Energy Storage - a *Need* for the Grid (and for Microgrids); an *Opportunity* for District Energy

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Outline

- Introduction
- Energy Storage Options
- Example: Batteries vs. Chilled Water (CHW) Thermal Energy Storage (TES)
- Widespread Use of CHW TES by Repeat Owners
- Ancillary Benefits from CHW TES
  - Emergency Cooling for Mission Critical Facilities (MCF)
  - Combined Heat & Power (CHP)
  - Turbine Inlet Cooling (TIC)
  - Dual-Use as TES + Fire Protection
- Conclusions and Recommendations

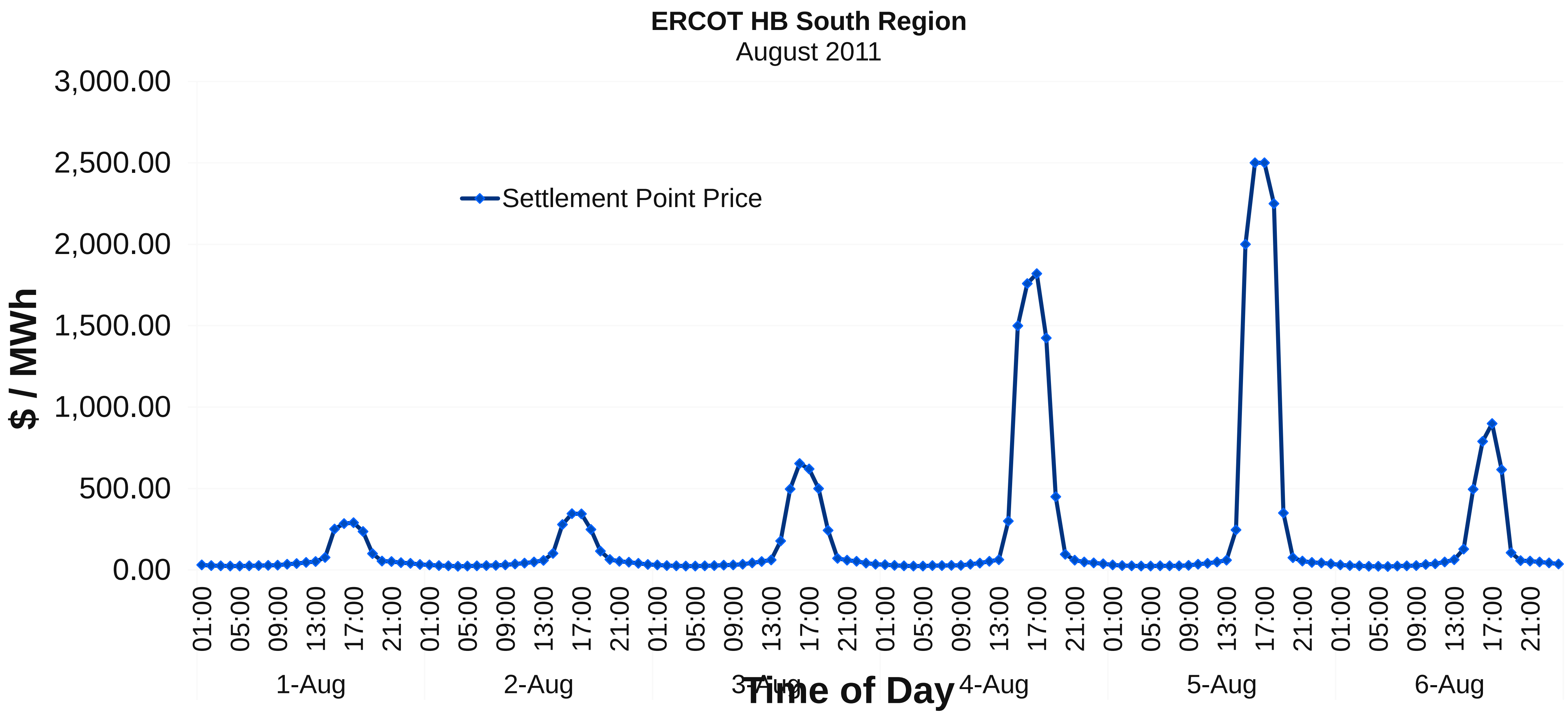
Impact of Renewable Power

- Renewable Portfolio Standards => increased Wind & Solar power
  - Intermittent and often out-of-phase with demand
  - Coal + Nuclear + Wind power often exceeds nighttime demand
  - Nighttime power trades <u>negative</u> at times, e.g.:
    - In TX, as low as negative $0.10/kWh
    - In NE, as low as negative $0.20/kWh
- Energy Storage is increasingly critical; one can consider:
  - Batteries, Pumped Hydro, Compressed Air, Flywheels, SMES, Fuel Cells . . .

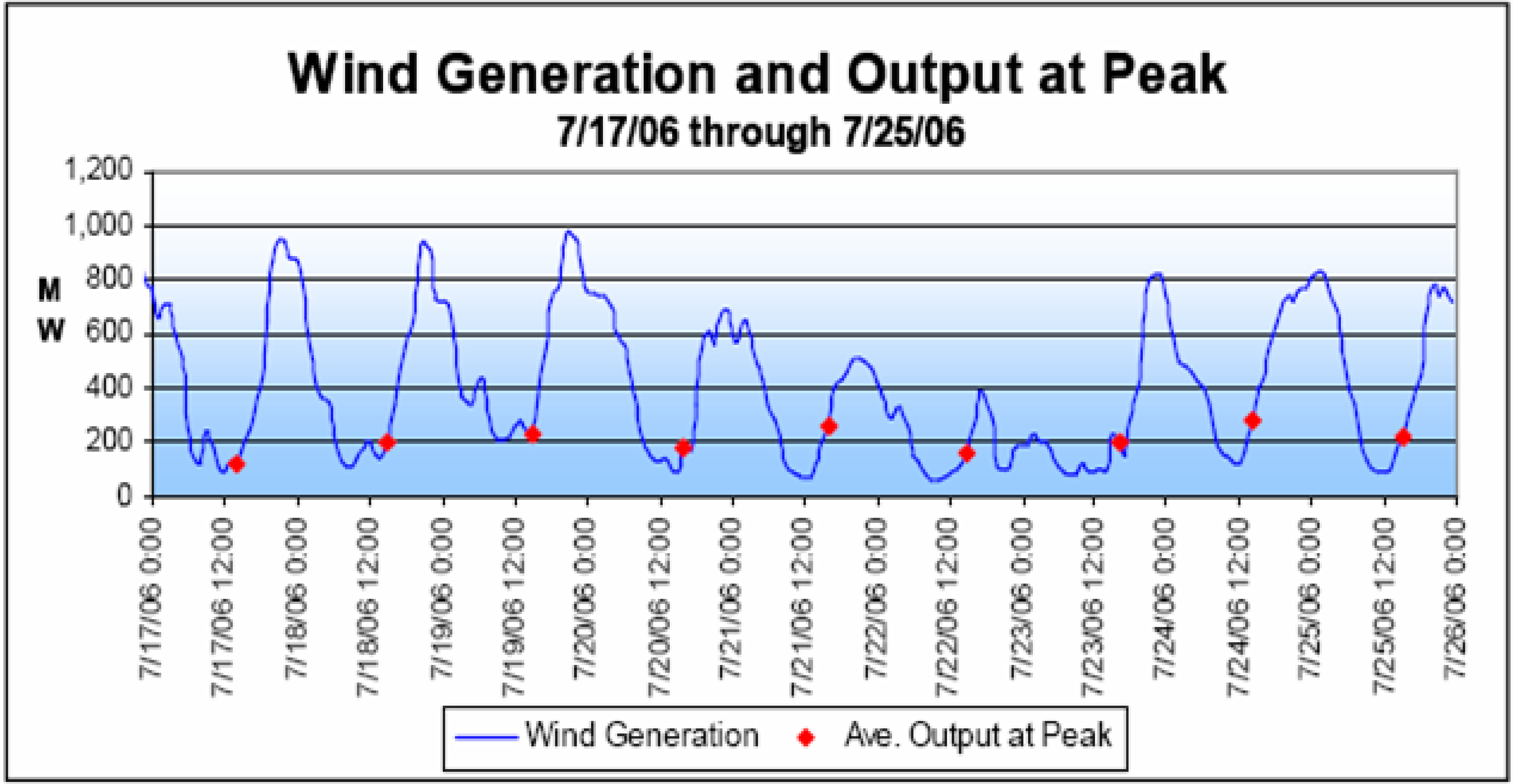
But large CHW TES often excels over all those in terms of:

maturity, safety, siting, permitting, schedule, lifetime, efficiency, cap$

While Grid Demand Varies from 100 to 50% of Peak, Power Value Varies from +$2.50/kWh to -$0.10/kWh



Wind Power Produces Only 20% at Peak Demand Times



Types of Energy Storage

- Mature storage technologies:
  - Pumped Hydro-electric (PH) Energy Storage
  - Traditional Batteries (Lead-Acid, Sodium-Sulfur)
- Developing storage technologies:
  - Advanced Electro-Chemical Batteries (Li-Ion, others)
  - Compressed Air Energy Storage (CAES)
  - Mechanical Flywheel Energy Storage
  - Superconducting Magnetic Energy Storage (SMES)
- An often overlooked option – Thermal Energy Storage (TES):
  - Hot TES (Hot Water, Hot Oil, Molten Salt, Rock, Concrete)
  - Cool TES (**Ice**, **Phase Change Material**, **Chilled Water**, **Low Temp Fluid**)

Chilled Water (CHW) TES

- An insulated tank , full of water at all times.
- Cool, dense CHW Supply in lower zone, at ~40 °F; warm, less dense CHW Return in upper zone; a with narrow “thermocline” (temperature gradient) in between.
- TES charging, off-peak (nighttime): CHWR pumped from top of tank, cooled in chillers, returned to bottom of tank; thermocline rises in tank, until tank is 100% cool water.
- TES discharging, on-peak (daytime): CHWS pumped from bottom of tank, meets cooling loads, returned to top of tank; thermocline falls in tank, until tank is 100% warm water.

No moving parts, except pumps and valves.

Key Characteristics to Consider for Energy Storage

- Technical development status; readiness for reliable & economical application
- Safety issues or concerns
- Ease of siting (considering both technical & environmental concerns)
- Schedule for permitting & installation
- Life expectancy and life cycle costs
- Round-trip energy efficiency
- Initial unit capital cost ($/kWh)

But characteristics differ for each individual storage technology.

Comparison of Energy Storage Options

Typical Characteristics	(Units)	Pump Hydro	Trad'l Batt's	Adv'd Batt's	Fly-wheel	Comp Air	CHW TES
Maturity Status		excell	excell	dev'l	dev'l	dev'l	excellent
Safety Issues		med	low	yes	yes	med	low
Flexibility of Siting		v. low	v. high	v. high	v. high	v. low	high
Ease of Permitting		diffic	simple	simple	med	diffic	simple
Overall Schedule	(years)	10+	1-2	1-2	1-2	3-5+	1-2
Expected Lifetime	(years)	40+	7-15	7-10	20	40+	40+
Round-trip Efficiency	(%)	70-85	80-90	85-90	90	70-80	near 100
Unit Capital Cost							
- Low	($/kWh)	310	500	350	7800	200	80
- High	($/kWh)	380	750	500	13760	???	200

CHW TES at University of Nebraska-Lincoln (UNL)

Two **CHW TES**,
each providing:
1) energy storage, plus
2) chilled water (CHW) peaking capacity

UNL East Campus

Storing 16,326 ton-hrs (12 MWh); and shifting 4,000 tons (3 MW)

UNL City Campus

Storing 52,000 ton-hrs (39 MWh); and shifting 8,333 tons (6.25 MW)

Example: 39 MWh at University of Nebraska-Lincoln

Storage Element	Lithium-Ion Advanced Batteries (hypothetical)	Chilled Water (CHW) Thermal Energy Storage (TES) (actual, 2017)
Peak cooling discharge	not applicable	8,333 tons
Peak electric discharge	6.25 MW	6.25 MW equivalent
Duration at peak disch.	6.24 hrs	6.24 hrs
Net storage (thermal)	not applicable	52,000 ton-hrs
Net storage (electric)	39.0 MWh	39.0 MWh equivalent
Storage unit cap cost	$350/kWh	$100/ton-hr
Storage capital cost	**$13.65 M**	**$5.20 M (38% of batteries)**
Full system cap cost	**$27.3 M**	**$11.7 M (43% of batteries)**
Full system unit cap cost	**$700/kWh**	**$225/kWh (43% of batteries)**

Example: 39 MWh at University of Nebraska-Lincoln

Storage System	Lithium-Ion Advanced Batteries (hypothetical)	Chilled Water (CHW) Thermal Energy Storage (TES) (actual, 2017)
Full system cap cost	$27.3 M	$11.7 M (43% of batteries)
Full system unit cap cost	$700/kWh	$225/kWh (43% of batteries)
Additional Chiller Plant		
Necessary capacity	4,016 tons	TES already provides 8,333 tons
Unit cap cost	$2,900/ton	not applicable
Installed cap cost	$11.6 M	zero
Total capital cost	**$38.9 M**	**$11.7 M (30% of batteries)**
Storage life expectancy	**7-10 years**	**40+ years**
Round-trip energy efficiency	**85-90%**	**near 100%**

Energy Efficiency of CHW TES

- TES inefficiencies: 1) heat gain, and 2) pumping.
- TES efficiencies: 1) cooler nighttime condensing temperatures, and 2) avoided low-load operation of chillers & auxiliaries.
- **CHW TES** round-trip energy efficiency is near 100%.
- Some examples even show net energy savings with TES:
  - **State Farm data processing campus in IL**
    - 89,600 ton-hrs **CHW TES**
    - annual kWh/ton-hr reduced by 3% (by modeling)
  - **Texas Instruments manufacturing facility in TX**
    - 24,500 ton-hrs **CHW TES**
    - annual kWh/ton-hr reduced by 12% (by measurement)

Some Owners with Multiple TES Installations

3M Corporation(3)
Alamo Colleges (3)
Austin Energy (3)
Boeing (2)
California State U system (**19**)
State of California (**5**)
Del Mar College (2)
Disney Theme Parks (3)
District Energy St. Paul (2)
Dominion Energy (for TIC, **5**)
DuPont (for MCF back-up, **5**)
Enwave (**5**)
Ford Motor Co. (**5**)

General Motors (**5**)
Honeywell (3)
IBM (2)
Lincoln Electric System (TIC, 2)
Lockheed Martin (3)
Los Angeles County, CA (3)
NASA & National Labs (**6**)
N. Harris/Montgomery Coll. (2)
NRG Energy (4)
Princeton U (2)
Riverside County, CA (4)
San Jacinto Jr. College (3)
San Joaquin Delta College (2)

Saudi Aramco (2)
Saudi Electricity Co. (for TIC, 3)
Siemens (3)
Stanford U (**5**)
State Farm Insurance (**5**)
Tabreed (**16**)
Texas Instruments (3)
TNB - Universiti Tenaga (3)
Toyota Motor Mfg N. Amer. (**5**)
U of California system (**8**)
U of Nebraska (2)
U of Texas system (**7**)
USAF/Army/CIA/FDA/NSA/VA (**15**)

Emergency Cooling for MCFs

- Back-up for Mission Critical Facilities (e.g. data centers)
  - Apple, AT&T, Bank of America, California ISO, Citibank,
  - Covidien, DuPont Fabros, eBay, Equinix, HSBC, MCI,
  - Nationwide, Princeton U, Target, US Bank, and many others.
  - **Capital One data center in VA**
    - **CHW TES**
    - 900 ton-hrs
    - 180,000 gals
    - 1,500 tons x 36 minutes

TES Flattens Load - Better for CHP

- Flattened cooling & electric profiles aid CHP economics
  - Chicago's Metro Pier & Expo Authority convention district (3 MW)
  - Climaespaco mixed-use district energy in Lisbon, Portugal (8 MW)
  - Princeton U campus (15 MW)
  - **TECO medical district (45 MW)**
    - **CHW TES**
    - 64,300 ton-hrs
    - 8.8 million gals
    - 10 MW / 45 MWh load shift

Turbine Inlet Cooling (TIC)

- TIC with TES for maximizing hot weather power output of CTs.
  - Calpine, Chicago MPEA, Climaespaco, Princeton U,
  - Reedy Creek Energy Services (Disney World), TECO,
  - Dominion Energy (five TIC in PA & VA with 80 MW from **CHW TES**).
  - **Saudi Electricity Company**
    - **CHW TES**
    - 193,000 ton-hrs
    - 7.9 million gals
    - 48 MW / 288 MWh TES load shift
    - 180 MW extra power from TIC
    - That extra power under $300/kW

Dual-use: TES and Fire Protection

- CHW TES doubles as fire protection.
  - Abbott Laboratories (IL), ARCO (TX), Chrysler Motors (MI),
  - GM (OK & MI), Phoenix Newspapers (AZ), Pratt & Whitney (CT),
  - Shell Development (TX), State Farm Insurance (GA & IL).
  - **3M Corporation campus in MN**
    - **CHW TES**
    - 32,000 ton-hrs
    - 4.1 million gals
    - 5 MW / 24 MWh load shift

Conclusions and Recommendations

- The need for Energy Storage grows with more wind & solar power.
- Many storage options; but large-scale **CHW TES** offers advantages.
- In 39 MWh example, **CHW TES** (vs batteries) is 50-70% lower $/kWh; plus it has higher efficiency (near 100%), and longer life (40+ yrs).
- 30 yrs of successful applications; many owners with multiple TES.
- Additional benefits for MCFs, CHP, TIC, and fire protection.

Grids and microgrids with large cooling needs (air-conditioning, process cooling, or Turbine Inlet Cooling) should consider incorporating CHW TES, as it likely offers lowest $/kWh of storage and lowest $/ton of cooling.

District Energy's aggregated thermal loads uniquely represent a prime opportunity to employ TES, rather than batteries or other ES.

Questions / Discussion ?

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