Heat Storage for Gen IV Reactors for Variable Electricity from Base-load Reactors

Changing Markets, Technology, Nuclear-Renewables Integration and Synergisms with Solar Thermal Power Systems

July 23, 2019: 8:15 am to 5:00 pm (plus dinner)
July 24, 2019: 8:30 to 12:00 Noon

Idaho Falls, Idaho
Role of Heat Storage in Changing Electricity Markets with the Need for Dispatchable Electricity

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Massachusetts Institute of Technology
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Electricity Markets are Changing

Addition of Wind and Solar

Goal of Low-Carbon Energy System
Large-Scale Solar or Wind Causes Price Collapse and Higher Prices at Other Times

Impact of Added Solar PV on California Wholesale Prices: Value of Wind and Solar Decrease With Scale
Seasonal Mismatch Between Demand and Wind/Solar California Negative Wholesale Prices by Month

End of Subsidies and Technology Modifications will Convert Negative-Price to Zero-Price Electricity over Time
Electricity Price (Revenue) Collapse Limits Non-Dispatchable Wind and Solar Without Storage Saturate Market Even If Large Subsidies

## Low Levelized-Cost-of-Electricity (Lazard 2017) Does Not Imply Large Market Share

<table>
<thead>
<tr>
<th>Technology</th>
<th>Energy Form</th>
<th>LCOE: $/MWh(e)</th>
<th>Dispatch</th>
<th>Low-Carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar PV: Thin Film Utility</td>
<td>Electricity</td>
<td>43–48</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Solar Thermal Tower with Storage</td>
<td>Heat</td>
<td>98–181</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Wind</td>
<td>Electricity</td>
<td>30–60</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Natural Gas Peaking</td>
<td>Heat</td>
<td>156–210</td>
<td>Yes</td>
<td>No</td>
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<td>Natural Gas Combined Cycle</td>
<td>Heat</td>
<td>42–78</td>
<td>Yes</td>
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</tr>
<tr>
<td>Nuclear</td>
<td>Heat</td>
<td>112–183</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

**Dispatchability Is as Important as LCOE**
Low-Carbon Energy Sources Have Different Economic Characteristics Than Fossil Fuels
No Change In Energy Policy for 300,000 Years, **Throw a Little Carbon on the Fire**

Cooking Fire  Natural-Gas Combined Cycle

Low-Capital-Cost Power Systems, Labor & Money in Collecting Fuel: Wood or Natural Gas: **Economic at Part Load**
Fossil Fuels Are Hard to Replace Because They Provide Three Services

• Source of energy
• Low-cost energy storage
• Low-cost dispatchable energy
Low-Carbon System Economics: High Capital Cost and Low Operating Cost

Operate At Half Capacity Doubles Energy Costs

Produce Electricity               Produce Heat
Rethinking Energy System Design for Heat Generating Technologies in a Low Carbon World

Nuclear (Fission), Concentrated Solar, Geothermal, Fossil Fuel With Carbon Capture and Fusion (Future)
What a Low-Carbon Electricity System Needs

• Sell dispatchable electricity
  – Low cost
  – Assured generating capacity for peak loads
• Buy very-low-price electricity from wind and solar PV at times of excess production: Sets a higher minimum price that improve economics
• Operate nuclear reactors and other heat-generating technologies at base-load to minimize costs

Replace the Storage, Dispatchability and Production Characteristics of Fossil Fuels
Require a New System Design

- Base-load nuclear or CSP
- Heat storage for peak electricity
- Low-price electricity to heat storage
- Backup furnace: assured peak capacity

Electricity Market (Grid)

Sell Dispatchable Electricity

Buy Low-Price Excess Electricity and Convert to Heat

Heat to Electricity

Base-load Heat Generation to Industry, Electricity and Storage

Low cost Heat Storage

Assured Peak Capacity (H₂ and Biofuels)
System Design Applicable to All Heat-Generating Technologies

Nuclear Power System  NREL CSP System
Low-Cost Heat Storage Couples to Nuclear: Same Technologies as Concentrated Solar Power

- Steam Accumulators
- Sensible Heat (Oil, salt, etc.)
- Cryogenic Air
- Hot Cement
- Geothermal (Seasonal)
- Hot Rock

Pilot Plant
Heat Storage Is Cheaper than Electricity Storage (Batteries, Pumped Hydro, etc.)

- DOE heat storage goal: $15/kwh(t)
- Battery goal $150/kWh(e), double if include electronics
- Difference is raw materials cost

<table>
<thead>
<tr>
<th>Gigawatt-Hour Heat Storage Technologies</th>
<th>Temperature Limits (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressurized Water</td>
<td>&lt;300</td>
</tr>
<tr>
<td>Geothermal</td>
<td>&lt;300</td>
</tr>
<tr>
<td>Counter Current Sat Steam</td>
<td>&lt;300</td>
</tr>
<tr>
<td>Cryogenic Air</td>
<td>&lt;1600</td>
</tr>
<tr>
<td>Concrete</td>
<td>&gt;600</td>
</tr>
<tr>
<td>Crushed Rock</td>
<td>800</td>
</tr>
<tr>
<td>Sand</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>Oil</td>
<td>&lt;400</td>
</tr>
<tr>
<td>Cast Iron</td>
<td>700/900</td>
</tr>
<tr>
<td>Nitrate Salt</td>
<td>&lt;650</td>
</tr>
<tr>
<td>Chloride Salt</td>
<td>&lt;1000</td>
</tr>
<tr>
<td>Graphite</td>
<td>&gt;1600</td>
</tr>
</tbody>
</table>
## Power System Coolant Temperatures Define Allowable Storage Materials

<table>
<thead>
<tr>
<th>Coolant</th>
<th>Nominal Inlet Temperature (°C)</th>
<th>Nominal Exit Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NP: Water</td>
<td>270</td>
<td>290</td>
</tr>
<tr>
<td>NP: Sodium</td>
<td>450</td>
<td>550</td>
</tr>
<tr>
<td>NP: Helium</td>
<td>350</td>
<td>750</td>
</tr>
<tr>
<td>NP: Salt</td>
<td>600</td>
<td>700</td>
</tr>
<tr>
<td>CSP: Nitrate</td>
<td>290</td>
<td>565</td>
</tr>
<tr>
<td>CSP: Chloride</td>
<td>500</td>
<td>725</td>
</tr>
<tr>
<td>CSP: Sodium</td>
<td>500</td>
<td>750</td>
</tr>
<tr>
<td>CSP: Sand</td>
<td>575</td>
<td>775</td>
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Storage Temperature Range Can be Decoupled from Nuclear /CSP System

- Some reactors have small delta T across core
- Large delta T reduce storage costs
Two Strategies for Peak Power

Heat from Reactor/CSP and Heat Storage

- Oversize Main Turbo-Generator
  - Fast response from operating turbine
  - Peak power capacity limited
  - Turbine efficiency highest at only one power level
  - Low-cost option

- Separate Peaking Turbo-Generator
  - Peaking turbine can be sized to any market
  - Return condenser water to main turbine
If Heat Storage, Buy Low-Price Electricity and Convert to Heat for Later Use

• When low-prices
  – Nuclear generator and grid electricity to heat storage
  – Electric resistance heaters

• Low-cost storage option
  – Same equipment (grid connections, transformers, switchgear) to buy and sell electricity
  – Own storage system and electricity peaking capability
  – Incremental addition to heat storage capacity

Improves Nuclear, Wind and Solar Economics
This System Can Address the Weekday-Weekend Market Challenge

- Low-carbon systems will have excess low-price electricity on weekends: low electricity demand
- Only added cost for weekend-to-weekday storage is incrementally larger heat storage: very low cost
If Heat Storage, Option to Buy Steam Generator for Assured Peak Power

• All storage devices can become depleted but need for assured peak power
• Burns (1) natural gas or (2) low-carbon biofuels and hydrogen
• Low-cost option
  – Use storage electricity peaking capability (turbine generator)
  – Half to third the cost of backup gas turbine for assured capacity

Seldom Used & Low-Carbon Fuel Options
Can Nuclear with Heat Storage Compete with Natural-Gas Peaking Plants?

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<td>112–183</td>
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<td>Yes</td>
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</table>

- Natural gas peaking plants expensive: High maintenance cost with very high temperature machine plus low capacity factor
- Nuclear with heat storage to replace peaking gas turbine
  - Sell peak power—same as NG peaking plant
  - Assured peak generating capability—same as NG peaking plant
  - Buy low-price electricity for heat storage and peak power—Added revenue
Conclusions

• Electricity market is changing: Volatile prices
  – Deployment of non-dispatchable wind and solar PV
  – Goals of low-carbon economy

• Low-carbon world requires a replacement for fossil fuels as (1) Energy source, (2) Storable energy and (3) Dispatchable energy

• Require heat storage on the gigawatt-hour scale
  – No market 5 years ago, market rapidly growing
  – Same challenges for all heat generating technologies
  – Enabling technology for economic larger-scale use of nuclear, wind and solar
Questions

Electricity Market (Grid)

Dispatchable Electricity Generation

Heat Source
Nuclear, CSP, Geothermal, Fossil with Sequestration

Low-Price Electricity to Heat

Non-Dispatchable PV/Wind Electricity

Heat Storage (Time Shift Output)

Combustion Heater (Assured Capacity)

Industrial Heat Market

Electricity Heat
References


Take Away Messages

• Restrictions on carbon emissions and the addition of wind and solar PV change the electricity market
  – Volatile electricity prices including zero and negative priced electricity (low marginal cost wind and solar)
  – Need economic assured peak generating capacity
• Require a **system solution**: Nuclear co-generation (electricity and heat) with large-scale heat storage and assured peak electricity generating capacity
  – Buy electricity at times of low prices
  – Sell electricity at times of high prices
  – Operate power systems at full capacity
• Same storage/power system technologies for CSP
The Characteristics of Fossil Fuels Enable Separate Energy Supply Chains for Electricity, Industry and Transportation

In a Low-Carbon World, Need to Integrate Separate Energy Supply Chains to Minimize Costs
<table>
<thead>
<tr>
<th>Technology</th>
<th>Storage Media</th>
<th>Receiver Outlet Temp (°C)</th>
<th>Hot Storage Temp (°C)</th>
<th>Cold Storage Temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSP Parabolic Trough</td>
<td>Na/K nitrate “solar salt”</td>
<td>390</td>
<td>385</td>
<td>295</td>
</tr>
<tr>
<td>CSP Molten-Salt Tower</td>
<td>Na/K nitrate “solar salt”</td>
<td>565</td>
<td>565</td>
<td>290</td>
</tr>
<tr>
<td>Gen3 CSP Chloride Salt Tower</td>
<td>Mg/K/Na chloride</td>
<td>725</td>
<td>720</td>
<td>500</td>
</tr>
<tr>
<td>Gen3 CSP Sodium Receiver + Chloride-salt TES</td>
<td>Mg/K/Na chloride</td>
<td>750</td>
<td>720</td>
<td>500</td>
</tr>
<tr>
<td>Gen CSP Particle Tower</td>
<td>Sand</td>
<td>775</td>
<td></td>
<td>575</td>
</tr>
</tbody>
</table>
Three Electricity Generating System Options for a Low-Carbon World that Meet the Three Requirements:

- Electricity Generation
- Energy Storage
- Assured Peak Generating Capacity
Nuclear Energy with Heat Storage and Backup Furnace (Biofuels, Hydrogen, etc.)

Heat Generation to Electricity and Storage

Backup Boiler for Depleted Storage

Concentrated Solar Power (CSP) has Same System Design
Wind / Solar PV System With Electricity Storage and Backup Gas Turbine

Seasonal Solar & Wind Input Requires Significant Operation of Gas Turbine Backup (Biofuels and H₂)
Fossil Plant with Carbon Capture and Sequestration

Petra Nova (Joint venture): NGR Energy and JX Nippon Oil and Gas Exploration

- Post combustion capture CO$_2$
- 240 MW
  - Added to Unit 8 (654 MW)
  - 37% of Unit 8 emissions
- 90% CO$_2$ capture
Comparison of the Three Energy Options
Some Mixture Likely Where Choices Depend upon Location

<table>
<thead>
<tr>
<th>Option/ Characteristic</th>
<th>Nuclear* with Storage + Fuel</th>
<th>Wind/Solar PV* With Storage + Fuel</th>
<th>Fossil with Carbon Sequestration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Base-load Fuel cost</td>
<td>Low</td>
<td>~0</td>
<td>High</td>
</tr>
<tr>
<td>2. GW&lt;sub&gt;total&lt;/sub&gt;/GW&lt;sub&gt;peak&lt;/sub&gt;</td>
<td>1</td>
<td>&gt;2</td>
<td>1</td>
</tr>
<tr>
<td>3. Low-carbon fuel (H&lt;sub&gt;2&lt;/sub&gt;, biofuels, etc.)</td>
<td>Low</td>
<td>High</td>
<td>None</td>
</tr>
<tr>
<td>4. Location Dependent</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Numbered Notes below coupled to characteristics
2. GW(e) nameplate rating divided by GW(e) assured peaking capacity. Wind and solar PV total generating capacity equals Wind/Solar PV + battery + gas turbine but if extended low wind/solar conditions, the only assured capacity is the gas turbine.
3. Low-carbon fuel required for assured peaking capacity when storage is depleted. For nuclear this peaking capacity above base-load nuclear. For wind/solar this is total power because no assured base-load capability from wind and solar.

*Concentrated Solar Power systems have some of the characteristics of nuclear systems and some of the characteristics of solar PV
Lowest Cost System Depends upon (1) System Option Cost and (2) Best Match Between Production and Demand

- Mismatch between full production and electricity demand implies more storage and higher costs; Nuclear with storage has the closest match

for United States Lower 48 (region), Hourly megawatthours

800,000
600,000
400,000
200,000

Dec ’15 Jan ’16 Feb ’16 Mar ’16 Apr ’16 May ’16 Jun ’16 Jul ’16 Aug ’16 Sep ’16 Oct ’16 Nov ’16
Most Economic **Nuclear System** Depends upon Three Factors

- **Markets.** Market with wind or solar will have different nuclear heat storage requirements because of different storage times (daily versus multiday cycles).
- **Storage technology.** Preferred storage technology depends upon market and reactor choice.
- **Reactor choice.** Higher temperature reactor implies lower heat-storage costs
  - If sensible heat storage, double hot-to-cold temperature swing reduces heat storage system in half per MWh (heat)
  - Heat-to-electricity efficiency depends upon temperature. If 50% more efficient, smaller heat storage system per MWh (electricity)
Same **Nuclear System** for Co-Generation

Produce Variable Heat and Electricity

- Industrial heat demand twice total electricity output of the United States
  - Electricity costs 4 to 6 times the cost of heat
  - Expensive to “electrify” industry by converting electricity to heat
- Large incentives for nuclear cogeneration
  - Existing fossil cogeneration plants sometimes vary production to maximize electricity sales when prices are high. Low-cost way for nuclear co-generation added assured peak generating capacity
  - Storable manufactured fuels (hydrogen, biofuels) have massive heat and electricity inputs. Incentives to vary production with electricity prices that couples utility and transportation energy markets
- Co-generation enables optimization of combined electricity, industrial, and transportation energy markets to minimize total costs
Questions?

**Electricity Market (Grid)**

- Dispatchable Electricity
- Low-Price Electricity
- Non-Dispatchable Electricity

**Heat to Electricity**

- Heat Generation
  - Base-Load Nuclear
- Low-Cost Heat Storage
- Backup Furnace
  - Seldom Used
- Wind/Solar