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Thermal Storage in the Era of Sustainability

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THERMAL STORAGE IN THE ERA OF SUSTAINABILITY

By William P. Bahnfleth, PhD, PE

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Integrating Indoor Air Quality and Energy Efficiency in Buildings

During the 1980s and 1990s, cool thermal energy storage (TES) was a key technology in US utility demand-side management (DSM) programs. Interest in TES declined steeply as incentives disappeared during utility deregulation. Today, the focus of design has shifted from energy cost savings toward sustainability and it is reasonable to ask whether TES has anything to offer in this environment. This presentation will review the essentials of cool thermal energy storage and examine its relevance to sustainable design. Specific issues examined will include the impact of TES on site and source energy consumption, the economic case for TES without the incentives of the DSM era and the role of TES in achieving net zero energy buildings and communities.

Learning Objectives

- ▶ Describe the basic concepts of cool thermal energy storage
- ▶ Explain how poor application of thermal storage detracts from sustainability
- ▶ Explain how thermal energy storage can contribute to sustainable operation of buildings
- ▶ Identify opportunities for effective integration of thermal energy storage in green buildings and energy systems

Outline

- ▶ Sustainability and buildings
- ▶ Thermal energy storage basics
- ▶ How thermal energy storage came to be a "non-green" technology
- ▶ How thermal energy storage can support sustainable buildings – site and source energy savings
- ▶ Case study
- ▶ Summary and conclusions

Sustainability

- ▶ *Our Common Future* (1987), United Nations Bruntland Commission

“Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.”

- ▶ What would the future like to inherit from us?
 - Food, water
 - Nature
 - Energy
 - Culture

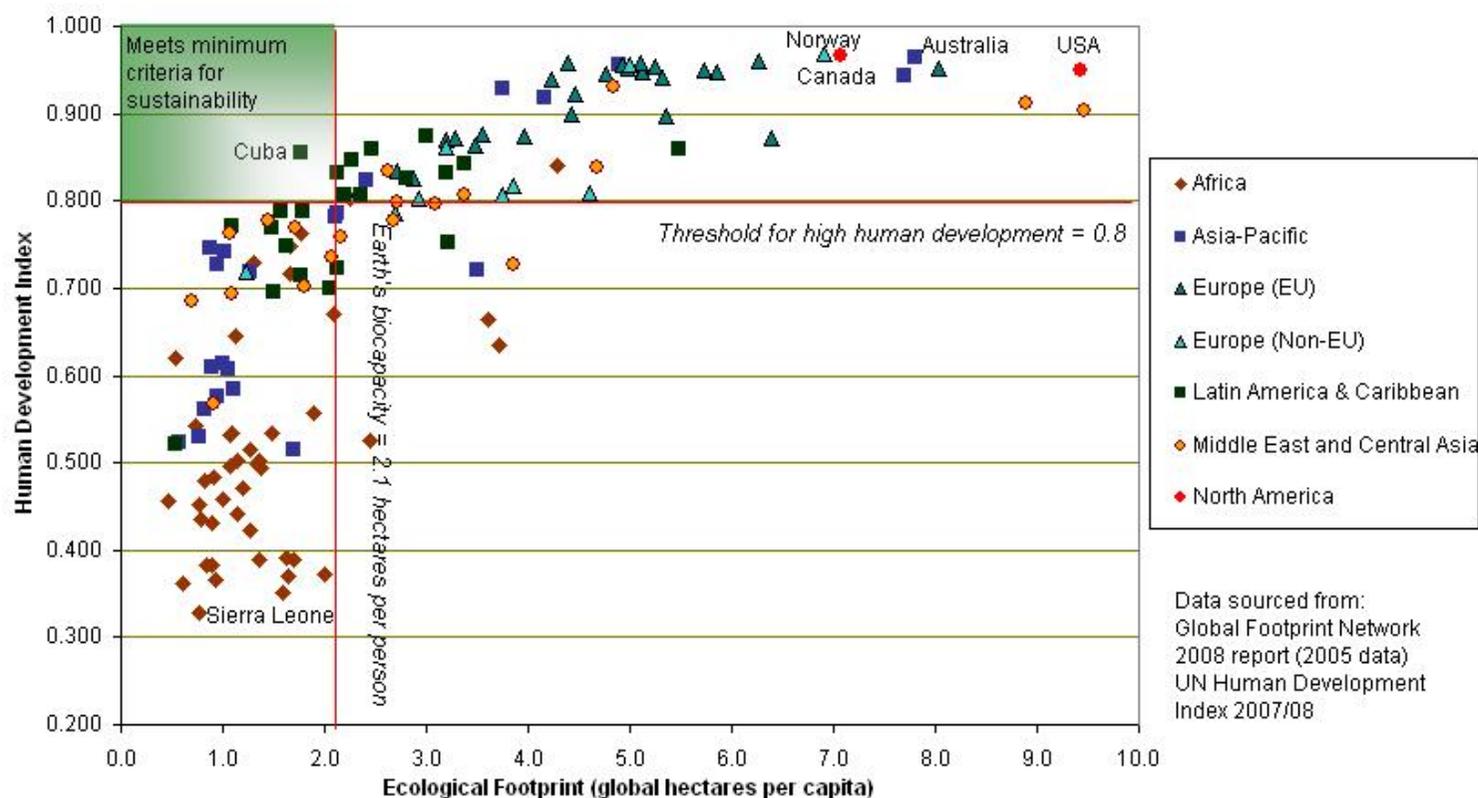
Built Environment and Sustainability

- ▶ Buildings are a high expression of human culture
- ▶ Essential to health and well-being
- ▶ Essential to productivity
- ▶ Major users of energy and water
- ▶ Major generators of pollution



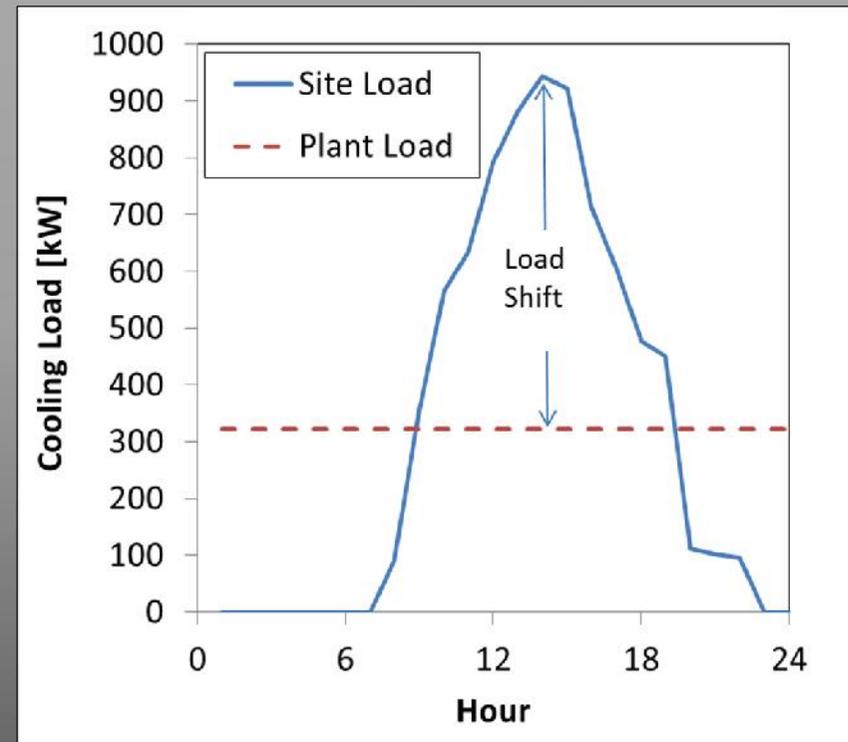
Acceptable Sustainability – Balance

Human Welfare and Ecological Footprints compared



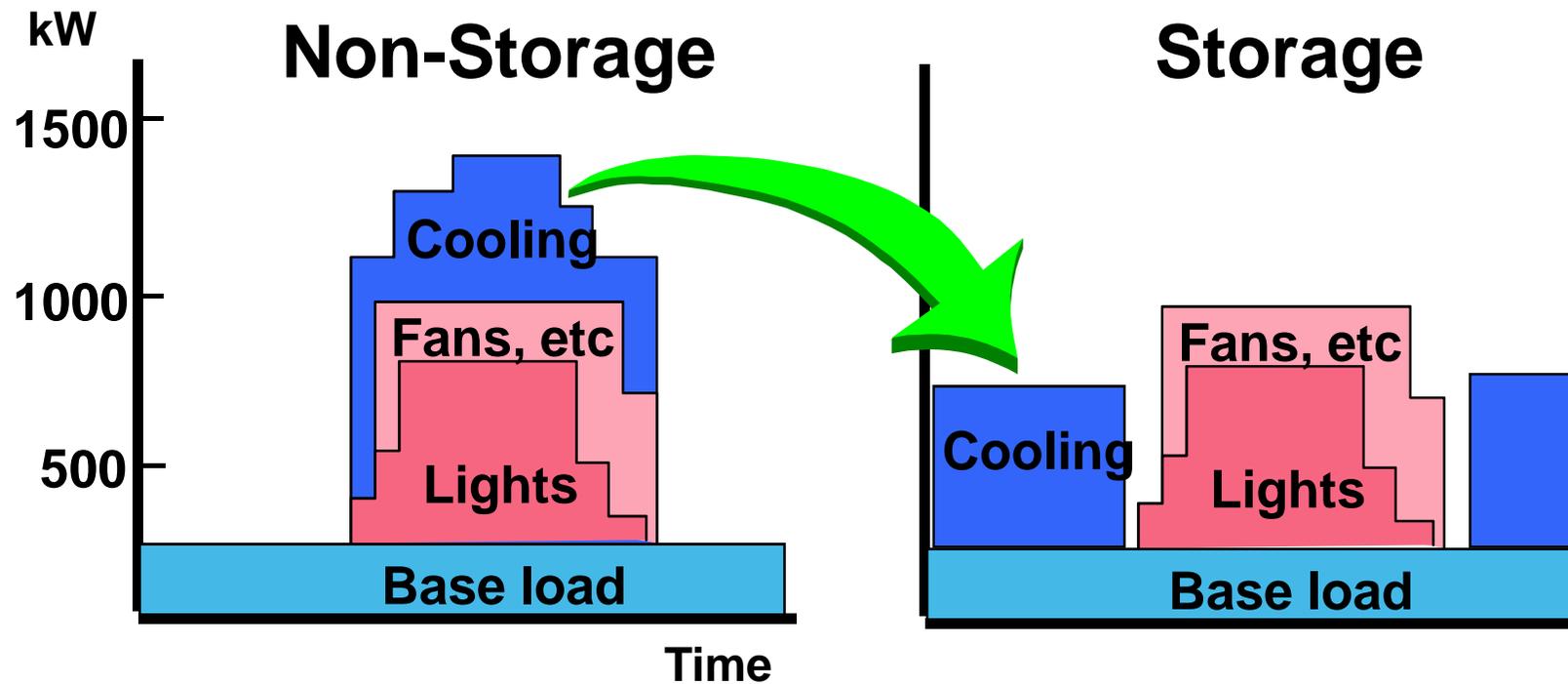
Cool Thermal Energy Storage (TES)

- ▶ Production of cooling capacity at one time for use at another time
- ▶ Uncoupling of system cooling load from plant cooling load
- ▶ Effects
 - Reduce peak demand
 - Increase load factor



1 kW_r = 0.284 ton

TES Effect on Electric Profiles

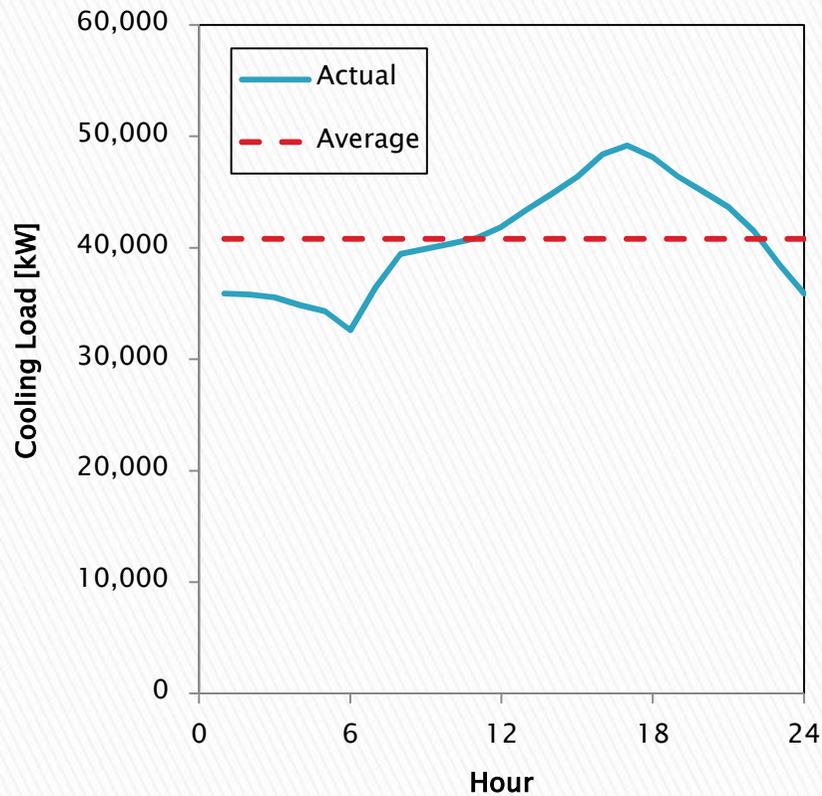


Thermal storage lowers peak electric demand, shifts use to evening

Load Factor

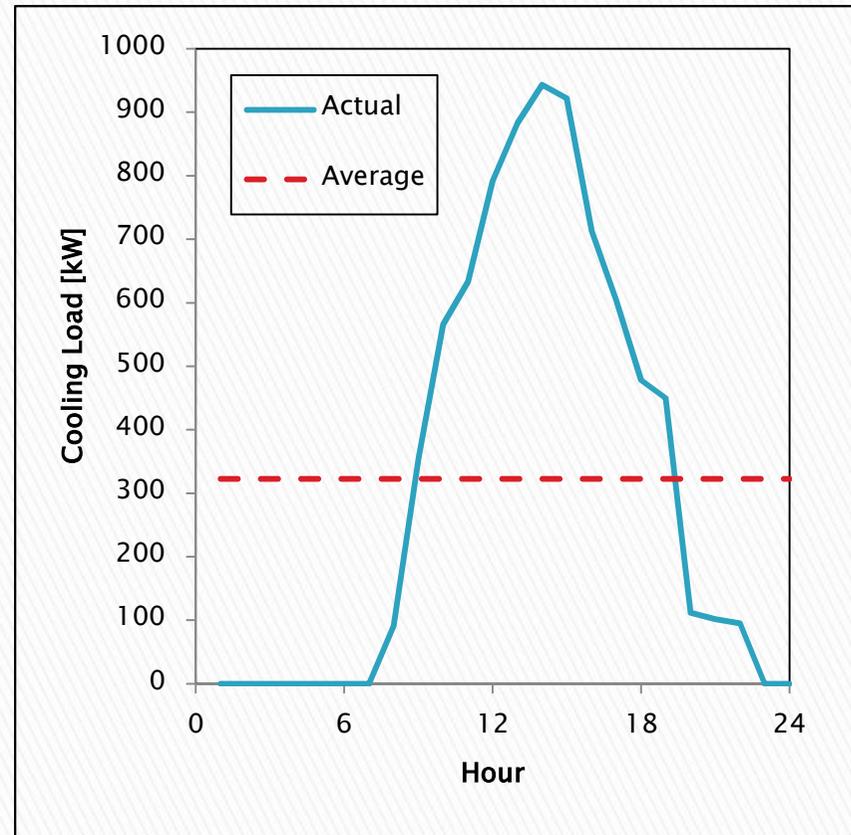
- ▶ Ratio of average load to peak load—measure of capacity utilization
- ▶ Low load factor →
 - Larger generation requirement
 - Lower efficiency
- ▶ Increasing load factor →
 - Reduces generation requirement
 - Improves efficiency
- ▶ TES increases load factors
 - Plant (thermal)
 - Site (electric)
 - Grid (electric)

Cooling Load Factor



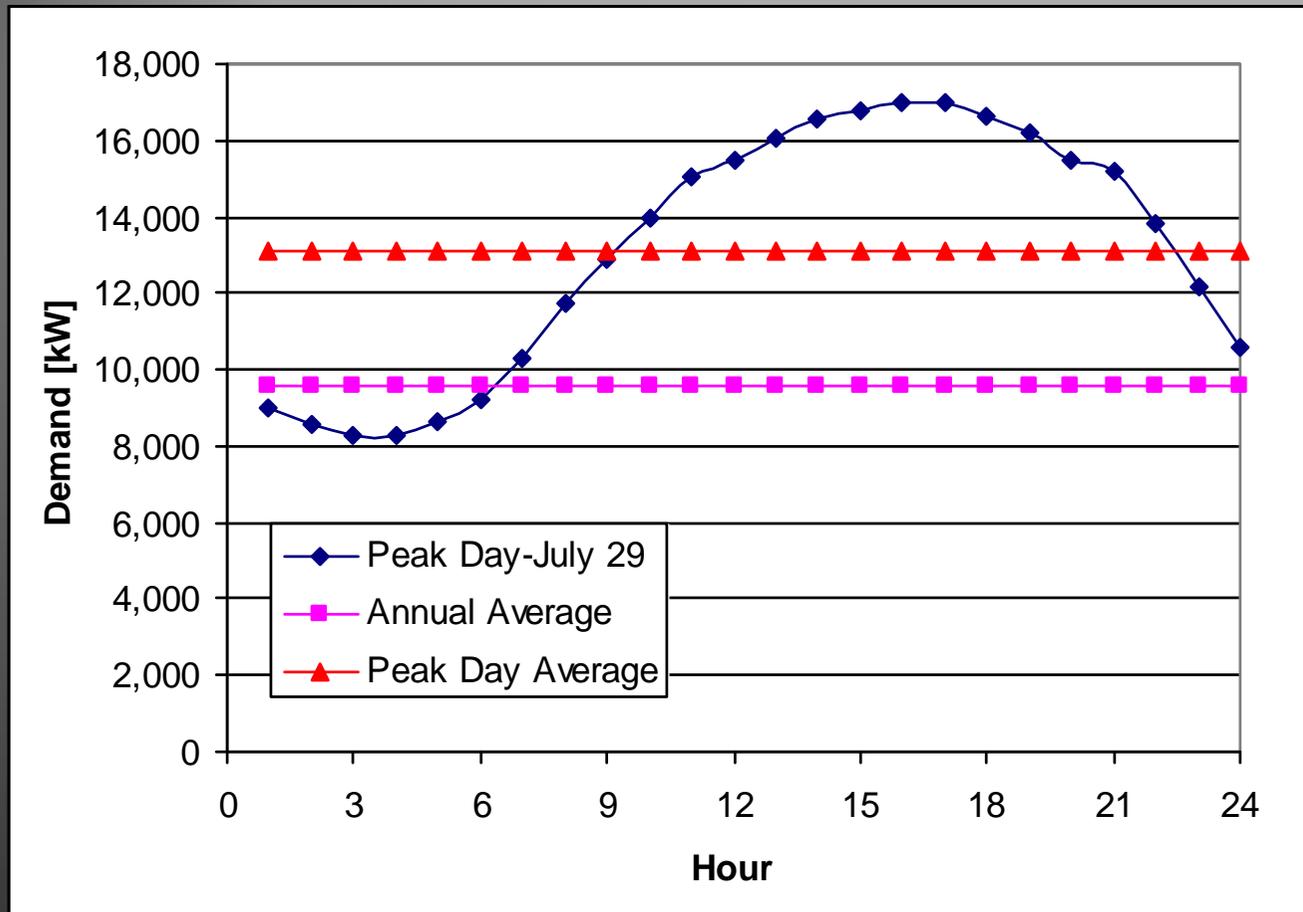
Campus: 83%

1 kW_r = 0.284 ton



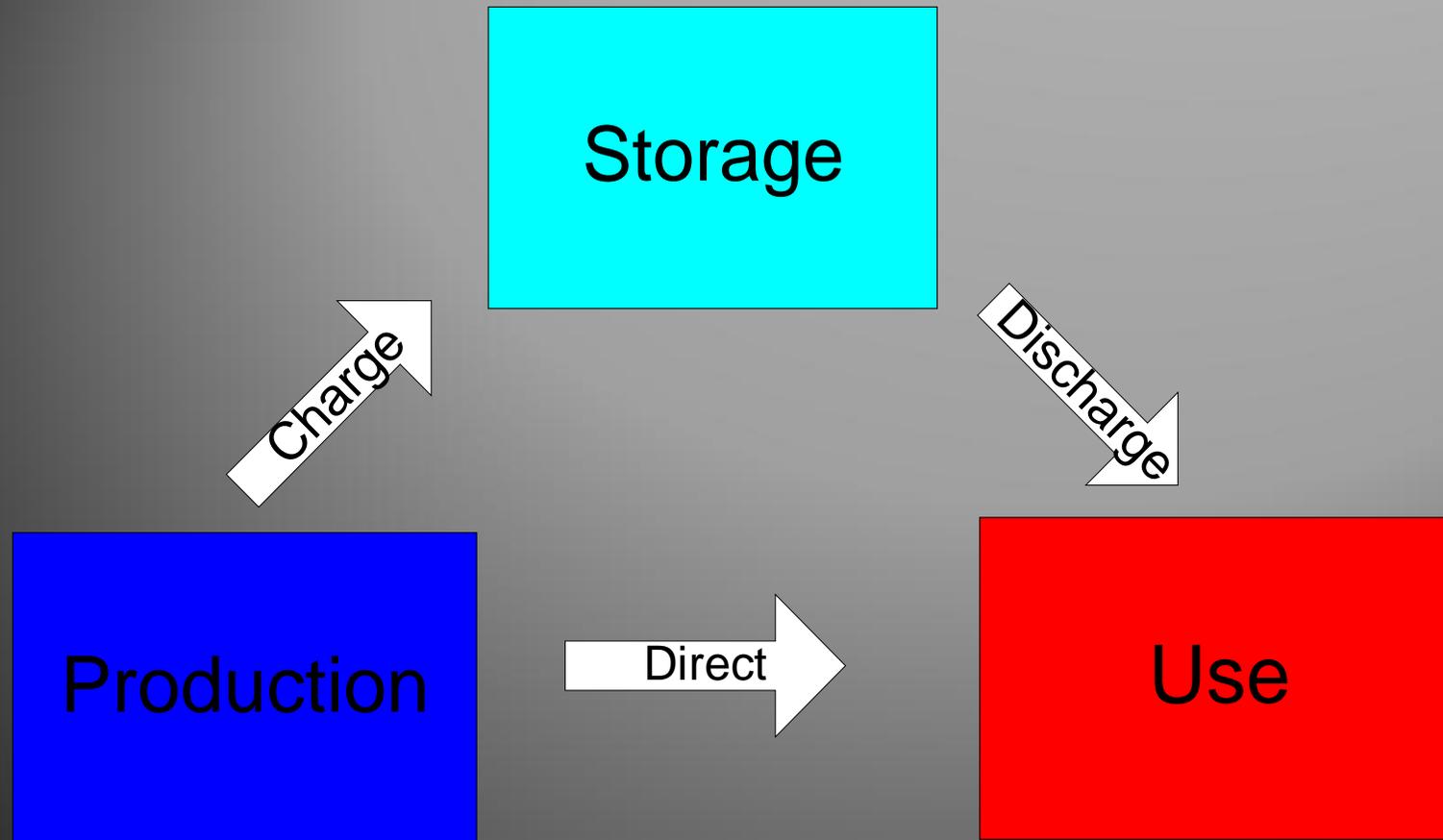
School/Office: 30%

Utility Load Factors can Benefit from TES

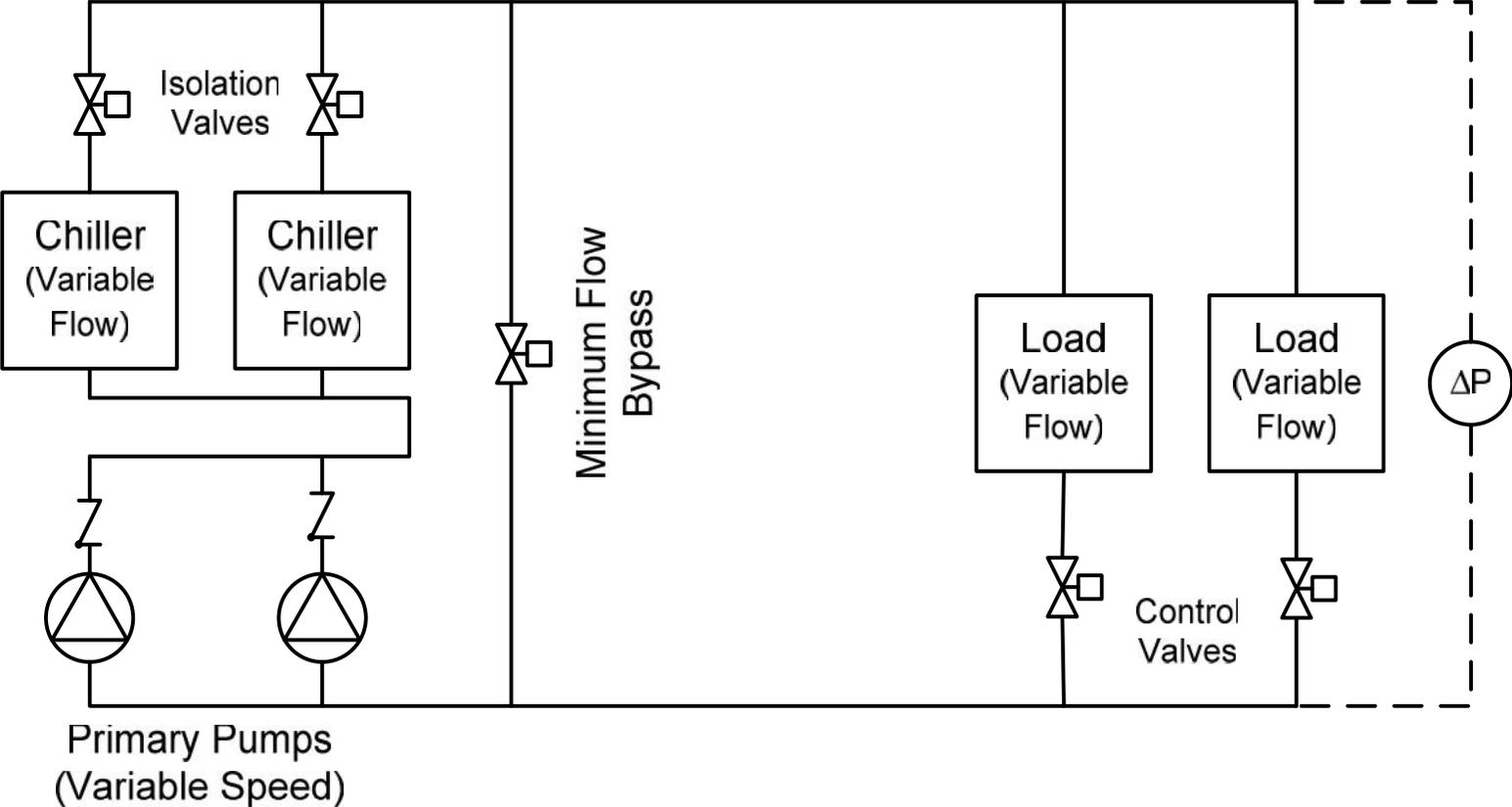


Western US Utility: 56% Annual, 77% Daily Load Factor

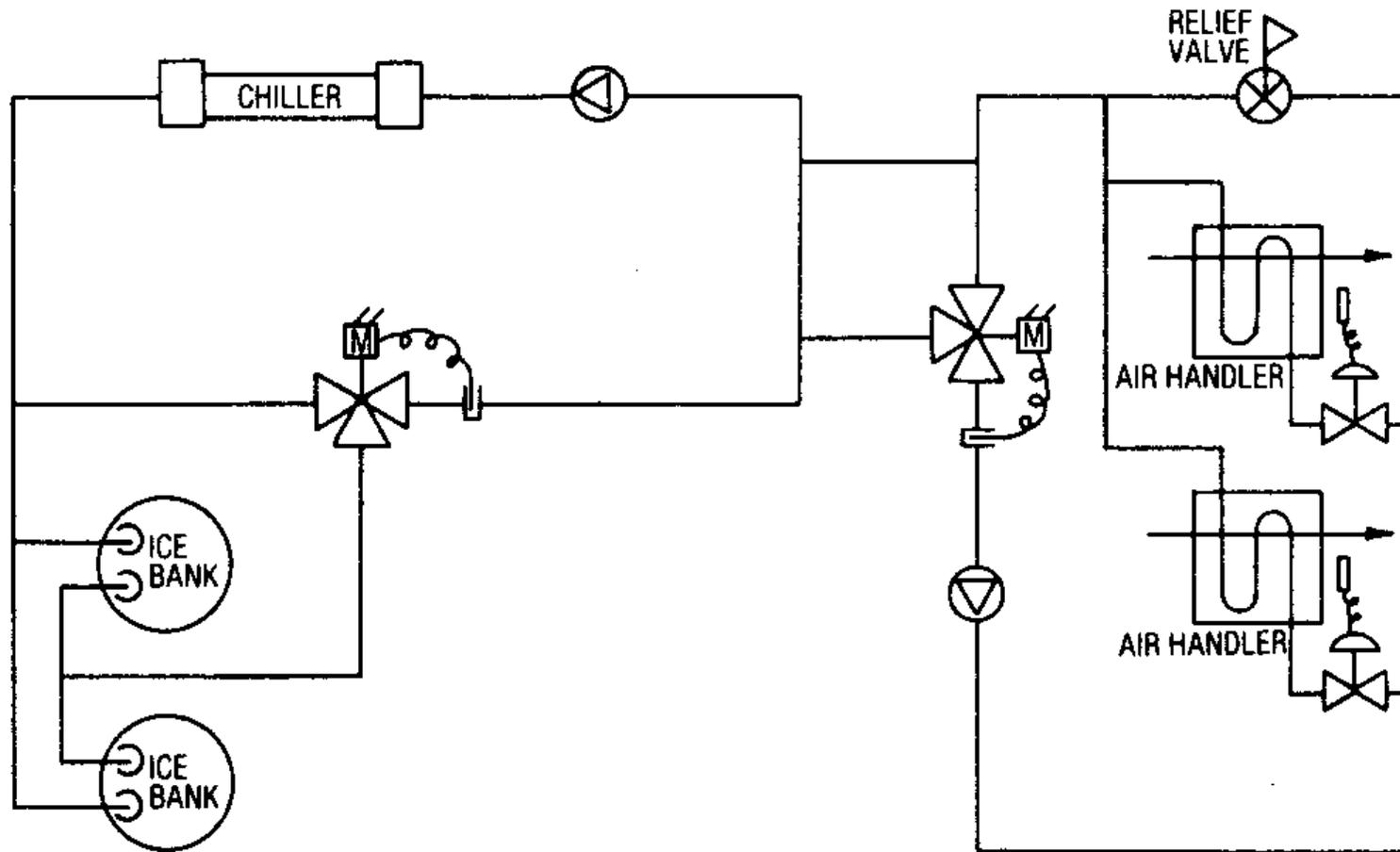
TES Operating Modes



Non-Storage Cooling System



Cooling System with TES



TES Benefits–Operating Cost Savings

- ▶ Electric cost savings from load shifting
 - Peak demand reduction
 - Favorable TOU charge differentials
 - Increased efficiency?
 - Site
 - Source and transmission

TES Benefits–Capital Cost Savings

- ▶ Smaller...
 - Chillers and ancillary equipment (cooling towers, pumps, etc.)
 - Electric service
- ▶ Reduced cost of distribution components by exploiting low temperature to increase ΔT on water and air
- ▶ Trade off with cost of TES components
- ▶ Good retrofit – may work with existing chillers

Recent History of TES

▶ Demand-side management

Capital cost benefit to electric producer: reducing demand cheaper than new capacity

Penalties/rewards in rate structure

Incentives

- Technical support
- Rebates
- Special rates

Viewed as an economic transaction between producer and customer, not an efficiency measure

Recent History of TES, cont'd

- ▶ Backlash and Deregulation

 - Belief that TES increases energy use – not “green”

 - Too many failed systems – unintended consequence of incentives

 - End of regulatory conditions that funded incentives

 - TES dead?

- ▶ “Crisis” for TES led to efforts to evaluate and identify its potential as a green/sustainable technology

How can TES Support Sustainability

- ▶ Site energy savings
- ▶ Source energy savings

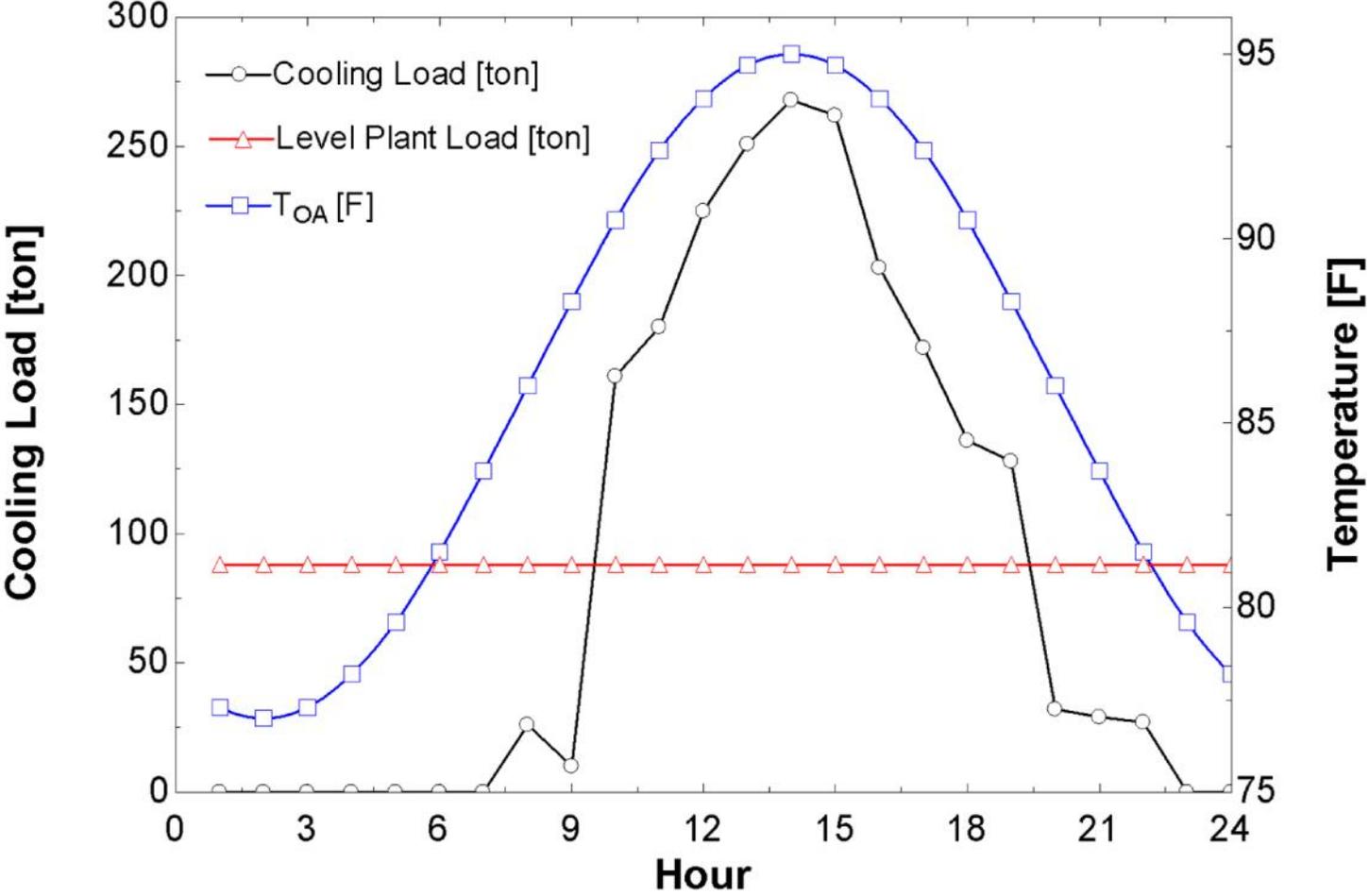
Site Energy

- ▶ Can thermal save energy on-site?
 - Day - night condensing ΔT is favorable
 - Less low part-load equipment operation is favorable
 - Standby capacity loss and added pumping are unfavorable
- ▶ Ice storage
 - Difficult - reduced evaporator temperature for charging
 - Possible if combined with low T air and water distribution for large ΔT
- ▶ Chilled water
 - More feasible - little or no charging penalty

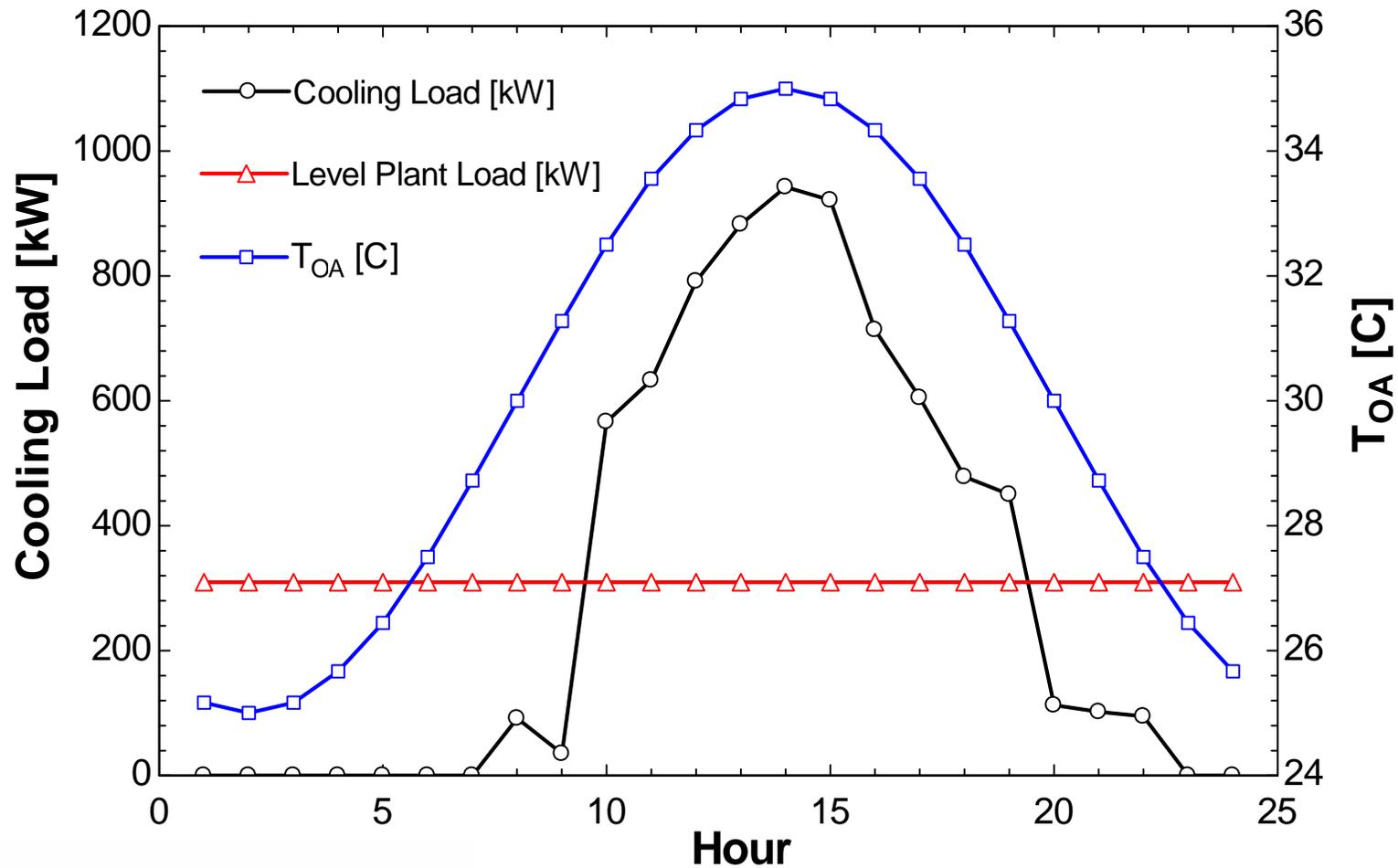
Site Energy Use Example

- ▶ Condensing temperature effect
 - Low load factor design-day profile
 - Air-cooled system
 - Sinusoidal OA dry-bulb variation with 95F (35C) peak and 18F (10C) daily range
 - Chiller performance
 - Air-cooled screw chiller
 - Neglect part load effects
 - kW/ton = f(OAT only) with 40F (4.4C) LCHWT
 - LCHWT same for TES, non-storage system

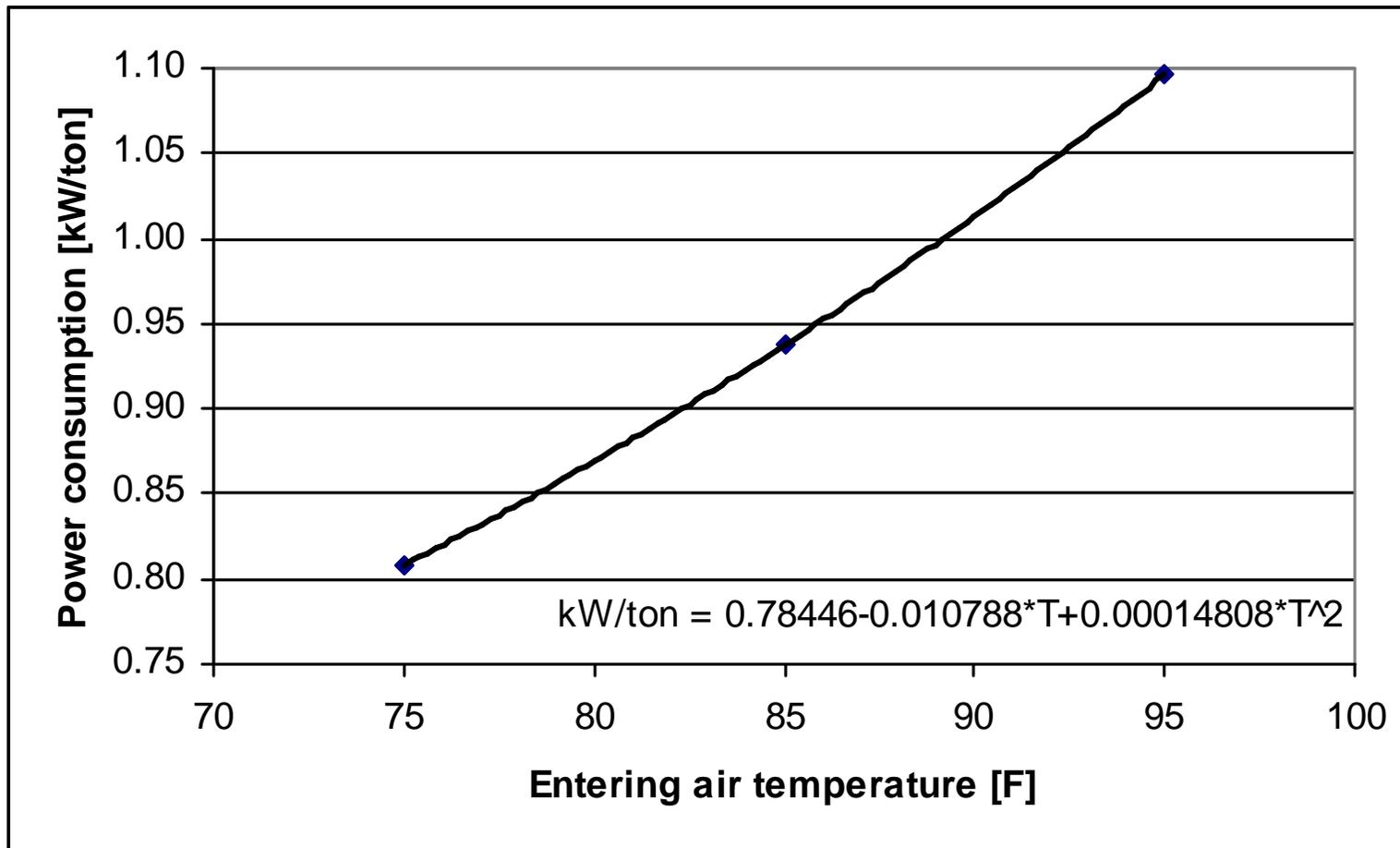
Loads and Ambient Temperature (IP)



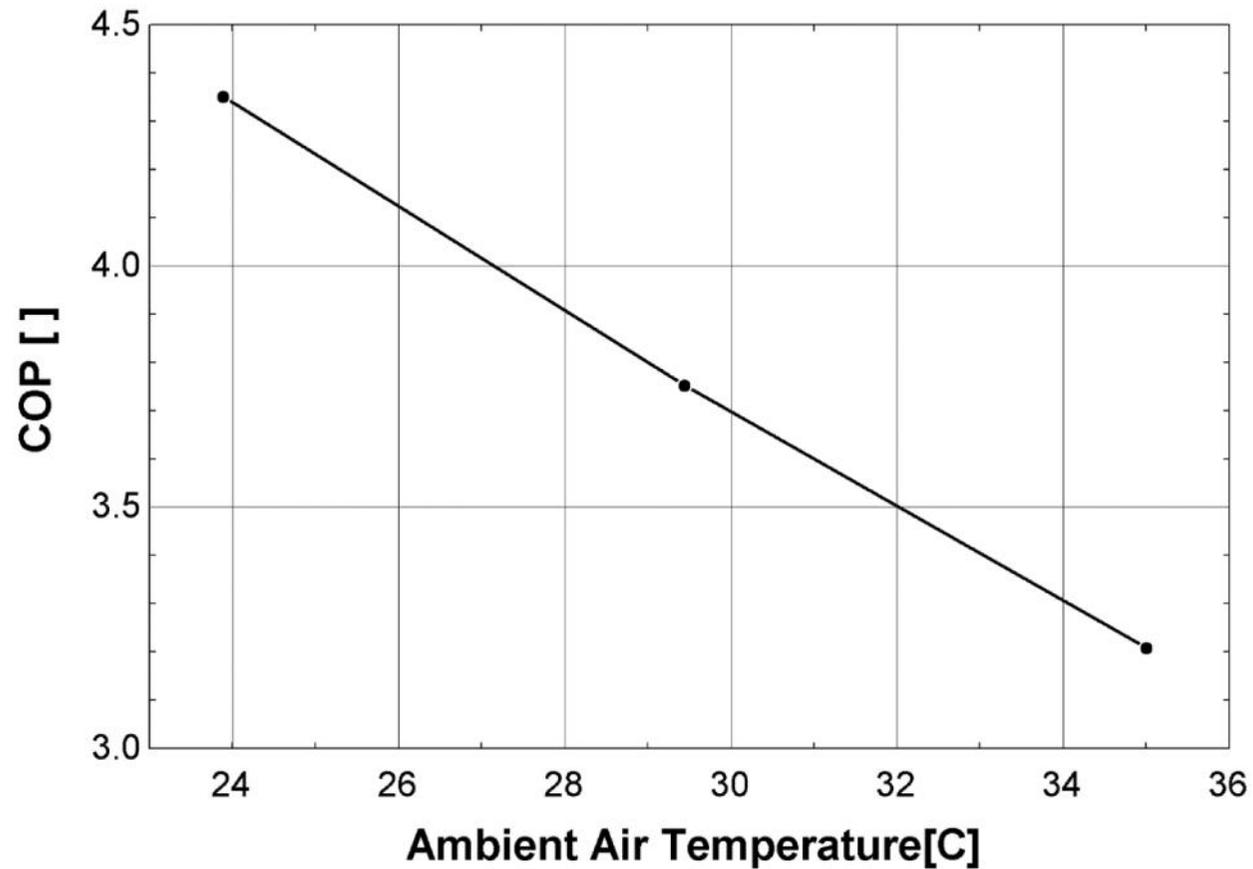
Loads and Ambient Temperature (SI)



Air-Cooled Chiller kW/ton

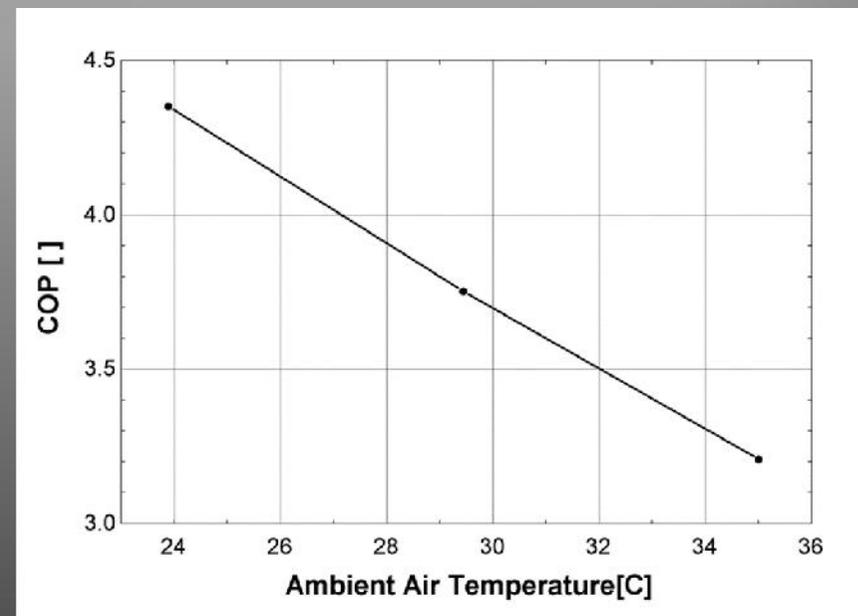
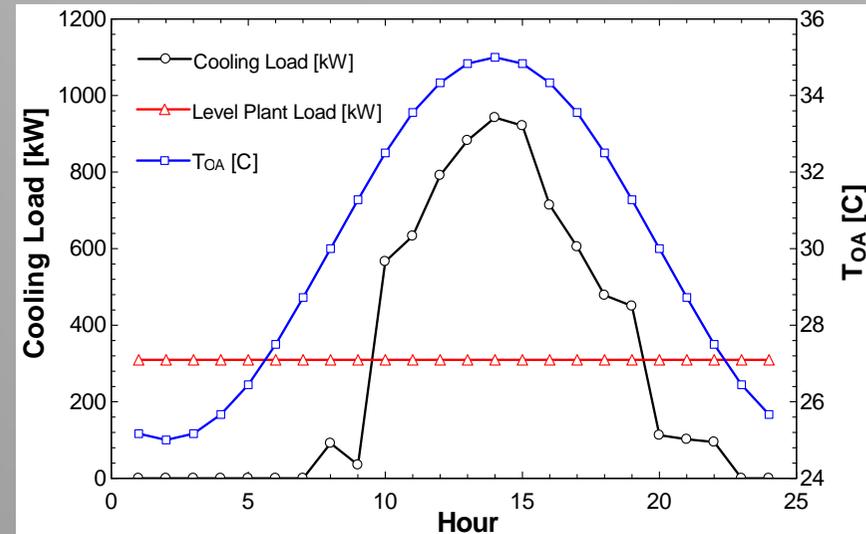


Air-Cooled Chiller COP



Results

- ▶ Load weighted outdoor dry-bulb
Charging: 81F (27.2C)
Discharging: 93F (32.9C)
- ▶ Total chiller energy consumption
TES: 2021 kWh
No TES: 2229 kWh (+10.3%)
- ▶ Charging storage vs. direct to load
Charge: 977 kWh
Direct to load: 1185 kWh (+21.3%)



Verified Energy Savings

a) 1991 Cooling Season--Operation without Thermal Storage

	Chilled Water Production		Electric Energy Use		Plant Efficiency	
	ton-h	MJ	kWh	MJ	kWh/ton-h	COP
CWP I	10,279,352	130,259,949	7,536,520	27,131,472	0.73	4.80
CWP II	4,337,653	54,966,739	5,017,600	18,063,360	1.16	3.04
CWP-III	<u>12,070,963</u>	<u>152,963,243</u>	<u>9,042,800</u>	<u>32,554,080</u>	0.75	4.70
Total	26,687,968	338,189,930	21,596,920	77,748,912	0.81	4.35

b) 1992 Cooling Season--Operation with Thermal Storage

	Chilled Water Production		Electric Energy Use		Plant Efficiency	
	ton-h	MJ	kWh	MJ	kWh/ton-h	COP
CWP I	7,810,603	98,975,961	5,094,560	18,340,416	0.65	5.40
CWP II	1,799,392	22,801,895	1,496,600	5,387,760	0.83	4.23
CWP-III	<u>14,036,213</u>	<u>177,866,891</u>	<u>10,338,000</u>	<u>37,216,800</u>	0.74	4.78
Total	23,646,208	299,644,748	16,929,160	60,944,976	0.72	4.92
Pct. Change, 1991-1992		-11.4		-21.6		11.1

Bahnfleth, W.P. and W.S. Joyce, 1994. Energy use in a district cooling system with stratified thermal energy storage. ASHRAE Trans.

Verified Energy Savings

Building	Location	TES Size (ton-hours)	Partial/ Full	New/ Retrofit	Summer kW Savings	% kWh Savings	Cooling Method**	Source	Comments
Commercial-Industrial									
Chilled Water Storage									
Electro-Optics Plant	Dallas, TX	24500	F	R	2900	12%	M, B	Energy Engineering, Vol. 89, 4	heat recovery
University	Fullerton, CA	40000	F	R	3360	13%	S	Brown & Caldwell	heat recovery
University	Tempe, AZ			R	7000	13%	B	ITSAC, Tech Bulletin, 1-92	
College	Houston, TX	4000		R		8-9%	B	CBI, ASHRAE, 6-93	
Prison	Lancaster, CA	12600		N		15-25%	S	ITSAC, Vol. 5.4	LTD water & water side economizer
Supermarket	Miami, FL					17%		EPRI, CU-3031	
Data Processing	Bloomington, IL	44800		N	5400	3%	S	CBI, ASHRAE, 6-93	
Chilled Water replacing rooftops									
Assembly	Windsboro, SC	7500		N		44%	S	ITSAC, Vol. 5.3	
Ice Storage with Cold Air Distribution									
School	Morristown, PA	720	P	N		30%	B	ITSAC, Vol. 9.6	includes Energy Mgmt System
Office	Chicago, IL					5-15%	B	ITSAC, Vol. 9.5	
Office		2000	P	N	400	6-14%	S	BAC Bulletin: Case Study 3-6	
Ice Storage replacing Rooftop/Unitary Systems									
Office	Vincennes, IN	25	P		7	16%	M	EPRI, TR-101038	
Assembly	Granston, RI	3000	F	R	700	50%	B	ITSAC, Vol. 9.6	
School	Cherry Hill, NJ		P	R		12%	M	EPRI	
Residential									
	Richmond, VA		F	N	3	12%	M	Virginia Power	heat recovery for hot water

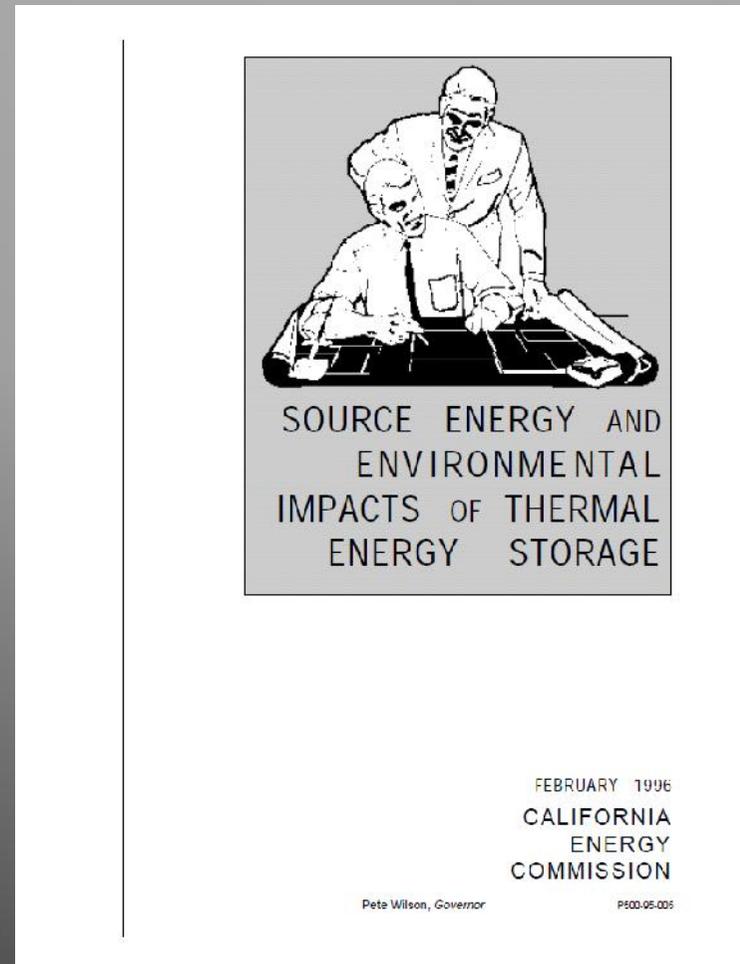
Systems with TES reviewed by California Energy Commission that achieved site energy savings over non-storage alternatives

3 - 50% reduction in cooling energy use

http://www.energy.ca.gov/reports/500-95-005_TES-REPORT.PDF

Source Energy and Emissions

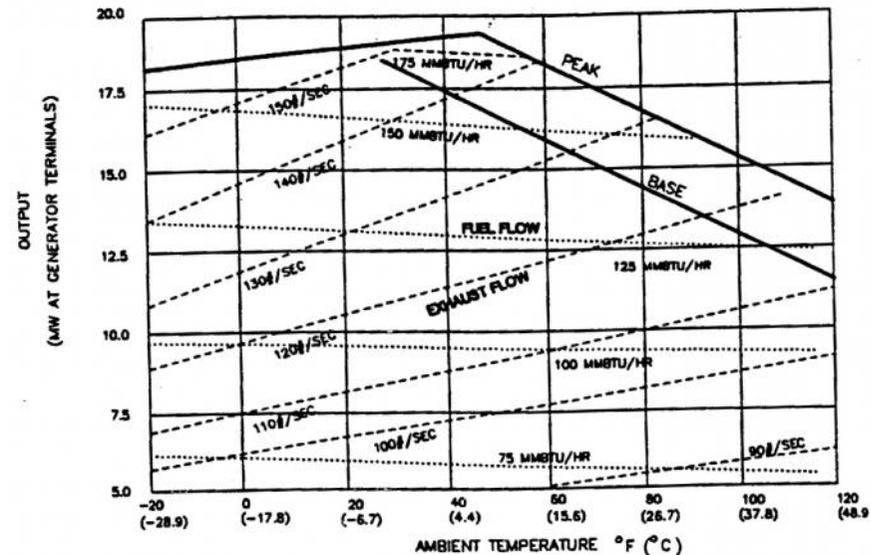
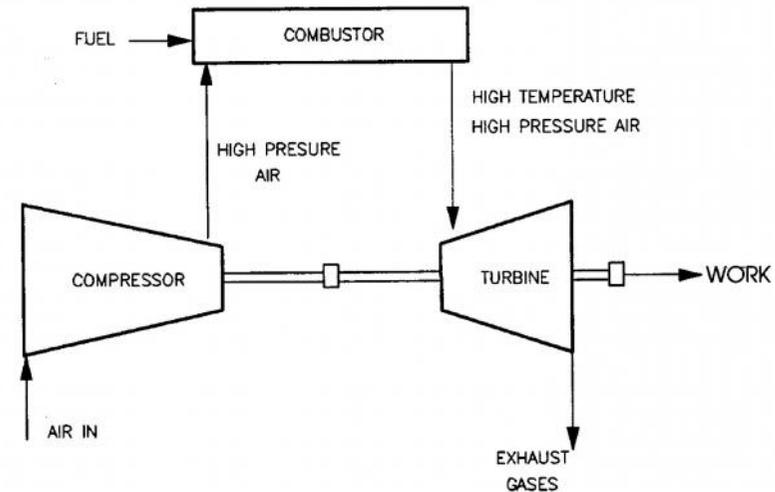
- ▶ How?
 - Use more efficient capacity
 - Lower transmission losses
- ▶ California Energy Commission
 - Source energy savings of 36–43% per kWh shifted for one utility, 20 – 30% for another.
 - Similar emissions savings



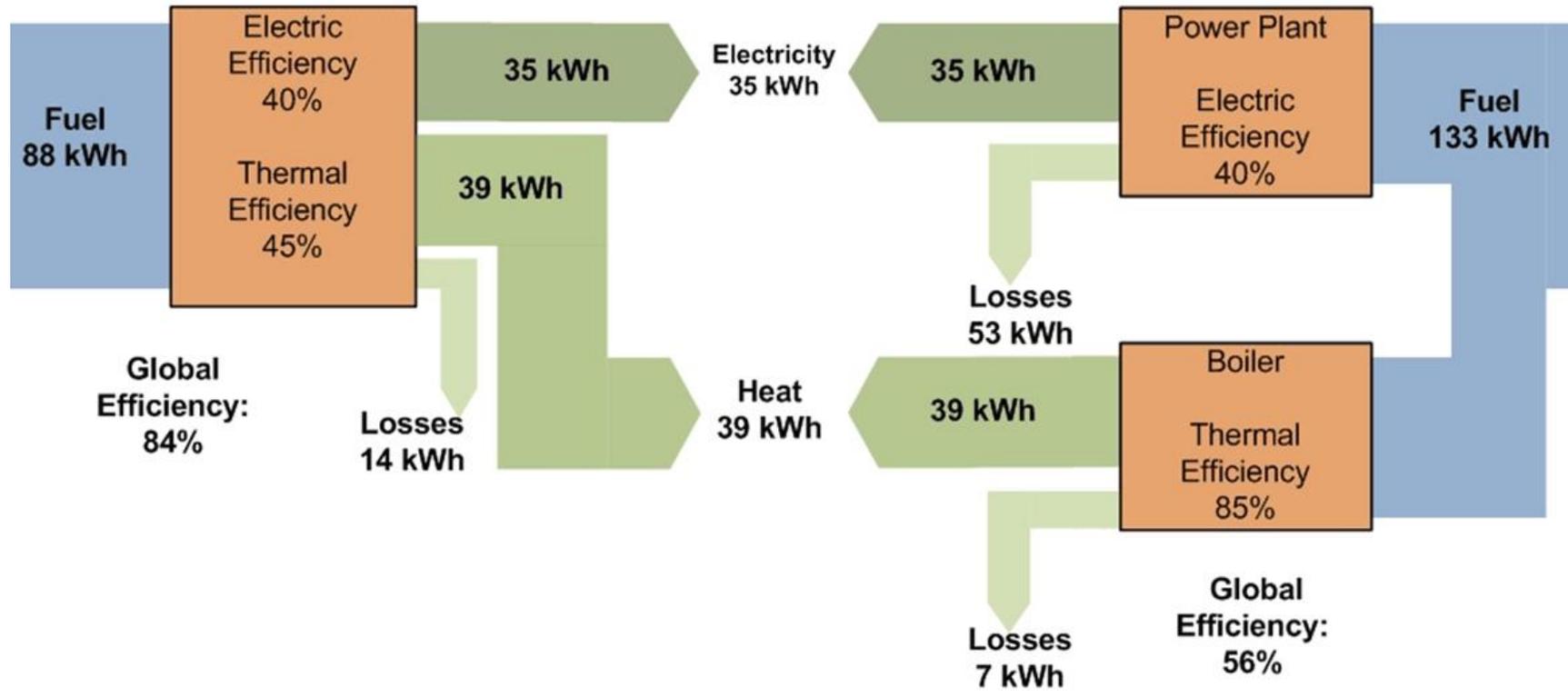
http://www.energy.ca.gov/reports/500-95-005_TES-REPORT.PDF

Power Production

- ▶ Thermal storage helps maximize power production and efficiency for gas turbines
- ▶ Using stored cooling capacity to boost turbine peak output maximizes net electric production



Combined Heat and Power



CHP efficiency depends on having simultaneous loads or storage to modify load profiles

Renewable Energy

- ▶ Storage will be important for maximizing use of renewable sources such as wind power and solar thermal that are intermittent.
- ▶ Excess electricity production can make cooling capacity an alternative to battery storage

Water Use

- ▶ Lower evening T_{wb} requires less condenser water evaporation
- ▶ Water-cooled absorption uses more CW than electric vapor compression
- ▶ If objective is demand response, VC + TES uses less water



Chilled Water Storage Case Study



Case Study

Cornell University, Ithaca NY

- ▶ 1st Place ASHRAE Technology Award

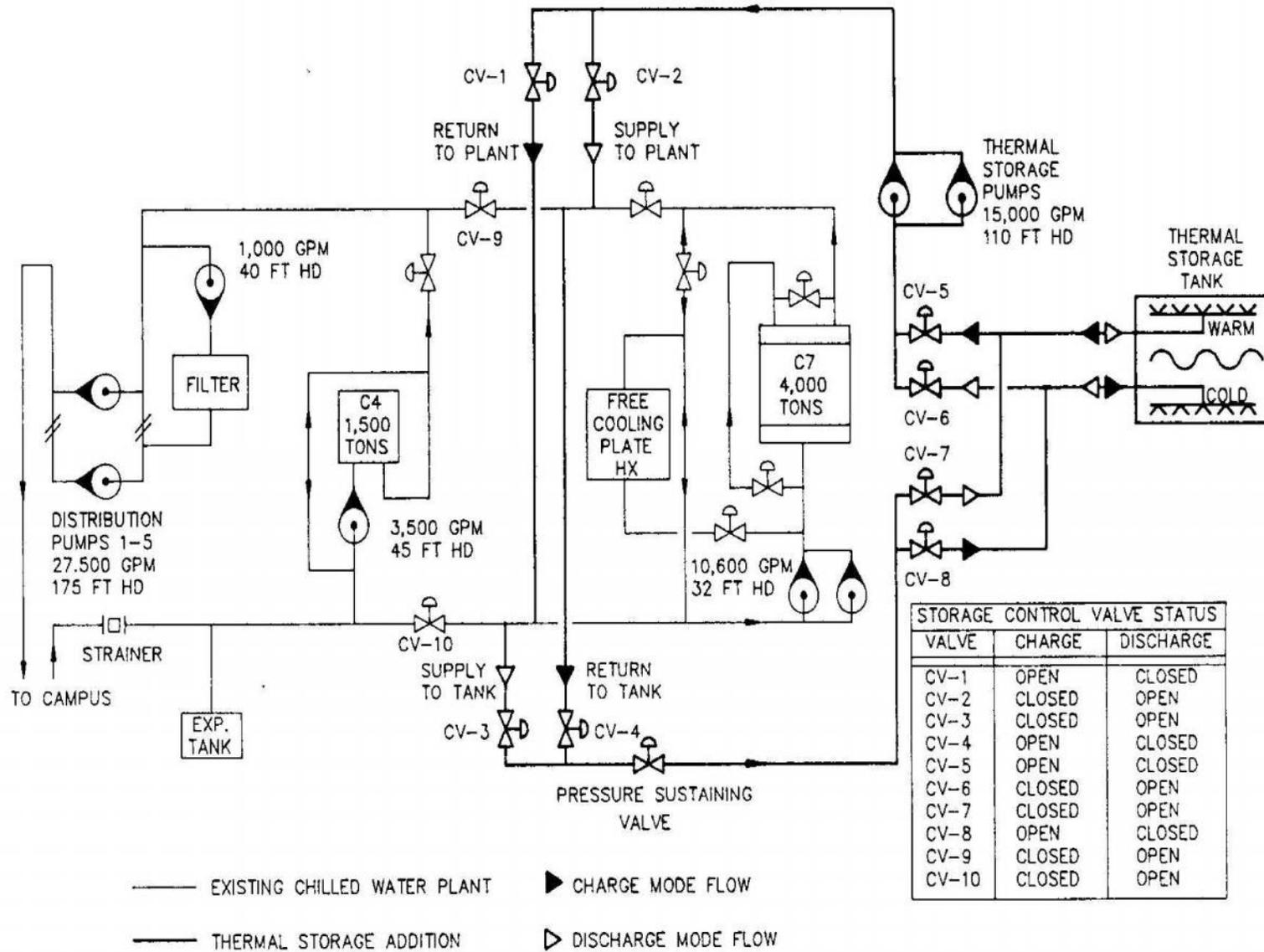


Pre-Conditions

- ▶ Peak load 11,500 ton (40,444 kW) with significant growth anticipated
- ▶ Capacity addition of 4,000 tons (14,067 kW) needed, including plant room, tower, pumps
- ▶ Three primary/secondary CHW plants

Feasibility Analysis

- ▶ 4.4 million gal (16,656 m³) of stratified chilled water storage cheaper of chiller addition
- ▶ Storage capacity 30,000 – 40,000 ton-hr (105,506 – 140,674 kWh) depending upon ΔT
- ▶ > 10,000 ton (35,169 kW) of short-term capacity



Storage Tank

- ▶ Above-ground AWWA D100 steel
- ▶ 65 ft (19.8 m) water column – 35 ft (10.7 m) below system level)
- ▶ 105 ft (32 m) diameter
- ▶ Octagonal diffusers
- ▶ Foam insulation
- ▶ Thermocline measured 2 – 3 ft (0.6 – 0.9 m)
- ▶ FoM measured > 0.9

Feasibility Analysis

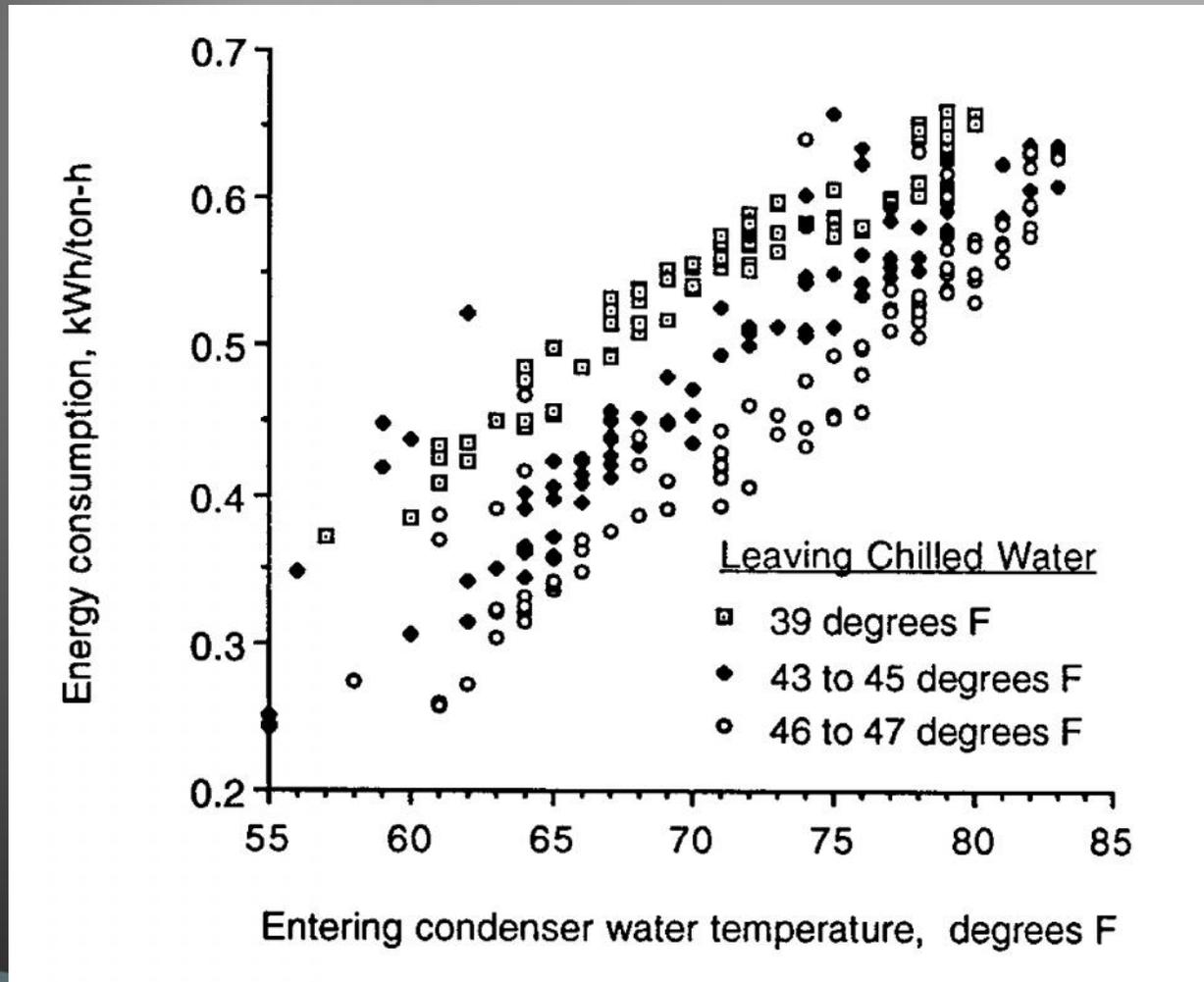
- ▶ \$4.6 million (~€ 3.5 million) budget cost (including unrelated plant modifications)
- ▶ \$500,000 (~€ 376,000) anticipated rebate from utility
- ▶ \$200,000 (~€ 150,000)/yr predicted electric savings

Actual Performance

- ▶ \$4.2 million (€ 3.2 million) construction cost
- ▶ \$600,000 (~€ 451,000) utility rebate
- ▶ > \$300,000 (~€ 226,000) in first-year energy cost savings
 - \$235,000 (~€ 177,000) in direct savings
 - \$65,000 (~€ 48,900) savings due to increased efficiency
- ▶ 8% increase in system COP (11% before adjustment for condensing conditions)

Actual Operation

$$1 \text{ kW/ton} = 0.284 \text{ kW}_e/\text{kW}_r$$



3.9 C
6.1-7.2 C
7.8-8.3 C

Actual Operation

Chiller 7 Charge and Discharge Mode Efficiency on a Typical Summer Day

Operating Mode and Chilled Water Temperature Range	Average Condenser Water Temperature		Efficiency		
	F	C	kWh/ton-h	COP	Difference in COP, %
Charge ¹ , 39F (3.9C)	69	21	0.53	6.65	4.7
Discharge ² , 43 - 45F (6.1 - 7.2C)	74	23	0.56	6.35	0.0 (reference)
Discharge ³ , 46 - 47F (7.8 - 8.3C)	74	23	0.47	7.44	17.2

Notes:

1. Total production: 30,143 ton-h (381,631 MJ).
2. Total production: 25,207 ton-h (319,138 MJ).
3. Total production: 18,515 ton-h (234,412 MJ).

Actual Operation

Load Distribution and Efficiency Impact of Thermal Storage

	Share of Chilled Water Production, Percent			Change in Efficiency, Percent
	Before	After	Change	
CWP I	38.5	33.0	-8.6	11.0 ¹
CWP II	16.3	7.6	-46.6	28.1 ¹
CWP-III	45.2	59.4	31.4	1.7 ²
Chiller 7	42.4	55.0	29.7	12.9 ³

Notes:

1. Includes chiller and distribution pumping energy.
2. Includes chiller, distribution, and thermal storage pumping energy.
3. Chiller 7 only.

Operating Strategy

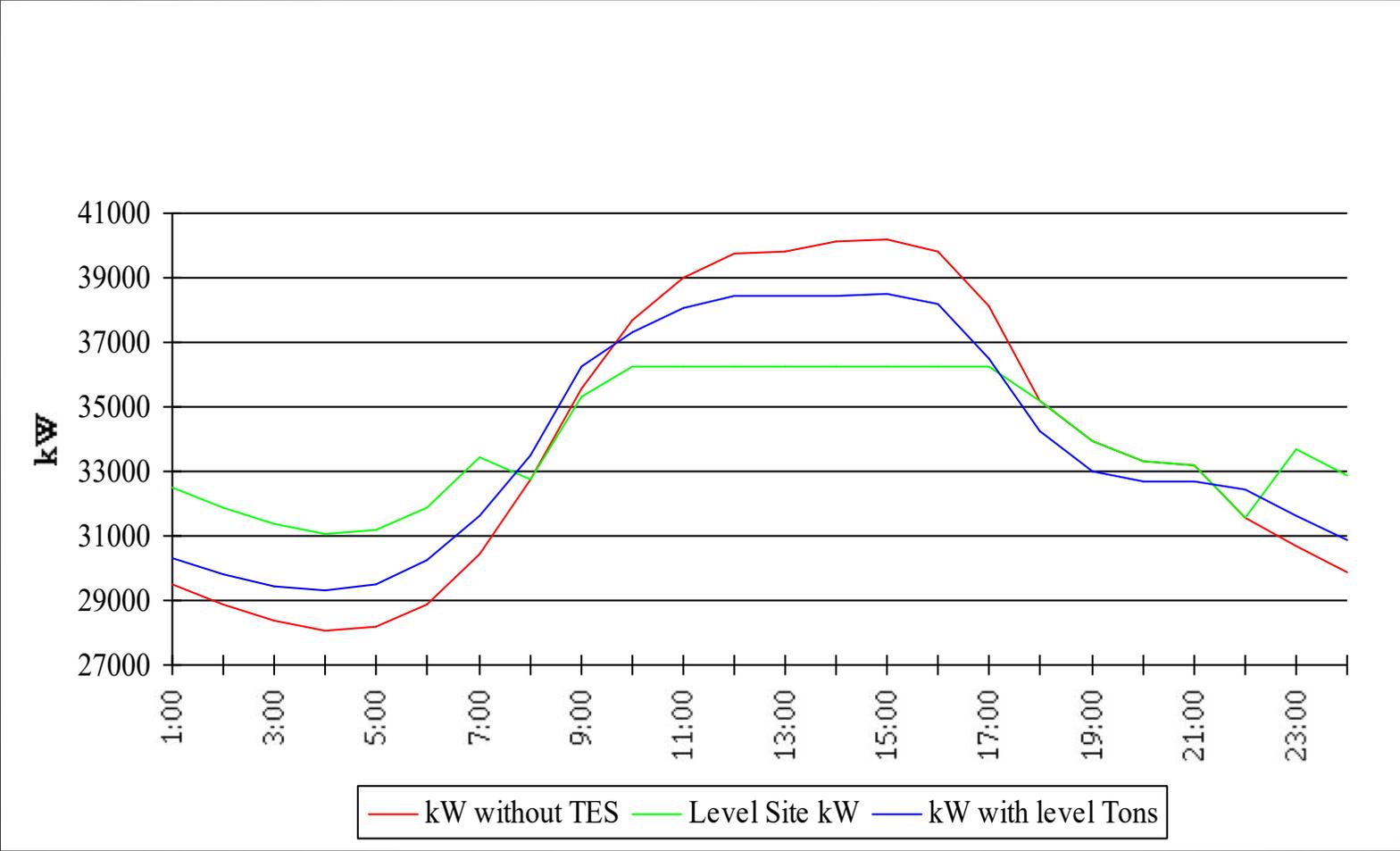
- ▶ Site demand limiting control
 - Set daily demand limit based on season and weather forecast
 - Modulate storage output on demand
 - Doubles peak demand reduction

Cooling Profiles

1 ton = 3.517 kW



Electric Profiles



Summary and Conclusions

- ▶ Thermal storage is a mature technology for load management – but underutilized
- ▶ Thermal storage can contribute to sustainability of buildings in many ways if it is properly applied
- ▶ Our challenge is to understand the sustainable uses of existing as well as new technologies and apply them in our practice

Thank you!

