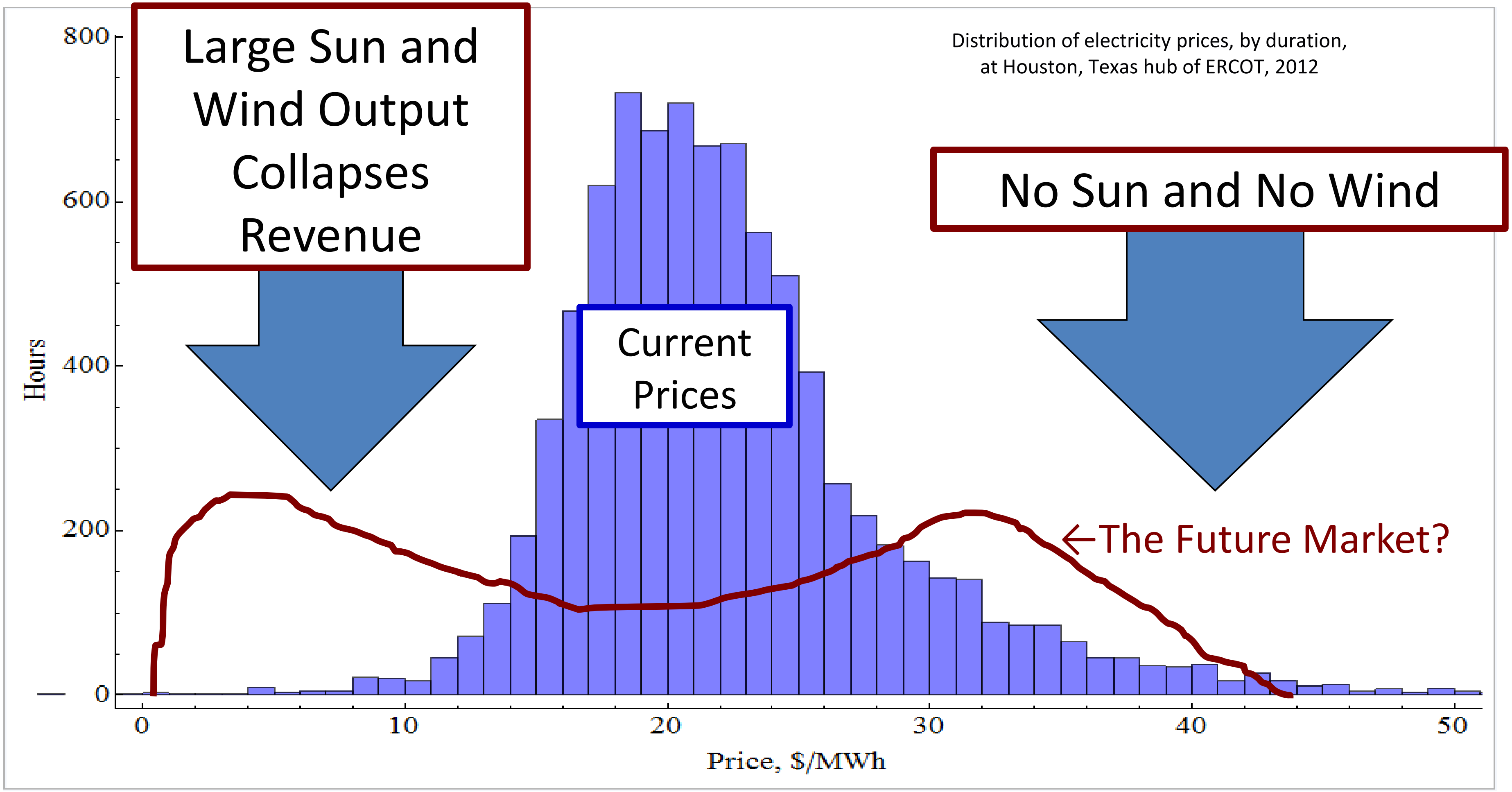
European Community Midterm Projections Assuming Sufficient Subsidies to Enable Growing Market Share



L. Hirth / Energy Economics 38 (2013) 218–236

Peak Winds Depress Electricity Prices So Wind Revenue Decreases As Wind Market Share Increases—Limits Wind Growth

Low-Carbon Electricity Free Market Implies More Hours of Low / High Price Electricity



Bad News for Capital-Intensive Low-Operating-Cost Nuclear and Renewables

EIA Cost Estimates for 2018 ($/MWh)

From: Levelized Cost of New Generation Resources in the Annual Energy Outlook 2013: January 2013

Plant type (Capacity factor)	Levelized Capital (Includes Transmission Upgrade)	Fixed/Variable O&M	Total
Dispatchable			
Coal (85%)	66.9	4.1/29.2	100.1
Coal with CCS (85%)	89.6	8.8/37.2	135.5
NG Combined Cycle (87%)	17.0	1.7/48.4	67.1
NG Turbine (30%)	47.6	2.7/80.0	130.3
Nuclear (90%)	84.5	11.6/12.3	108.4
Non Dispatchable			
Wind (34%)	73.5	13.1/0.0	86.6
Wind offshore (37%)	199.1	22.4/0.0	221.5
Solar PV (25%)	134.4	9.9/0.0	144.3
Solar thermal (20%)	220.1	41.4/0.0	261.5

High Operating Cost Fossil

High Capital Cost Non-Fossil

All Except Natural Gas Turbine Assumed to Operate at Maximum Capacity: Very Expensive Part Load

Notes on EIA Cost Estimates

- Solar high cost is a consequence of low capacity factors from 20 to 25% (night-day summer-winter variations in sun light); thus, the cost per kilowatt can be lower than many other generating sources but there is no output at night. There is about a factor of two variation in the cost across the country due to differences in solar input. Requires gas turbine backup for times of low solar output. Total costs are shown. The rapid price drops in PV that are reported are for the cells, not the total system.
- Economic wind is almost all on the Great Plains from Texas to the Dakotas. Costs rise dramatically as wind speeds decrease. Offshore wind extremely expensive because costs of foundations and cost of operations at sea. Requires gas-turbine backup for times of low wind output.
- Some advanced nuclear renewable options such as the Nuclear Renewable Oil Shale System (NROSS: viewgraph 55 forward) have been proposed to avoid the need for expensive gas turbine backup systems for renewables.
- All assumed to operate at maximum capacity except for the natural gas turbine with its 30% capacity factor. In the U.S. gas turbines are the preferred method to meet variable electricity demand. Old coal plants are often used for variable electricity production. In countries such as France, nuclear plants have operated with variable output for decades.

Revenue Collapse Challenge for High-Capital-Cost Low-Operating Cost Systems

Revenue Collapse at 10 to 15% Solar (Annual Basis), 20 to 30% Wind, and ~70% Nuclear

Nuclear Operating at Expensive Part Load

Wind and Solar With Blackouts or Expensive Energy Storage

How Can One Fully Utilize Low-Carbon High-Capital-Cost Low-Operating-Cost Energy Production Systems to Minimize Societal Costs

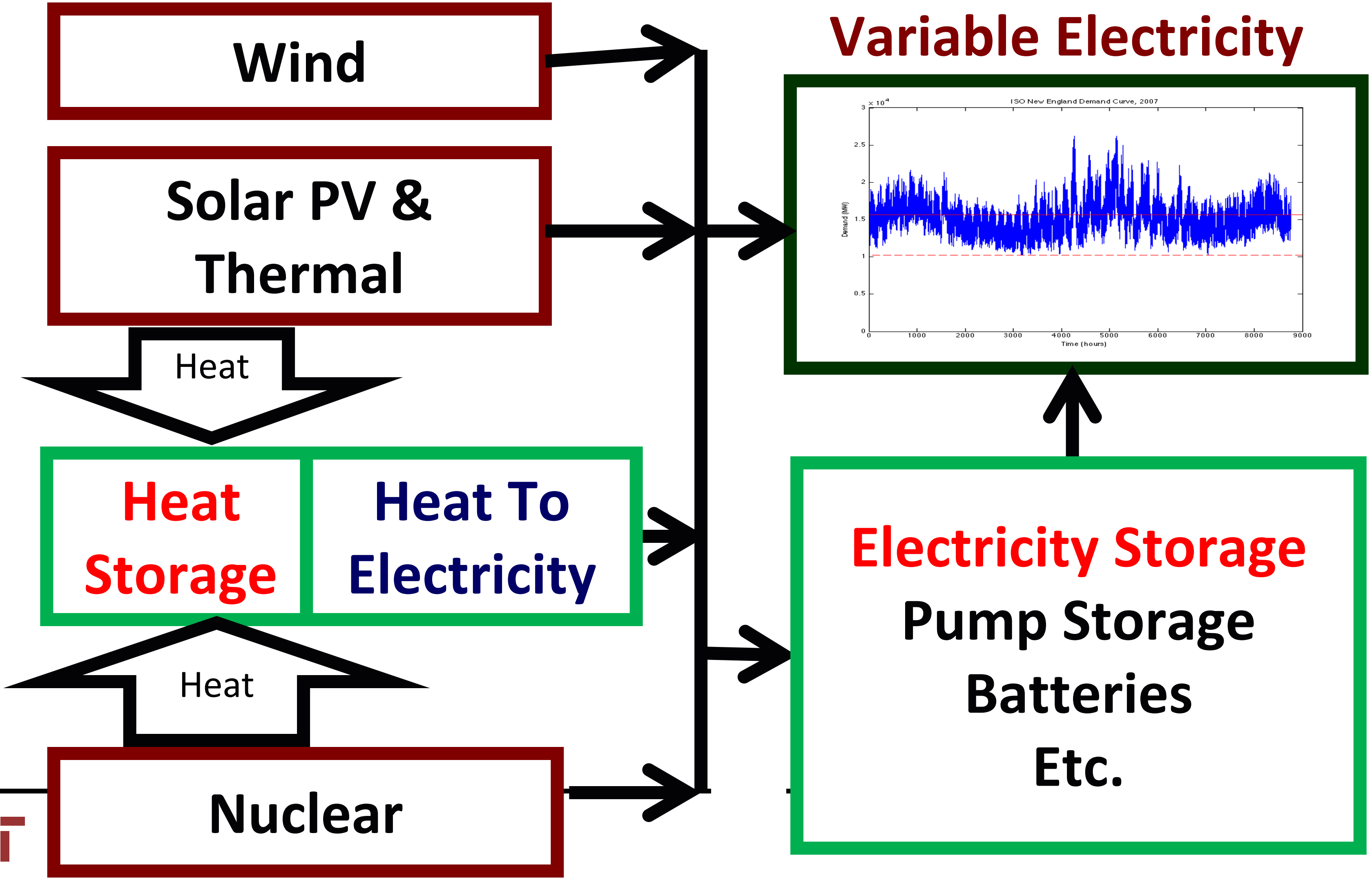
Solutions to Zero-Carbon Electricity Grid Challenge

Strategies to Fully Utilize Capital-Intensive Low-Operating-Cost Nuclear and Renewables Capacity

- Store excess electricity for use when needed
- Use excess energy for industry and transportation
- Change characteristics of nuclear power

Energy Storage Systems

Using Storage to Fully Utilize Generating Assets to Meet Demand



Wind

Solar PV & Thermal

Heat

Heat Storage

Heat To Electricity

Heat

Nuclear

Variable Electricity

Electricity Storage

Pump Storage

Batteries

Etc.

Three Storage Challenges

- Different storage durations and viable storage media
  - Hourly: chemical (batteries), smart grid (delay demand)
  - Days: water (pumped storage), compressed air storage
  - Seasonal: hydrogen and heat
- Required storage depends upon mismatch between generation and demand
- The big economic challenge is seasonal storage
  - Hourly storage device used (cycled) 365 days per year
  - Seasonal storage device used (cycled) 1 to 2 uses per year
  - Seasonal storage media has to cost less than 1/100 of a storage media used for hourly storage

California Electricity Storage Requirements As Fraction of Total Electricity Produced

Assuming Perfect No-Loss Storage Systems

Electricity Production Method	Hourly Storage Demand	Seasonal Storage Demand[a]
All-Nuclear Grid	0.07	0.04
All-Wind Grid	0.45	0.25
All-Solar Grid	0.50	0.17

[a] Assume smart grid, batteries, hydro and other technologies meet all storage demands for less than one week

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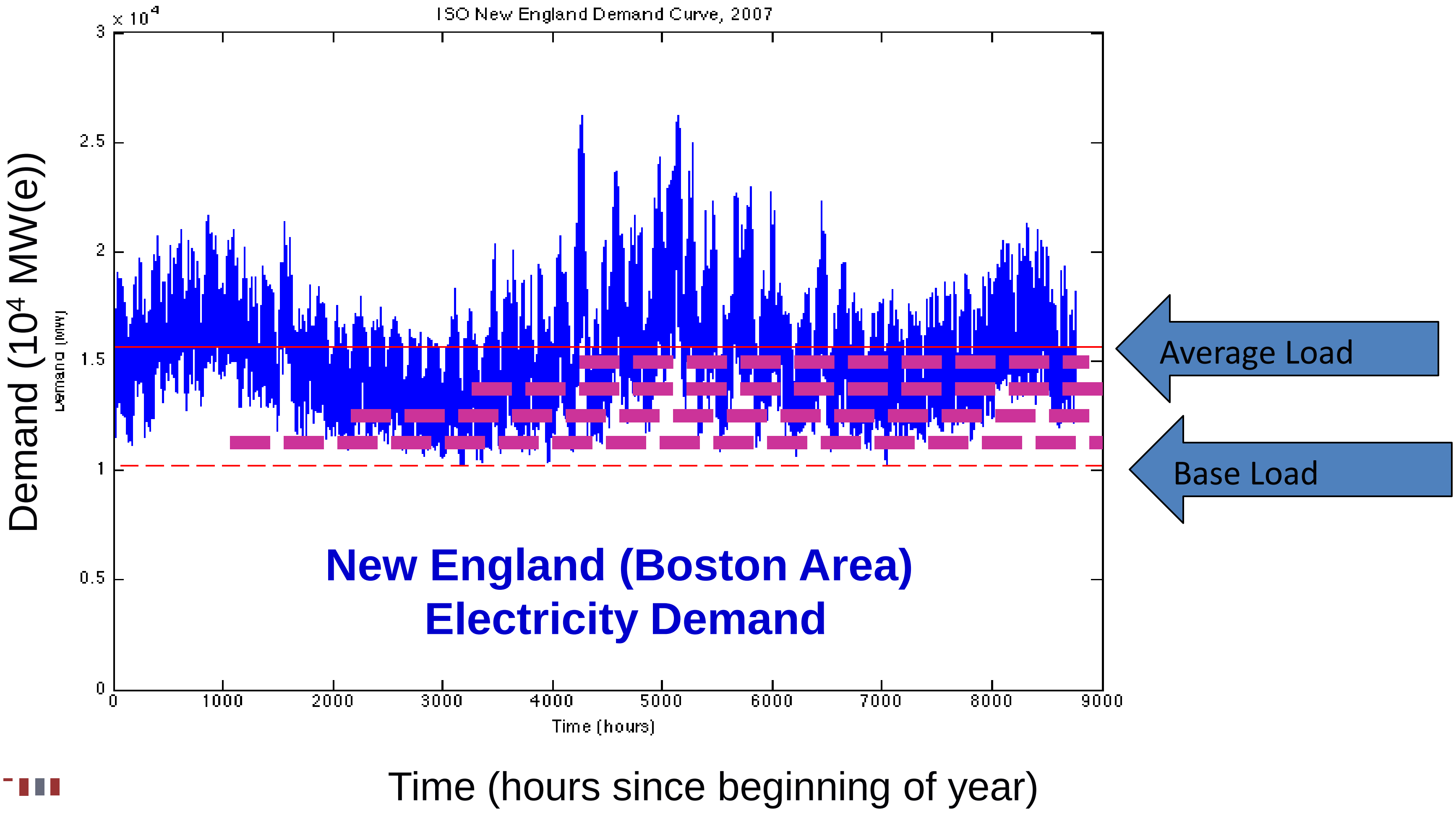
Massachusetts Institute of Technology

C. W. Forsberg, "Hybrid Systems to Address Seasonal Mismatches Between Electricity Production and Demand in a Nuclear Renewable Electricity Grid," *Energy Policy*, **62**, 333-341, November 2013

The Low Nuclear Storage Requirements Reflect the Electricity Demand Curve

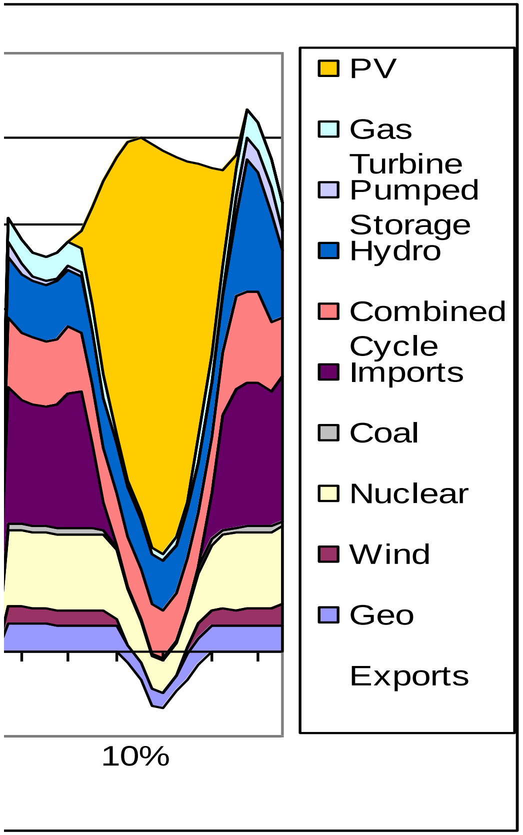
Most Output (▬ ▬ ▬) of First Nuclear Plants Above Base-load Goes to the Grid Reducing Storage Requirements, Less to Storage



The Large Solar Storage Requirement Reflects Daytime Generation

Spring California PV Solar if Meet 10% Total Yearly Electricity Demand

- Solar output primarily in the middle of the day
- Quickly exceed demand so extra solar goes to storage
- Implies high storage requirements for solar once meet peak demand any time of year



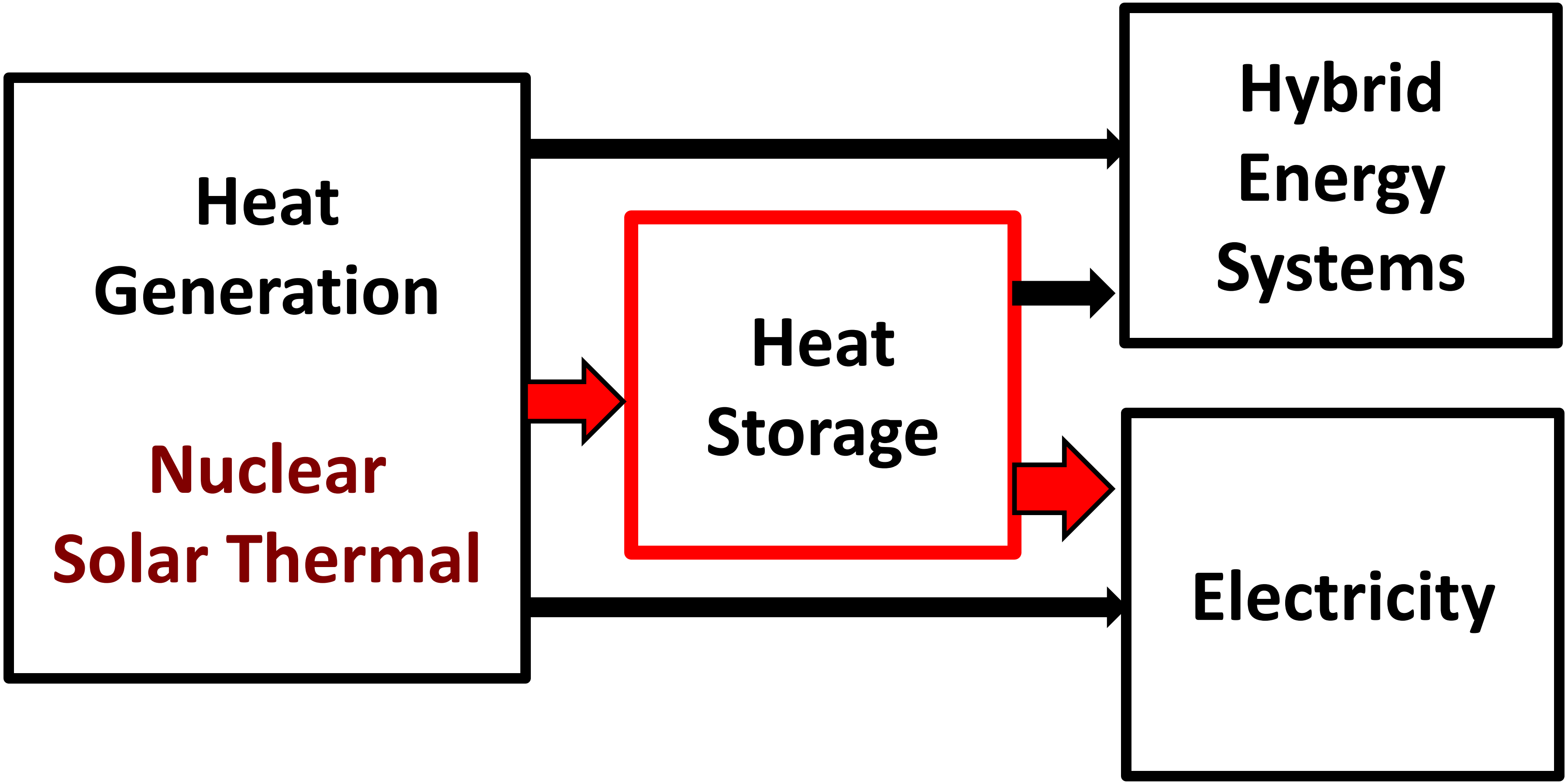
Heat Storage to Peak Electricity Options

Heat Storage for Light Water Reactors (LWRs): Steam Accumulators

Using Nuclear Strength (base-load heat source) to Meet Variable Electricity Demand

Charles Forsberg (MIT) and Eric Schneider (UTexas). "Increasing Base-load Light-Water Reactor Revenue with Heat Storage and Variable Electricity Output," Transactions 2014 American Nuclear Society Annual Meeting , Paper 10016; Reno, Nevada, June 15-19, 2014

Conventional LWR Heat Storage to Peak Electricity Options



Heat Generation

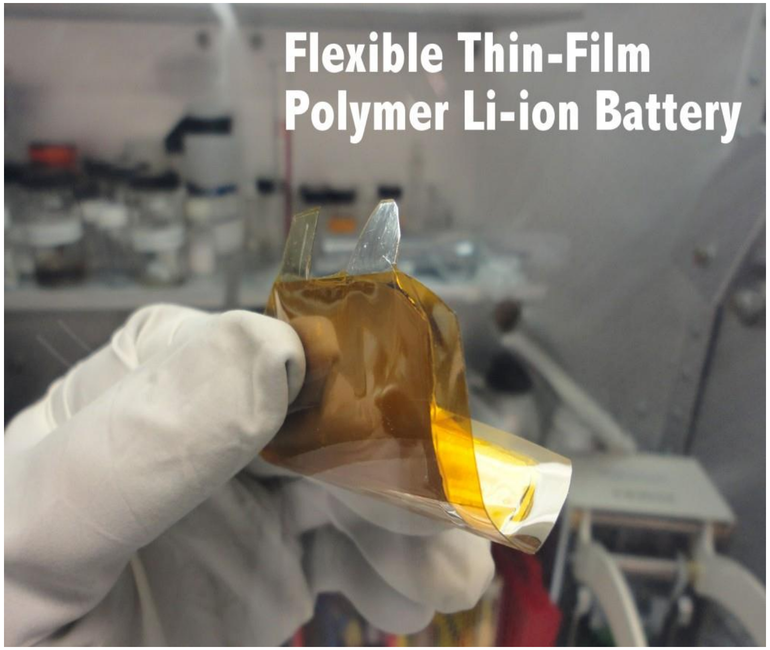
Nuclear
Solar Thermal

Heat Storage

Hybrid Energy Systems

Electricity

Heat Storage Is Cheaper Than Electricity Storage



Liquid Nitrate Salt

(Courtesy of Abengoa Solar)

Battery

Nuclear Heat Storage Systems Have Two Competitive Advantages

- Can use year-round, more storage cycles per year relative to solar thermal systems
- Economics of scale from larger nuclear system; increasing system size by factor of 10 reduces capital cost per unit of capacity by a factor of three to five

LWR Heat Storage Technologies

Technology	Description	Storage Time (Hr)	Size (MWh)
Solid-Liquid Heat Capacity*	Store nitrate or other material at low pressure	10^1 Same as Solar	To 10^4
Steam Accumulator*	Store high-pressure water-steam mix	10^1 Fast Response	To 10^4
Geothermal Hot Water	Store hot water 1000 m underground at pressure	To 10^2	10^4 to 10^6
Geothermal Rock	Heat rock to create artificial geothermal	To 10^4	10^6 to 10^7

***Near-term Technical Options for Peak Power with Heat Storage, Economics Not Understood**

C. W. Forsberg and E. Schneider, “Increasing Base-load Light-Water Reactor Revenue with Heat Storage and Variable Electricity Output,” *2014 American Nuclear Society Annual Meeting*, Reno, Nevada, June 15-19, 2014

Steam Accumulators for Peak Electricity

Old Technology Used For Many Applications

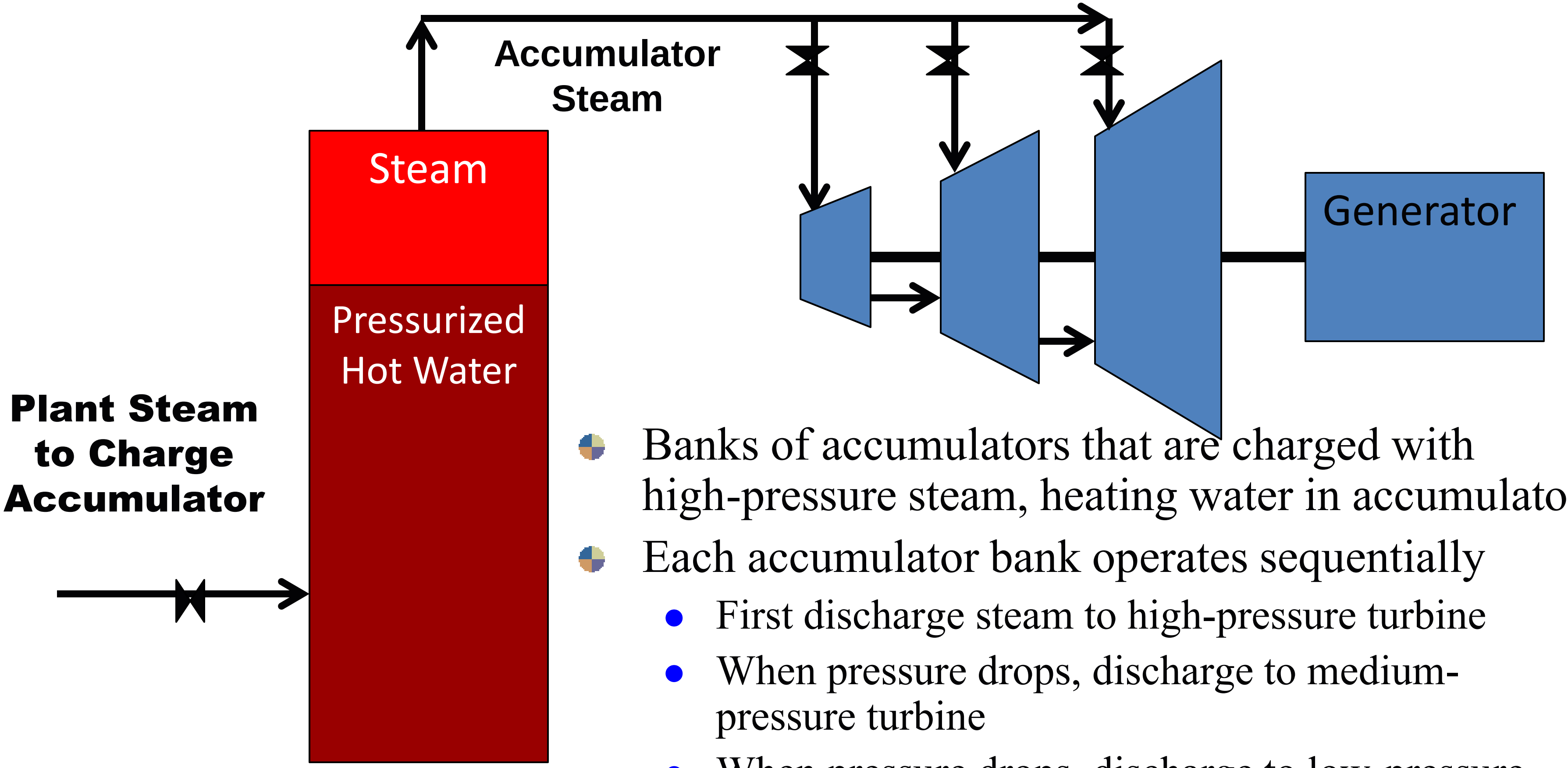
Example: U.S. Navy Aircraft Carriers Launch Aircraft with Catapult Powered by a Steam Accumulator→

Used in Solar Power Systems

Designs for Nuclear Systems

Peak Electricity From Steam Accumulators

Abengoa Khi Solar One (50 MWe) Will Have 2-Hour Steam Accumulator, Nuclear Steam Accumulator Studies Done in the 1970s



- Banks of accumulators that are charged with high-pressure steam, heating water in accumulator
- Each accumulator bank operates sequentially
  - First discharge steam to high-pressure turbine
  - When pressure drops, discharge to medium-pressure turbine
  - When pressure drops, discharge to low-pressure turbine

Applicable to Nuclear and Some Solar Thermal Systems

Power Plant Steam Accumulators Are Being Built By Abengoa for Concentrated Solar Power Systems

ABENGOA

R&D makes cost reductions a reality

Abengoa Sanlucar test facility – Seville, Spain

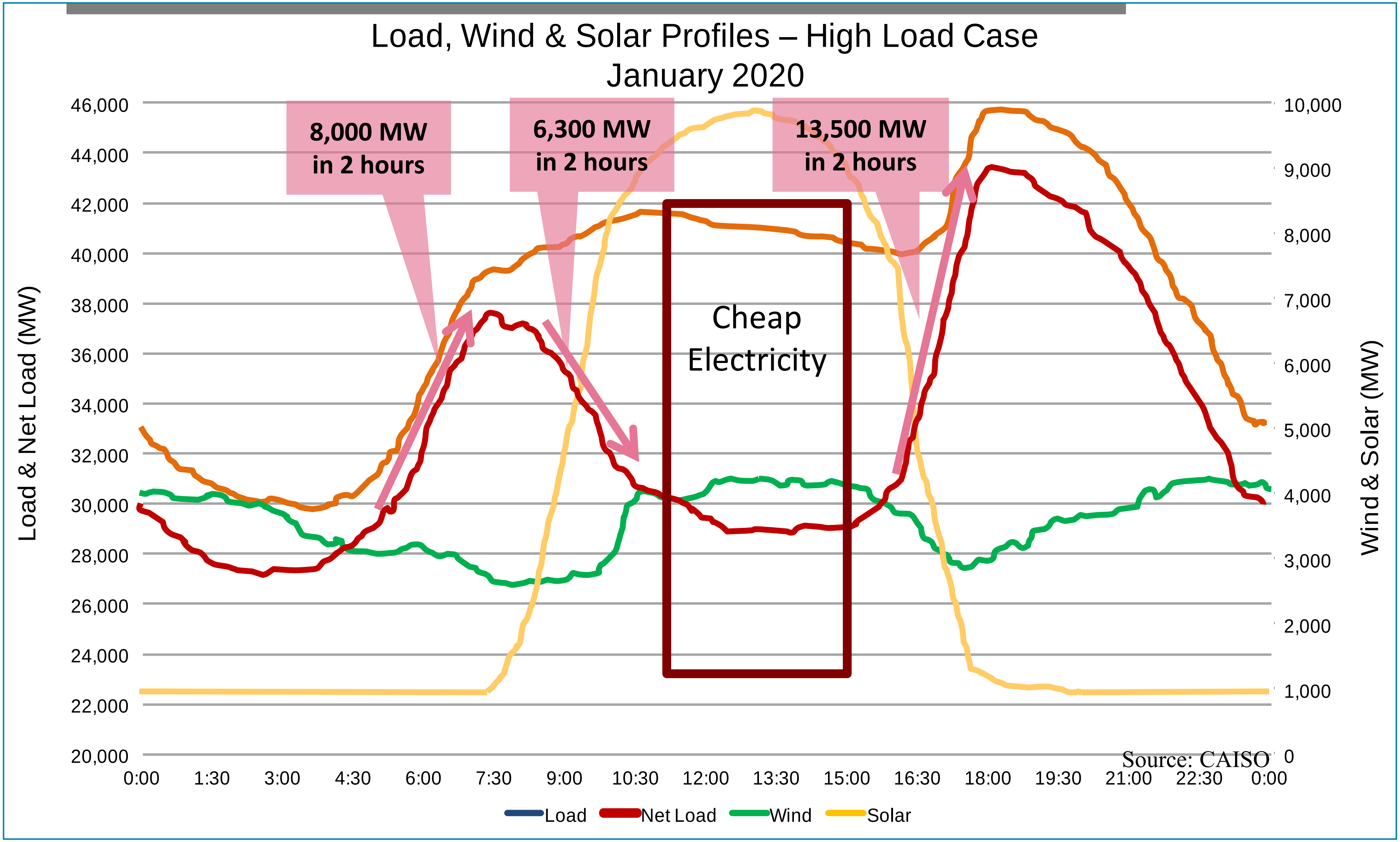
Applicable to LWRs

Heat Storage With Nuclear Plants For Peak Electricity Was Investigated in the 1970s

- Peak electricity generated by oil
- Oil embargo raised price of peak electricity
- Options examined heat storage from nuclear plants at times of low prices and produce peak electricity from stored heat
- Was marginally competitive in the 1970s
- **Changing price curve for electricity creates new incentives to examine option today**

Large Scale Solar Implies Two Peaks / Day

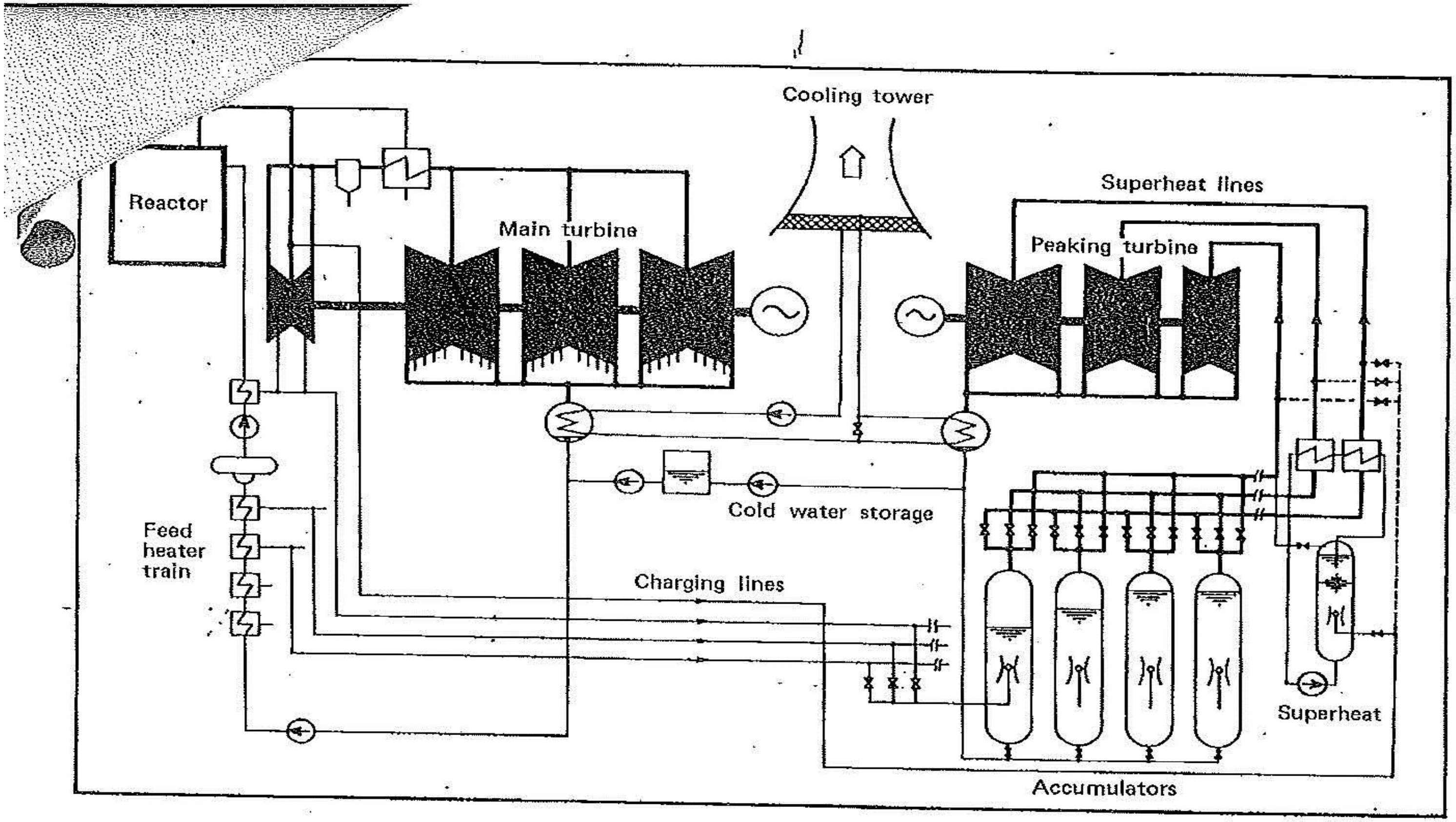
California Illustrative Load, Wind, & Solar Profiles: Double Peak



Source: CAISO

Accumulator Economics Improved If Two Solar Creates 2 Peaks/Day

Two Peaks per Day Cuts Capital Cost per Use in Half



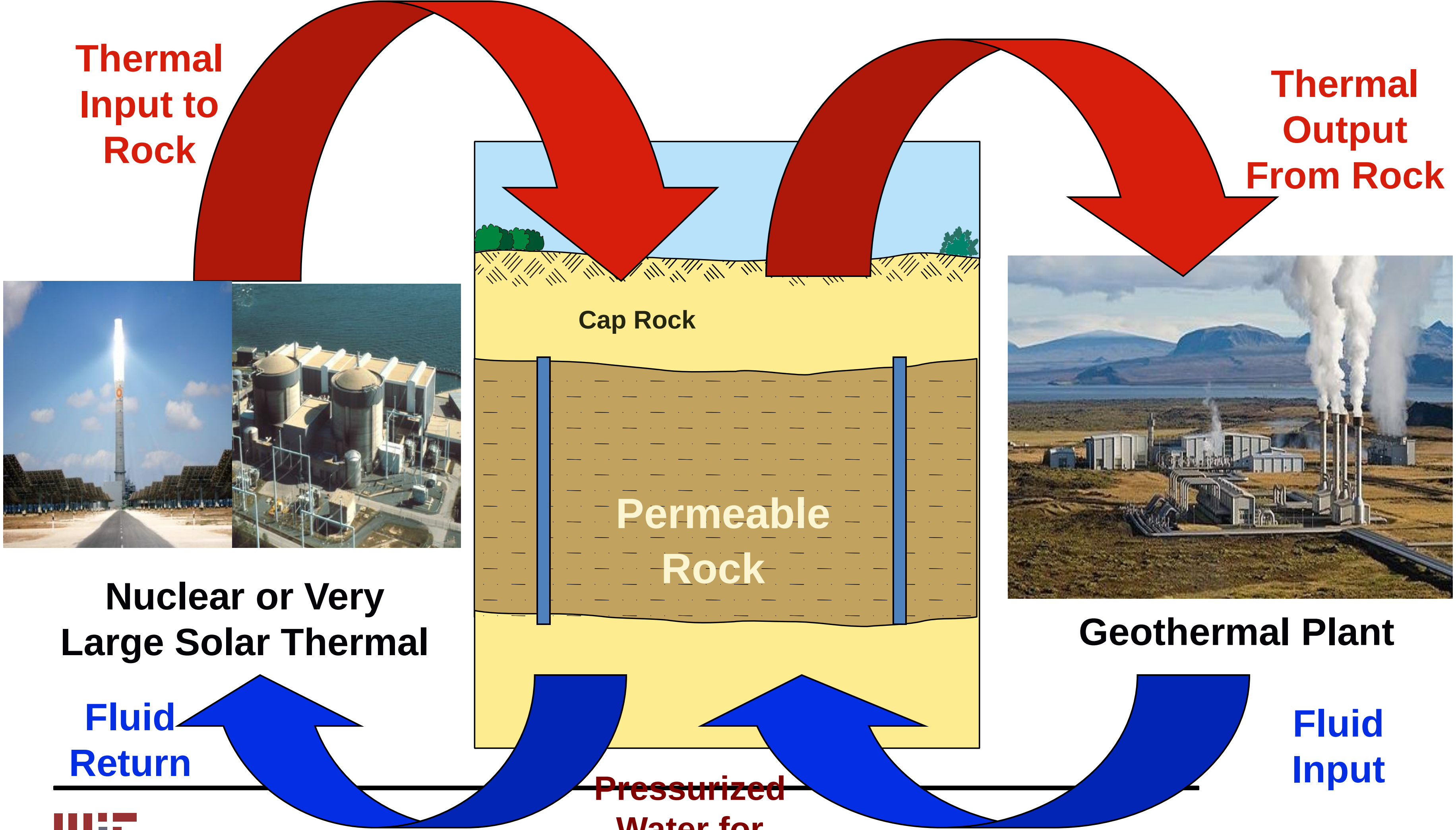
Can Nuclear Plants with Steam Accumulators Be the Enabling Technology for Solar By Solving the Storage Challenge?

Nuclear Heat Storage For Peak Electricity Has a Competitive Advantage

- ***Year-round usage***. More storage cycles per year relative to solar thermal systems with spring and summer but not fall and winter
- ***Economics of scale***. Larger nuclear systems; increasing system size by factor of 10 reduces capital cost per unit of storage capacity by a factor of three to five
- **Economics may drive zero-carbon grids to (1) nuclear with thermal heat storage and (2) renewables**

MIT: Seasonal Heat Storage Technology: Hot-Rock Geothermal Storage

System Physics Requires ~0.1 GWy Storage Capacity: Long-Term Option



Thermal Input to Rock

Thermal Output From Rock

Cap Rock

Permeable Rock

Nuclear or Very Large Solar Thermal

Geothermal Plant

Fluid Return

Fluid Input

Pressurized Water for Heat Transfer

Nesjavellir Geothermal power plant; Iceland; 120MW(e); Wikimedia Commons (2010)

Early R&D Stage

Electricity Storage Technologies

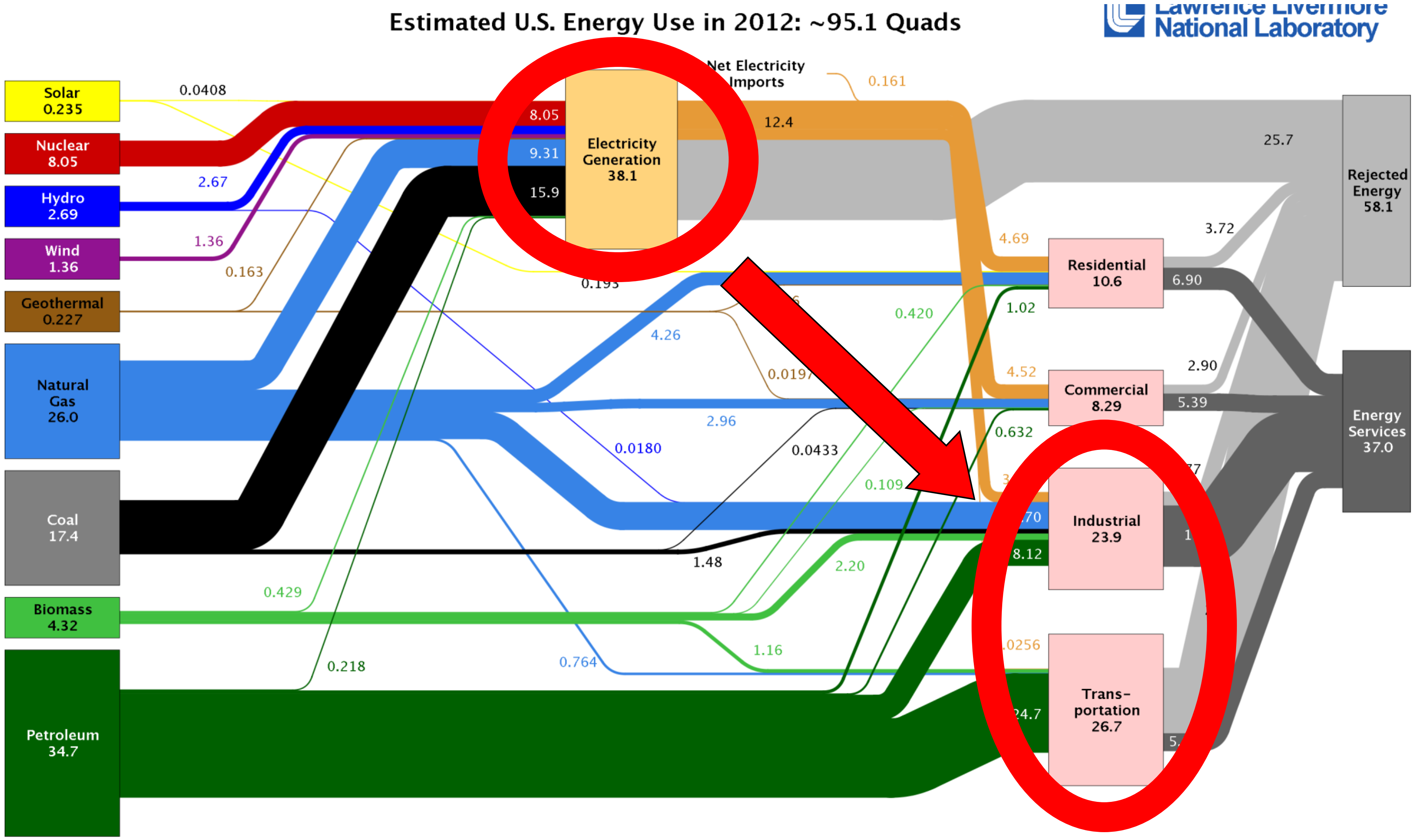
Technology	Storage Mechanism	Storage Time (Hr)	Size (MWh)
Flywheel	Mechanical	To 10^0	To 10^0
Batteries	Chemical	To 10^1	To 10^2
Compressed Air	Pressure	To 10^2	10^3
Pump Storage	Gravity	To 10^2	10^4

Scale of Storage Challenge ~ 10^9 MWhr/Year

Electricity Storage only Viable for Short-Time Periods

Hybrid Energy Options

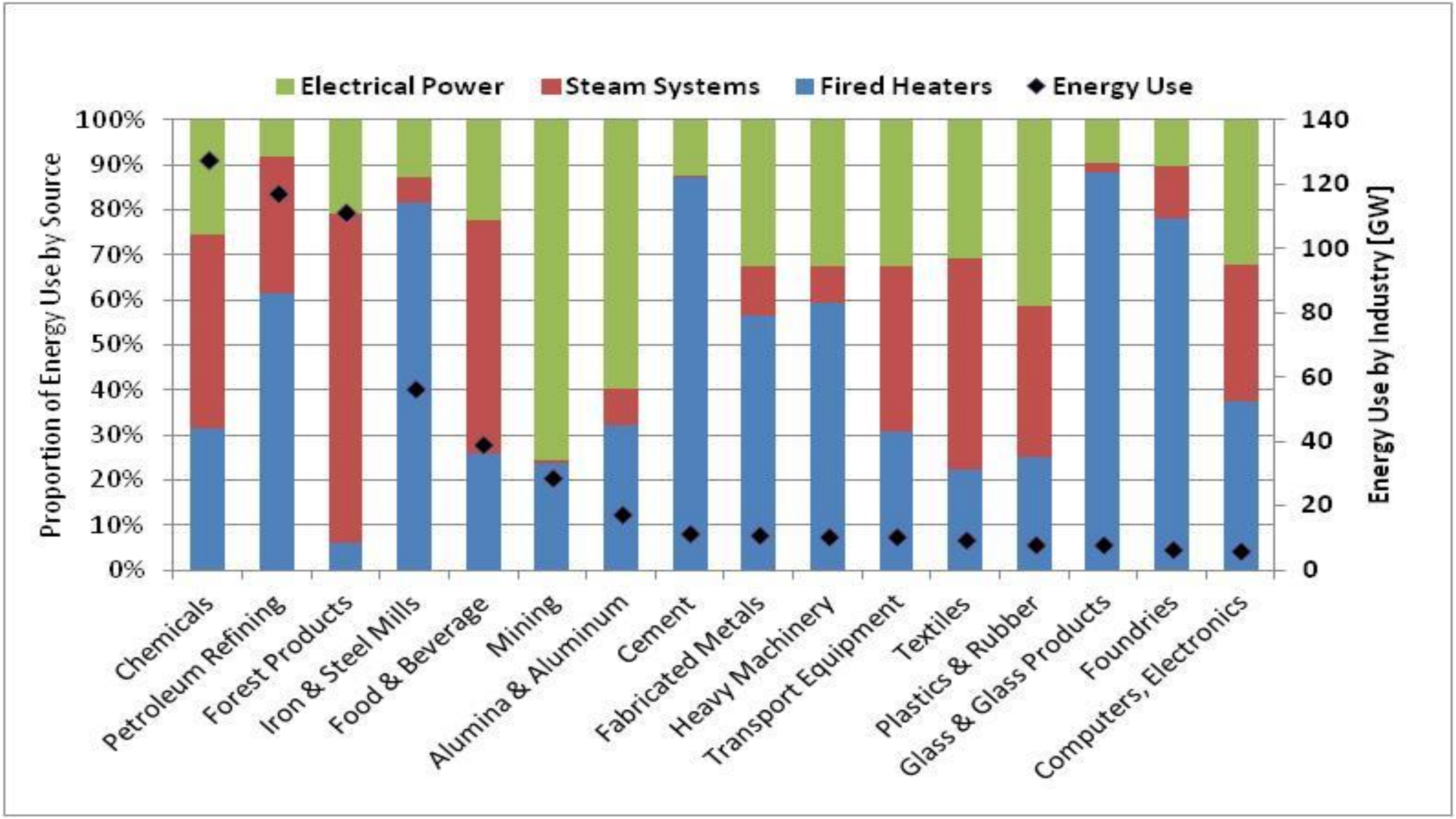
Hybrid Systems Move Excess Energy From Electric Sector to Industrial / Fuels Sector


Estimated U.S. Energy Use in 2012: ~95.1 Quads

Estimated U.S. Energy Use in 2012: ~95.1 Quads (LLNL)

Industrial Energy Use in the U.S.

Market for Hybrid Energy Systems

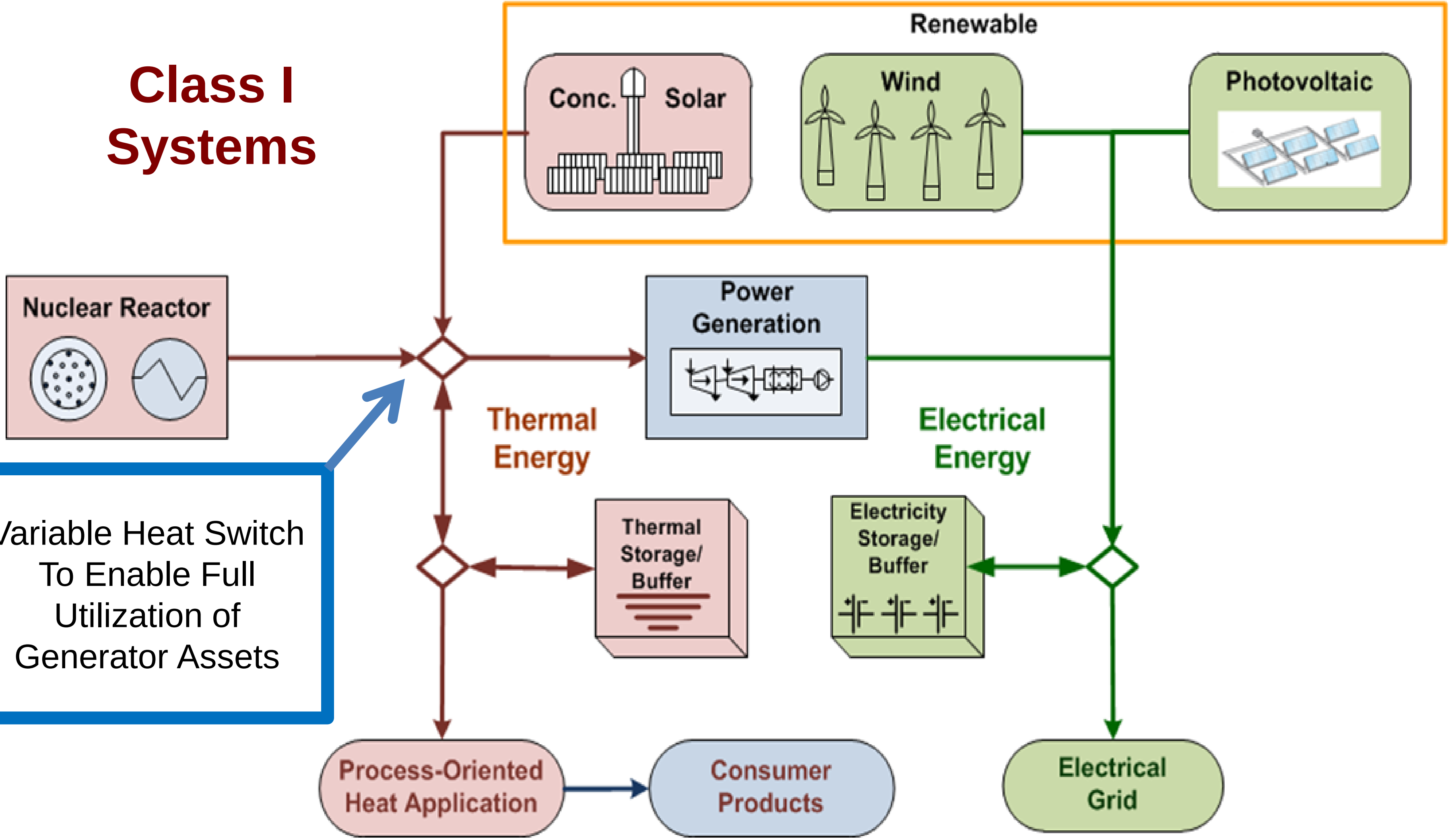


LWRs Produce Steam

M. F. Ruth et al., “Nuclear-Renewable Hybrid Energy Systems: Opportunities, Interconnections, and Needs, *Energy Conversion and Management* **78**, 684-694, 2014

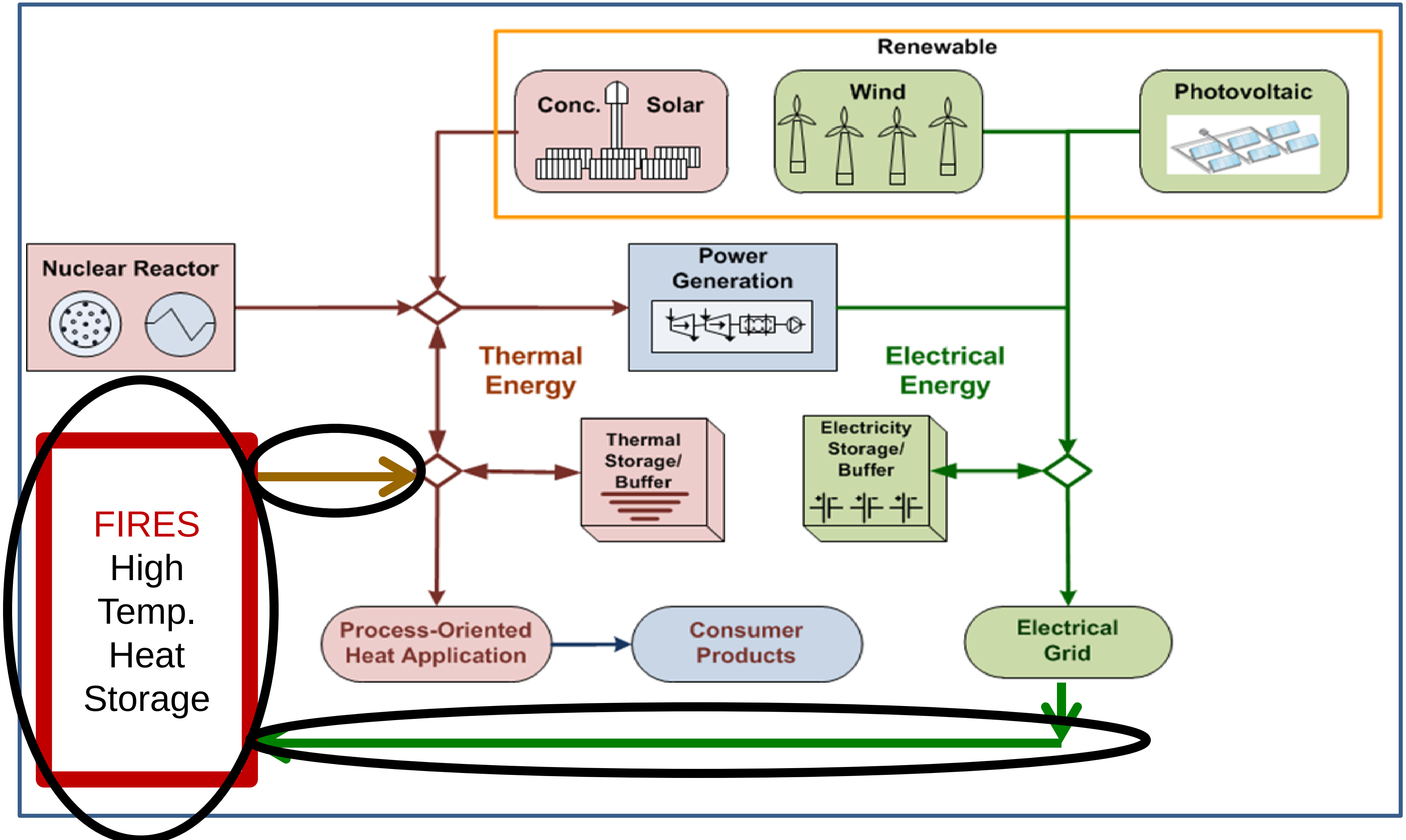
Thermal Hybrid Systems For Better Utilization of Generating Resources Via Heat From Nuclear Reactors and Solar Thermal Systems

Class I Systems



Variable Heat Switch To Enable Full Utilization of Generator Assets

Electric Hybrid Systems For Better Utilization of Generating Resources Via Electricity from Grid at Times of Low Prices



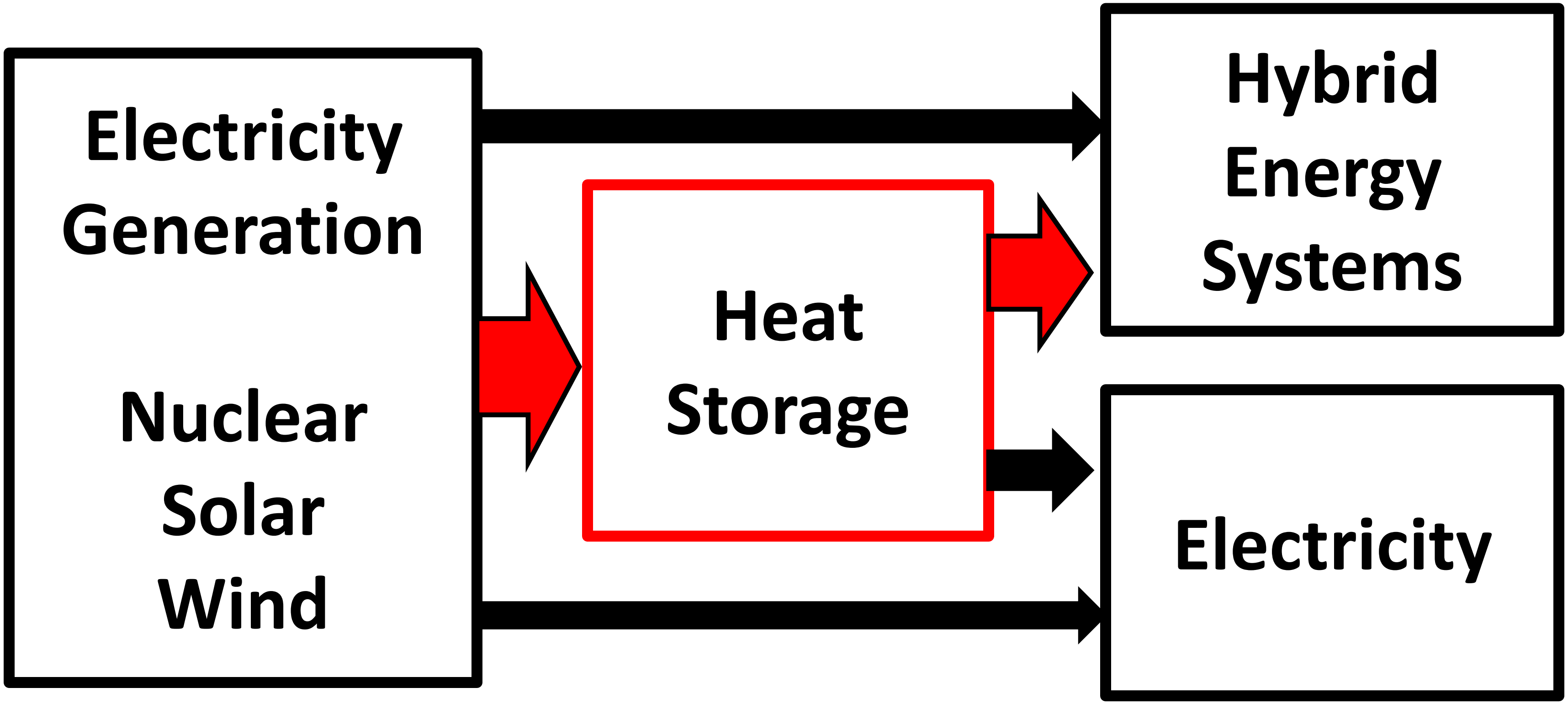
Electric Hybrid Systems

Example: Firebrick Resistance-Heated Energy Storage (FIRES)

Setting a Minimum Price for Electricity Equal to the Cost of Fossil Fuels and Thus a Minimum Revenue Stream at Times of Large Solar / Wind Input while Reducing Greenhouse Gas Emissions

Advanced Heat Storage Options

Electricity → Heat Storage → High-Temperature Heat



Electricity
Generation

Nuclear
Solar
Wind

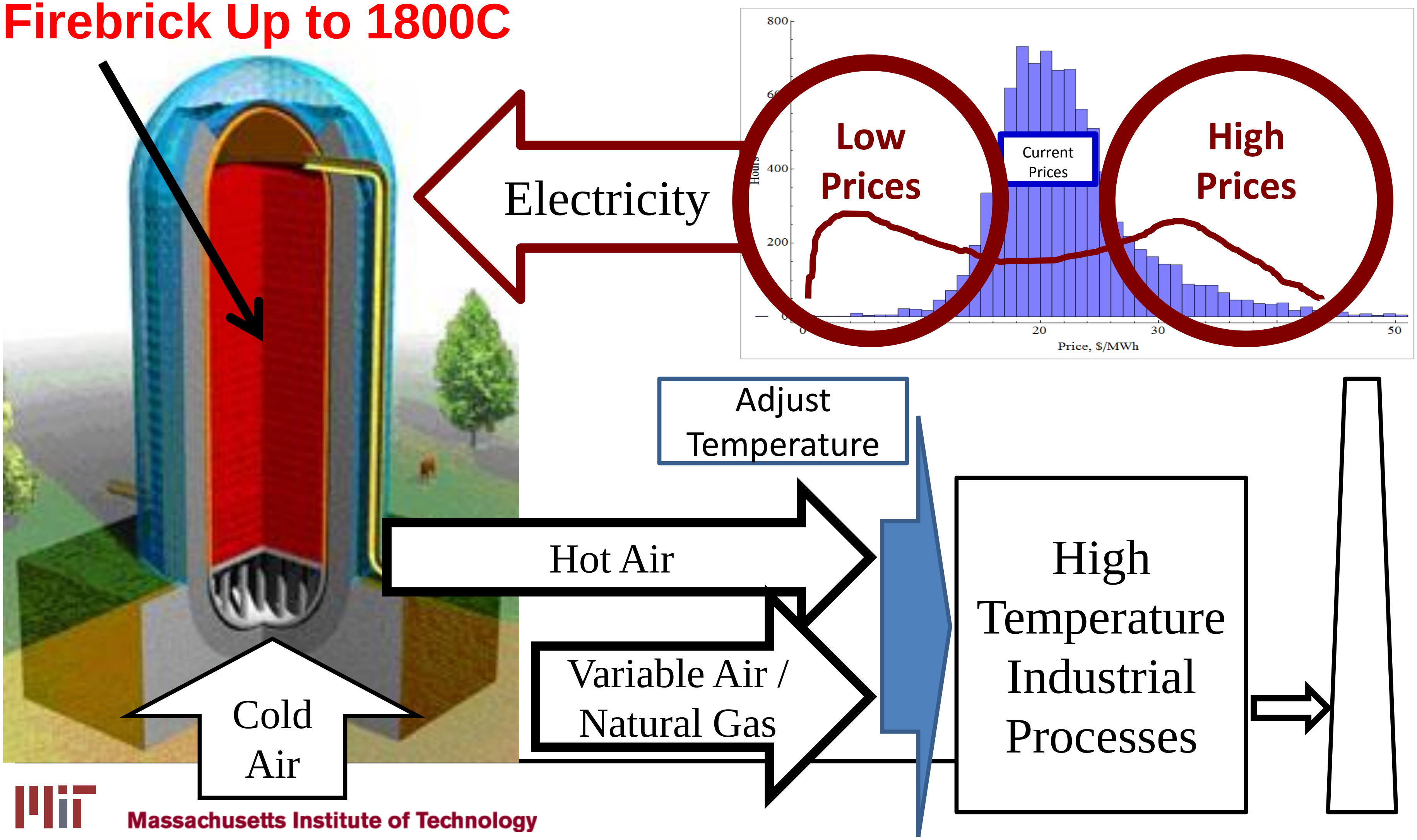
Heat
Storage

Hybrid
Energy
Systems

Electricity

Leading Option Described

FIRES Converts Low-Price Electricity to High-Temperature Stored Industrial Heat



Firebrick Up to 1800C

Electricity

Low Prices

Current Prices

High Prices

Adjust Temperature

Hot Air

Variable Air / Natural Gas

Cold Air

High Temperature Industrial Processes

Massachusetts Institute of Technology

Figure of pressurized brick recuperator courtesy of GE/KWU Adele Project, See appendix for details. No electrical Heat, NOT FIRES

FIRES

Firebrick Resistance-Heated Energy Storage

- Electrically heat firebrick up to 1800°C to create high-value industrial heat
- Recover heat by circulating air or other gas through firebrick
- Similar to non-electric heated recuperators used in 1890s steel plants
- Conductive firebrick to enable resistance heating developed in 1950s for electric arc furnaces

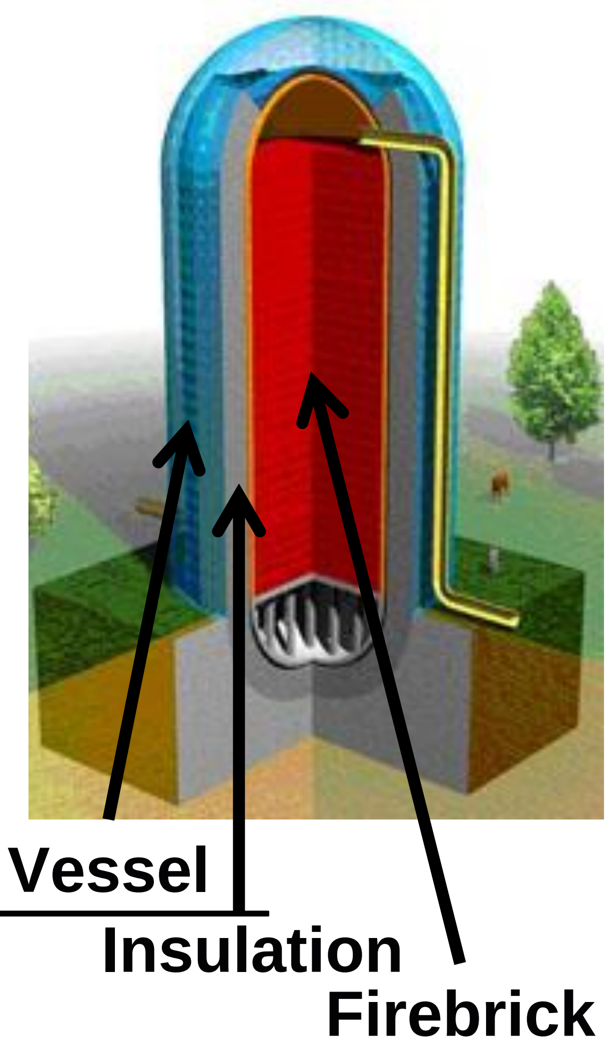
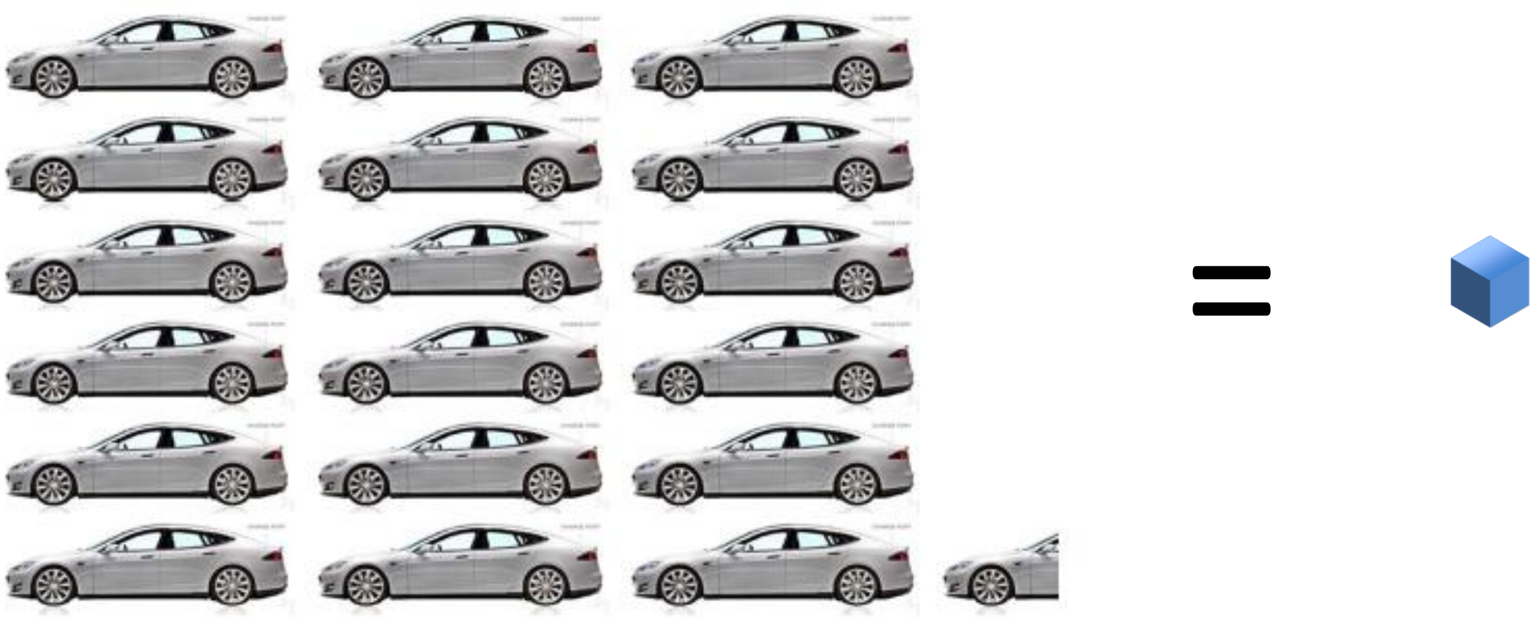


Figure of pressurized brick recuperator courtesy of GE/KWU Adele Project, See appendix for details. No electrical Heat, NOT FIRES

Firebrick is Cheap (~$1/kWh) with High Volumetric Storage Capacity Thanks to Large Hot-Cold Temperature Difference

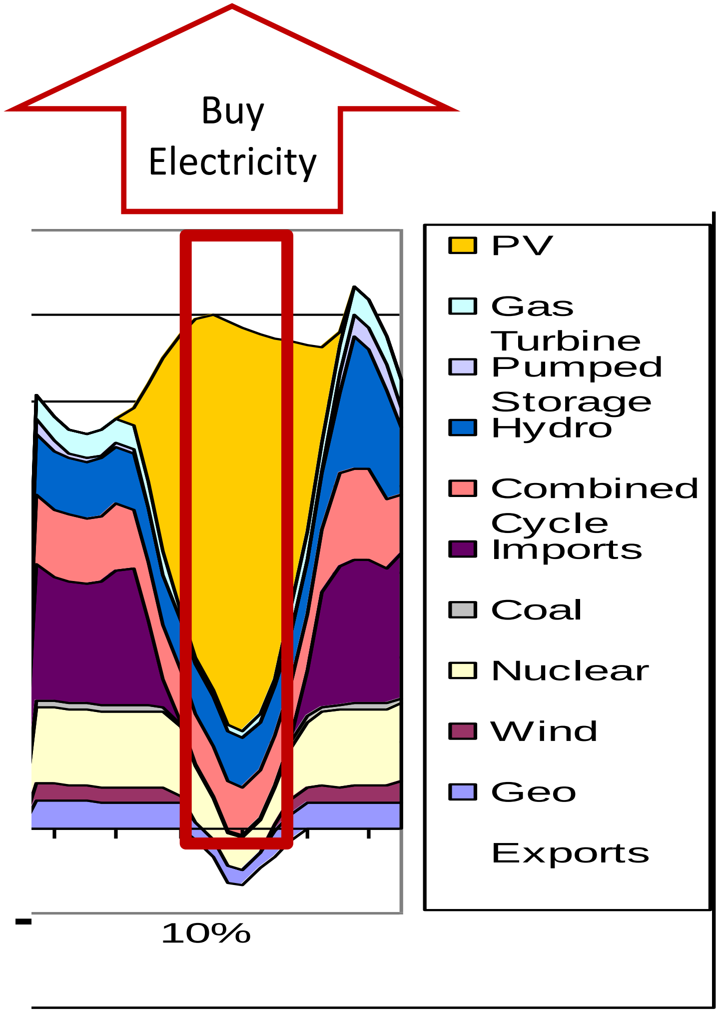
Energy Storage Capability: 1 m^3 hot rock versus Tesla S



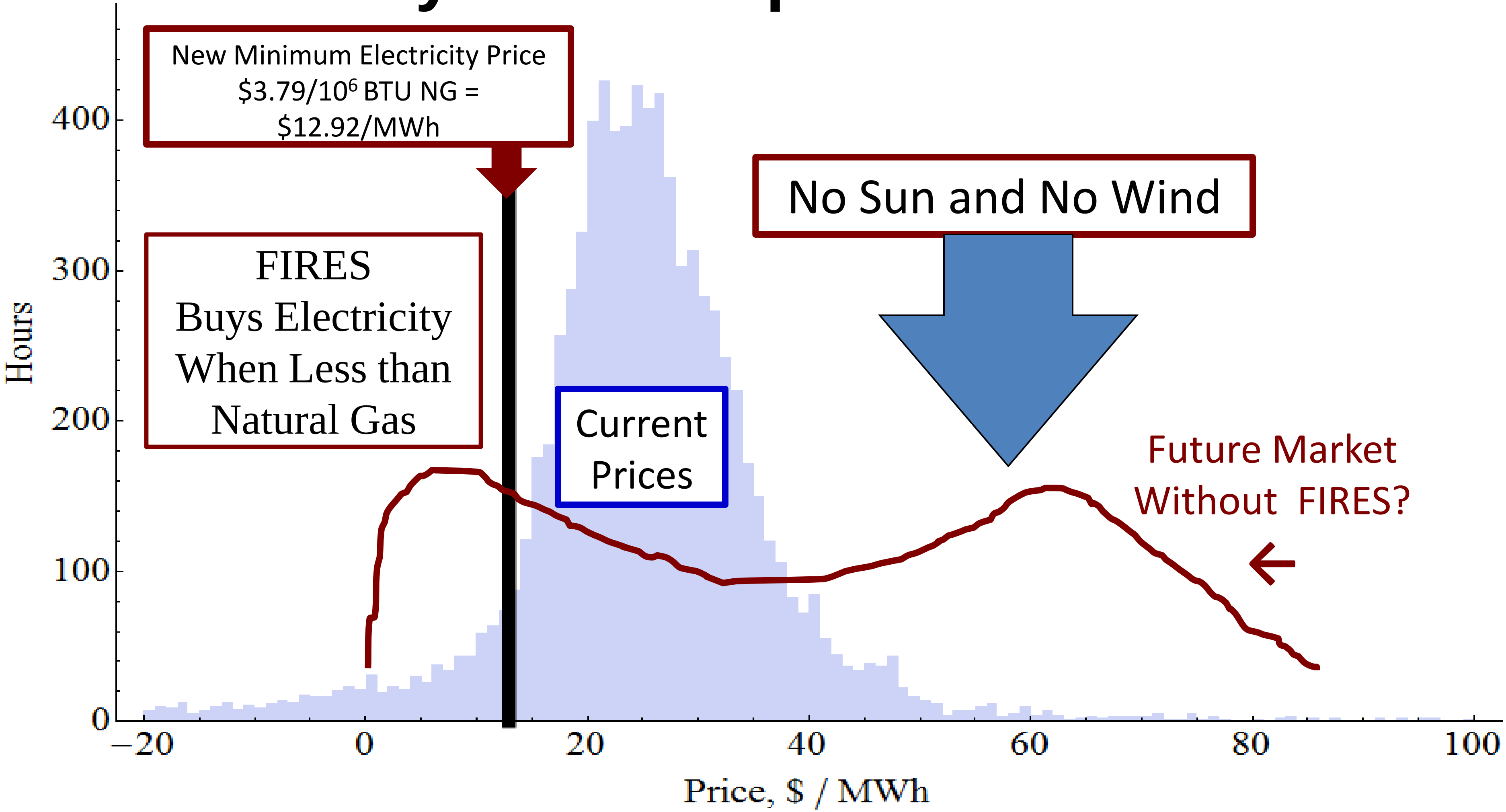
High-Temperature Heat-Storage Cost Potentially an Order of Magnitude Less than Alternatives

FIRES: Unused Electric Generating Capacity Partly Replaces Fossil Fuels in High-Temperature Processes

- Buy electricity when the price is less than that of natural gas
- Firebrick is the material of furnace linings: To 1800C
- FIRES hot air partly replaces natural gas in heating applications
  - Cement production (1450°C)
  - Glass production
  - Chemical / refinery thermal cracking



FIRES Enables Full Utilization of Nuclear Renewable Output and Places a Floor On Electricity Prices Equal to Natural Gas



New Minimum Electricity Price
$3.79/10^6 BTU NG =
$12.92/MWh

No Sun and No Wind

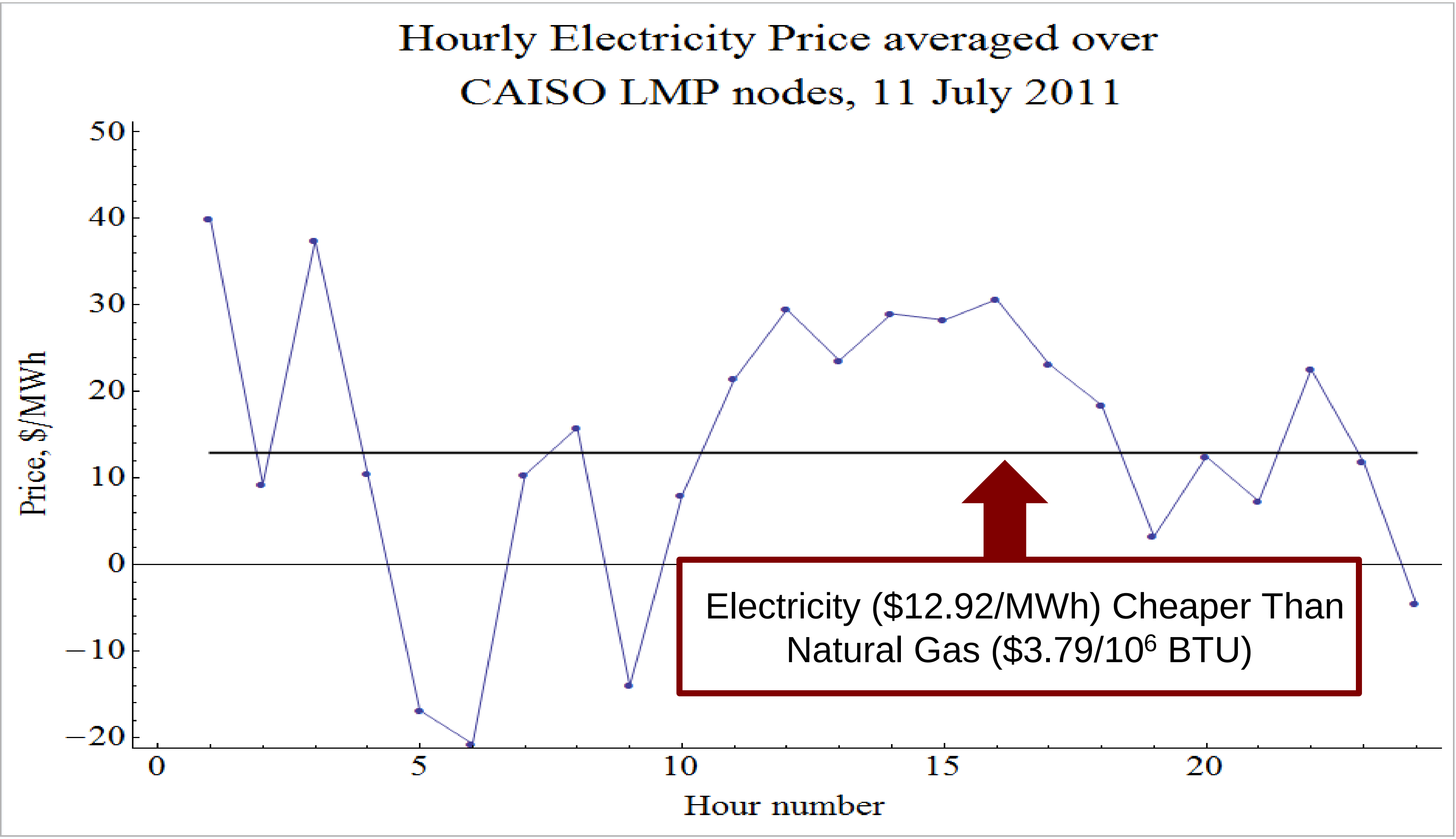
FIRES
Buys Electricity
When Less than
Natural Gas

Current
Prices

Future Market
Without FIRES?

Distribution of Hourly Electricity Prices Averaged Over
CAISO LMP nodes, July 2011 – June 2012

California Price Curve Shows Times When Electricity Cheaper then Natural Gas

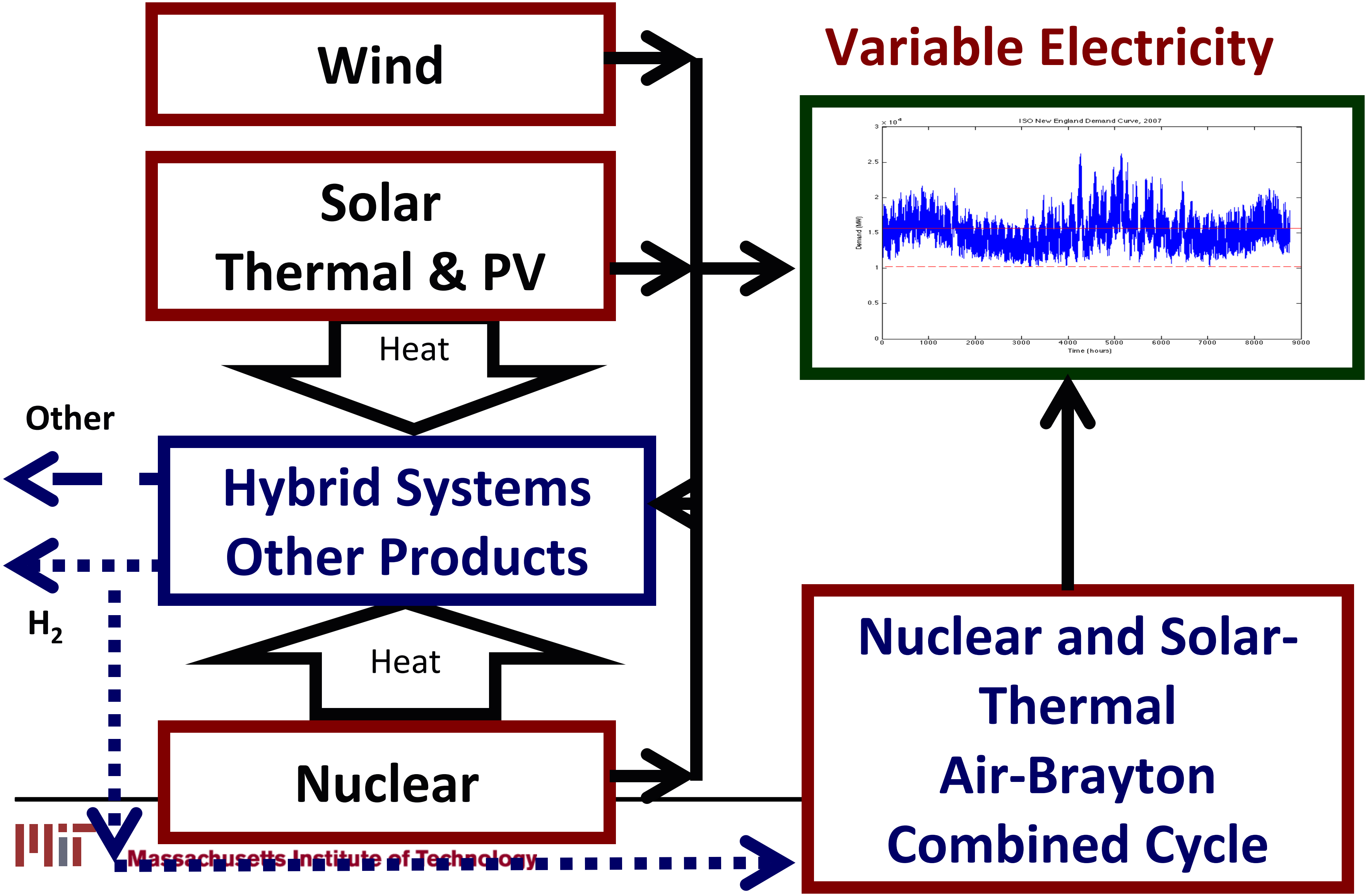


Electricity ($12.92/MWh) Cheaper Than Natural Gas ($3.79/$10^6$ BTU)

Thermal Hybrid Systems

Example (Midterm)
Nuclear Renewable Oil Shale System (NROSS)

Using Hybrid Systems to Fully Utilize Electricity Generating Assets



Wind

Solar Thermal & PV

Heat

Other

Hybrid Systems Other Products

H_2

Heat

Nuclear

Variable Electricity

Nuclear and Solar-Thermal Air-Brayton Combined Cycle

Nuclear-Renewable Oil-Shale System (NROSS)

Lowest Carbon Emissions per Liter of Gasoline or Diesel of any Fossil Fuel Option

Enable Zero-Carbon Electric Grid

Maximize Economics

C. Forsberg and D. Curtis: “Nuclear Renewable Oil Shale System (NROSS): Making Oil Shale the Fossil Fuel with the Lowest Greenhouse Impact per Liter of Diesel or Gasoline While Improving Economics; *34th Oil Shale Symposium*; Boulder, Colorado, 13-17 October 2014

The U.S. Has The World's Largest Oil-Shale Resources

- Over 1 trillion barrels-of-oil equivalent in "high grade" shales (> 25 gallons per ton shale)
- Over 2 trillion barrels in medium grade or better shales (> 10 gallons per ton shale)
- Over 1 million barrels per acre in high-grade shales

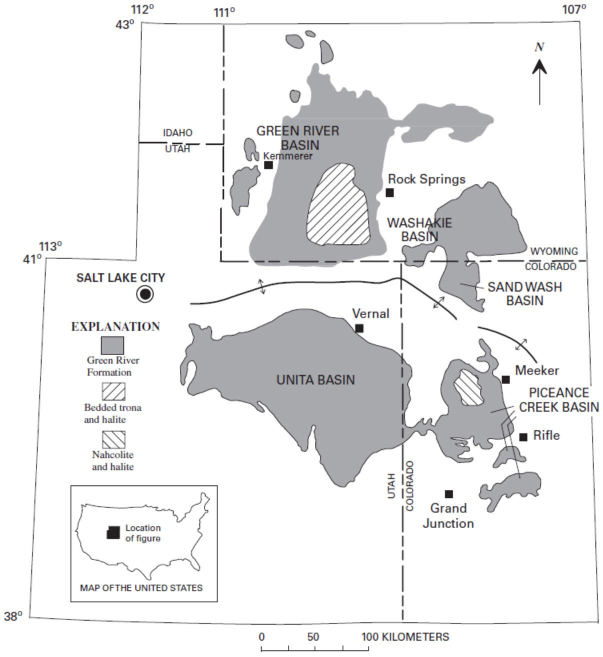
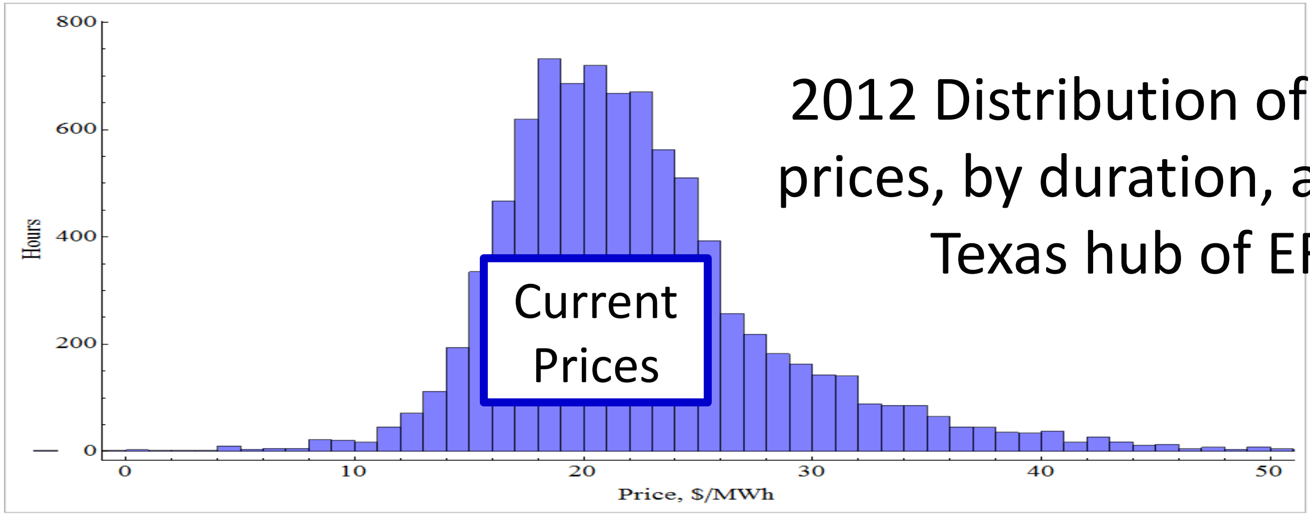


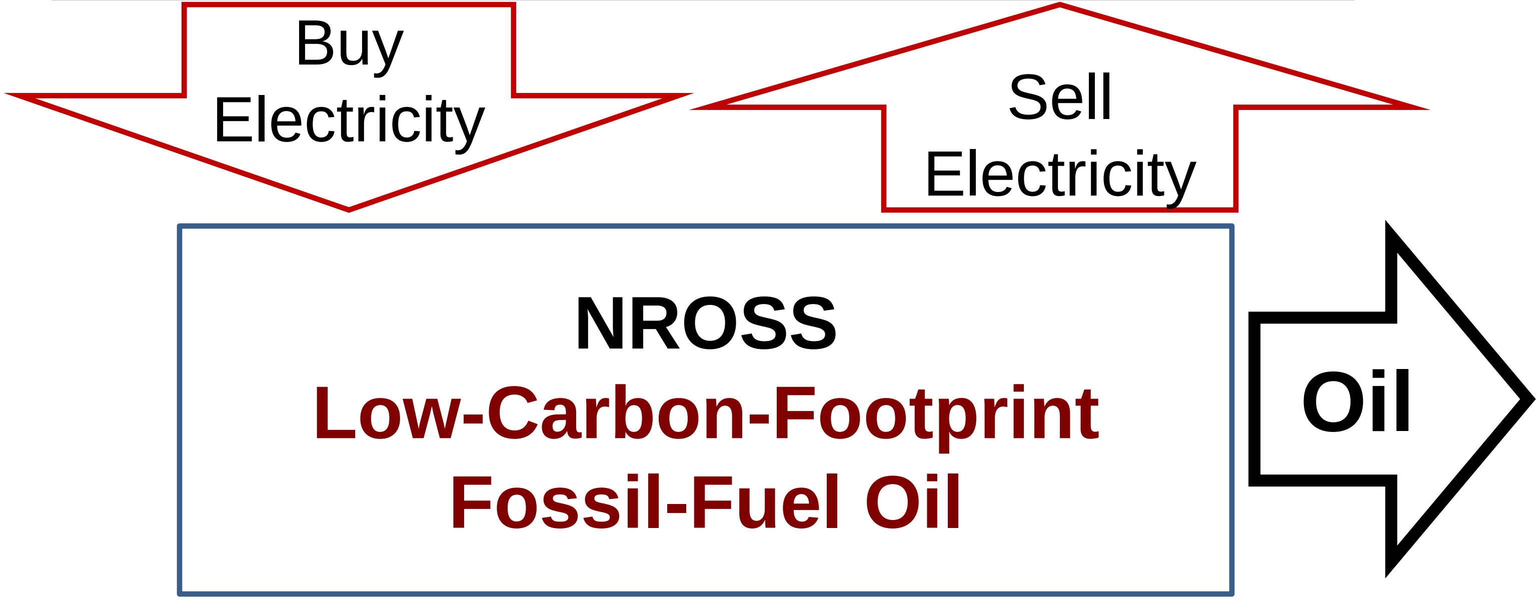
Figure 16. Areas underlain by the Green River Formation in Colorado, Utah, and Wyoming, United States.

Exceeds Total Historical Global Oil Production

NROSS Integrates Shale Oil Production and the Electricity Grid to Reduce Greenhouse Gas Releases and Improve Economics



2012 Distribution of electricity prices, by duration, at Houston, Texas hub of ERCOT



Buy Electricity

Sell Electricity

NROSS

Low-Carbon-Footprint Fossil-Fuel Oil

Oil

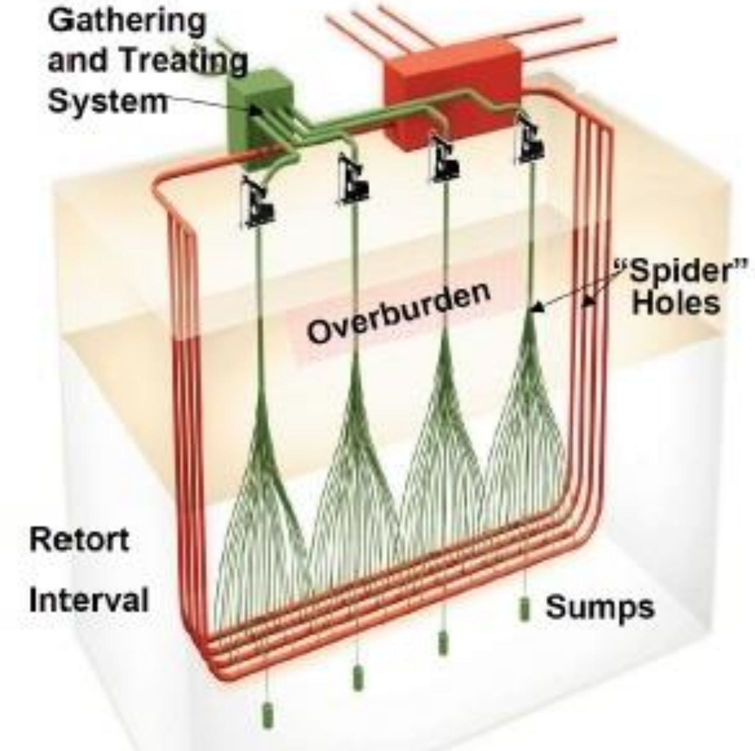
NROSS is a Two Part Story

Oil Shale (Kerogen) Production

Zero-Carbon Electric Grid

Use Heat from Nuclear Reactor For Oil Shale Retorting

- Slow heating kerogen shale over 1 to 3 years
  - Solid kerogen decomposes
  - Liquid and gaseous decomposition products
  - Carbon char sequestered
- Avoids burning fossil fuels to produce heat for oil
- Low conductivity rock does not require constant heating

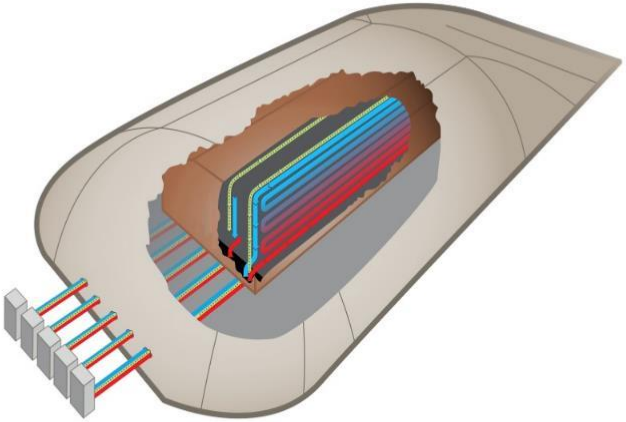


Courtesy of Idaho National Laboratory

Closed Heat Transfer Lines

NROSS Viable for Many Shale Oil Processes

- Surface Retort: Red Leaf
  - Open pit mine
  - Create clay lined retort (150’ high, 150” wide, 1000’ long)
  - Steam lines to heat oil shale to minimize greenhouse gas releases
  - Clay-lined retort also is high-integrity disposal facility
- Goal: Total environmental impact less than conventional oil (partly because concentrated resource)



Surface Retort

Courtesy of
Red Leaf Resources

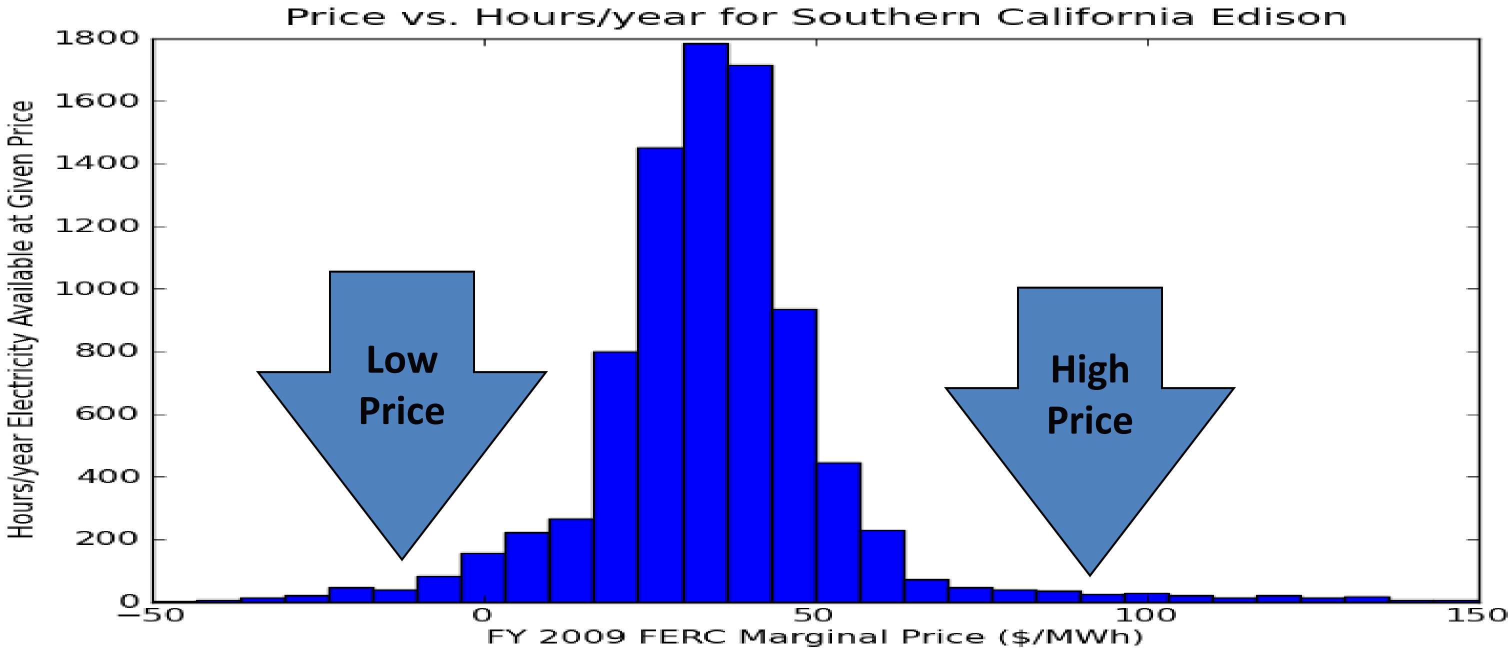
[1]Discussion herein assumes use of commercially available light-water reactors with peak temperatures of ~290°C

Light Water Reactor (LWR) Peak Steam Temperatures Are Insufficient

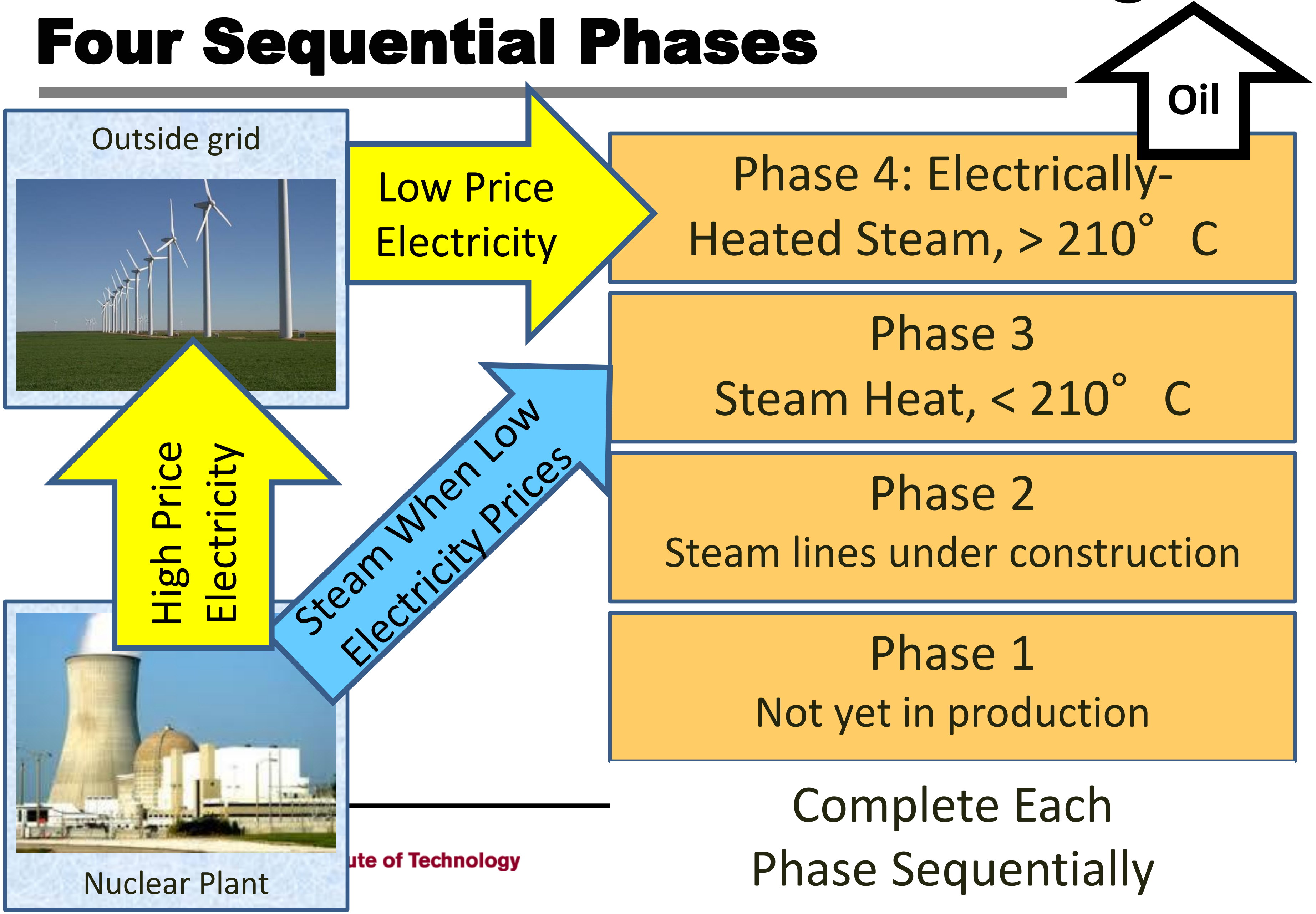
Require Two-Phase Heating of Shale to ~370 C

- Phase 1: Heat oil shale to 210 C with steam heat
- Phase 2: Buy electricity to heat steam to peak temperatures when the price of electricity is low

Electricity Price Distribution



Each Shale-Oil Zone Goes Through Four Sequential Phases



Phase 4: Electrically-Heated Steam, > 210° C

Phase 3
Steam Heat, < 210° C

Phase 2
Steam lines under construction

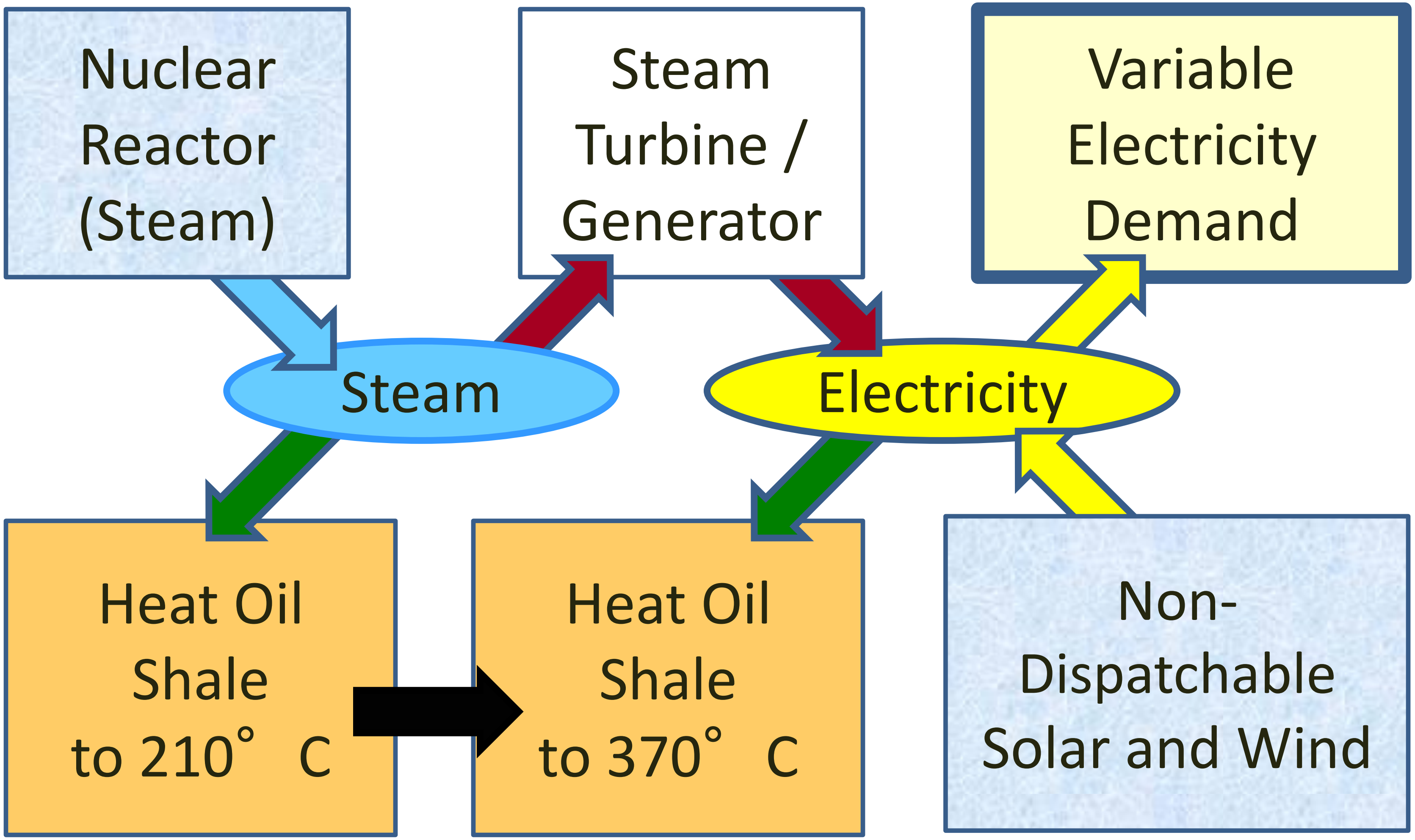
Phase 1
Not yet in production

Complete Each Phase Sequentially

NROSS with LWRs

High Electricity Prices: Electricity to Grid:

Low Energy Prices: Energy to Shale Oil Production



Nuclear Reactor (Steam)

Steam Turbine / Generator

Variable Electricity Demand

Steam

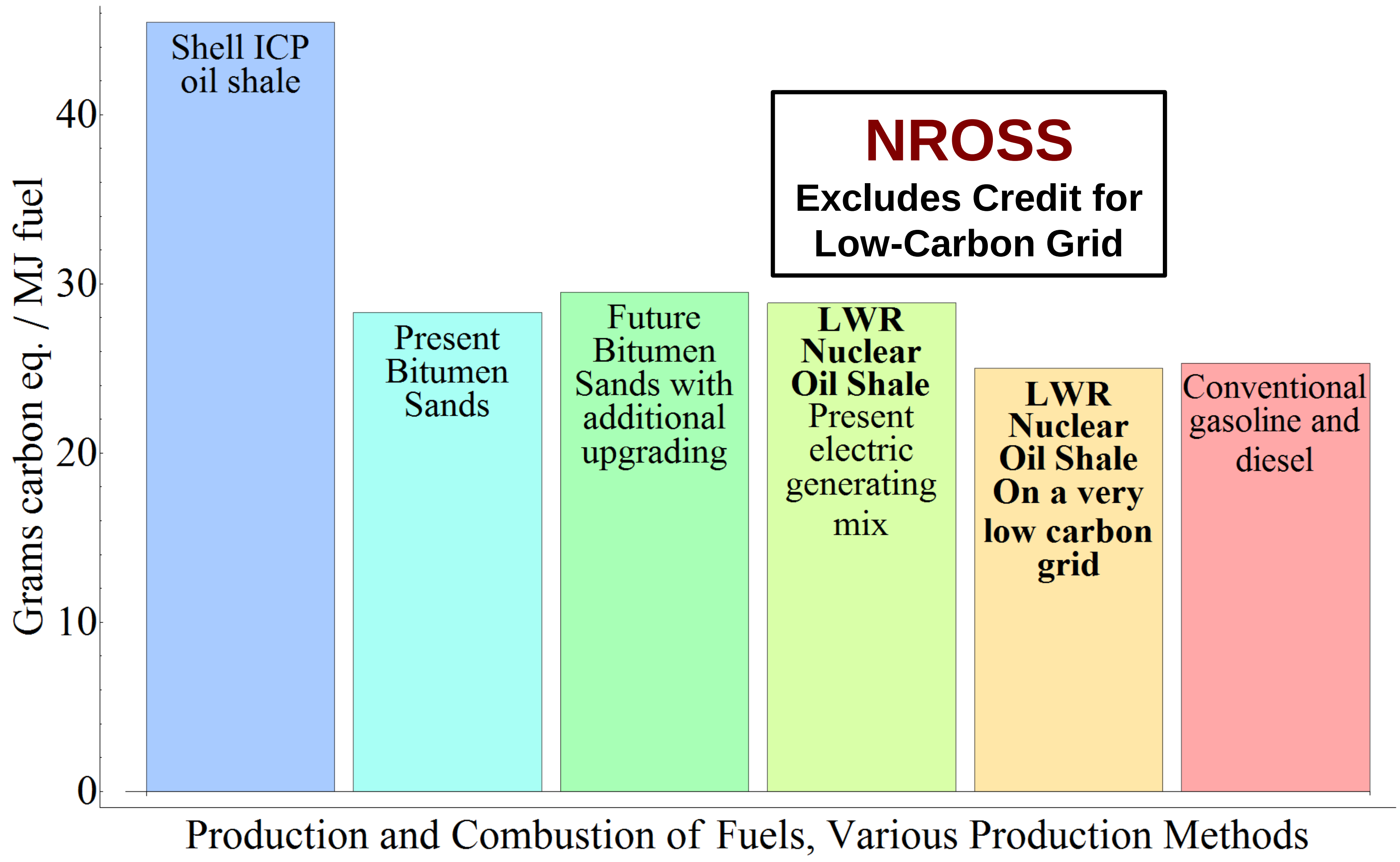
Electricity

Heat Oil Shale to 210° C

Heat Oil Shale to 370° C

Non-Dispatchable Solar and Wind

Greenhouse Footprints for Liquid Fuels Production



NROSS

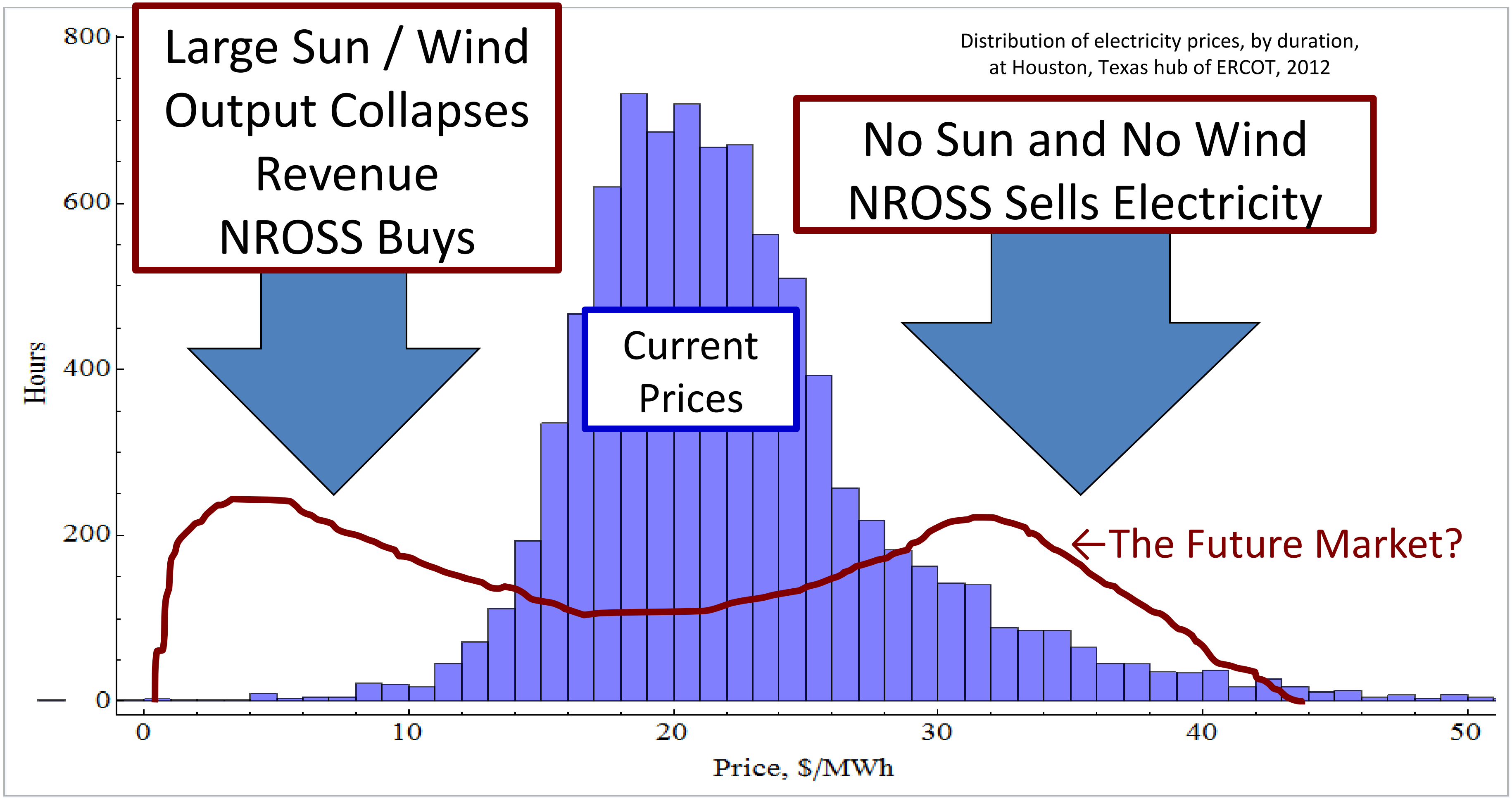
Excludes Credit for Low-Carbon Grid

NROSS is a Two Part Story

Oil Shale (Kerogen)

Zero-Carbon Electric Grid

Low-Carbon Electricity Free Market Implies More Hours of Low / High Price Electricity

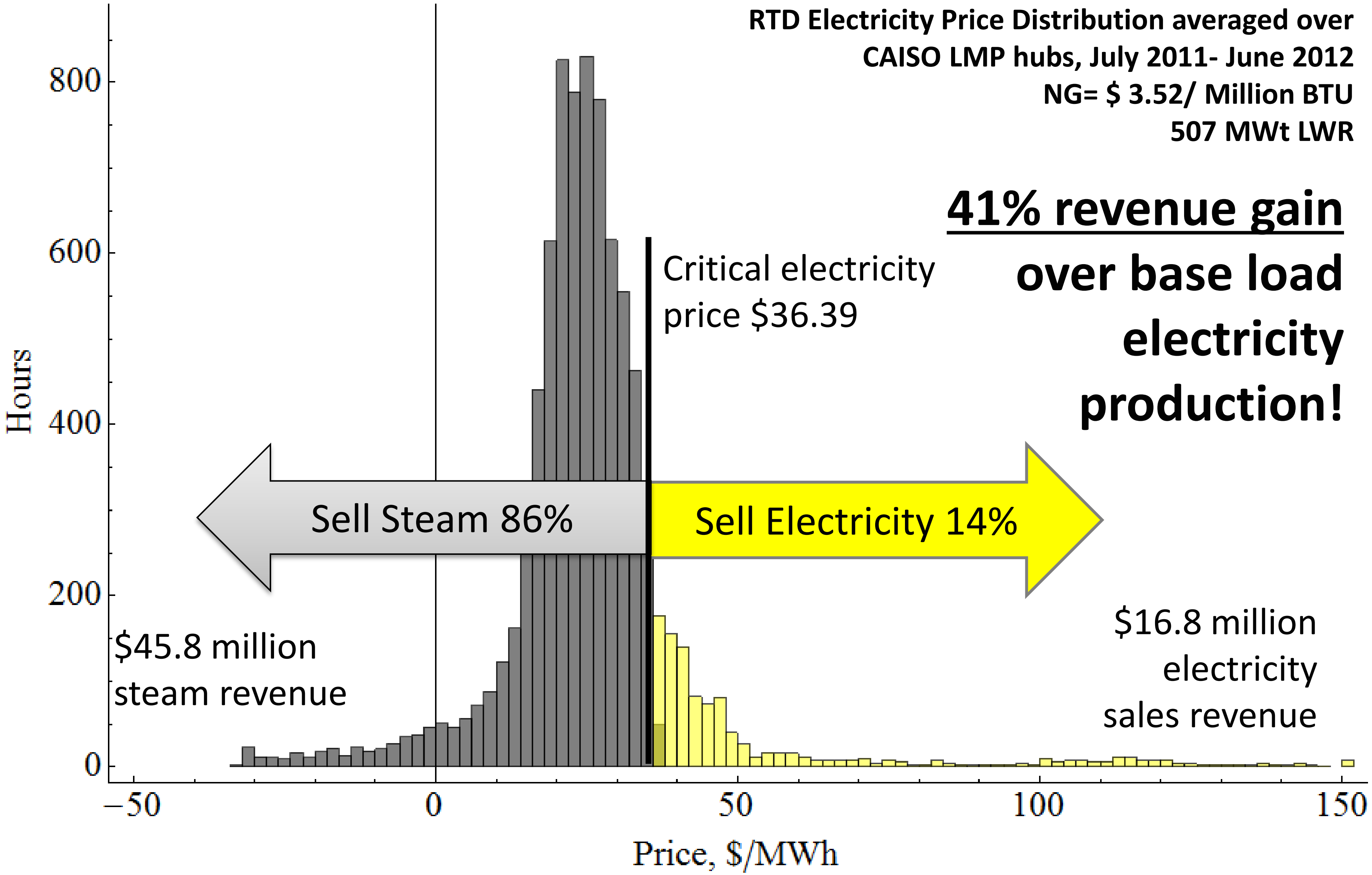


NROSS Economics Helped by Price Curve

NROSS Enables Zero-Carbon Grid

- Reduces large revenue collapse for renewables that enables larger-scale use of renewables
- Provides non-fossil nuclear electricity when low wind or solar conditions—eliminating expensive fossil fuel backup to renewables
- Full utilization of low-operating-cost high-capital-cost nuclear and renewable electricity generators
- Maximizes NROSS revenue: buy electricity when low prices and sell electricity when high prices

Revenue Assessment Results



RTD Electricity Price Distribution averaged over
CAISO LMP hubs, July 2011- June 2012
NG= $ 3.52/ Million BTU
507 MWt LWR

<u>41% revenue gain</u> over base load electricity production!

Critical electricity price $36.39

Sell Steam 86%

Sell Electricity 14%

$45.8 million steam revenue

$16.8 million electricity sales revenue

Who Gets Credit for Zero-Carbon Grid?

- NROSS enables economic zero-carbon grid
- Without NROSS zero-carbon grid expensive
  - Low capacity factors for wind, solar, and nuclear
  - Expensive energy storage systems
- **If NROSS oil gets the credit for zero-carbon grid, CO_2 emissions assigned to liquid fuels is less than from combustion of liquid fuels**

NROSS Conclusions

- Economic benefits for nuclear, renewable (wind and solar), and oil shale operators
- Enables renewable expansion by supplying electricity when low wind/low solar and absorbing excess electricity when high wind/high solar
- **Potentially the least-carbon-intensive fossil source of liquid fuels—makes oil shale (kerogen) the green fossil fuel**
- Significant development work required

Hydrogen

Zero-Carbon Futures Always Have Hydrogen (H_2)

Why Low-Carbon Futures Always Have Hydrogen

- Fossil fuel substitutes for low-carbon economy
- Massive current and future hydrogen market: 1% of U.S. energy consumption today
  - Fertilizer production (ammonia)
  - Transportation
    - Used in oil refining: convert heavy oil to gasoline
    - Can double liquid fuel yields per ton of biomass
    - Direct fuel use options: hydrogen, ammonia, or other forms
  - Replace coal in the production of iron and other metals
- Large-scale storage is cheap—same technologies as used for natural gas (underground caverns and permeable geologies)

Hydrogen: Sink for Excess Electricity

Electro-Thermal Processes More Efficient

Electricity Production → H_2 / O_2 From Water → Markets

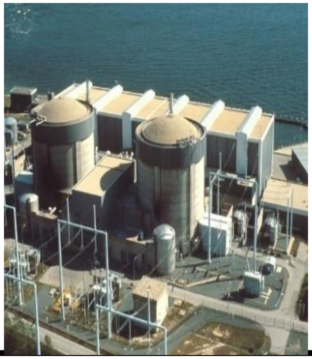
Electricity

→ Electricity →

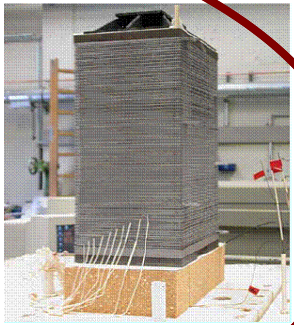
Pressure electrolyzer (Lurgi System) for hydrogen production, capacity 760 Nm^3/h H_2

Electrolysis

Electricity and Heat

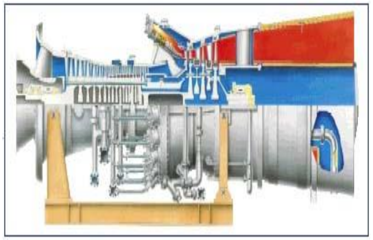


Heat →



HTE

Fuels, Fertilizer, Metals



Peak Power

Hydrogen Can Be Used For Seasonal Electricity Storage: But Inefficient

Can We Get 50% Round-Trip Efficiency?

Electricity Production → H_2 / O_2 From Water → H_2 / O_2 Storage → Peak Power

Electricity

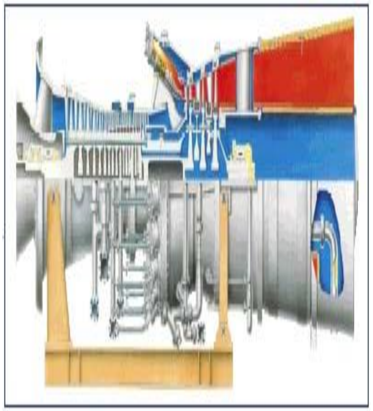
→

Electricity

Pressure electrolyzer (Lurgi System) for hydrogen production, capacity 760 Nm³/h H_2

Electrolysis

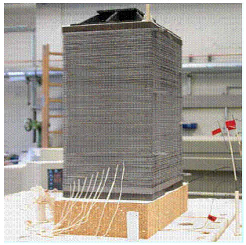
Storage



Electricity and Heat

→

Heat →



HTE

Peak Power

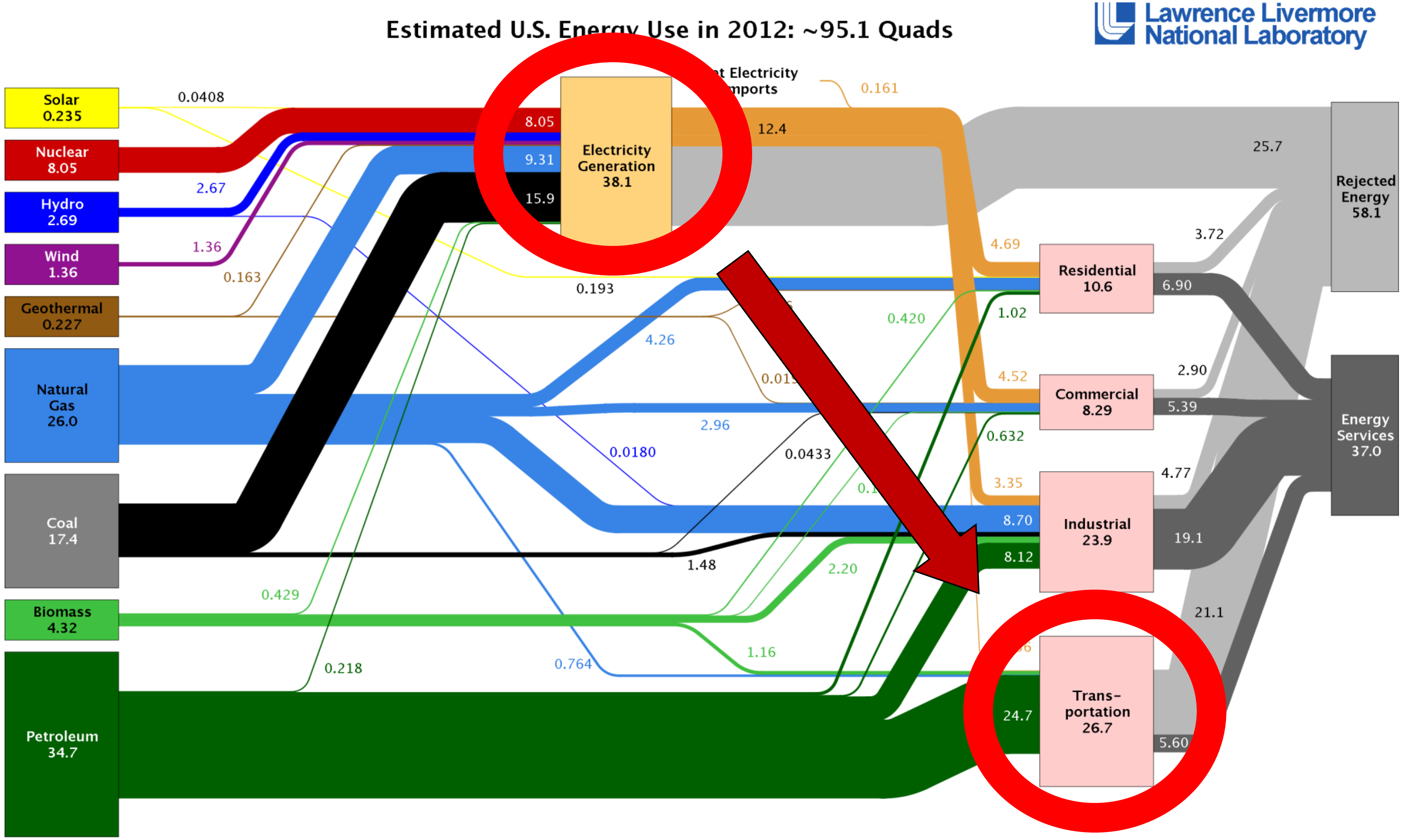
Some technologies Commercial, others Early R&D Stage

Zero-Carbon Liquid Fuels

The Grand Challenge

Fossil Liquid Fuels with CO_2 Sequestration
Biofuels
Fuels from Air and Water

Liquid Fuels Is The Largest Zero-Carbon Energy Challenge and Potentially the Largest User of Excess Energy from the Grid



Estimated U.S. Energy Use in 2012: ~95.1 Quads

Lawrence Livermore National Laboratory

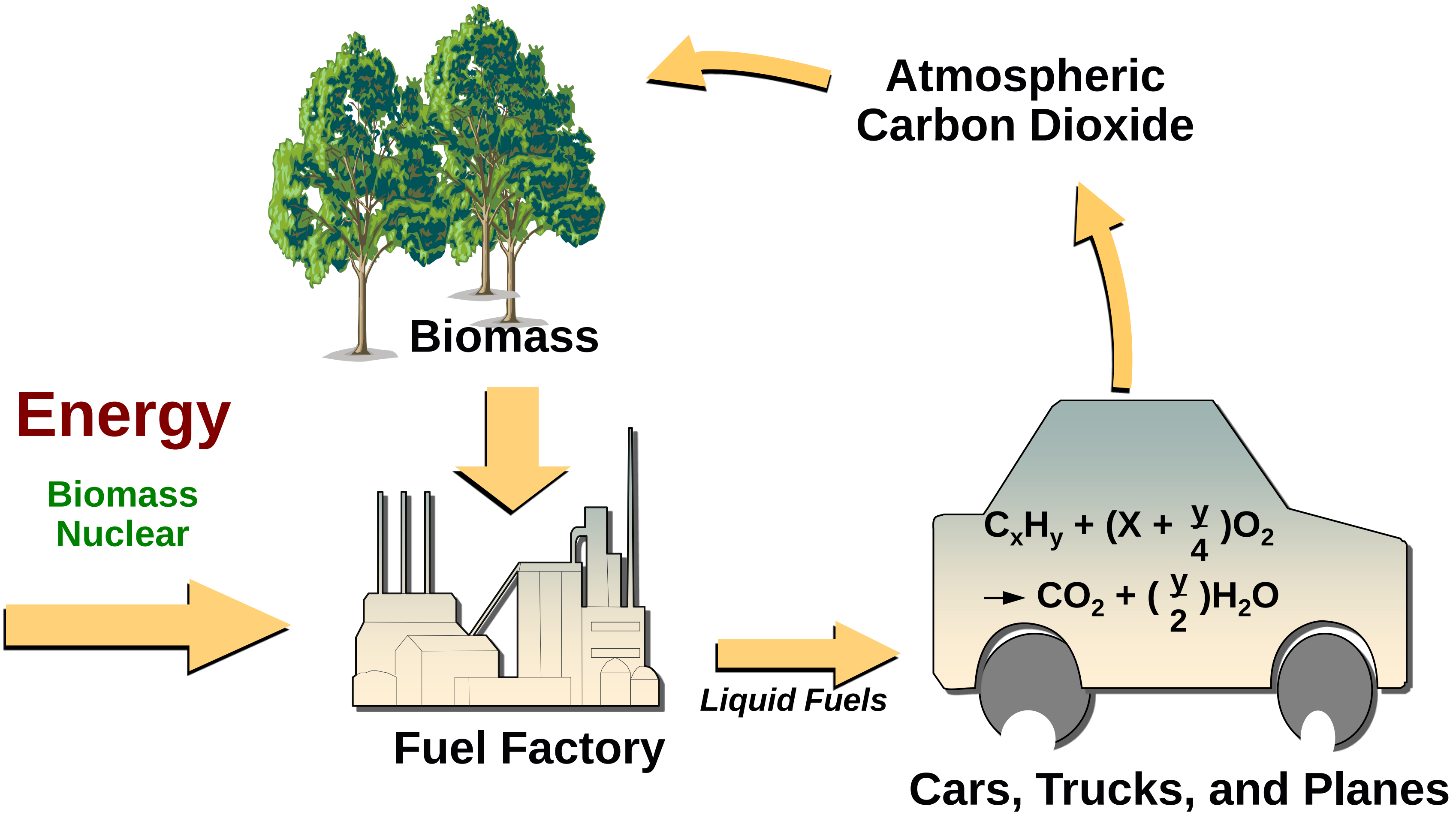
Option 1: Remove and Sequester CO_2 from Air or Water

- Burn fossil liquid fuels
- Remove carbon dioxide from air and sequester carbon dioxide
  - Work underway to capture CO_2 from air
  - Energy costs appear to be fraction of energy value of fuel
  - Locate anywhere on planet with sites chosen for the lowest total costs
- Are the Siberian Traps (basalt rock in Russia) the ultimate sink for carbon dioxide from transport fuels?

Option 2: Biofuels

- Plants produce biomass by removing CO_2 from atmosphere so no net CO_2 emissions if convert to liquid fuels and burn
- Production limited by feedstock availability so need efficient use of biomass
- U.S. biomass potential in barrels oil-equivalent / day
  - Energy if burn: ~10 Million barrels per day
  - Liquid fuel if biomass feedstock and used as energy input to biofuels plant: ~ 5 Million barrels per day
  - Liquid fuel if biomass feedstock and external energy and H_2 for biofuels plant: ~12 Million barrels per day
- **Potential for biofuels production depends upon external energy sources and hydrogen**

Biomass: A Potent Low-Greenhouse-Gas Liquid-Fuel Option



Atmospheric Carbon Dioxide

Biomass

Energy

Biomass
Nuclear

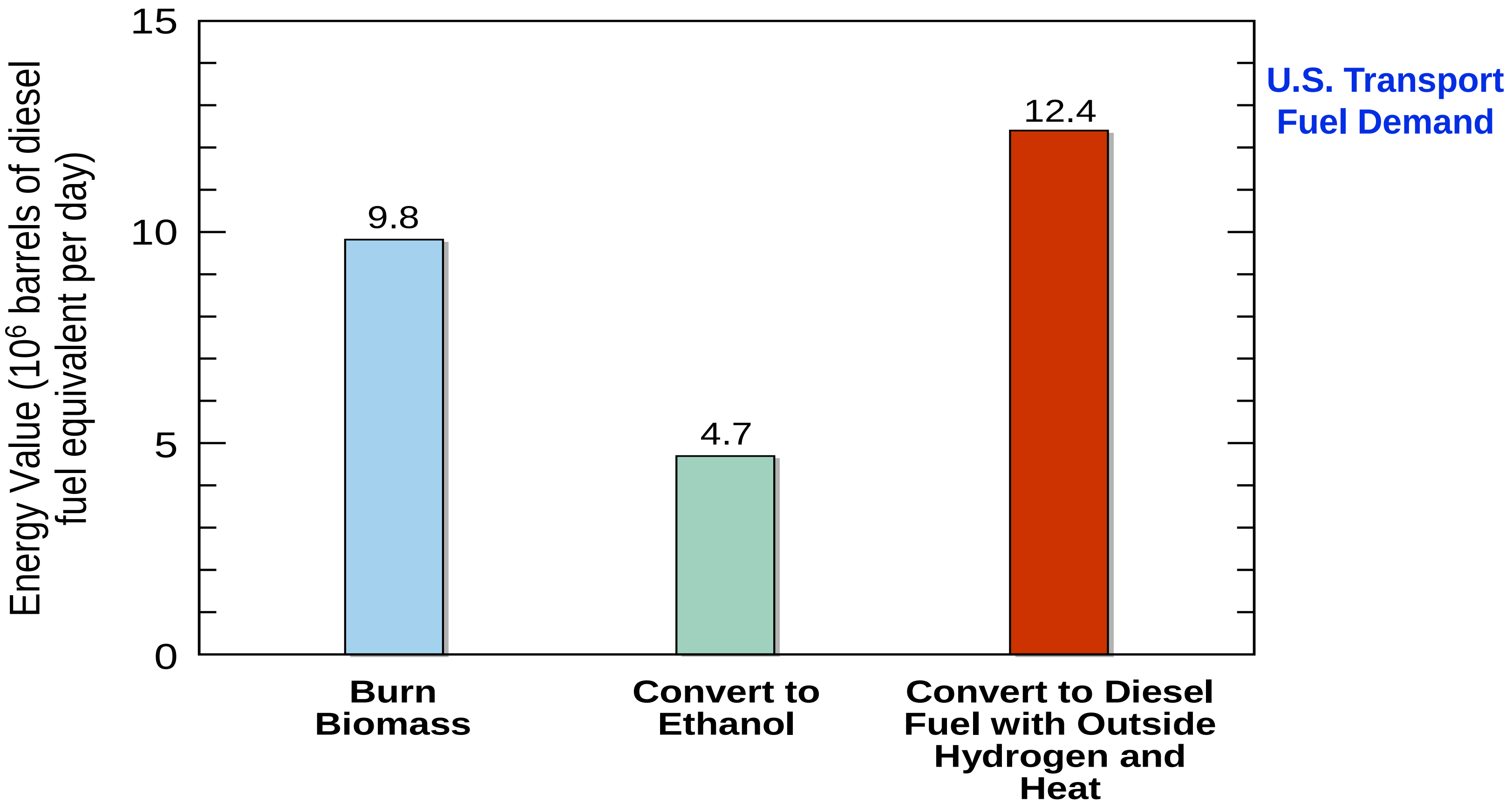
Fuel Factory

Liquid Fuels

$$C_xH_y + (X + \frac{y}{4})O_2 \rightarrow CO_2 + (\frac{y}{2})H_2O$$

Cars, Trucks, and Planes

Biomass Conversion to Liquid Fuel Requires Energy



Energy Value of 1.3 Billion Tons/year of U.S. Renewable Biomass Measured in Equivalent Barrels of Diesel Fuel per Day

MIT Examining Two Nuclear Hybrid Biofuels Options

- Paper and Liquid Fuels Hybrid System (Near-term)
  - Paper mills are among the top three industrial energy users
  - Currently burn biomass wastes to supply energy
  - Alternative option: Nuclear provide heat to paper mill and convert biomass wastes to transport fuels. Biomass already collected
    - Large-scale demo of paper mill wastes to transport fuels (Sweden) but collect more biomass to fuel paper mill
    - Nuclear heat source maximizes paper and transport fuel production per unit of biomass (the limiting resource)
- Kelp liquid-fuels hybrid system (Wildcard)
  - Biomass resource about 10 times U.S. land resource
  - Potentially capable of meeting all liquid fuels demand
  - Massive heat load required to reduce moisture content of feedstock for processing

Kelp: The Big Biofuels Resource

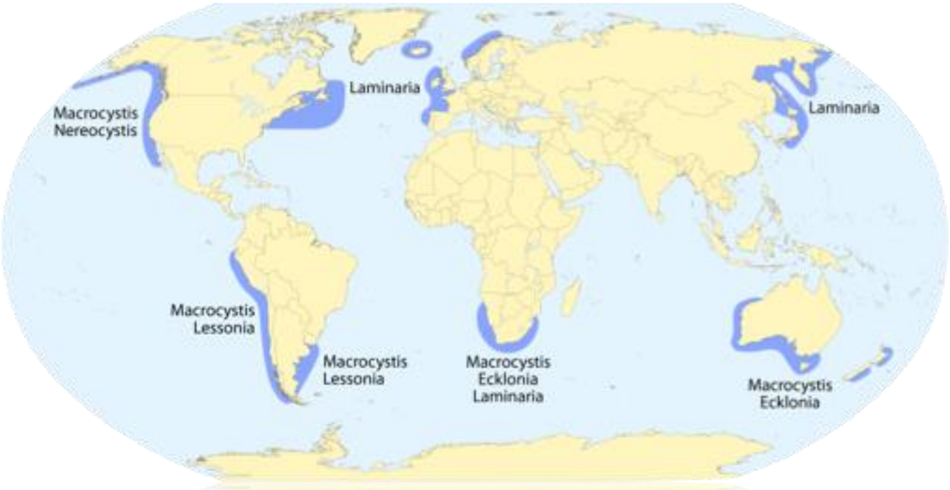
Seven Billion Ton Resource for U.S.

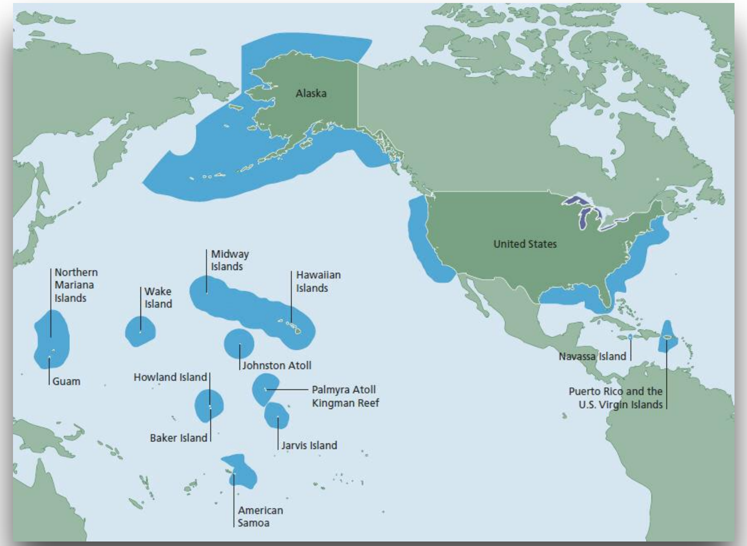
Stef Maruch / CC-BY-SA-2.0

- On paper, the great biomass resource for fuel
- Tough technical challenges to economically grow and recover kelp in the quantities required
- Social acceptance questions with ocean use

Images from the Library of Congress

Distribution U.S. Kelp Resources





Global
Kelp Zones

United States
Exclusive Economic Zone

Option 3: Liquid Fuels from Air or Water: Hydrogen Intensive

Extract CO_2

Convert CO_2 and H_2O To Syngas

Heat + Electricity

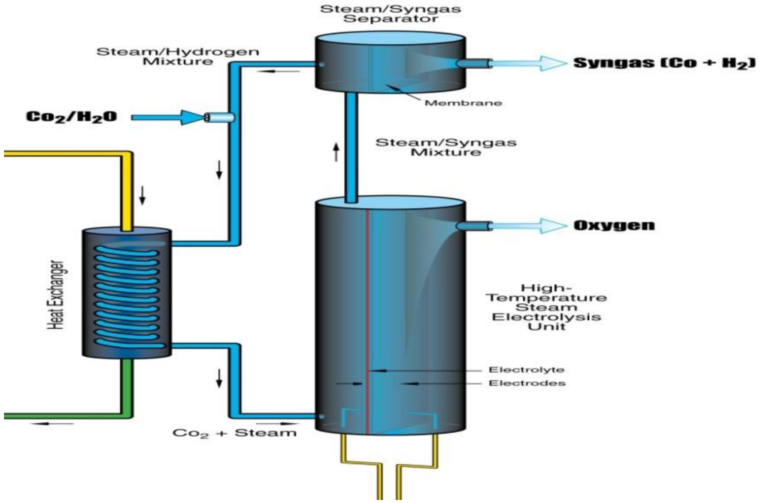
$CO_2 + H_2O \rightarrow CO + H_2$

Conversion to Liquid Fuel

$CO + H_2 \rightarrow$ Liquid Fuels

Carbon Dioxide From Air

Early R&D Stage



High Temperature Electrolysis (One Option)

Fischer-Tropsch Process

Change Characteristics of Nuclear Energy

Advanced Reactor Option

Fluoride-salt-cooled High-temperature Reactor (FHR) with Nuclear Air-Brayton Combined Cycle (NACC) and Firebrick Resistance-Heated Energy Storage (FIRES)

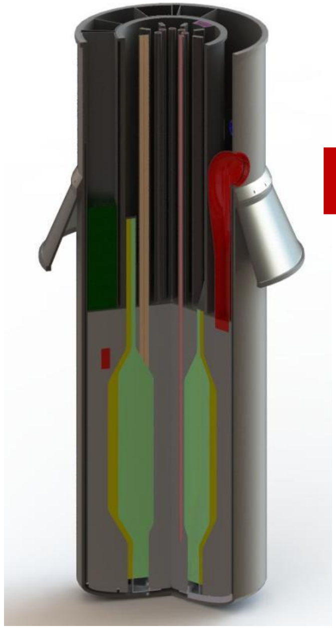
Integrating Nuclear and Heat Storage for Base-Load and Peak Electricity

NEUP Nuclear Energy University Programs
U.S. Department of Energy

Base-Load FHR with NACC and FIRES Produces Variable Electricity

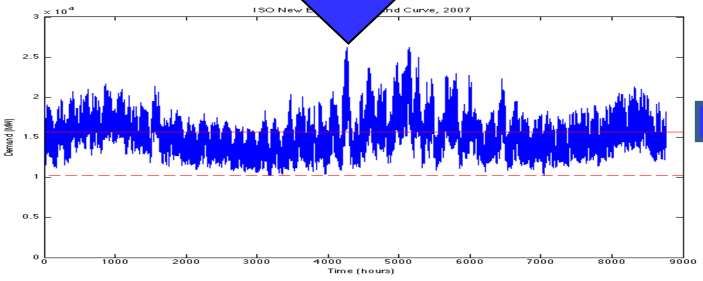
Constant High-Temperature Heat (600 to 700 C)

Reactor (FHR)



Combustible Fuels

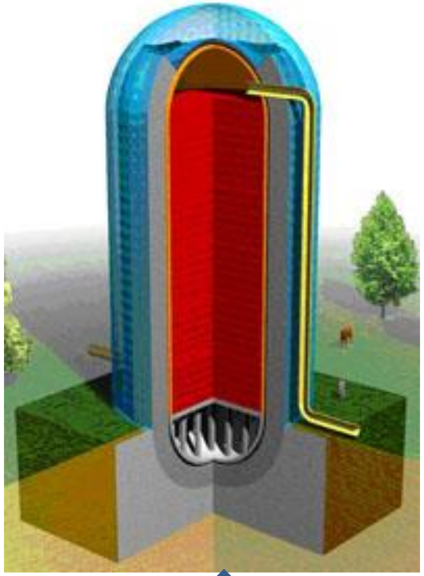
Gas-Turbine (NACC)



Variable Electricity

FIRES

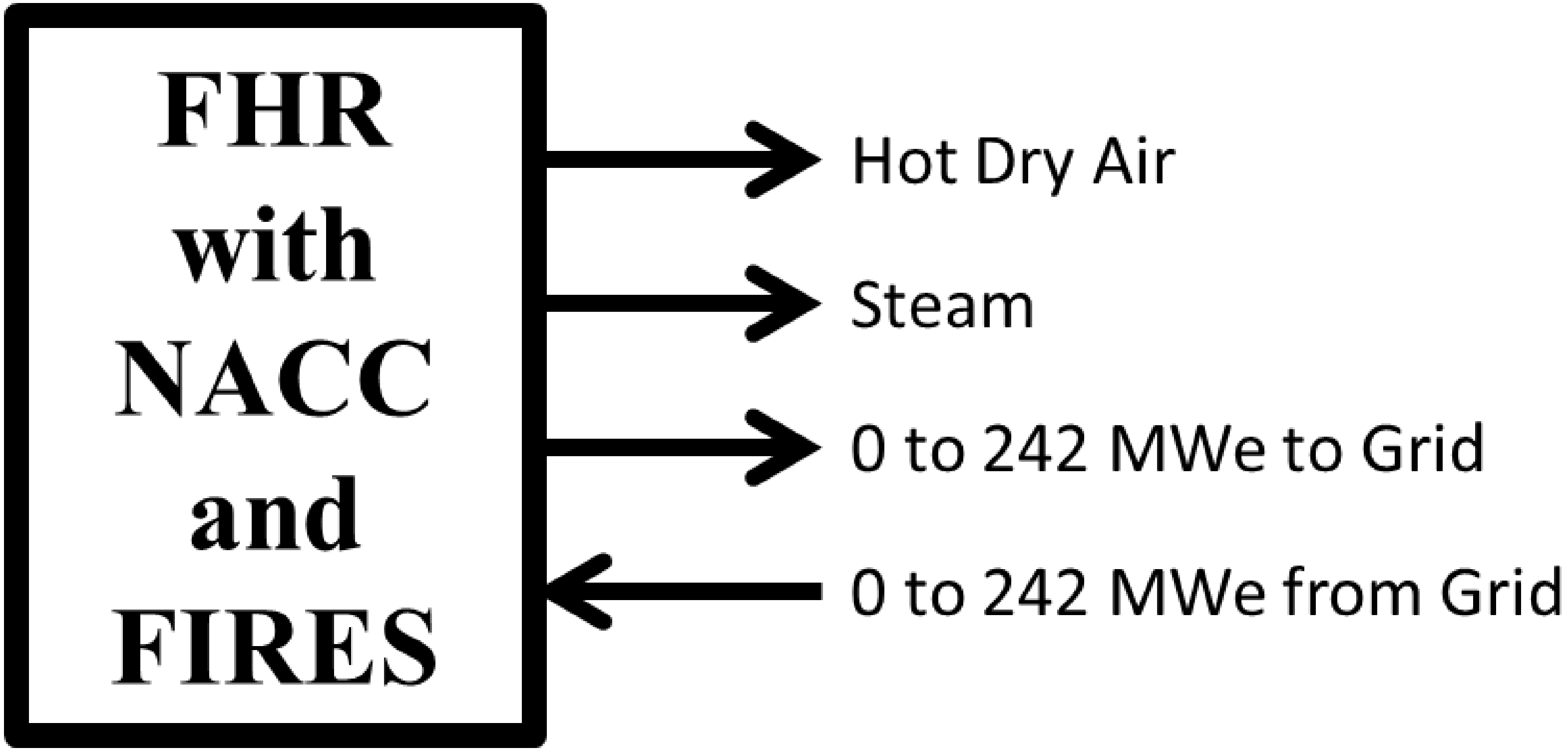
Stored Heat



Buy Electricity When Price is Low, Store as High-Temp. Heat

Modular FHR as a Black-Box

Can be Built in Different Sizes



FHR
with
NACC
and
FIRES

Hot Dry Air

Steam

0 to 242 MWe to Grid

0 to 242 MWe from Grid

NACC: Nuclear Air-Brayton Combined Cycle
FIRES: Firebrick Resistance-Heated Energy Storage

Not Your Traditional Nuclear Reactor

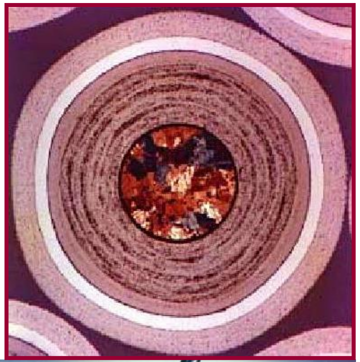
Modular FHR as a Black-Box

Can be Built in Different Sizes

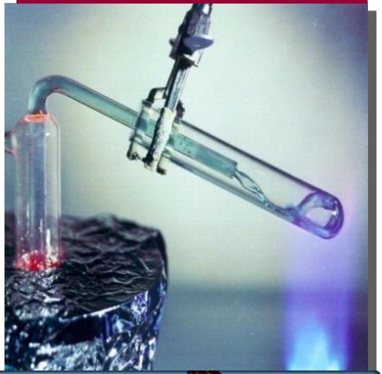
- Average electricity prices: 100 MWe baseload to grid
- High electricity prices: 242 MWe to grid
  - Peak power using auxiliary natural gas or stored heat
  - 66% NG or stored heat-to-electricity efficiency
- Low or negative electricity prices: Buy 242 MWe
  - Buy when electricity prices less than natural gas
  - Electricity from FHR and grid into heat storage
  - Round-trip electricity-to-heat-to-electricity efficiency: 66%
- Implications
  - Increase plant revenue relative to base-load electricity
  - Enable zero-carbon nuclear-renewable grid (May replace hydro pumped storage, batteries, back-up gas turbines)

Not Your Traditional Nuclear Reactor

FHR Combines Existing Technologies



Fuel: High-Temperature Coated-Particle Fuel Developed for High-Temperature Gas-Cooled Reactors (HTGRs) with Failure Temperatures >1650°C

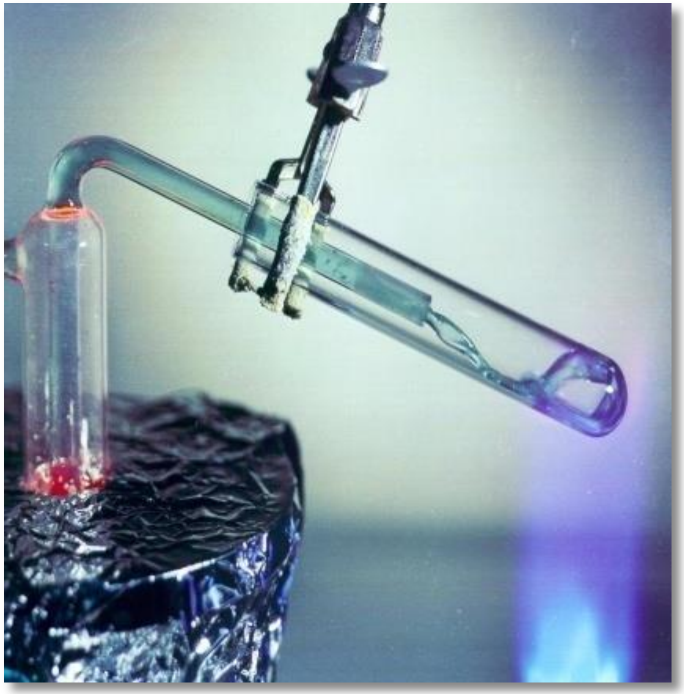


Coolant: High-Temperature, Low-Pressure Liquid-Salt Coolant ($^7Li_2BeF_4$) with freezing point of 460°C and Boiling Point >1400°C (Transparent)

Power Cycle: Modified Air Brayton Power Cycle with General Electric 7FB Compressor

FHR Uses Fluoride Salt Coolants

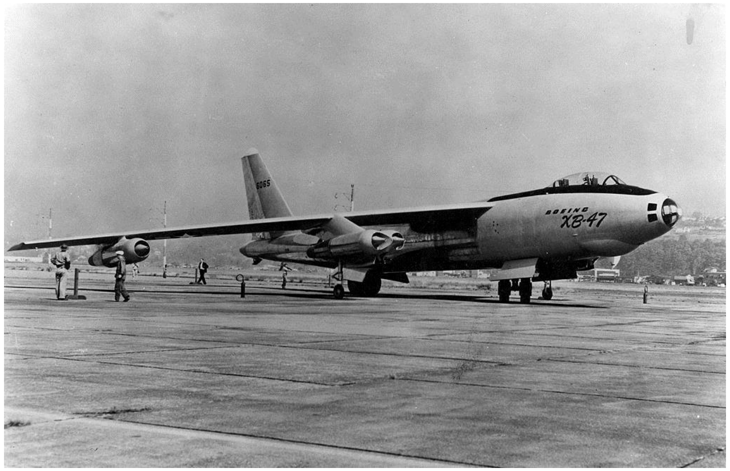
- Low-pressure high-temperature coolant
- Base-line salt Flibe ($^7LiBeF_4$)
  - Melting point 460° C
  - Boiling point: >1400° C
- Heat delivered to power cycle between 600 and 700° C
  - Avoid freezing salt
  - Limits of current materials



Alternative Fluoride Salt Options Exist

Fluoride Salt Coolants Were Developed for the Aircraft Nuclear Propulsion Program

Salt-Cooled Reactors Designed to Couple to Jet Engines



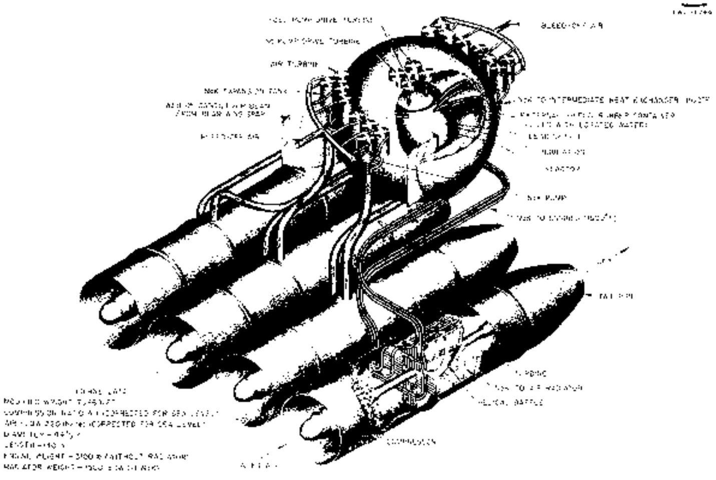
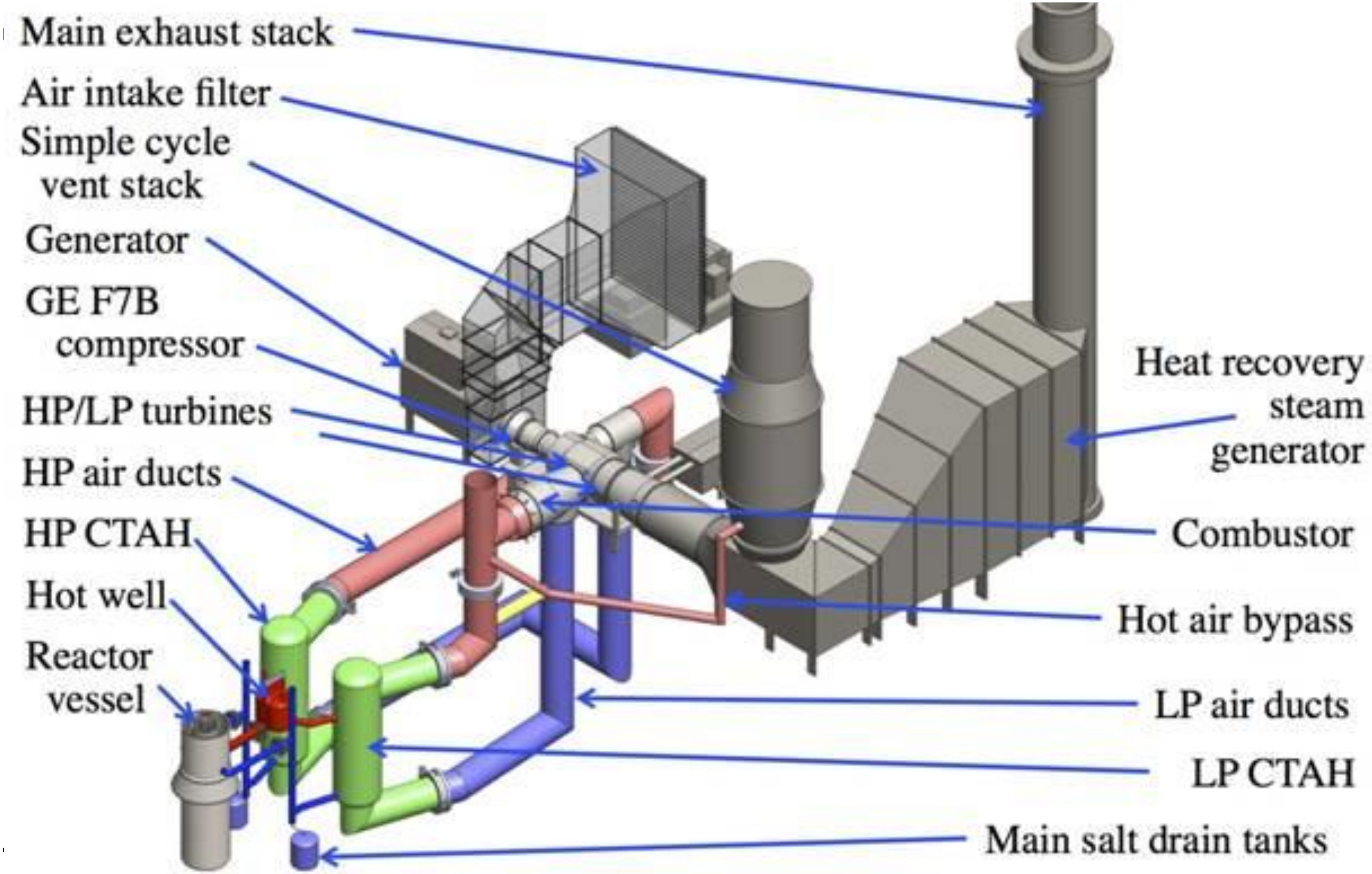


Fig. 4.33. Aircraft Power Plant (200 Megawatts).

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

Massachusetts Institute of Technology

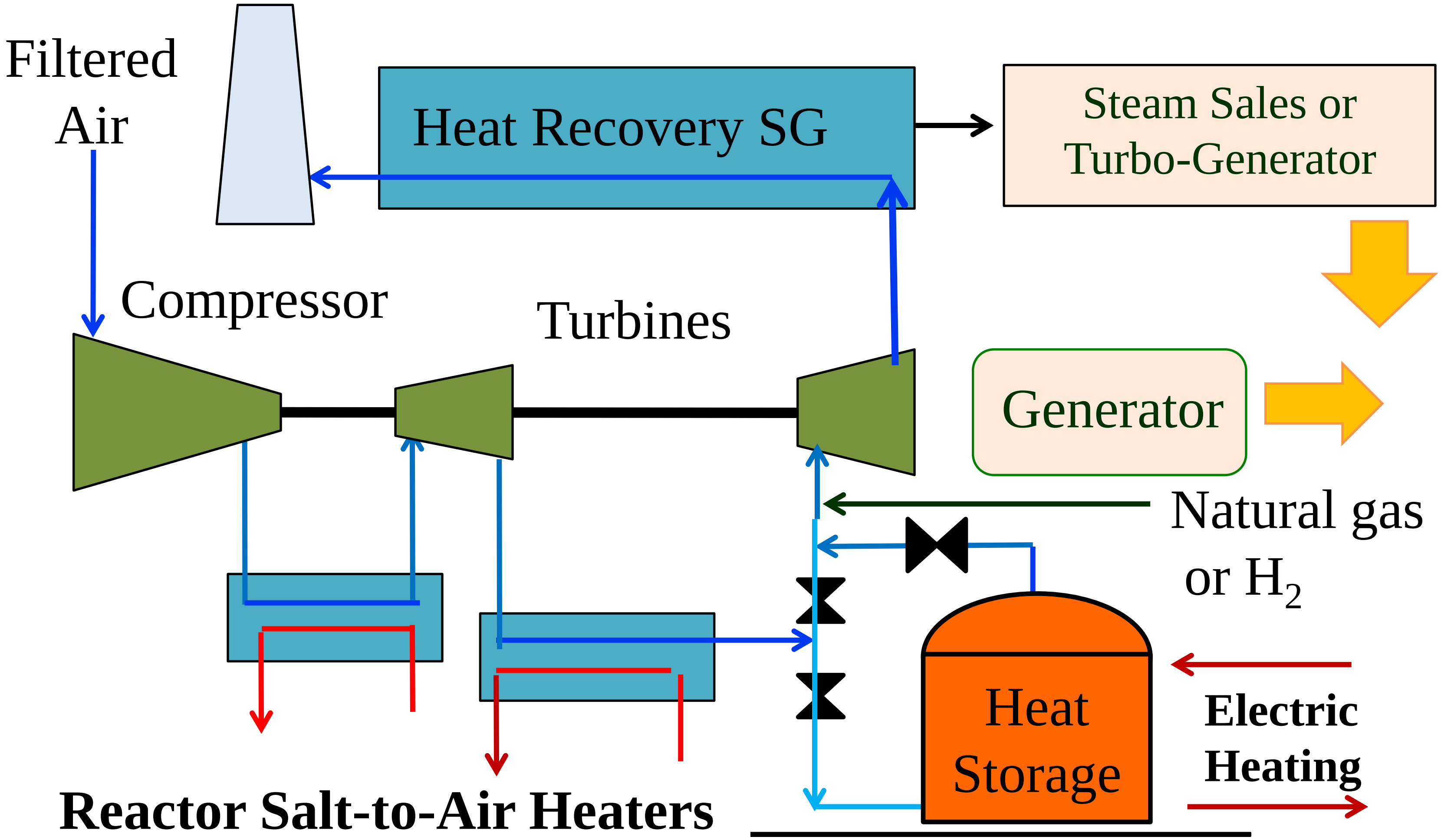
FHR with Nuclear Air-Brayton Combined Cycle (NACC)



Reactor ← Power Cycle →

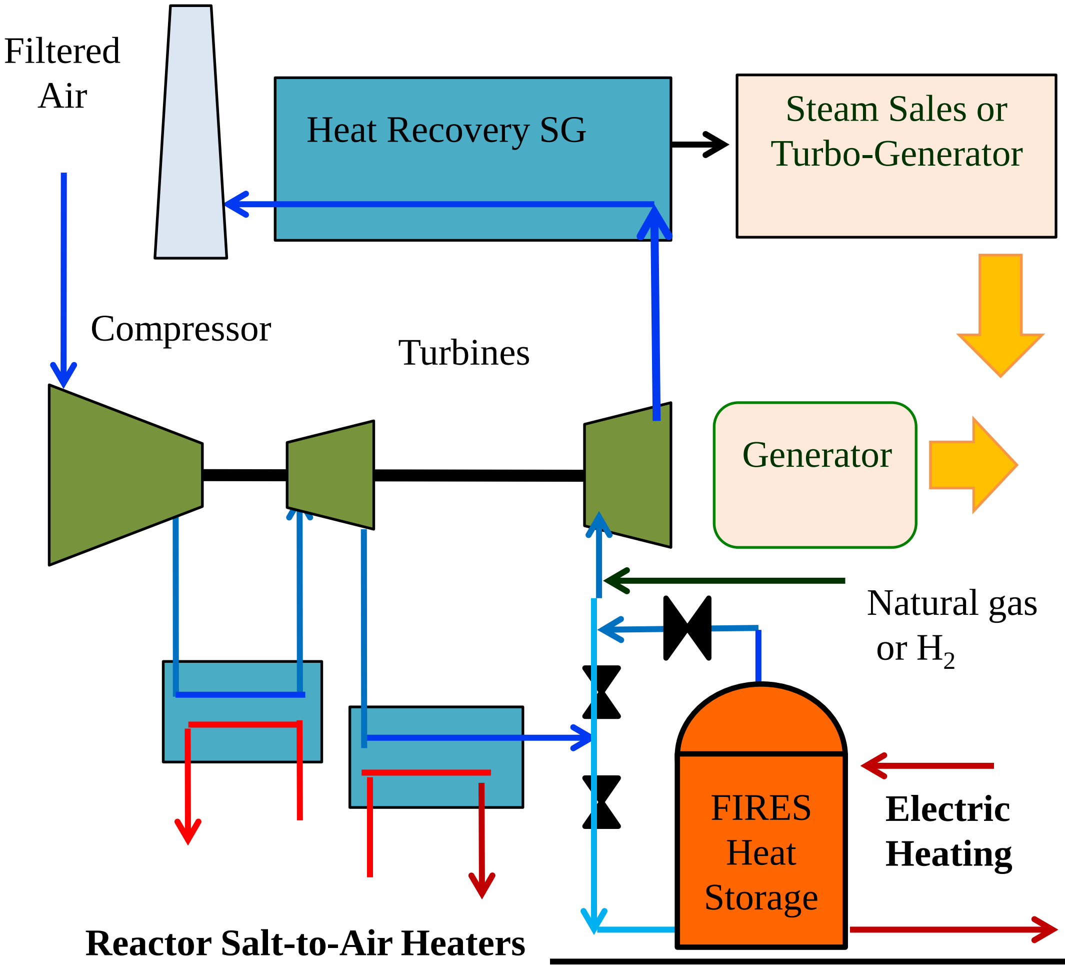
NACC Power System

Modified Natural-Gas-Fired Power Cycle



NACC Power System

Gas-Turbine Enables Peak Power



- Gas turbines can operate up to 1300C
- Nuclear peak temperatures to 700C
- Enables adding NG or stored heat after nuclear heat to gas turbine cycle for peak power

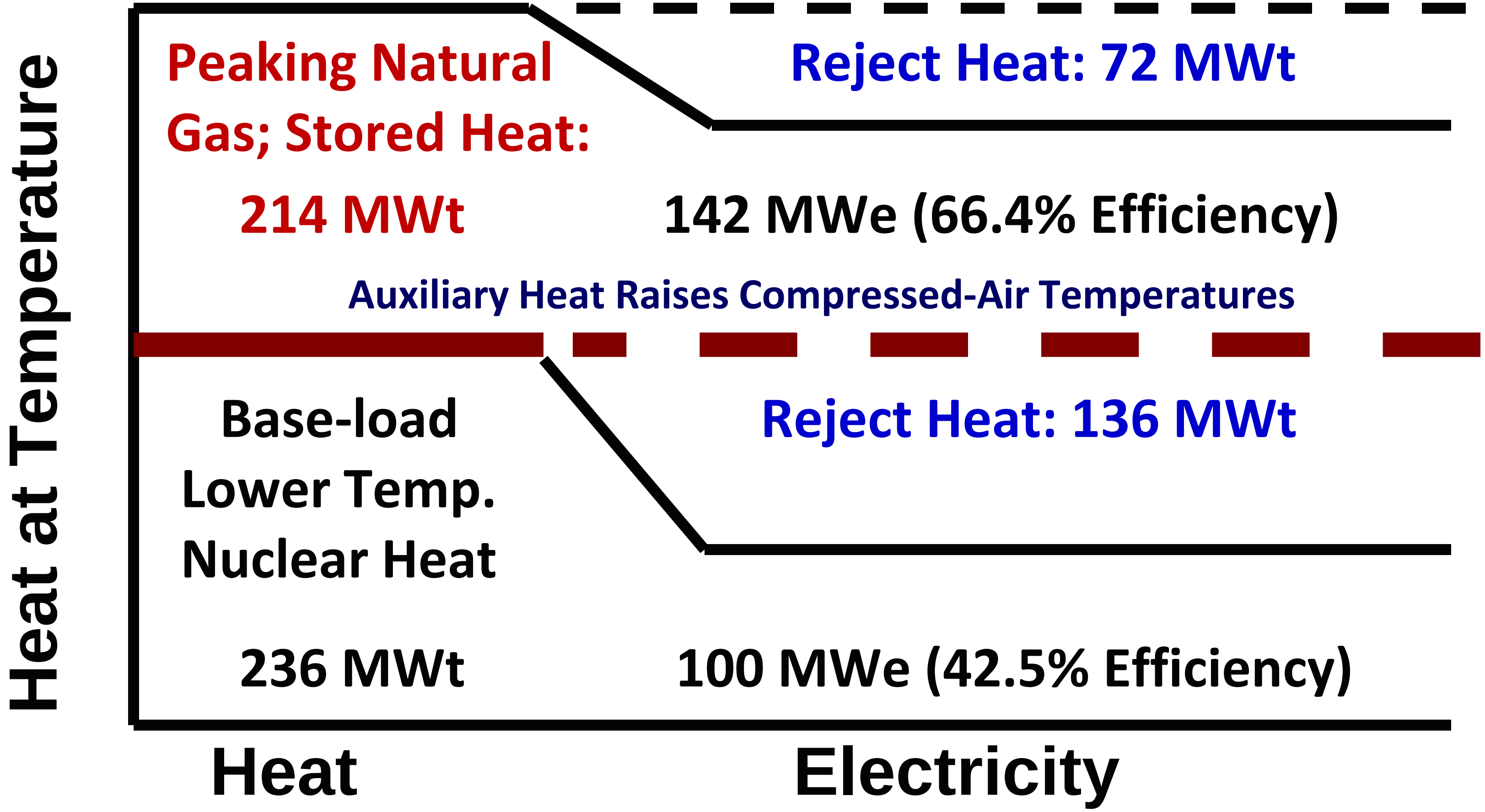
Unique Features of NACC

- Capability to provide peak power with auxiliary fuel
  - Increase revenue after paying for fuel
  - Natural gas today, hydrogen and bio-fuels in future
- Fast response because always hot and spinning—peak power starts from base-load NACC
- Most efficient natural gas to electricity conversion
  - 66.4% heat to electricity efficiency
  - Stand-alone natural gas combined cycle plant: 60%
  - Highest efficiency H_2 to electricity option
- 40% water cooling requirement of LWR per KW(e)h
- Efficient process heat option with HRSG
  - No isolation steam generator with capital cost and temperature drop penalty, No tritium concern
  - High temperature steam

Base-Load Nuclear With Peak Power

High Natural Gas/ Stored Heat-to-Electricity Efficiency

Base load: 100 MWe; Peak: 241.8 MWe



Peaking Natural Gas; Stored Heat:

214 MWt

Reject Heat: 72 MWt

142 MWe (66.4% Efficiency)

Auxiliary Heat Raises Compressed-Air Temperatures

Base-load Lower Temp. Nuclear Heat

236 MWt

Reject Heat: 136 MWt

100 MWe (42.5% Efficiency)

Heat at Temperature

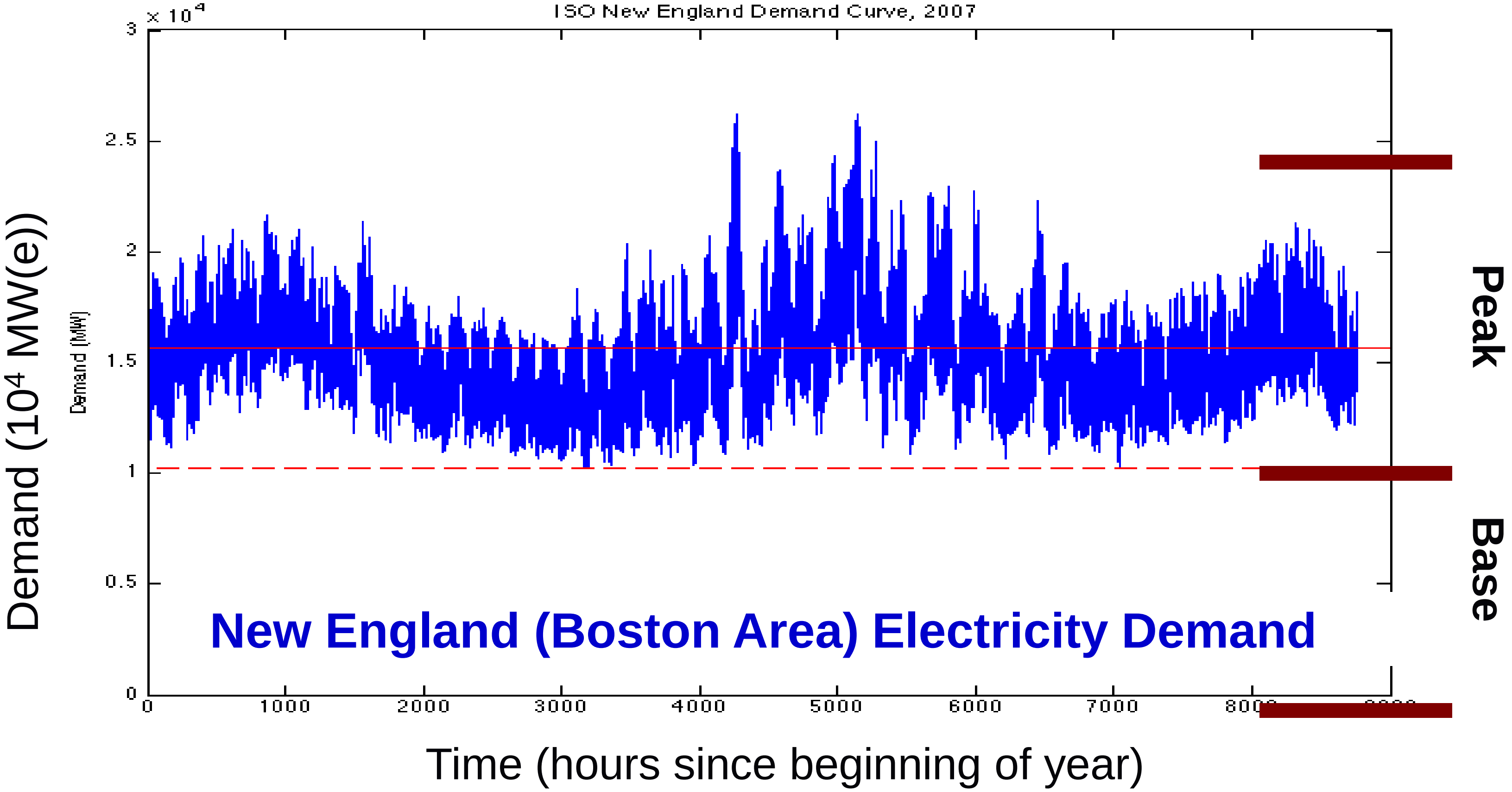
Heat

Electricity

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

FHR with NACC Can Meet Variable Electricity Demand

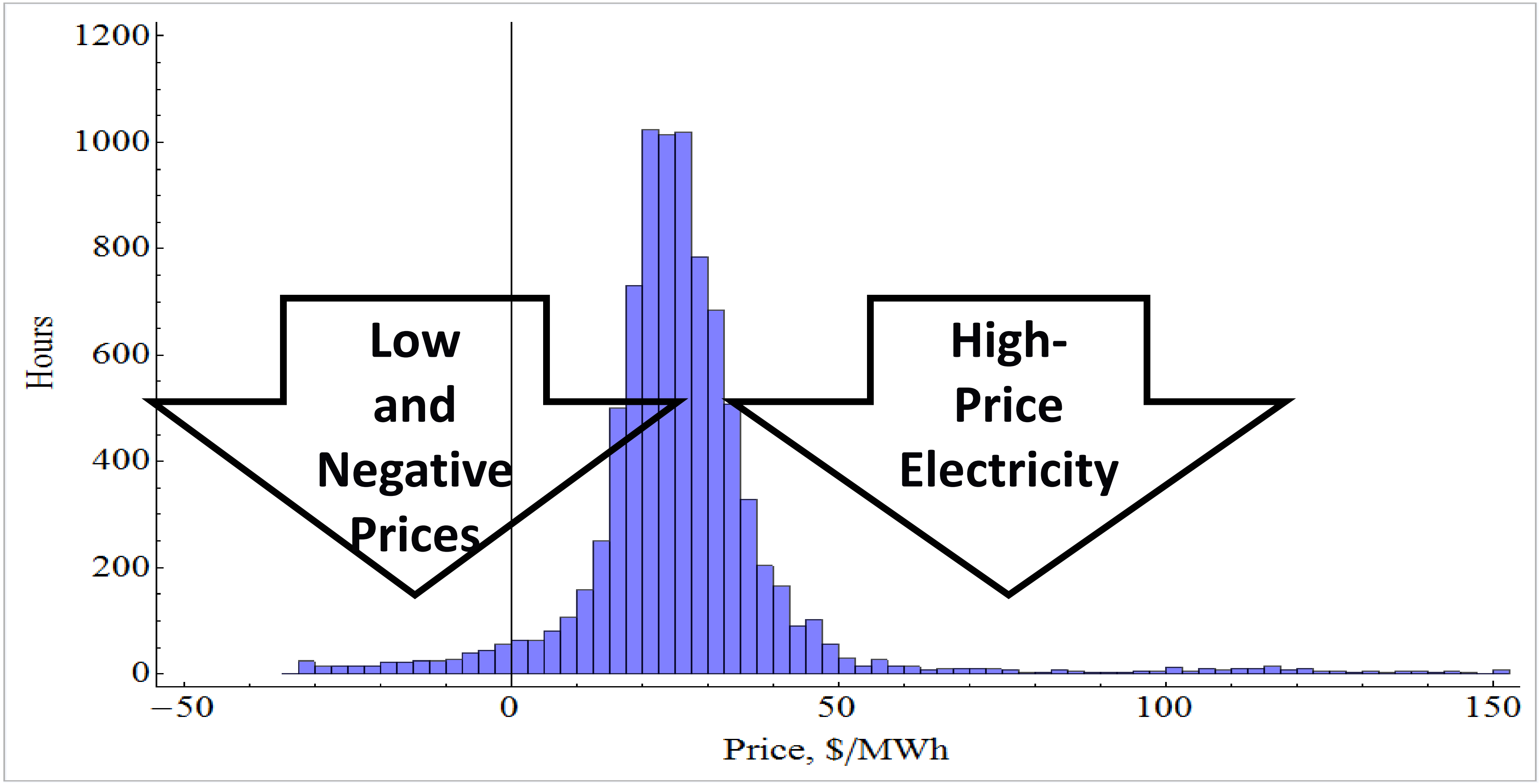
For Every GW Base load, 1.42 GW of Peaking Capability



Dispatchable Nuclear Electricity Option for Electricity Grid with Base-Load Reactor Operations

Natural Gas Peaking Option

Base-load When Low Electricity Prices; Natural Gas Peaking When High Electricity Prices



2012 California Electricity Prices

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

1. Base on 2012 Henry Hub natural gas at $3.52.
2. Methodology in C. W. Forsberg and D. Curtis, “Meeting the Needs of a Nuclear-Renewable Electrical Grid with a Fluoride-salt-cooled High-Temperature Reactor Coupled to a Nuclear Air-Brayton Combined Cycle Power System,” *Nuclear Technology*, March 2014
3. Updated analysis in D. Curtis and C. Forsberg, “Market Performance of the Mark I Pebble-Bed Fluoride-Salt-Cooled High-Temperature Reactor, *American Nuclear Society Annual Meeting*, Paper 9751, Reno, Nevada, June 15-19, 2014

FHR Revenue Increases Rapidly With Increased Natural Gas Prices

- Economics of all nuclear options improves with rising natural gas (NG) prices
- FHR with NACC revenue doubles relative to base-load nuclear as NG prices increase
  - Assumed stand-alone NG plants control electricity prices
  - As prices rise, FHR higher efficiency of incremental NG-to-electricity versus stand-along NG plants improves FHR revenue
  - Most of the increase occurs as NG prices double

Why the 50 to 100% Gain in Revenue Over Baseload Nuclear Plants?

- Sell electricity when high prices
  - Base load: 100 MWe
  - Peak: 242 MWe
- Higher peak power efficiency (66.4% vs. best natural gas plant at 60%) so dispatch before stand-alone natural gas plants and boost revenue
  - California: Peak power on 77% of year
  - Texas: Peak power on 80% of year
- Steam sales (if possible) minimizes sales of low-price electricity

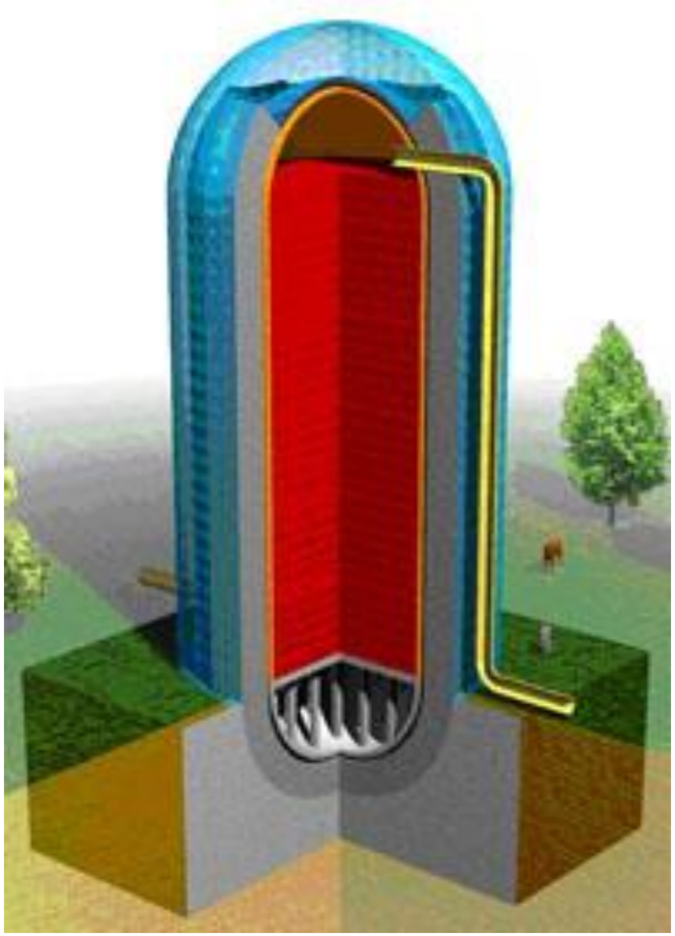
Economics = Revenue - Costs

Increasing natural gas prices or limits on greenhouse gas emissions improves FHR/NACC economics because most efficient device to convert natural gas to electricity

Notes on NACC

- NACC is more efficient in converting natural gas or hydrogen to electricity than a stand-alone natural gas combined cycle plant. Effectively the natural gas or hydrogen is a topping cycle operating above the 700° C salt coolant. The first generation design has natural gas to electricity efficiency of 66%--far above state-of-the-art conventional gas turbines but with lower peak temperatures in the turbine. At part load the efficiency differences are much larger. This creates major economic incentives for NACC relative to a traditional nuclear power plant and a separate stand-alone natural gas plant as the price of natural gas increases or if there are ultimately carbon taxes on emissions. In a low-carbon world it becomes the most efficient method to convert hydrogen to electricity..
- The response times for NACC are shorter than stand-alone natural gas plants. The NACC air compressor is running on nuclear heat. It does not know if there is auxiliary natural gas injection. In contrast, in a conventional natural gas plant (or aircraft jet engine), there is a lag between fuel injection and added power for the compressor to boost air flow. In natural gas or jet fuel Brayton turbines, operating windows are controlled by the need to control the fuel to air ratio to assure combustion. In NACC the air temperatures are above the auto-ignition temperatures. One can add a small or large amount of fuel and the air flow through the machine does not change.
- NACC opens up a variety of industrial heat markets. There is the option for steam sales where the cost and the design of the plant does not change if one is producing electricity or electricity and steam for sale—the heat recovery steam generator remains the same. The air cycle isolates the steam generator from the reactor assuring no possibility of contamination of the steam. This has major implications in terms of reducing carbon dioxide emissions in non-electrical markets by displacing natural gas. It also produces hot air without combustion products—carbon dioxide and water. The ultra-low humidity of the air enable drying of biomass and agricultural products with less energy inputs because one does not need added heat to compensate for the water added by the combustion process in normal gas-fired dryers. For processes such as cement production, the preheated hot air can replace air heated with fossil fuels but without the carbon dioxide from burning those fossil fuels. This favorably changes the chemical equilibrium. In cement we want to remove CO_2 from $CaCO_3$ and the presence of CO_2 in the hot air retards the calcination process. The industrial implications of hot air without combustion products are only partly understood.

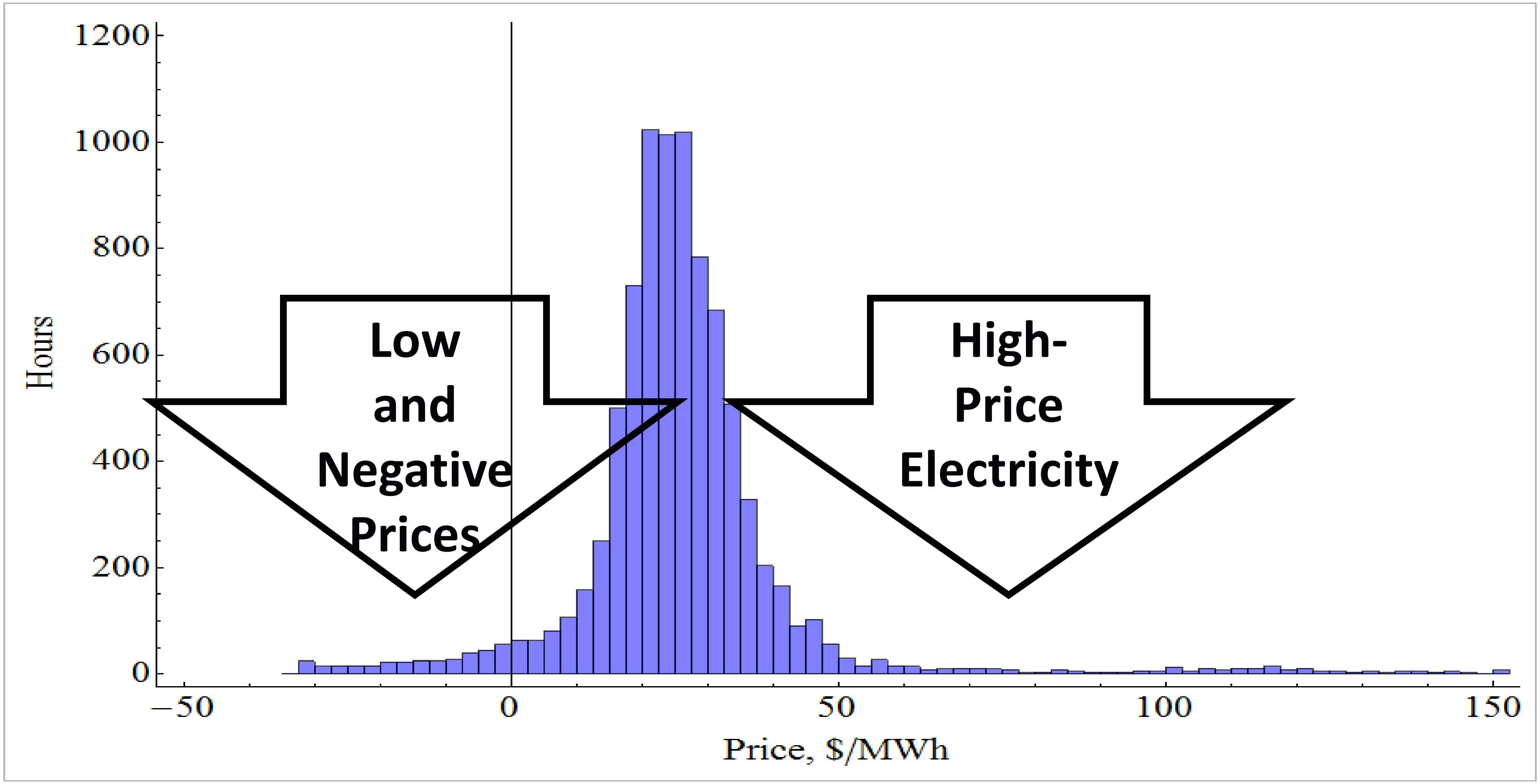
Peak Electricity Using Firebrick Resistance-Heated Energy Storage (FIRES)



- Electrically heat firebrick in pressure vessel
- **Firebrick heated when low electricity prices; less than natural gas**
  - 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)

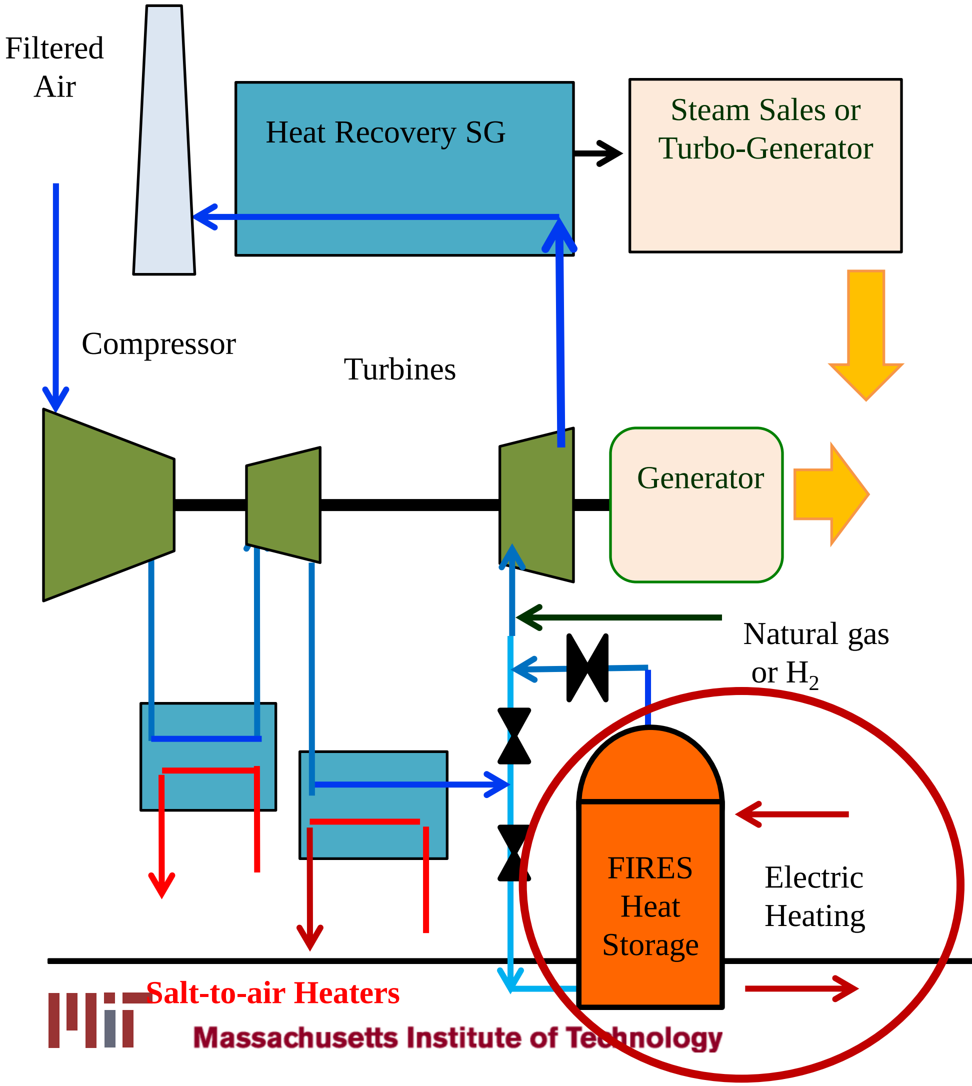
Figure courtesy of General Electric Adele Adiabatic Compressed Air Storage Project

In a Free Market Electricity Prices Vary



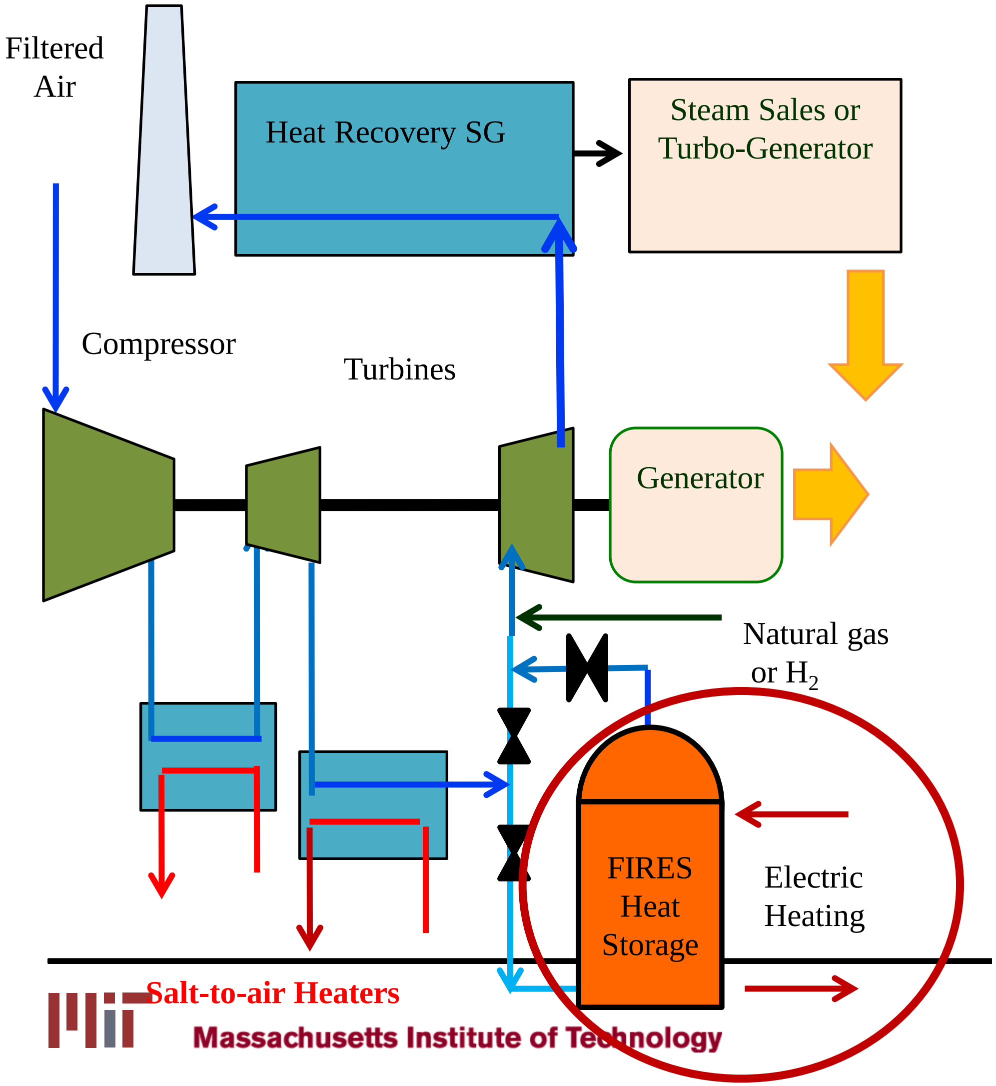
2012 California Electricity Prices

FHR "Electricity Storage" Does Not Require Backup Generating Capacity



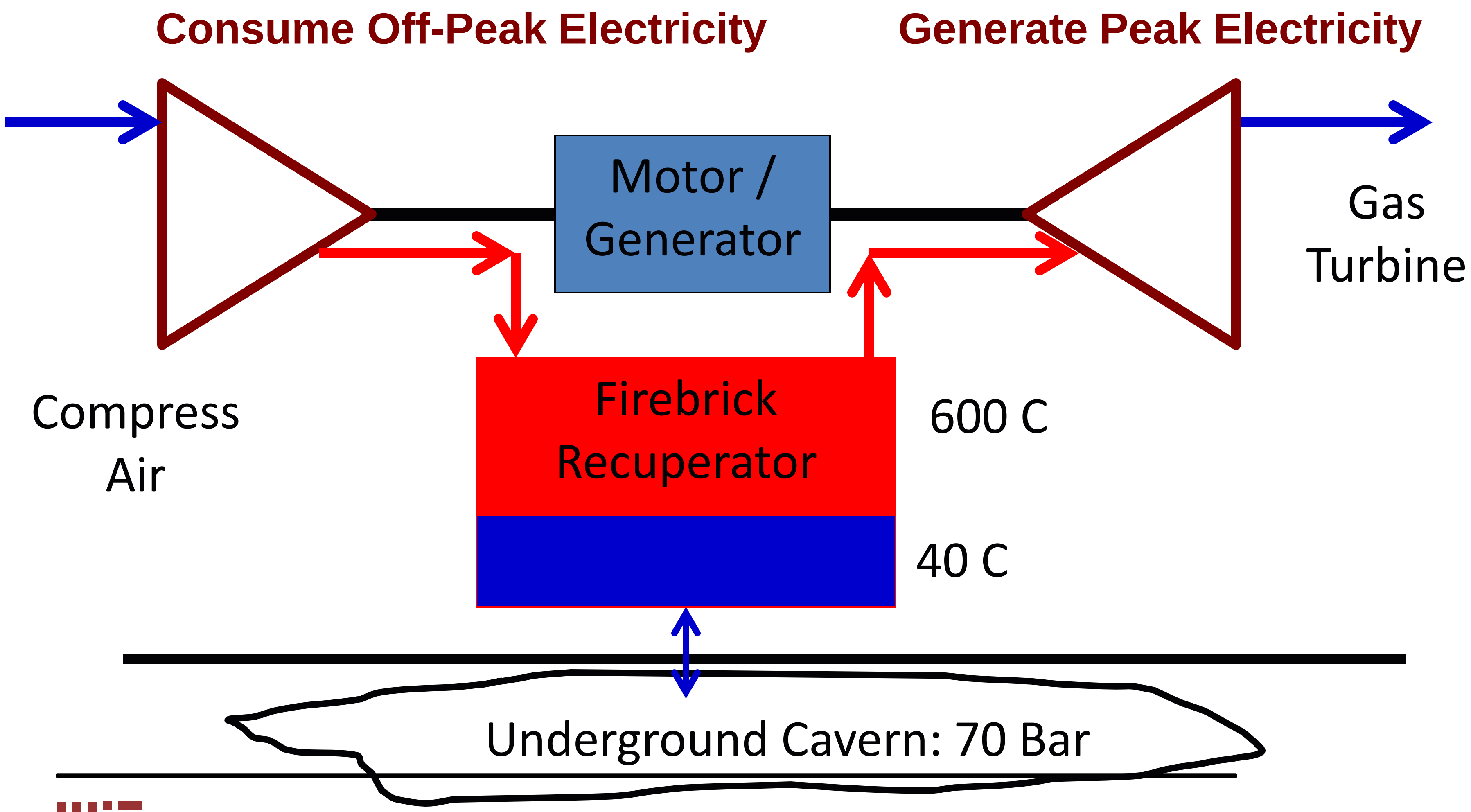
- Batteries and other storage technologies require backup generating capacity for when storage capacity is depleted
- **FHR backup is natural gas or hydrogen if heat storage depleted**
- **Economic advantage over traditional storage technologies**

FHR FIRES Operating Strategy



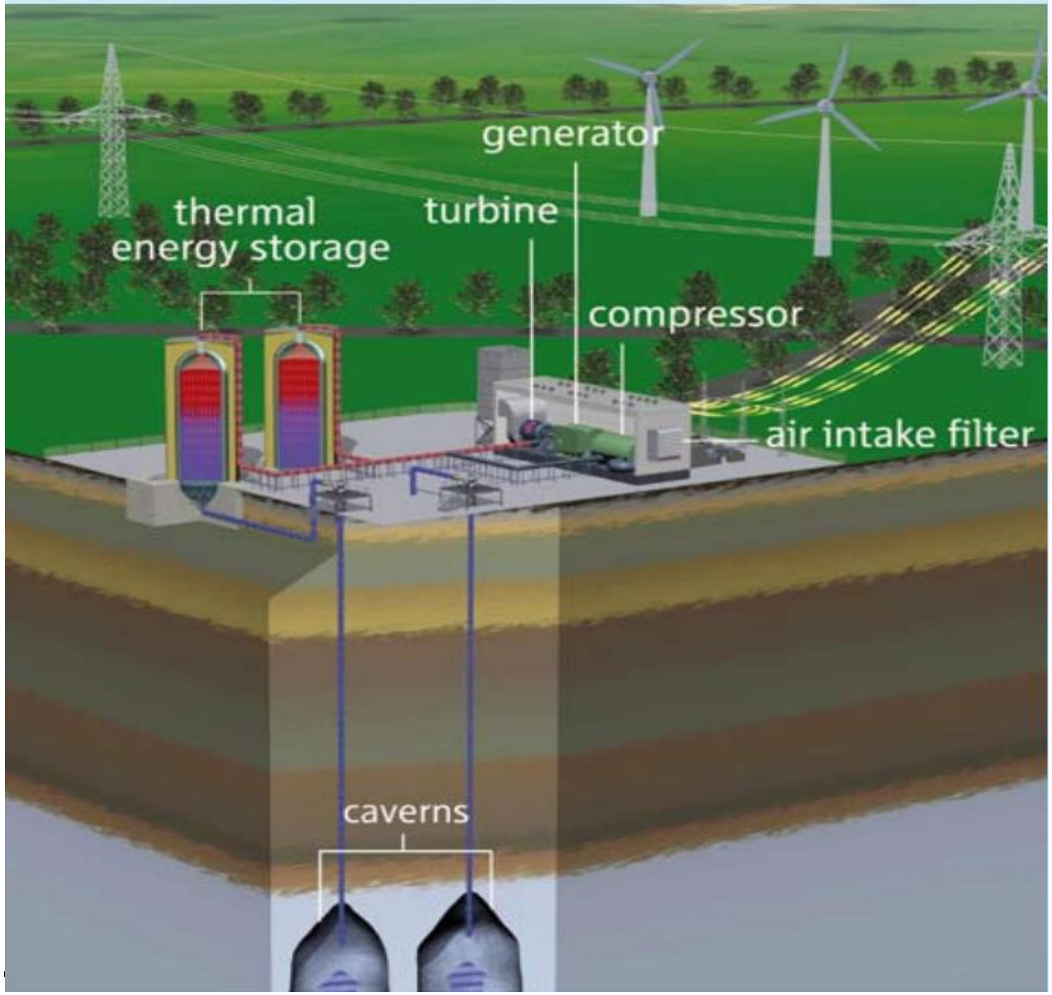
- Buy electricity and store heat when electricity prices less than natural gas
  - 100 MWe baseload to storage
  - Buy 242 MWe from grid for storage (equal max plant output)
- Use stored heat for peak electricity output (242 MWe) replacing natural gas

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



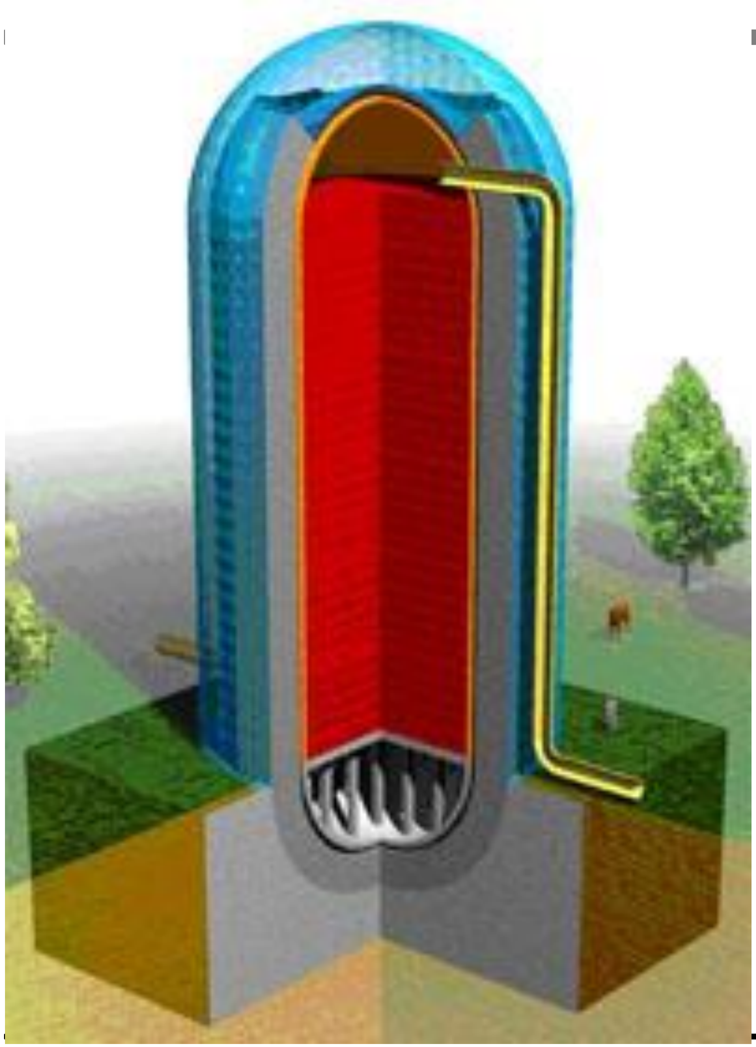
General Electric - RWE Adiabatic Compressed Air Storage (Adele) Project

Developing Most of the Technology Required for FHR Heat Storage



- Grid Electricity into Storage
  - Compress air to 70 bar and 600° C
  - Cool air to 40° C by heating firebrick
  - Compressed air to underground storage
- Electricity from Storage to Grid
  - Heat compressed air with firebrick
  - Turbine produces electricity

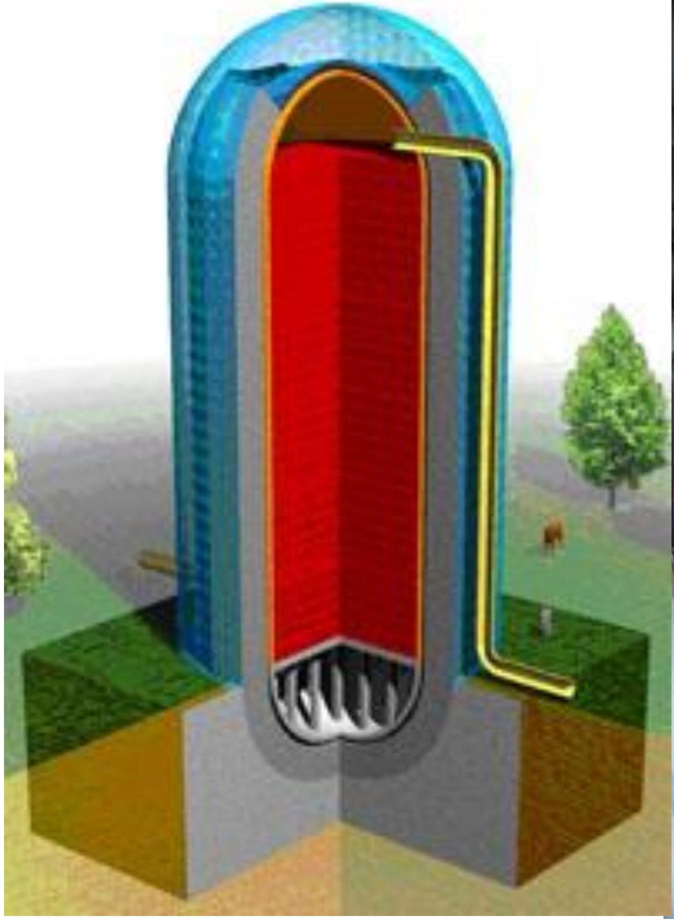
Adele Heat Storage: Firebrick in Prestress Concrete Pressure Vessel



- Heat storage to 70 bar and 600° C
  - Lower temperature than Gathes
  - Higher pressure
  - Designs similar
- Common characteristics
  - Compressor input
  - Similar pressure drop constraints
- FIRES has electric heat coupled to storage

Adele Storage Vessel Testing Underway

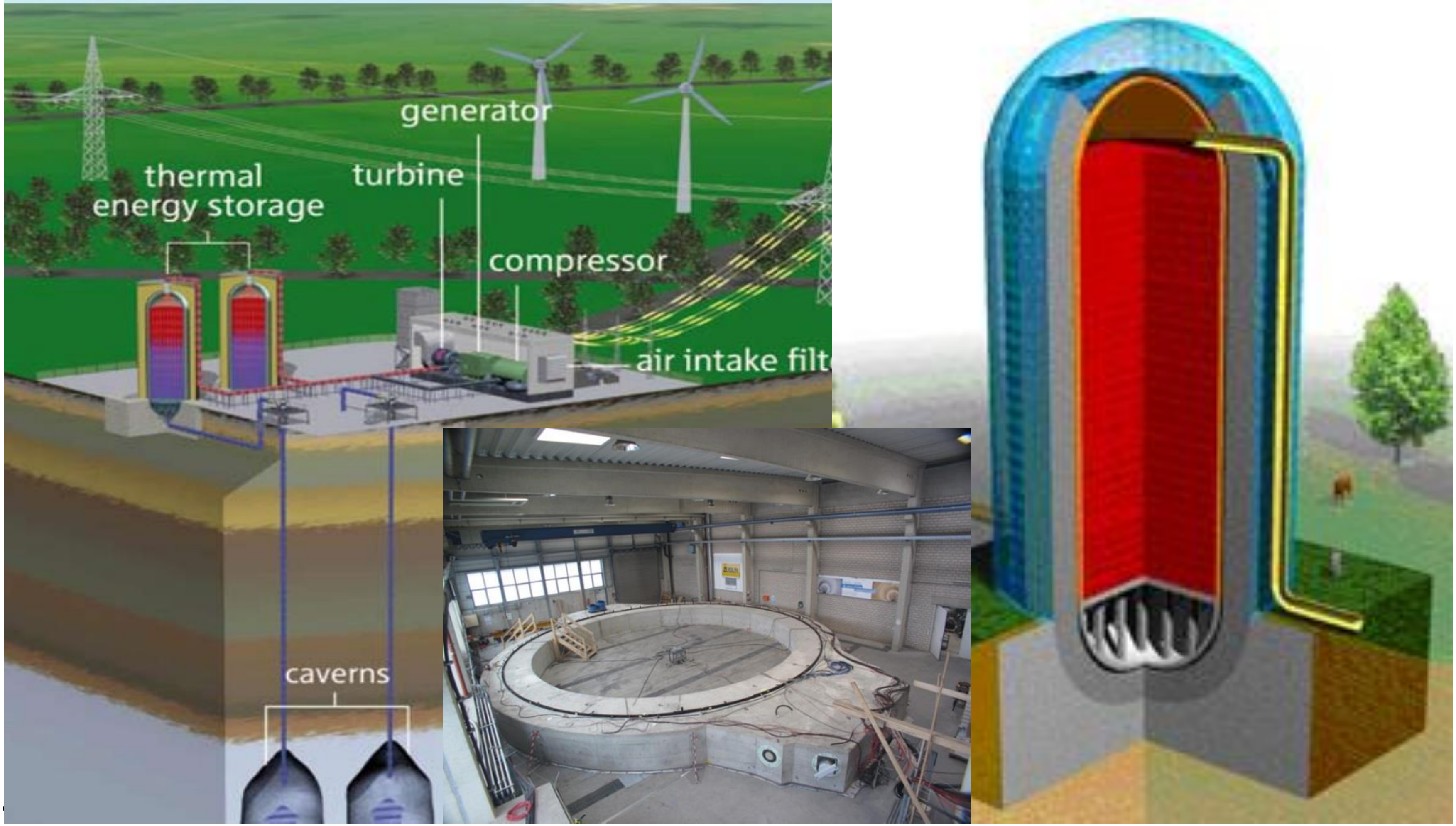
Integrating Heat Storage and Gas Turbine Technology



FHR NACC with Stored Heat Differences:
Lower Pressure, Higher Temperature and Electric Heating

General Electric - RWE Adiabatic Compressed Air Storage (Adele) Project

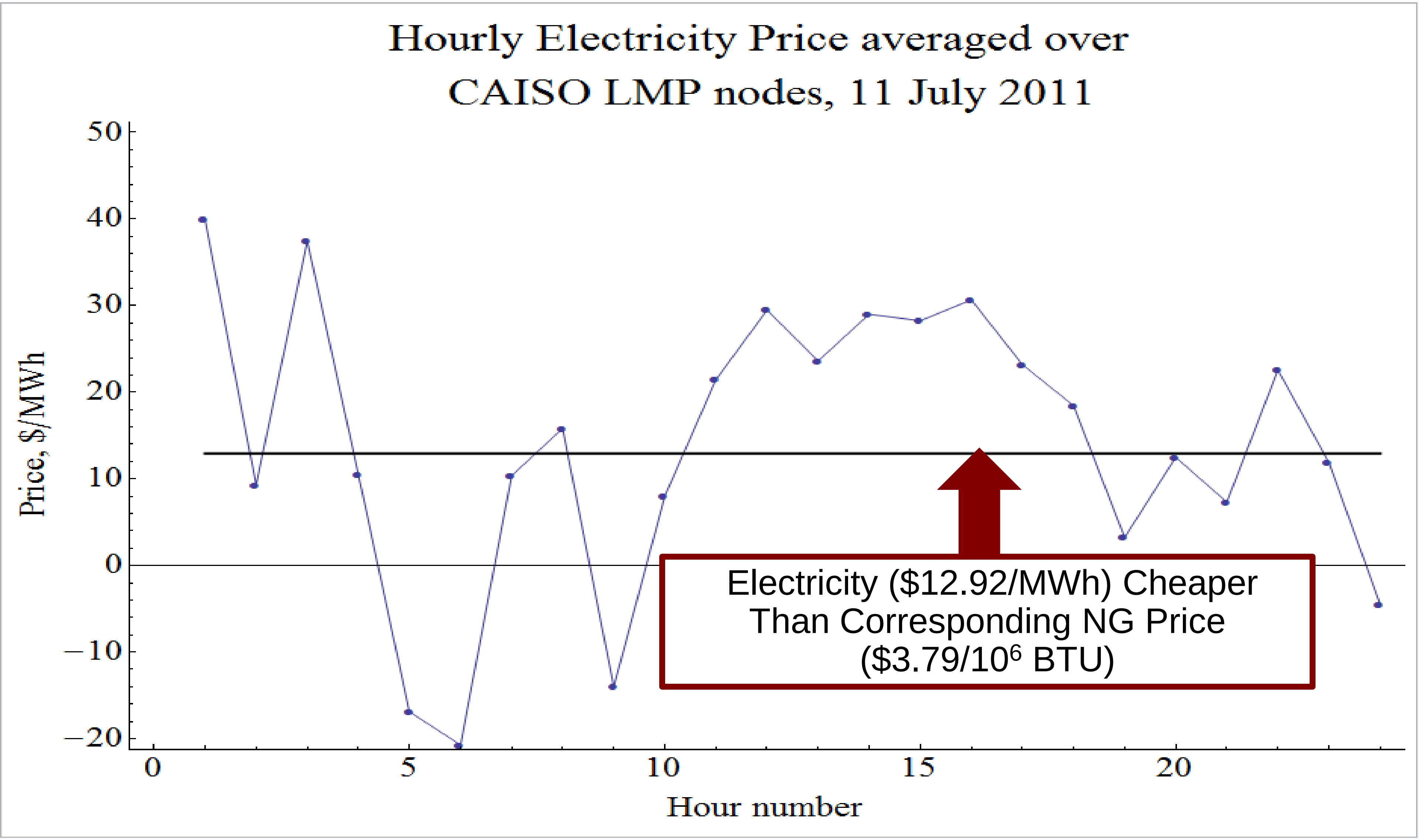
Developing Most of the Technology Required for FHR Heat Storage



Adele Notes

- Adele is being developed in Germany by RWE, General Electric, and others with support of the German government.
- It is a large-scale electricity storage system with a projected electricity to storage to electricity efficiency of ~70%, similar to pumped storage but with the same weakness of all other pure storage devices—can run out of storage capacity
- Electricity to stored heat and compressed air. Air is compressed to ~70 bars. Compression raises the temperature to ~600° C. The air is cooled by flowing through a firebrick recouperator that is inside a pressure vessel operating at 70 bars. The cooled compressed air goes into an underground storage cavern at pressure and ~40° C.
- Electricity from stored heat and compressed air. The compressed air is reheated going through the firebrick recouperator in the opposite direction. The hot compressed air then goes to a turbine that drives a generator. The air exits the compressor at ~1 atmosphere.
- The heat storage system is similar to that required for Gathers except Gathers is at lower pressures, higher temperatures, and has internal electrical heating.
- The requirement for compressed air storage places major siting constraints on Adele—limiting to certain geologies such as salt.

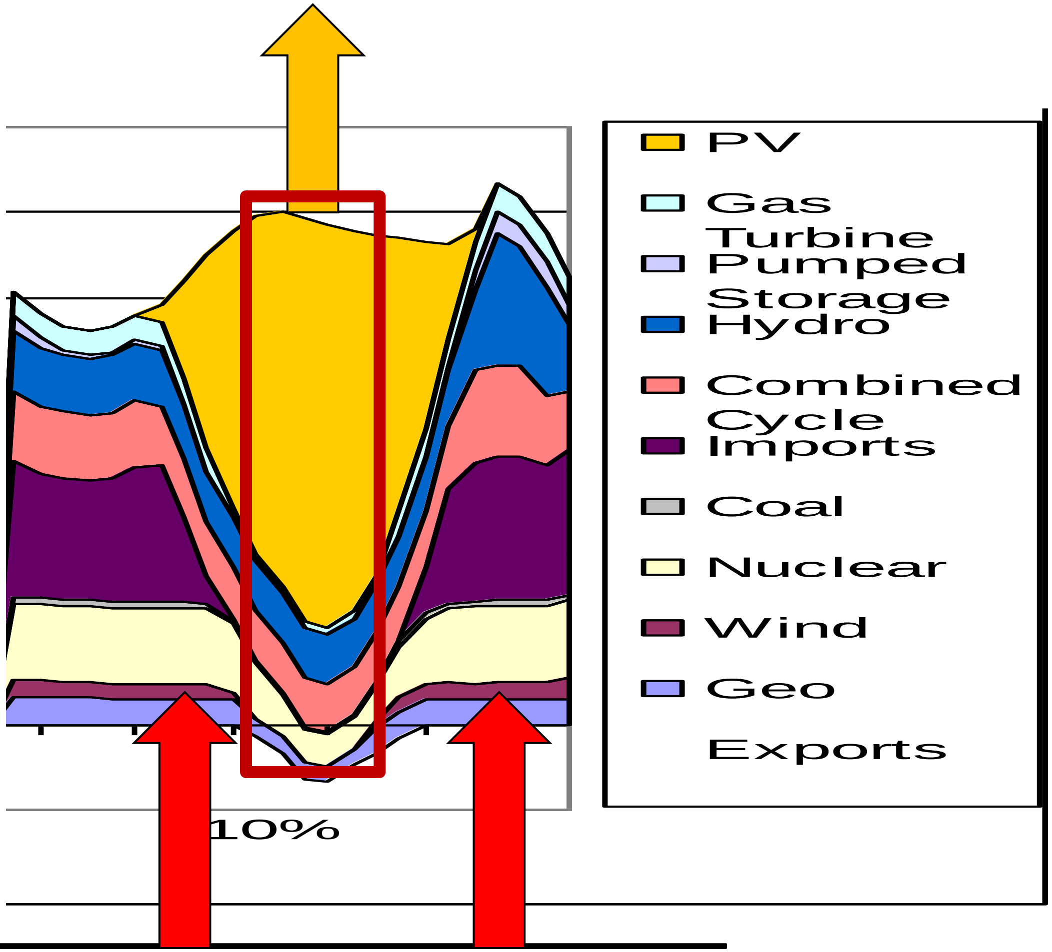
California Price Curve Shows Times When Electricity Cheaper then Natural Gas



Electricity ($12.92/MWh) Cheaper Than Corresponding NG Price ($3.79/$10^6$ BTU)

FHR with NACC and Heat Storage May Be an Enabling Technology To Use Excess Electricity from Renewables

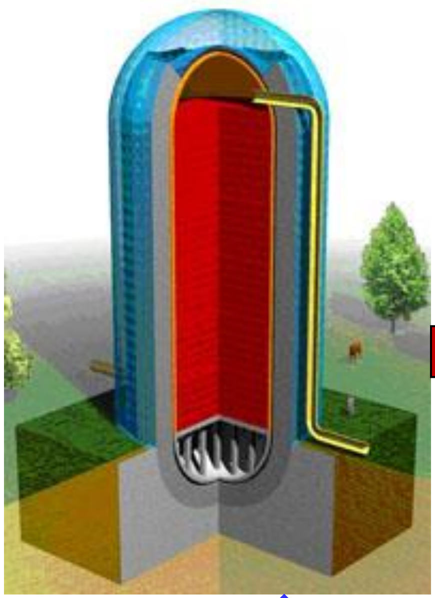
Electricity Input to Heat Storage When Low Prices



NACC Peaking Electricity with Heat Storage

The Base-Load FHR Produces Variable Electricity to Match Market Needs

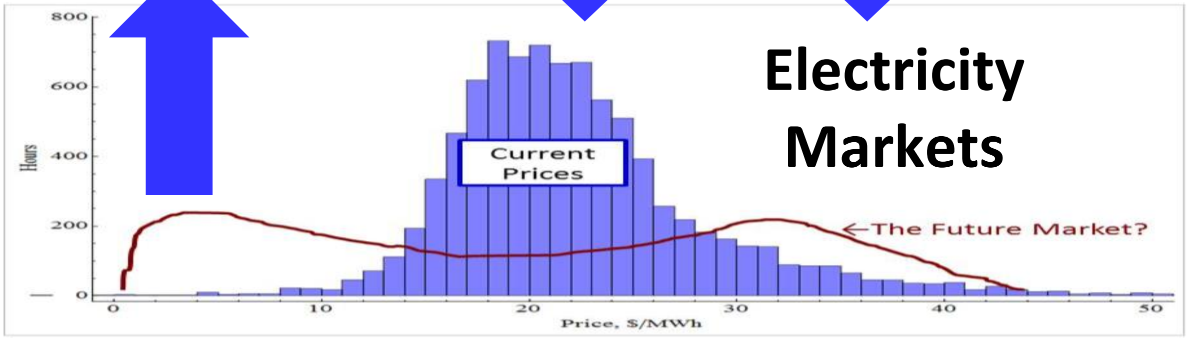
FIRES
Stored Heat



Combustible Fuels

Gas-Turbine (NACC)

Constant High-Temperature Heat (600 to 700 C)
Reactor (FHR)



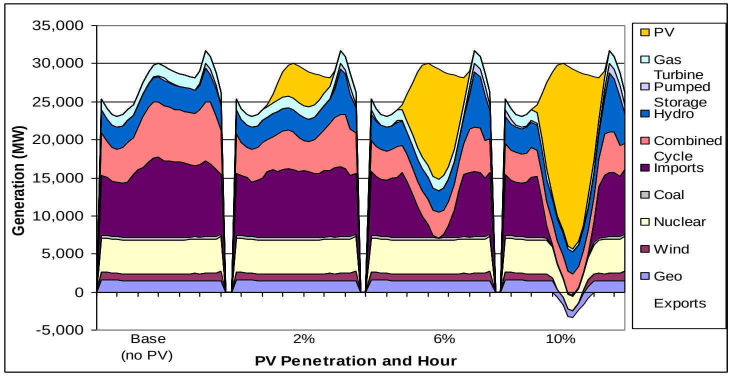
Electricity Markets

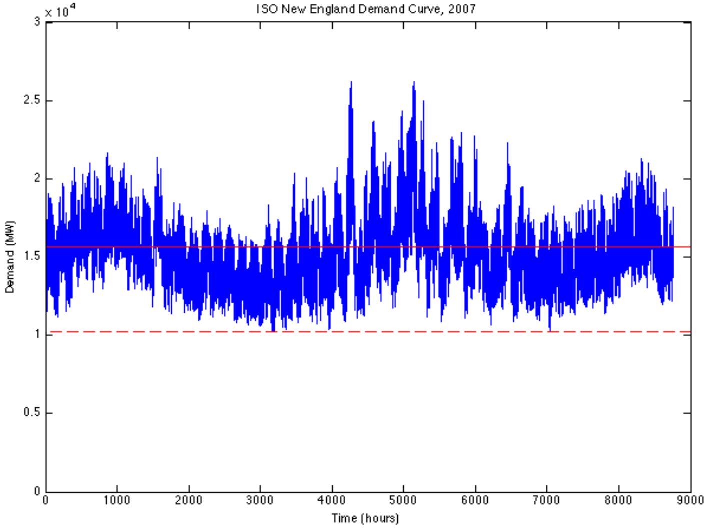
High Storage Efficiency for a Zero-Carbon World: FHR/NACC/FIRES

- Long term energy storage options
  - Hydrogen
  - Heat
- Hydrogen long-term efficiency for electricity storage
  - Electricity to hydrogen ~60%
  - Hydrogen to electricity ~70% (Long-term with NACC)
  - **Round-trip efficiency ~42%**
- FIRES
  - Electricity to heat ~100%
  - Heat to electricity ~70% (Long-term with NACC)
  - **Round-trip efficiency ~70%**

Zero-Carbon World Would Use Hydrogen & Heat Storage with FHR for Variable Power

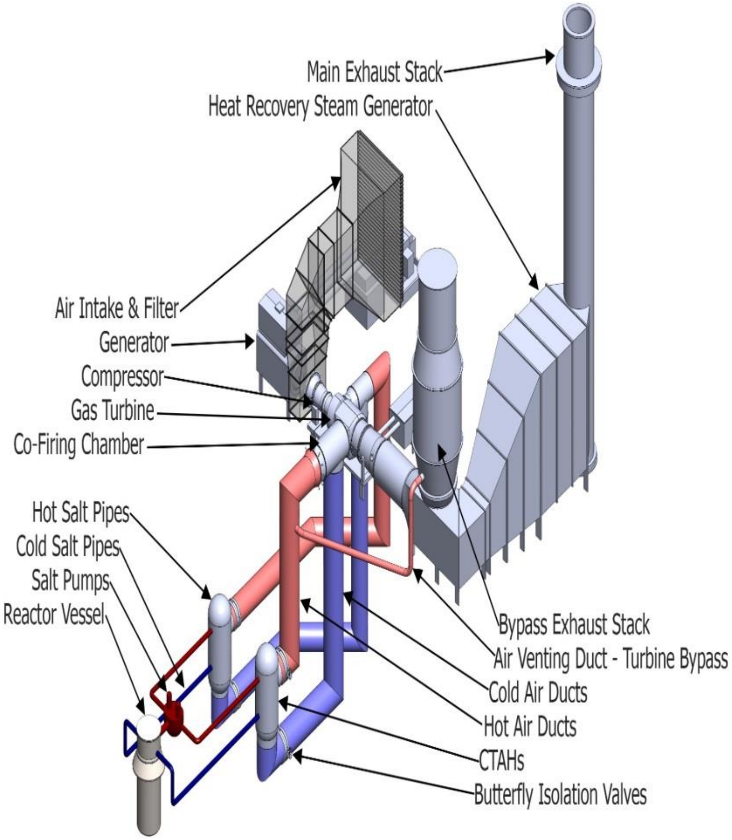
- Daily electricity variations
  - Heat storage
  - More efficient
- Weekly and seasonal variations
  - Hydrogen
  - Low-cost underground weekly and seasonal storage
  - Heat storage not viable





FHR / NACC / FIRES Characteristics Match Nuclear-Renewable Needs

- Very fast response to match load
  - Peak power on top of base load
  - No cold start
- Efficient use of peaking fuel (NG, H_2 or biofuels)
  - Reactor heat to 700° C
  - Auxiliary fuel further raises gas temperatures (topping cycle)
  - NG to electricity 66% today versus 60% for best stand-alone combined-cycle plant at full load
  - Exceed stand-alone gas turbine efficiency at part-load electricity production



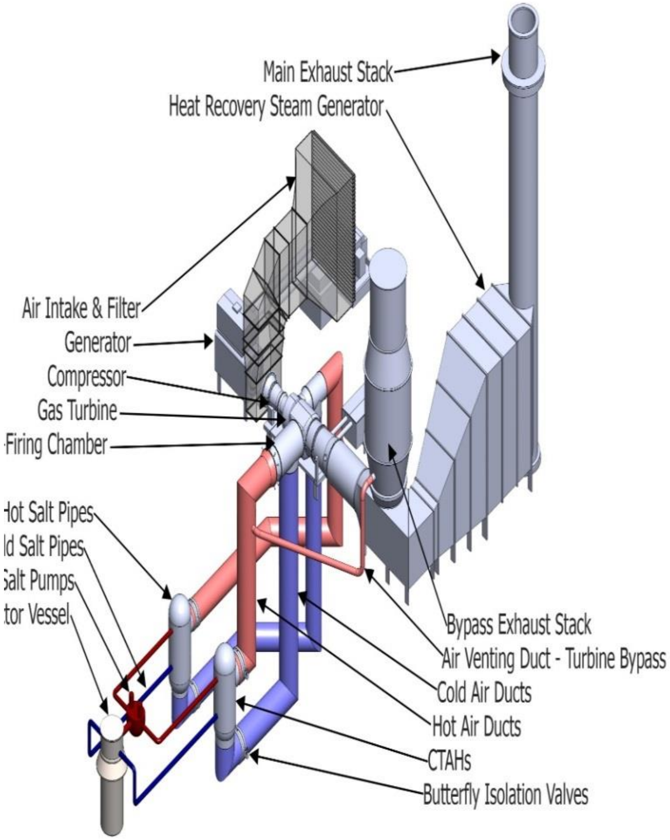
FHR/NACC Has 4 Operating Modes

Enable Variable Steam to Industry

- Base-load Electricity (Nuclear heat)
  - Brayton-cycle electricity to grid
  - Steam to Rankine-cycle electricity to grid
- Peak Electricity (Nuclear & Natural Gas (NG) heat)
  - Add natural gas / H_2 to boost heat input
  - Increased Brayton and Rankine electricity to grid
- Electricity and Steam Sales (Nuclear)
  - Base-load Brayton-cycle electricity to grid
  - HRSG steam to industry (Sell steam at 90% cost of natural gas so industry turns down their boilers)
- Electricity and Steam Sales (Nuclear and NG)

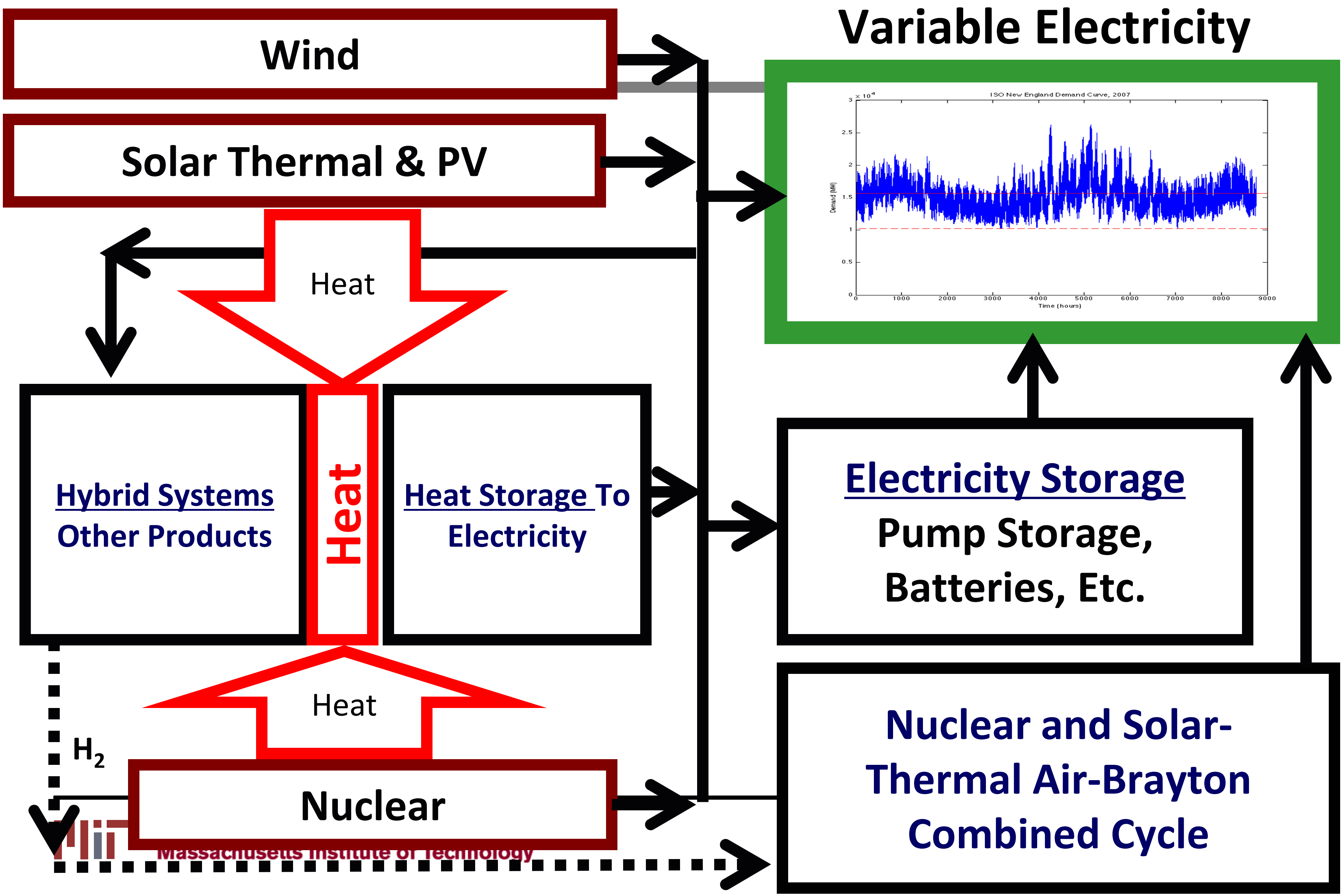
FHR with NACC Creates Hybrid Biofuels and Industrial Markets

- Steam production without secondary heat exchanger
  - Industrial heat
  - Ethanol biofuels
- Dry hot air (100/670C) with <u>no combustion products</u> (H_2O or CO_2)
  - Drying of biomass for seasonal storage to provide year-long feedstocks for biomass to fuels production
  - Preheat air for high-temperature processes (cement, sulfide ore processing, etc.) to reduce or eliminate need for fossil fuel or hydrogen



Conclusions

Low-Carbon Electricity Grid



Variable Electricity

Wind

Solar Thermal & PV

Heat

Heat

Hybrid Systems Other Products

Heat Storage To Electricity

Electricity Storage

Pump Storage, Batteries, Etc.

Heat

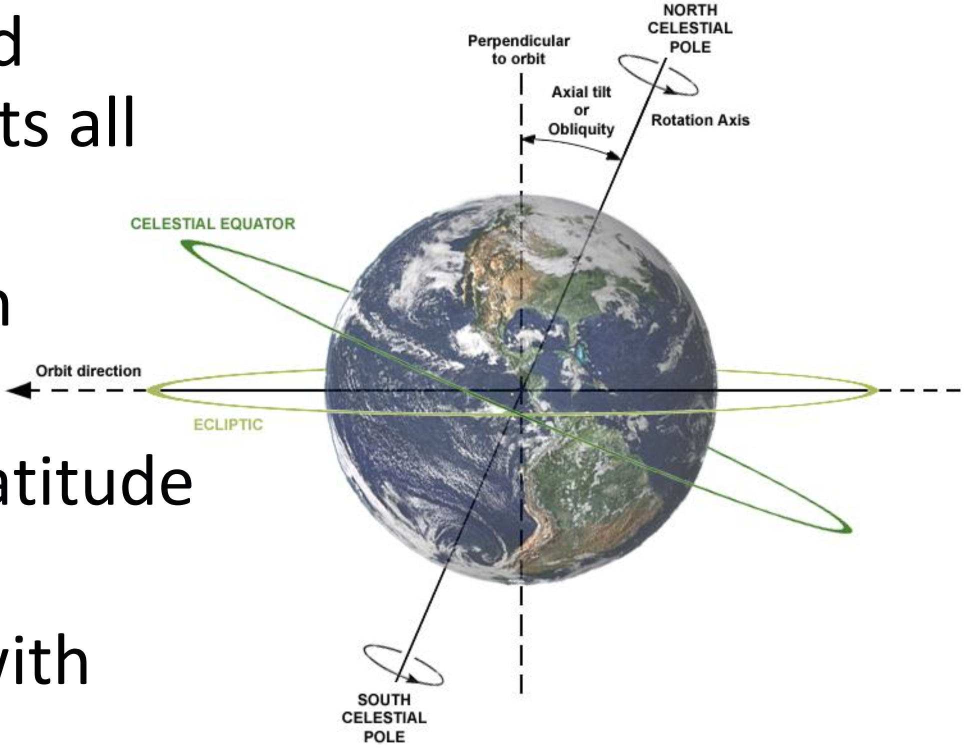
H_2

Nuclear

Nuclear and Solar-Thermal Air-Brayton Combined Cycle

Fossil to Low-Carbon Grid Transitions from Universal to Regional Solutions

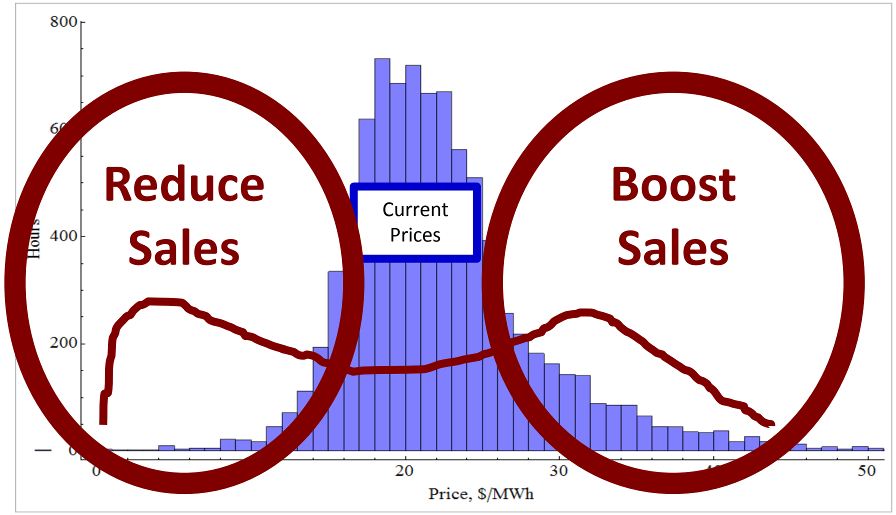
- Fossil fuels can be shipped anywhere; one solution fits all
- Low carbon grid will have renewables that vary with latitude and climate
- Nuclear independent of latitude and climate
- Energy choices will vary with location

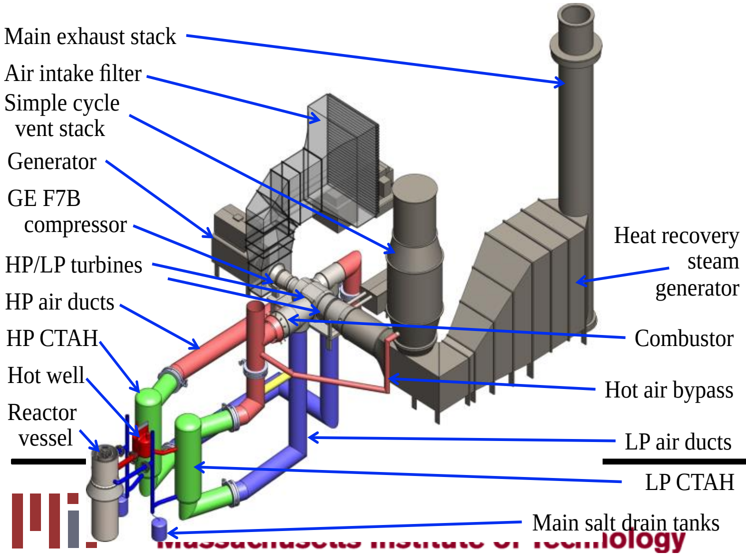


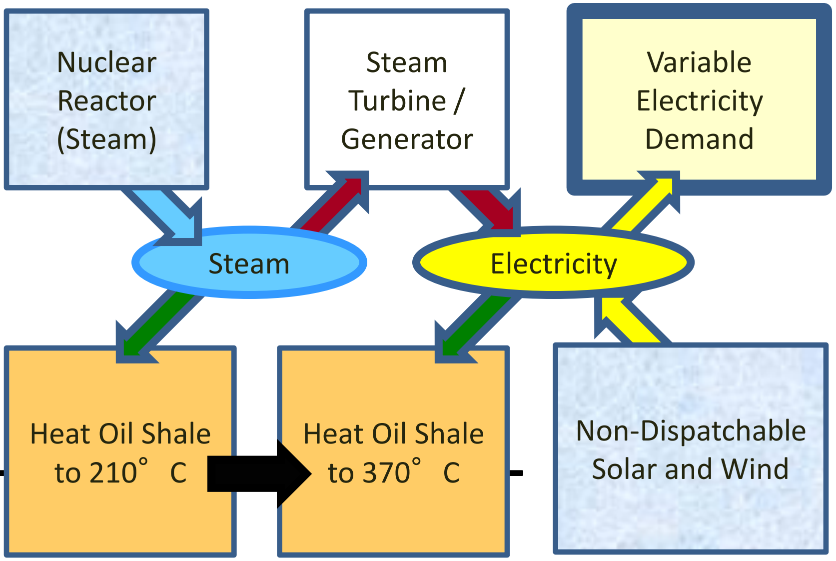
Conclusions

- A low-carbon world is coming in this century
- Must use capital-intensive nuclear and renewable power systems at maximum capacity to minimize societal costs
- Three strategies for efficient use of generating assets
  - Storage
  - Hybrid systems with excess electric-sector energy to industry / transportation
  - Change nuclear power characteristics: FHR / NACC / FIRES
- Major technical challenges: particularly production of liquid fuels

Questions







Nuclear Reactor (Steam)

Steam Turbine / Generator

Variable Electricity Demand

Steam

Electricity

Heat Oil Shale to 210° C

Heat Oil Shale to 370° C

Non-Dispatchable Solar and Wind

END

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 was the Executive Director of the Massachusetts Institute of Technology 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 will be receiving the ANS 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 11 patents and has published over 200 papers.

http://web.mit.edu/nse/people/research/forsberg.html