New Mexico
Research Spotlight Forum

10.17.2019 Grid Resiliency

Advanced Small Nuclear Reactors to Enhance Grid Stability

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SAND2019-13650 PE

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Patrick McDaniel

BS in ES, USAFA (1965), MS in ME, CalTech (1966), PhD in NE, Purdue(1977), MS in RM, ICAF(1996)

- 8 years pilot/maintenance officer in USAF
- 25 years at Sandia, retired as Department Manager
- 10 years at AFRL, retired as GM-15 (equiv)
- 40+ years as Adjunct and Research Professor at UNM
- Research group interests – Power Conversion Systems for Nuclear Systems
- Research Group Size - 2 at UNM, 2+ at MIT, 2+ at INL , 2+ at Univ Idaho
- Currently no centralized funding

Keywords: Advanced Power Conversion, Small Modular Reactors, GEN IV Reactors, Combined Cycles .

Nuclear Power Challenges In the US*

- Nuclear is not Cost Competitive with Natural Gas
- Electrical Generation Limited by Available Water Resources for Cooling
- Traditional Baseload Plants Affected by Rise of Renewable Energy Plants

* Taken from **Advanced Smaller Modular Reactors** by B. Zohuri and P. McDaniel, Springer, 2019

The Impact of Wind and Solar Electricity

- As more renewable electric power systems come on line, their intermittent nature disrupts the cost structure of electrical utilities.

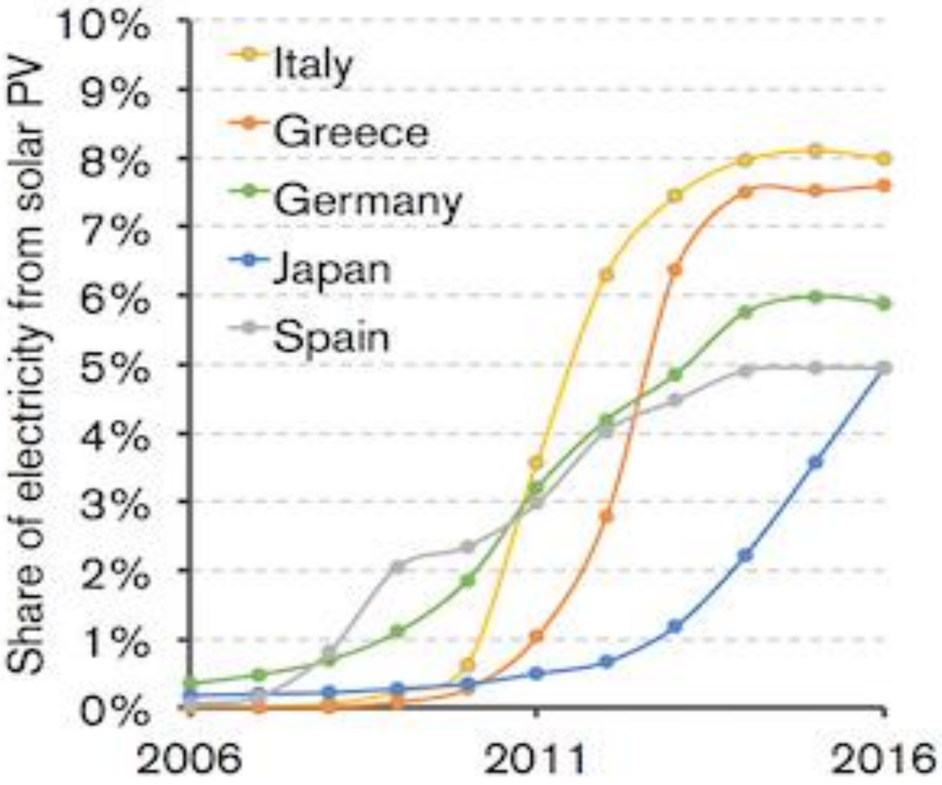
- When the sun is shining, or the wind is blowing, there is plenty of electricity from these intermittent sources. The price of electricity drops significantly, sometimes going negative.

- When the sun isn’t shining, or the wind is not blowing, these intermittent sources are not available, causing the price of electricity to rise greatly.

- The best commercial strategy is to sell electricity when the price is high, and do something else when the price is low, or zero.

Electricity Price (Revenue) Collapse Limits Non-Dispatchable Wind and Solar Without Storage
(Charles Forsberg, MIT)

Impact of PV Expansion in California on Electricity Prices: Spring Day from 2012 to 2017

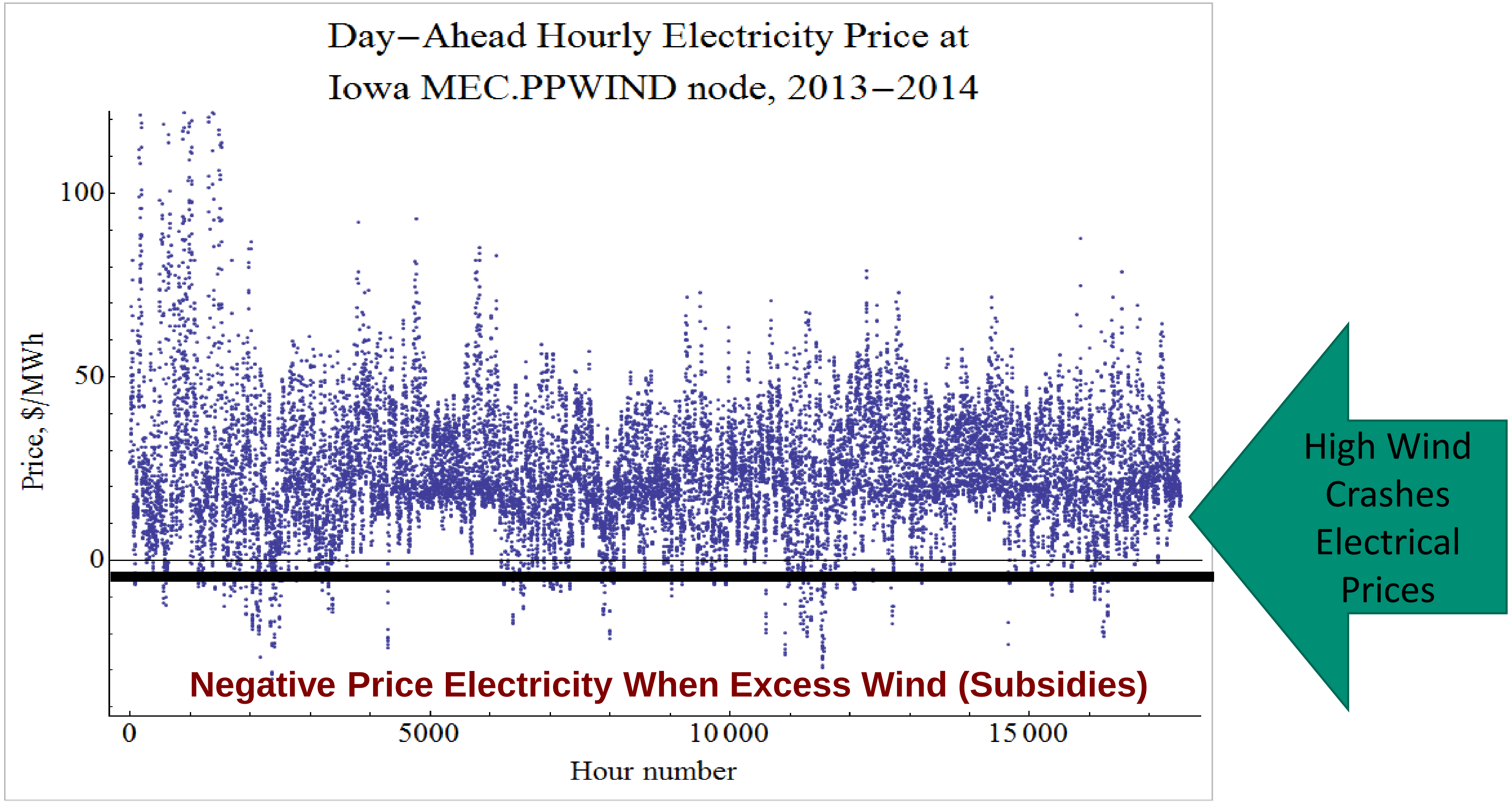


Collapsing Prices Limit Use of Non-dispatchable PV

Varum Sivaram,, “A Tale of Two Technologies”, THE BREAKTHROUGH JOURNAL, NO. 8 / WINTER 2018.

Iowa Wholesale Electricity Prices: Two Years

Large Incentive to Sell Peak Electricity and Avoid Sales at Other Times



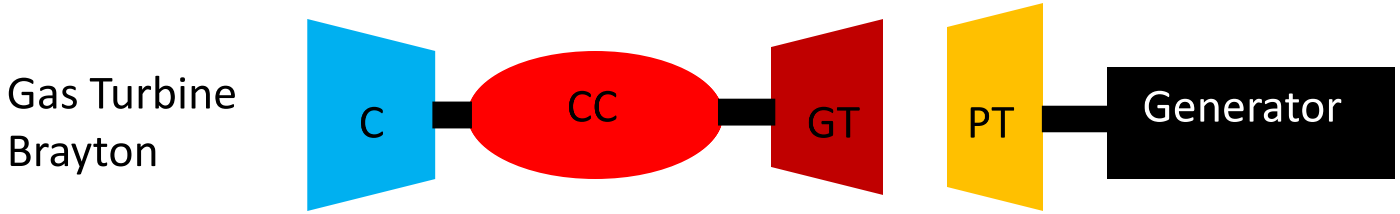
Air-Brayton Power Conversion Systems

- Nuclear Air-Brayton Power Conversion Systems are an adaptation of Gas Turbine Systems with the combustion chamber replaced by a heat exchanger.
- In a Gas Turbine System the actual working fluid temperature can be several hundred degrees above the wall temperature. In a Nuclear System, the working fluid will be tens of degrees below the wall temperature as the heat transfer is in the opposite direction.
- Combustion chambers typically drop the pressure on the working fluid about 5%. Heat exchangers have been built with a less than 1% pressure drop for the working fluid.
- Thus since the composition of the working fluid is not changed in a heat exchanger, the fluid can be reheated and expanded several times in a nuclear heated system.

Nuclear Air Brayton Systems

- It is difficult, but not impossible, for LWR systems to take advantage of lower cost heat storage.
- For advanced reactors, particularly Small Modular Reactors, Nuclear Air-Brayton systems may be effective.
- Nuclear Air-Brayton Combined Cycle (NACC) Systems can be built that operate similar to Gas Turbine Combined Cycle Systems
- Nuclear Air-Brayton Recuperated Cycle (NARC) Systems can be built based on the Same Technology
- The only innovation will be a liquid metal/molten salt-to-air heat exchanger. These have been demonstrated in the past on the 1960s ANP program and as heat dumps for the FFTF and are currently proposed for the VTR.

Simple Air-Brayton Cycles



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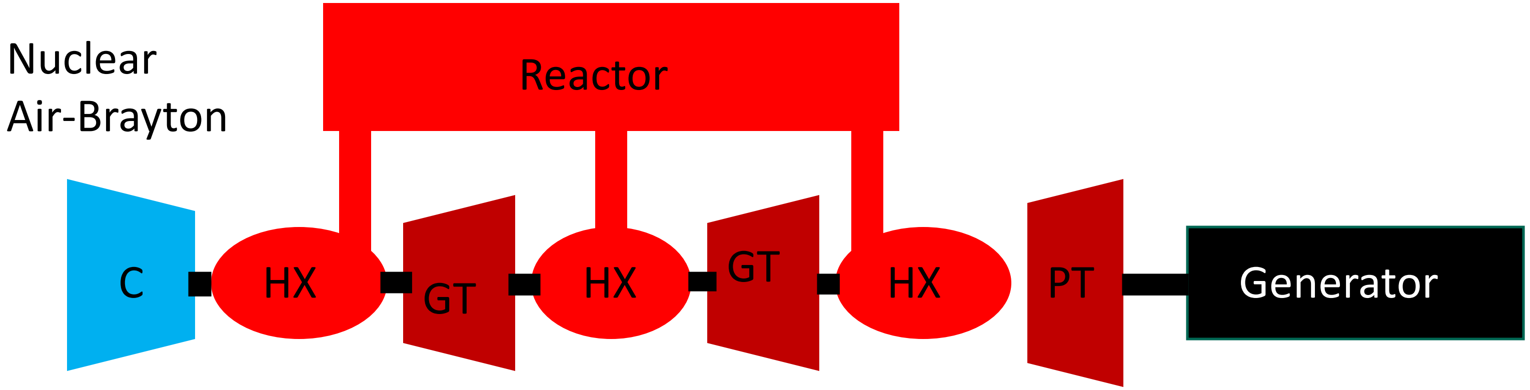

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Typical NACC System Layout (4T)

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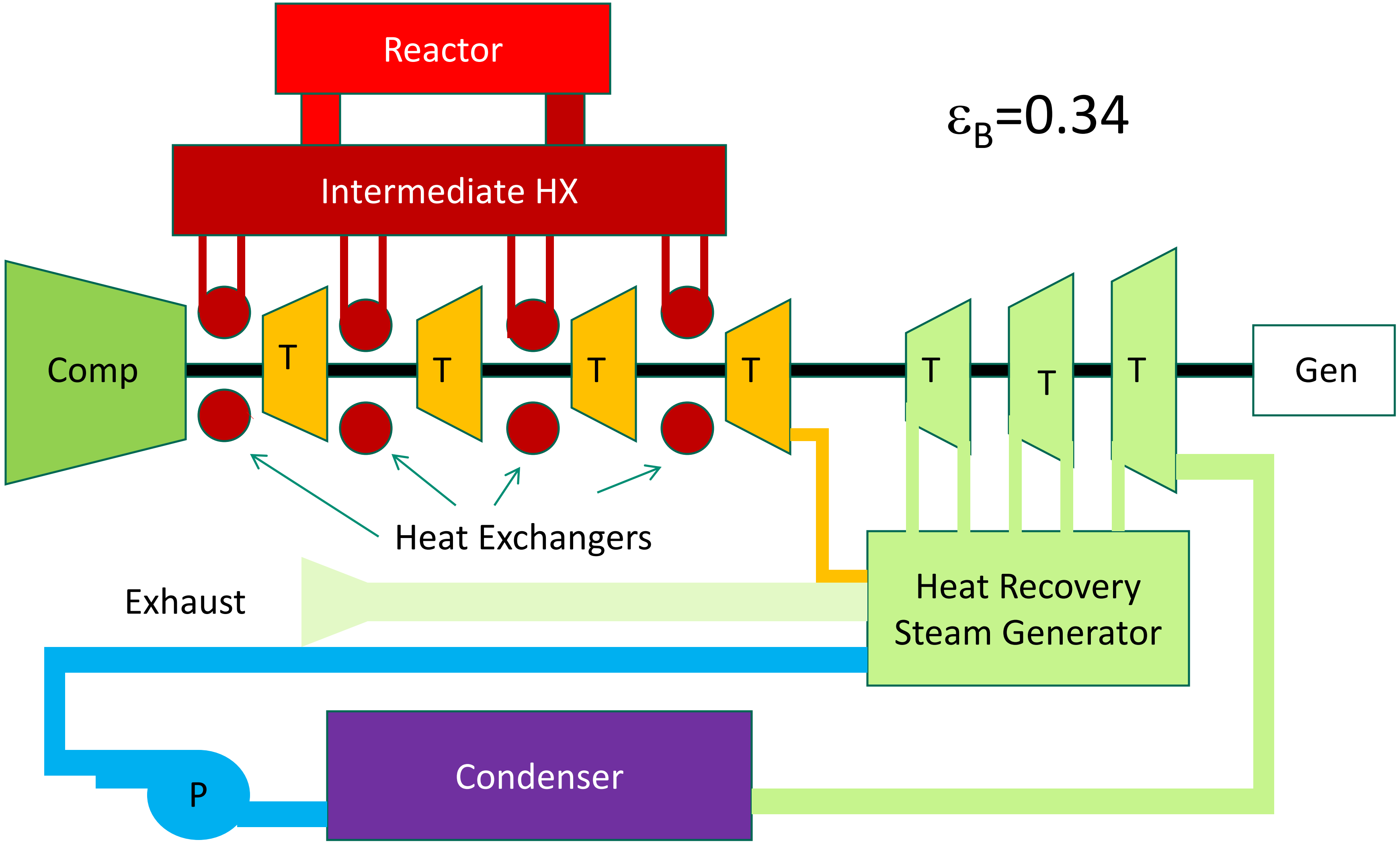
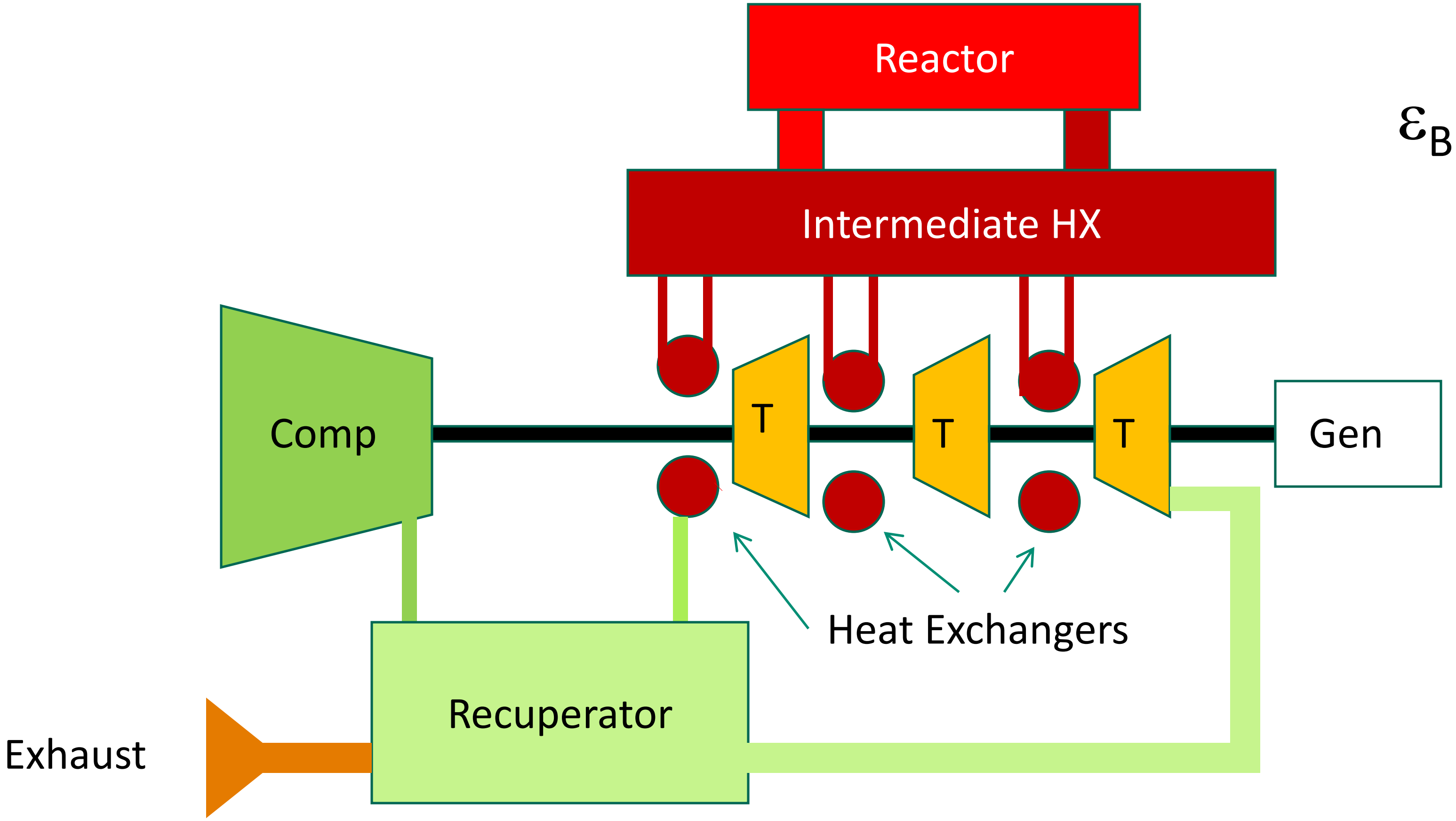


Typical NARC System Layout(3T)



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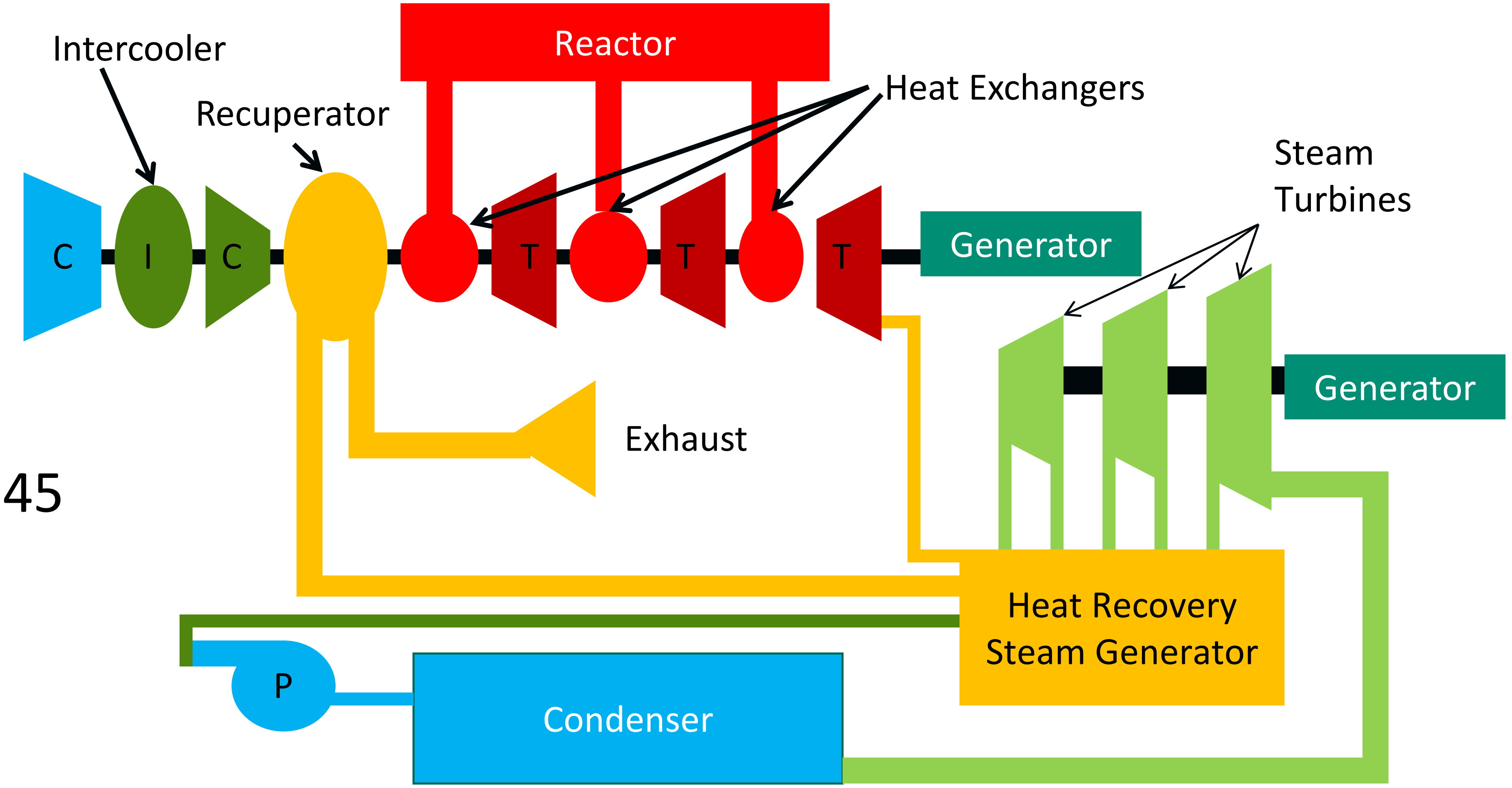
Intercooled Nuclear Air-Brayton Combined Cycle (NACC)



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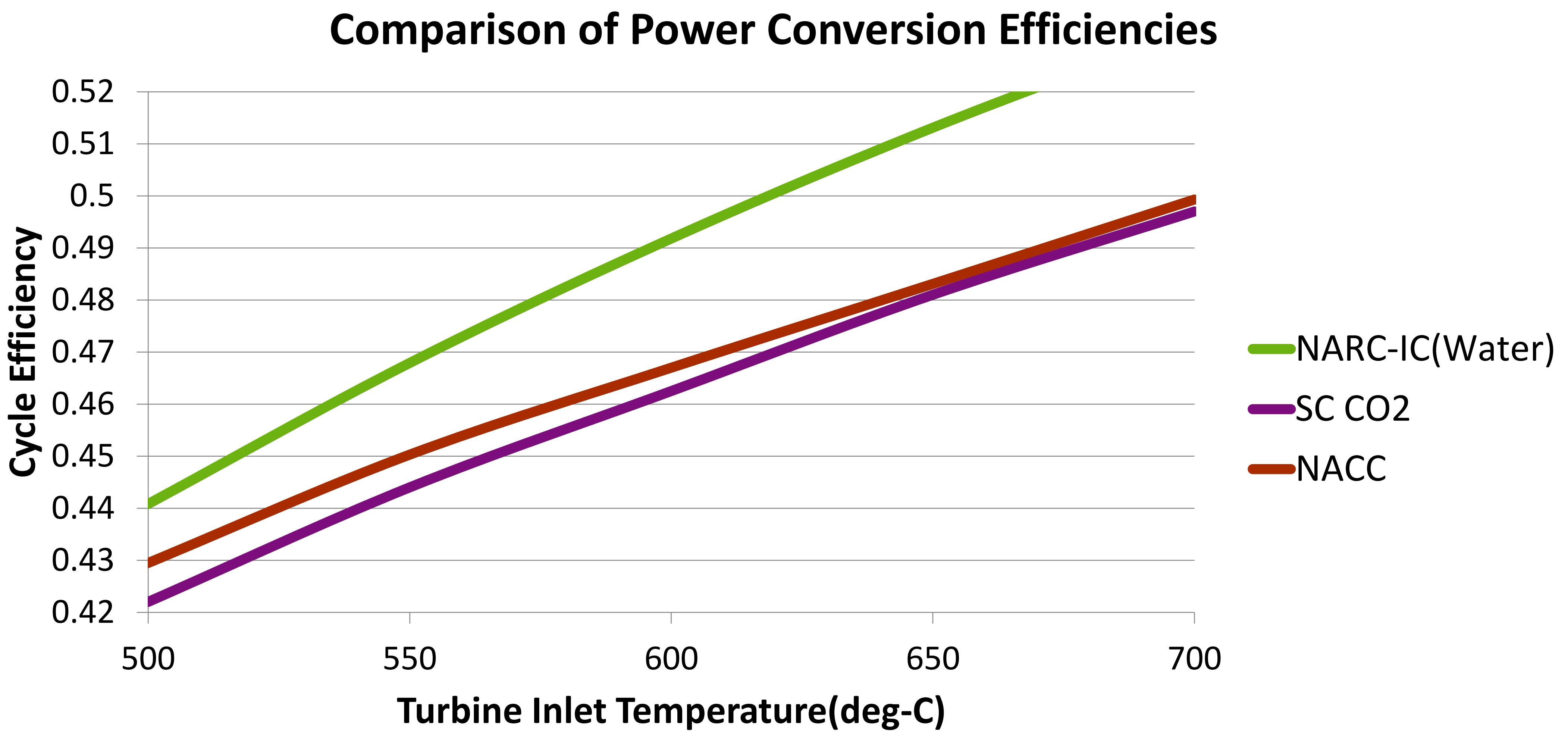
Meeting the Challenges

- Ramping up and down to meet demand is very difficult to impossible for the current generation of LWRs
- Generation IV Reactor Concepts
  - Very High Temperature Reactor
  - **Molten Salt Reactor**
  - **Sodium-Cooled Fast Reactor**
  - Super-Critical-Water-Cooled Reactor
  - Gas-Cooled Fast Reactor
  - **Lead-Cooled Fast Reactor**
- Air Brayton Power Conversion Systems can impact the three systems in bold above.

Baseline Efficiencies vs. Turbine Inlet Temperature



Cooling Water Heat Dumps

50 MW(e) Systems - 3 Turbines

		Req. LWR Eq. Eff.
LWR at 35% Efficiency	92.9 MW(t)	35%
NuScale at 31% Efficiency	111.3 MW(t)	31%
Sodium NACC at 40.0% Efficiency	40.3 MW(t)	55%
Molten Salt NACC at 44.5% Efficiency	25.5 MW(t)	66%
Sodium IC NACC at 42.0% Efficiency	39.8 MW(t)	56%
Molten Salt IC NACC at 45.6% Efficiency	38.4 MW(t)	57%
Sodium IC NARC at 46.1% Efficiency	23.6 MW(t)	68%
Molten Salt IC NARC at 51.1% Efficiency	18.6 MW(t)	73%

Of course the basic NARC system requires no cooling water for a heat dump and therefore can be placed anywhere in the world.

High Penetration of Renewables Dramatically Changes the Demand Curve

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- The intermittency of renewable electrical energy generators cries out for coupling all power plants to an energy storage system.
- There are two types of storage available at an arbitrary site.
- Electrical Storage (Obvious choice, typically batteries)
  - Currently approximately \$280-\$400 /kWh(e) at Terrawatt Scale
  - Essentially doubles the price of electricity
  - DOE is pursuing electrical storage research – Goal is \$150/kWh(e)
- Heat Storage (Phase Change Material, Firebrick, Hydrogen Electrolysis)
  - DOE Heat Storage – Goal \$15/kWh(t)
  - Can be used by Solar Thermal Plants but not PV
  - Even with conversion losses heat storage can be recovered at less cost

A Grid with Large Penetration of Renewable Systems

To address the fluctuation in power demands caused by very intermittent renewable energy systems, and still maintain a near baseload operation for the nuclear reactor, two schemes have been proposed and are being investigated.

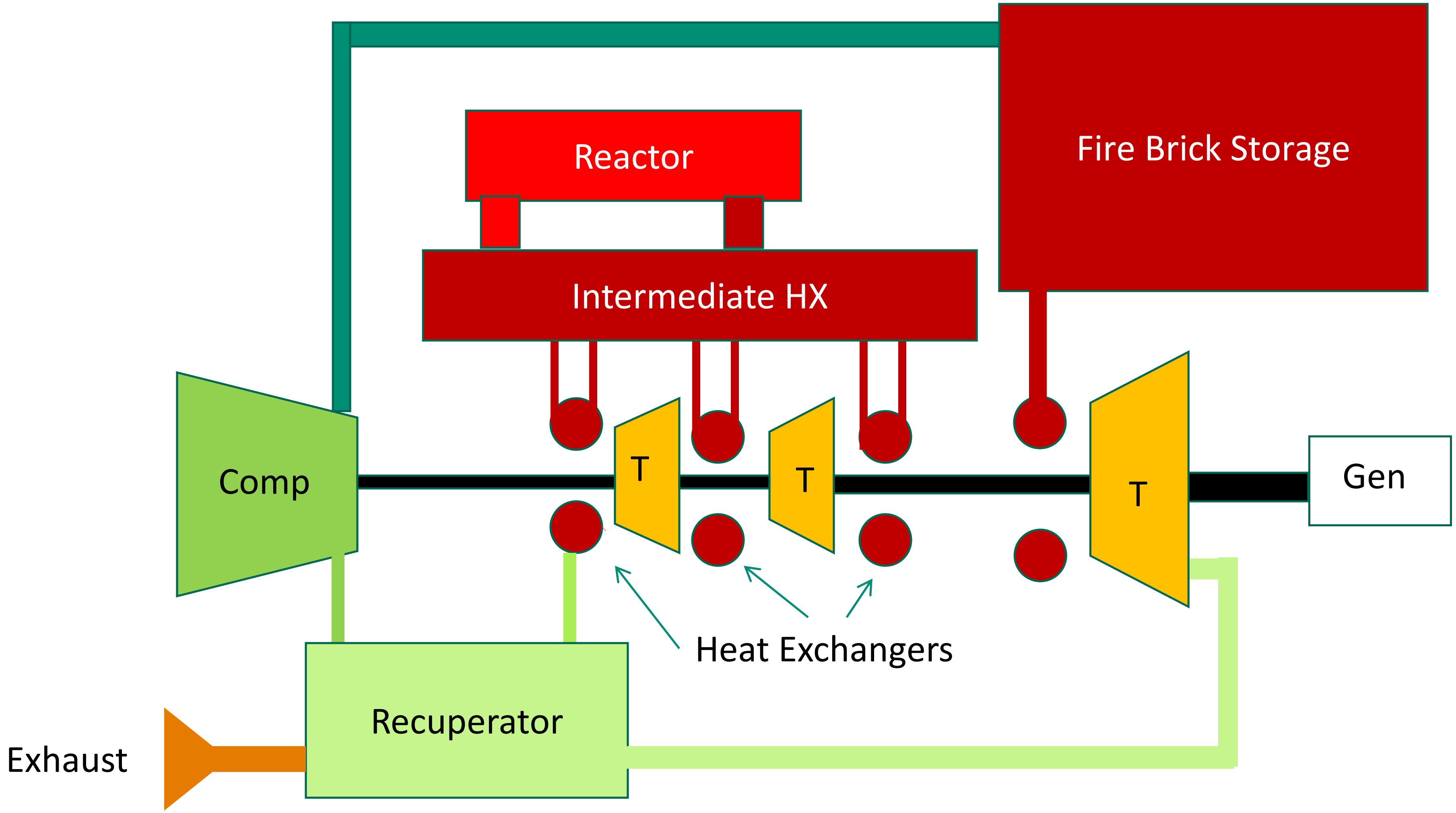
1) During periods of cheap electricity, the nuclear system electricity could be used to heat firebrick to a high temperature. Then the gas exiting the last nuclear heat exchanger could be passed over the firebrick to increase the turbine inlet temperature for the power turbine during periods of high demand for nuclear electricity.

2) During periods of cheap electricity due to an abundance of renewable capability, the nuclear system electricity would be converted to producing and storing hydrogen. The hydrogen could then be burned to increase the turbine inlet temperature of the power turbine during periods of high demand for nuclear electricity.

Coupling to Storage Systems - Firebrick

- The most efficient system is probably the Firebrick system
- Firebrick is heated electrically to ~ 2000 K
- This can be accomplished with nuclear system electricity or excess solar electricity
- The stored heat is then recovered by passing compressed air over the Firebrick
- The heated air is mixed with the nuclear heated air and exhausted over the last air turbine
- A variable throat nozzle is required before the last turbine
- The exhaust passes to either the Heat Recovery Steam Generator or Recuperator

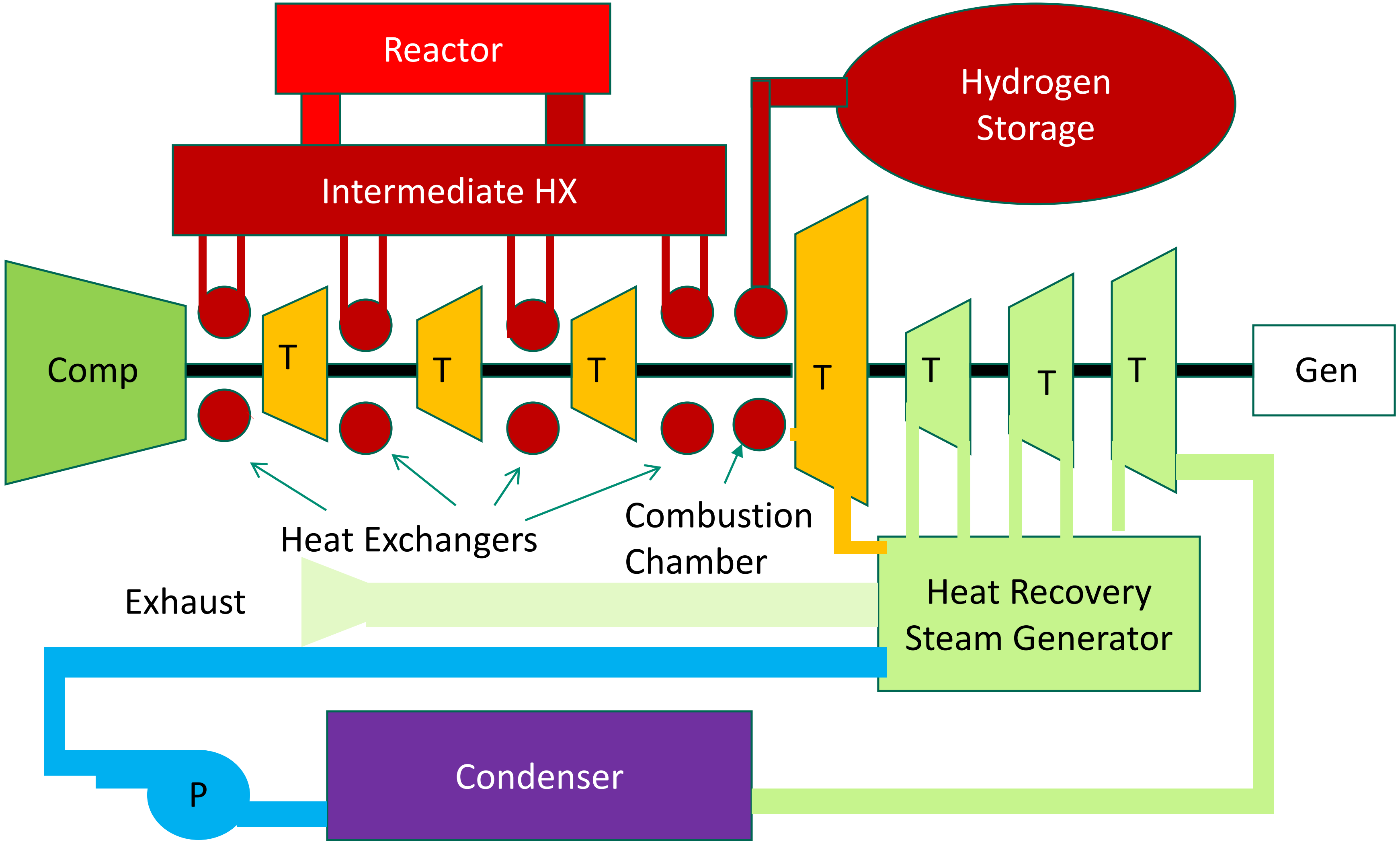
NARC System W/Firebrick Storage



Coupling to Storage Systems – Hydrogen
(The Afterburner System)

- Produce hydrogen by high temperature electrolysis – 60-80% efficient
- Use nuclear, excess solar, or excess wind electrical power
- Hydrogen Storage is a developed technology
  - Store hydrogen under pressure ~3000-5000 psi
  - Store at ambient temperature
- For power peaking burn hydrogen in a combustion chamber after last sodium/molten salt heat exchanger, prior to last turbine
- If we run out of hydrogen, natural gas or other suitable fuel can be substituted.
- Excess hydrogen production can be marketed to other industries and possible fuel cell transportation systems.

NACC System with Hydrogen Combustion



NACC Performance w/Storage

- Consider two levels of final turbine inlet temperature with hot gas injection or hydrogen burn - 1100 K (uncooled), 1700 K (cooled)
- Evaluate a Three Gas Turbine system

Turb 1&2 Nom Exit Temp	Turb 3 Nom Exit Temp	Turb 3 Aug Inlet Temp	Base Efficiency	Burn Efficiency	Combined Efficiency	Brayton Gain	Overall Gain
Sodium Near Term System (Normal Inlet Temperatures - 773 K)							
680.5 K	640.5 K	1100 K	32.8%	71.1%	48.4%	1.464	2.522
680.5 K	640.5 K	1700 K	32.8%	74.2%	60.4%	2.347	5.744
Molten Salt Advanced System (Normal inlet Temperature – 973 K)							
792.5 K	722.5 K	1100 K	45.5%	74.5%	51.1%	1.168	1.403
792.5 K	722.5 K	1700 K	45.5%	75.0%	61.6%	1.834	3.070

NARC Performance w/Storage

- For NARC Systems the peak augmented last turbine temperatures are driven by the output temperature of the Recuperator to the first heat exchanger. When the Recuperator delivers air at the outlet temperature of the first heat exchanger the burn temperature can go no higher. The reactor must also be throttled back as it is no longer providing heat to the first heat exchanger.
- Evaluate a Three Gas Turbine system

Turb 1&2 Nom Exit Temp	Turb 3 Nom Exit Temp	Turb 3 Aug Inlet Temp	Base Efficiency	Burn Efficiency	Combined Efficiency	Brayton Gain	Fractional RX Power
Sodium Near Term System (Normal Inlet Temperatures - 783 K)							
765.5 K	655.5 K	958.7 K	40.9%	78.8%	47.2%	1.390	0.220
Sodium Near Term System (Normal Inlet Temperatures - 783 K, intercooled)							
748.0 k	618.0 K	1011.6 K	43.7%	83.4%	51.1%	1.447	0.285
Molten Salt Advanced System (Normal inlet Temperature – 973 K)							
922.5 K	762.5 K	1204.2 K	48.5%	81.1%	54.8%	1.409	0.203
Molten Salt Advanced System (Normal inlet Temperature – 973 K, Intercooled)							
902.5 K	722.5 K	1268.7 K	51.5%	84.7%	58.4%	1.448	0.276

Conclusions

- Air-Brayton Power Conversion Systems contain a lot of flexibility for building a more resilient grid.

- Many of the techniques we have identified for Nuclear Systems can be applied to Concentrating Solar Systems to enable them to be more dispatchable.

- We are interested in talking to the Sandia research group working Concentrating Solar Systems to discuss interest overlaps.

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Backup Slides

Nuclear is Not Cost Competitive

Levelized Cost of Electricity $/MWh

Coal w/30% Carbon Capture Sequestration	$130.1
Conventional Gas Turbine Combined Cycle	$50.1
Advanced Gas Turbine Combined Cycle	$49.0
Conventional Gas Turbine	$98.7
Advanced Gas Turbine	$85.1
Advanced Nuclear	$92.6

A number of older nuclear plants have been shut down as even though the capital costs have been paid off, operating and refueling costs are still not competitive.

Some states are taking action to preserve a nuclear base load capability with subsidies.

Limitations on Available Cooling Water

- Thermal Power Plants (Gas, Coal, and Nuclear) are major consumers of fresh water to remove waste heat.
- Nuclear (LWRs) tend to be slightly worse than coal and significantly worse than Gas Turbine Combined Cycle Plants.
- Some fresh water is returned to the bodies from which it was withdrawn, at a higher temperature.
- Cooling towers remove fresh water from the surface and exhaust it into the atmosphere.
- Several reactor stations in the US are restricted from expanding due to lack of a reliable water source.

Water Use in the US

In 2010, more surface water than groundwater was withdrawn for all uses except domestic, livestock, and mining. Thermoelectric power accounted for 51 percent of the total fresh surface-water withdrawals and irrigation accounted for 29 percent.