Thermal Energy Storage in High Performance Buildings

Photo credit Bruce Coldham

Photo credit Hillside

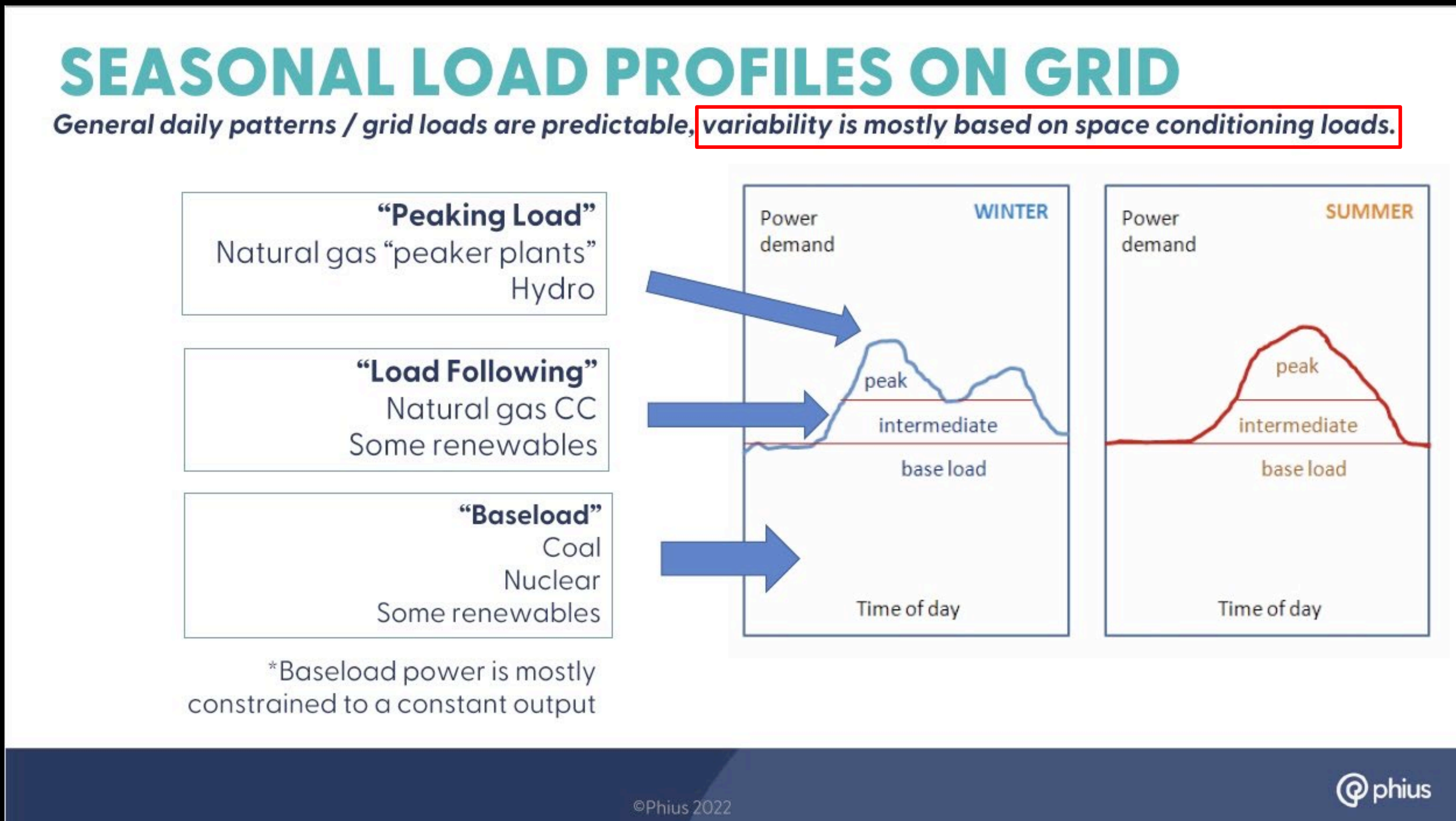
Photo credit Amanda Nickerson

Twenty-Sixth Westford Symposium on Building Science

Marc Rosenbaum, PE, CPHC, MA CSL – Energysmiths – West Tisbury, MA

Why Bother?

Grid Stability and Integration of Renewable Energy Sources

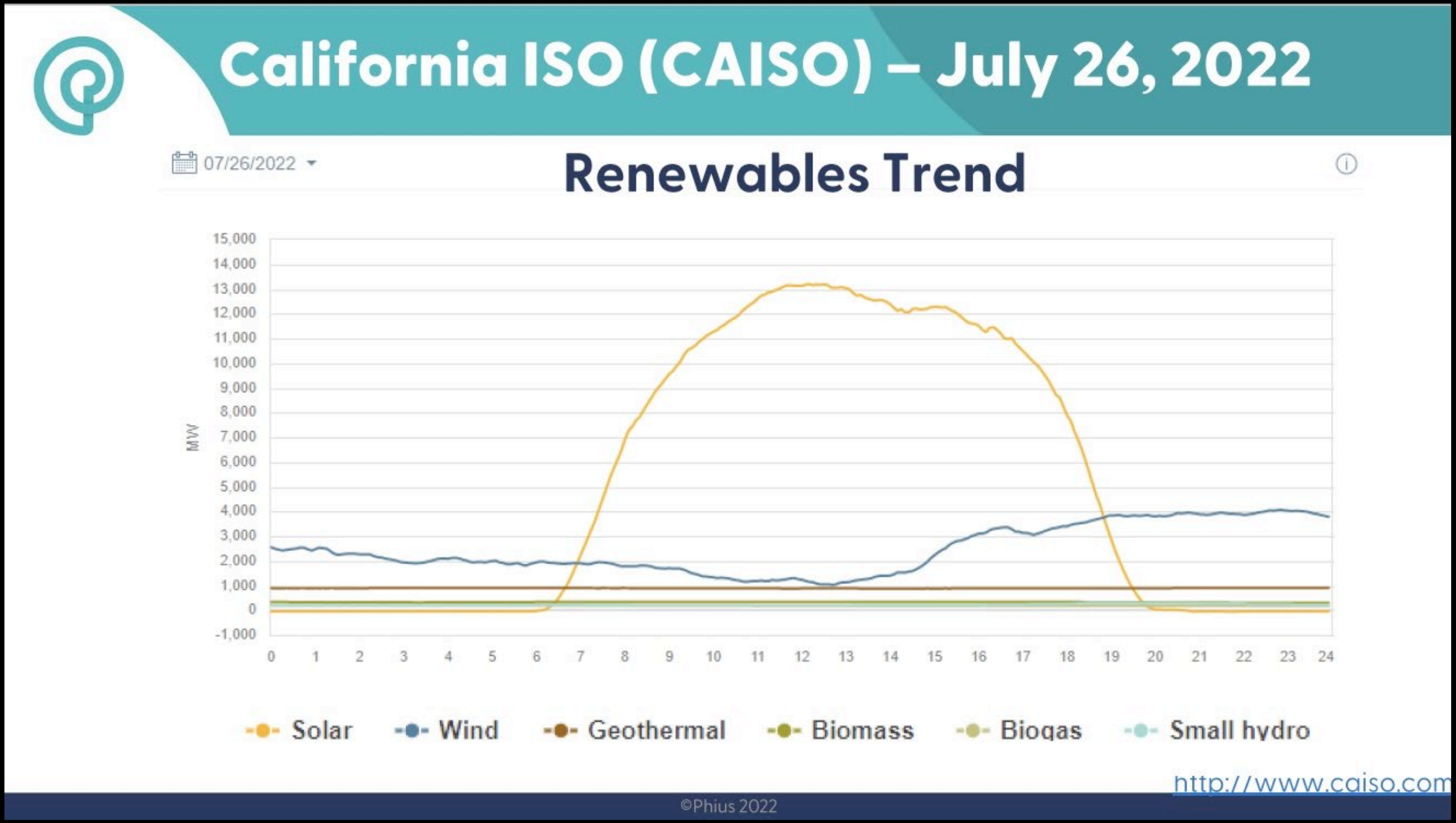


Huge Thanks to Lisa White and PHIUS for these slides

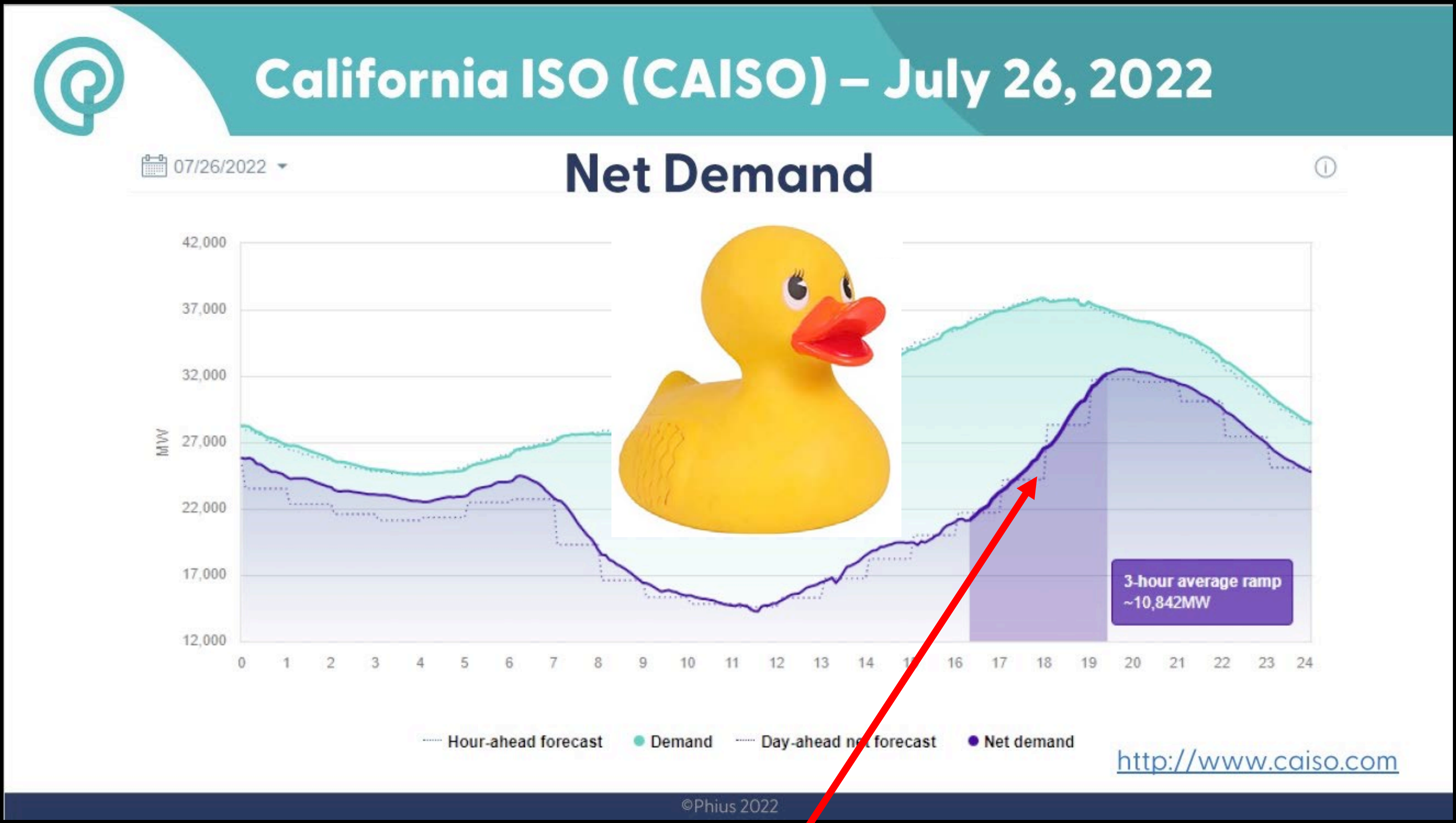
CA ISO Load

California ISO (CAISO) – July 26, 2022
07/26/2022
Demand Trend
42,000
37,000
32,000
27,000
22,000
MW
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Day-ahead forecast
Hour-ahead forecast
Demand
http://www.caiso.com
©Phius 2022

CA ISO Renewable Generation

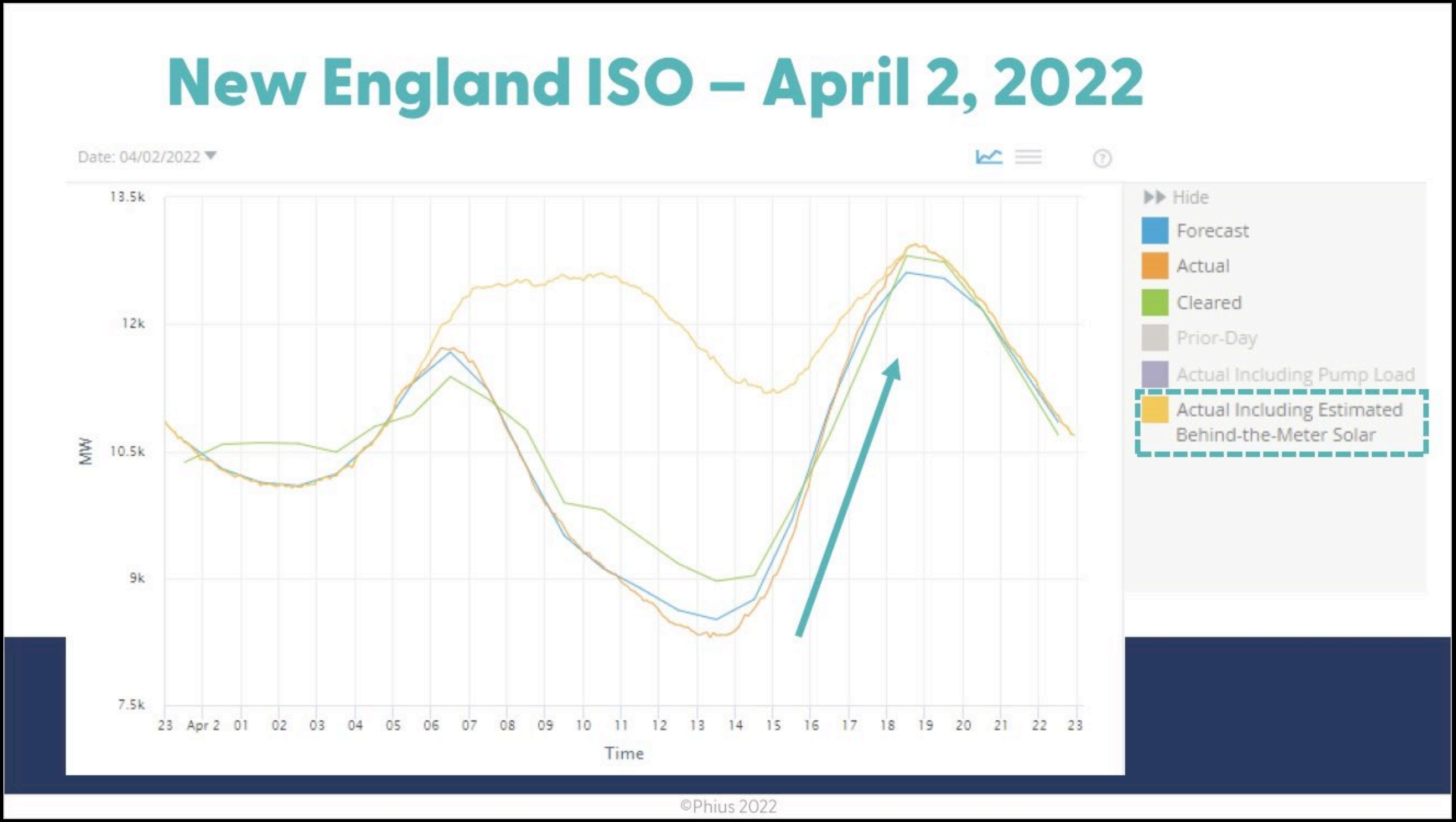


CA ISO Load After Renewables



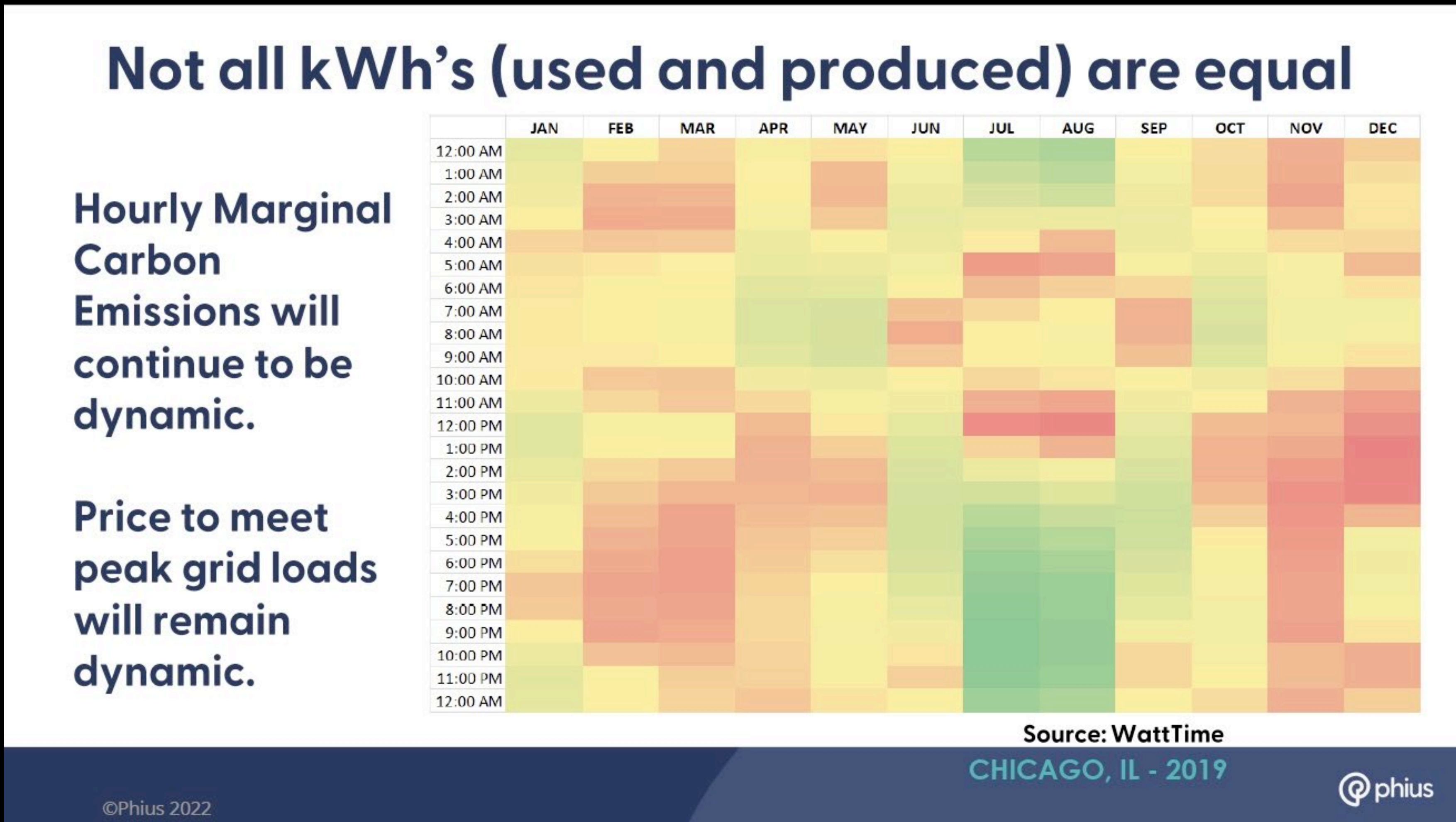
11 GW in 3 hours! (MA PV capacity ~3 GW)

ISO-NE



New England ISO – April 2, 2022
Date: 04/02/2022
13.5k
12k
10.5k
9k
7.5k
MW
23
Apr 2
01
02
03
04
05
06
07
08
09
10
11
12
13
14
15
16
17
18
19
20
21
22
23
Time
Hide
Forecast
Actual
Cleared
Prior-Day
Actual Including Pump Load
Actual Including Estimated Behind-the-Meter Solar
©Phius 2022

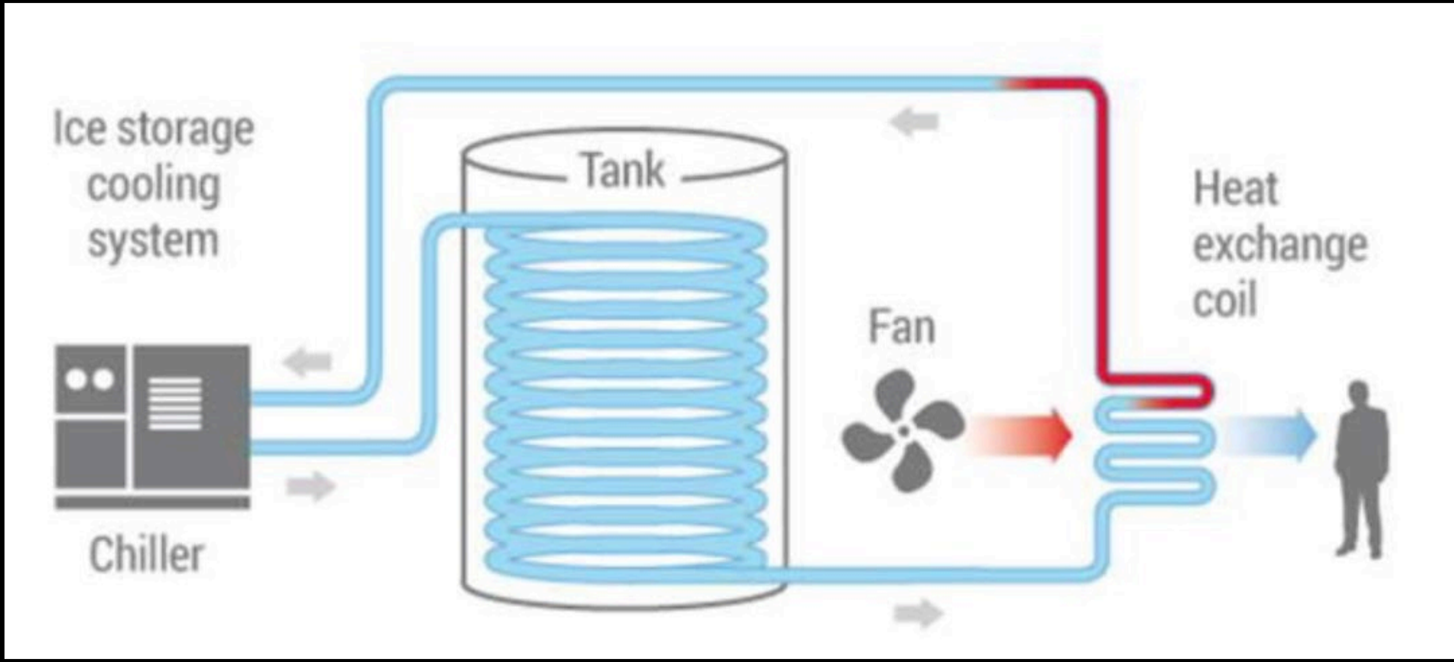
Emissions Vary



Strategies

- Load reduction in buildings, both thermal and electrical
- Grid-interactive control – two way grid
- Load shifting in time

Energy storage is a load-shifting strategy



Why Bother?


Solar Net Metering Is Under Threat All Over The US

NET METERING UNDER ATTACK (AGAIN)!

February 21, 2023 | 2 min read

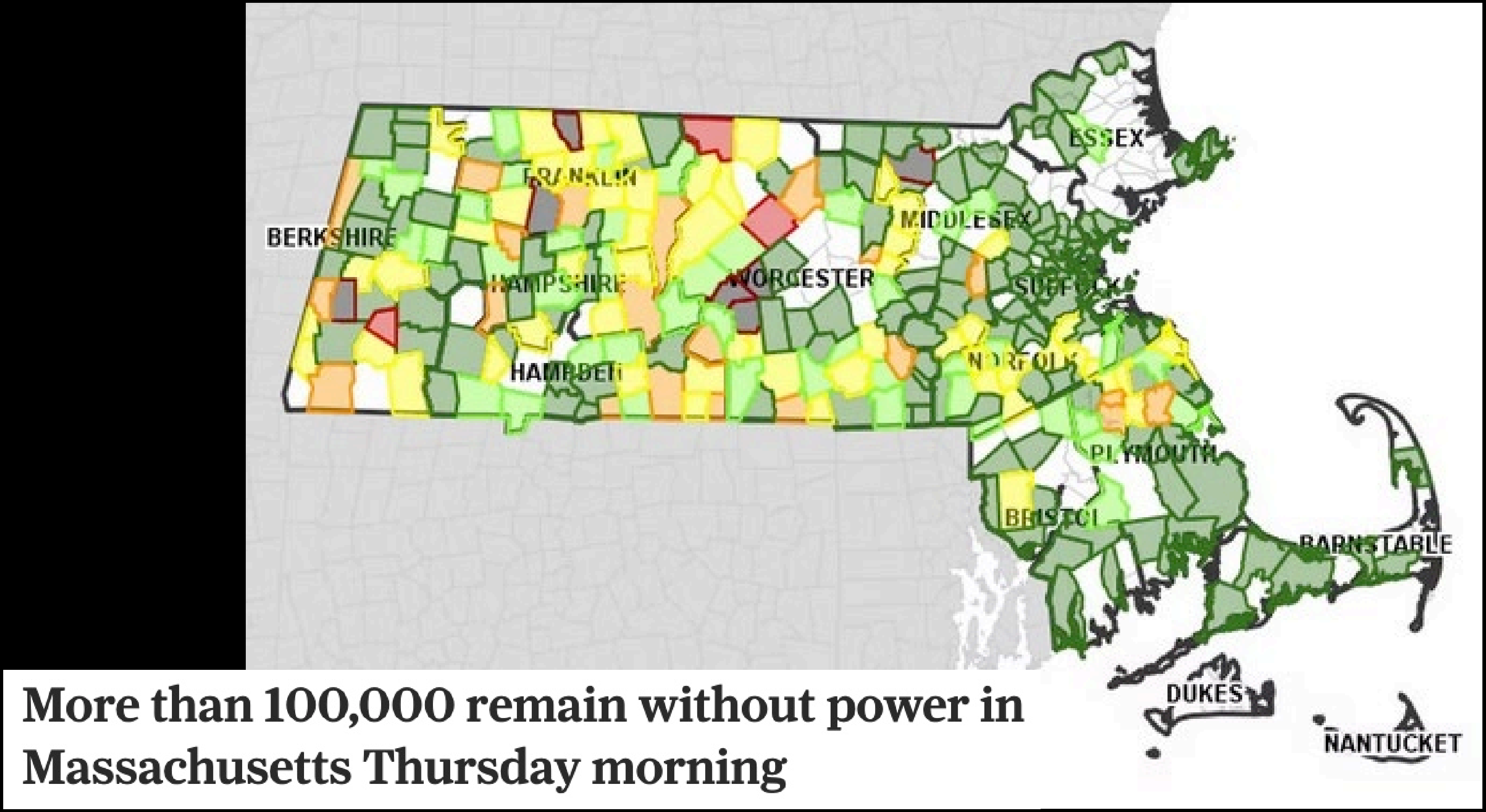
Solar energy under attack in Florida

uest Post: Why Is Net Metering Under Attack?

The utilities' net metering math doesn't add up.

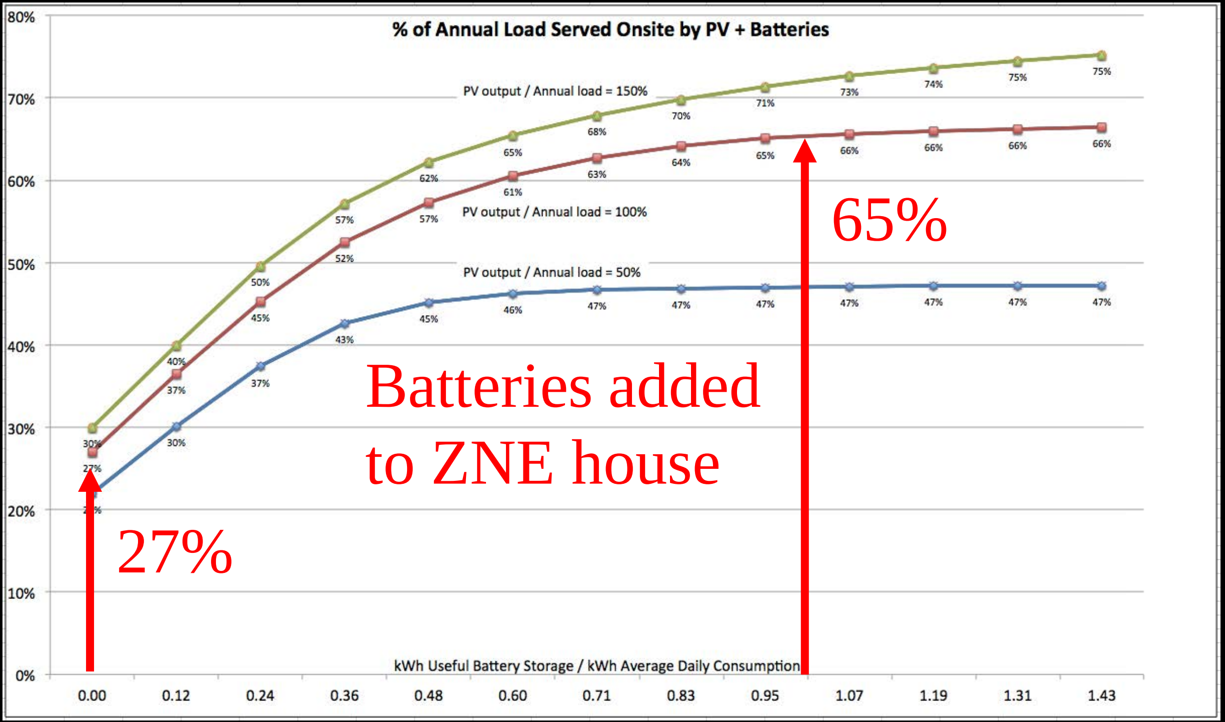
Why Bother?

Resilience in Grid Outage Events



Electric Storage Batteries

- Most flexible type of storage
- Provides grid outage resilience
- Provides load shifting and peak shaving
- Boosts % of site-generated energy that is consumed on-site



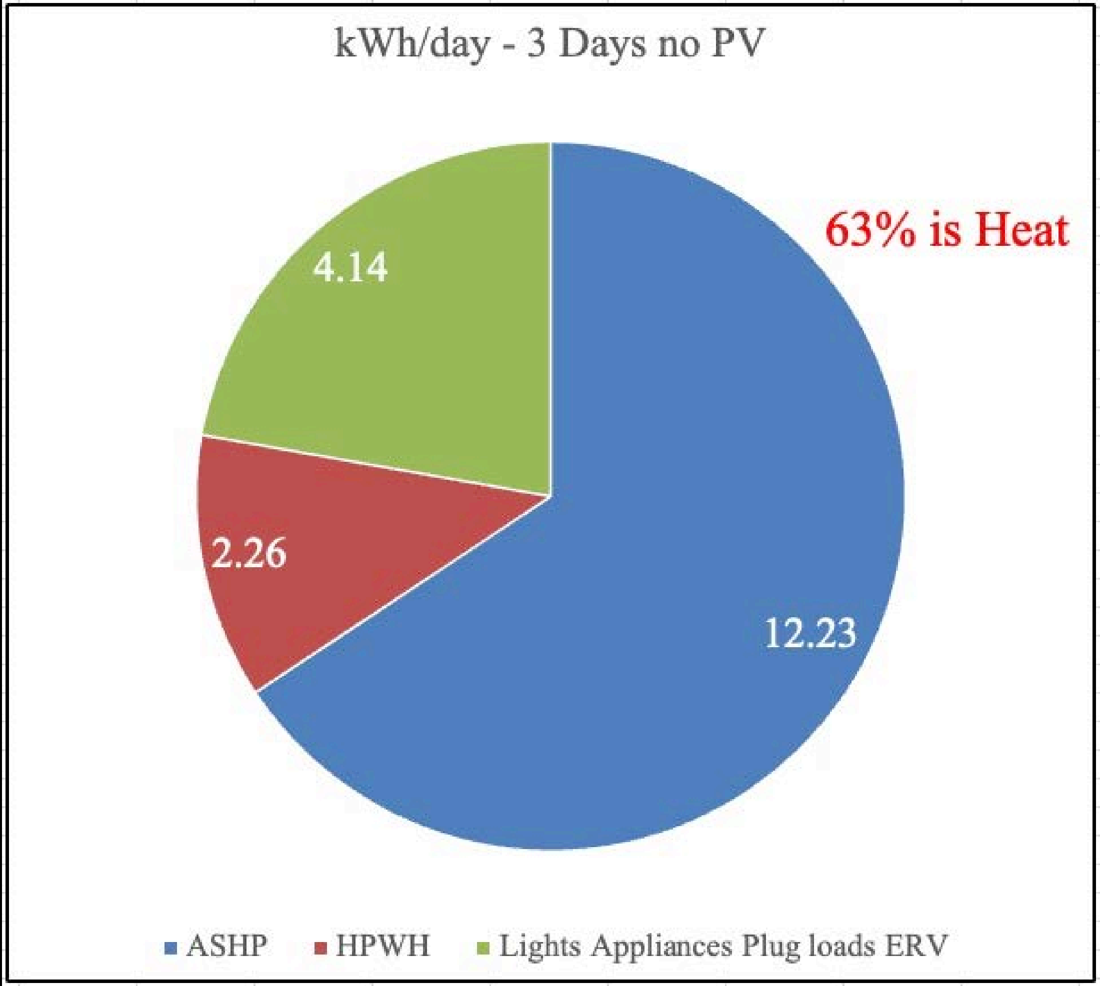
Marc Rosenbaum, PE – Energysmiths – West Tisbury, MA

Electric Storage Batteries

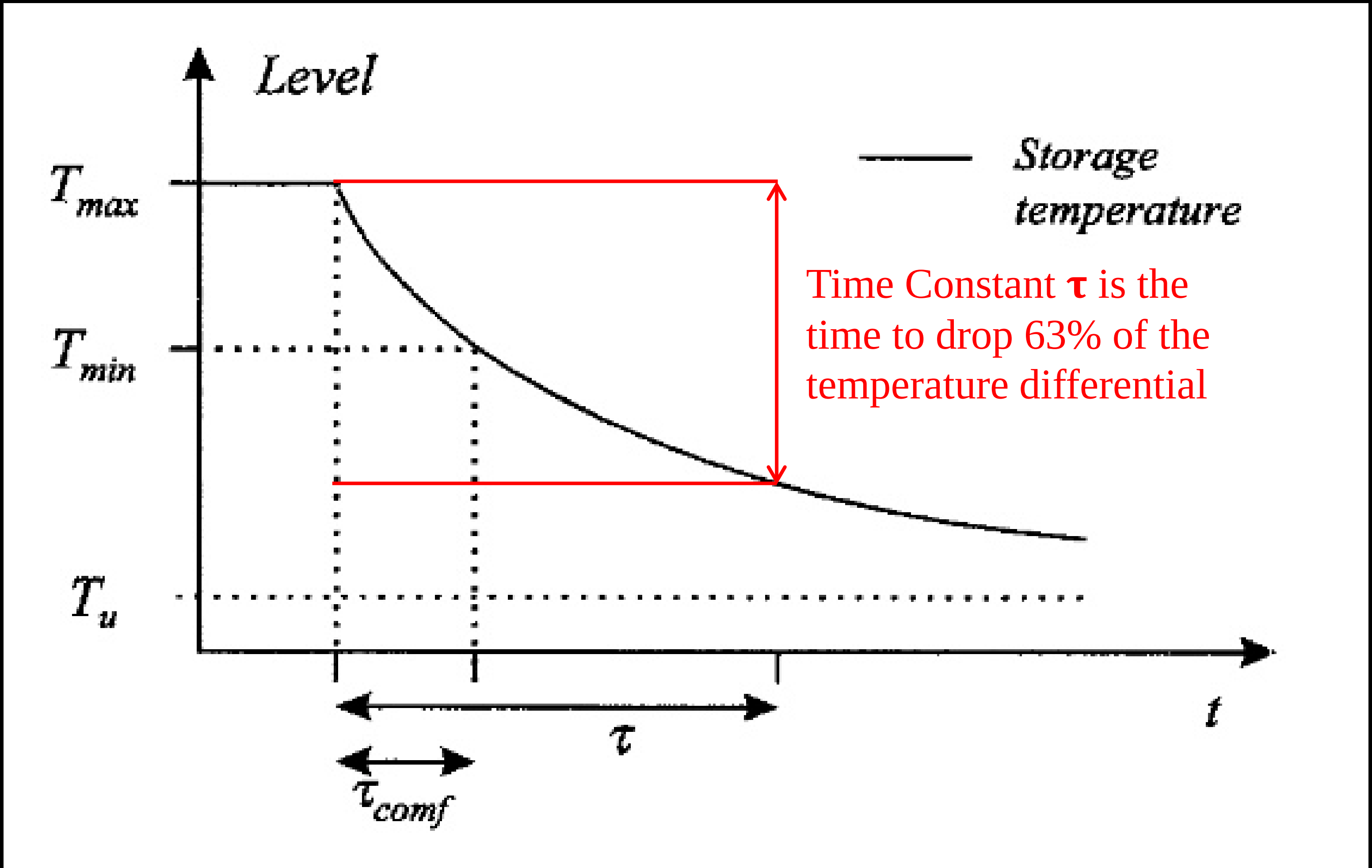
- Expensive
- Capacity drops over time
- Don't provide the inherent resilience of a superb enclosure with thermal storage
- Best application may be in distributed microgrids
- For many of us as homeowners, V2B is the future

Heat is the Biggest Load

Electric usage February 8th-10th 2016 after snowstorm covered the PV system. Superinsulated house with passive solar gain



Time Constant



From *On the thermal inertia and time constant of single family houses*, Hedbrant

Time Constant for Buildings

$$\frac{\text{Thermal Capacity per °F change in temperature (BTU/°F)}}{\text{Heat loss coefficient, UA (BTU/hr-°F)}}$$

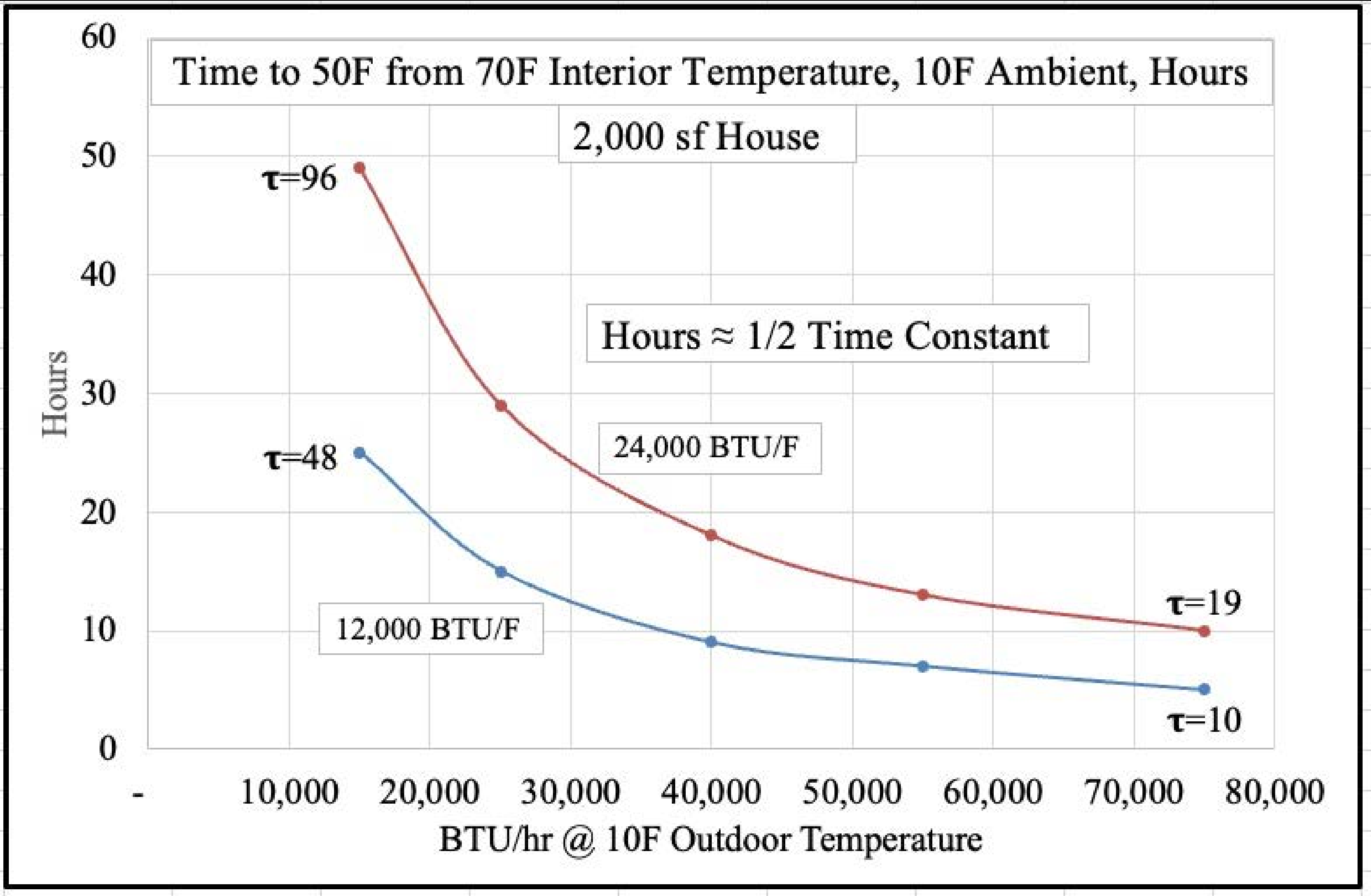
A range of thermal capacity of light frame houses might be 5-7 BTU/sf-˚F

A range of UA of light frame houses might be 0.125 – 0.625 BTU/hr-sf-˚F (2000 sf house 15-75,000 BTU/hr)

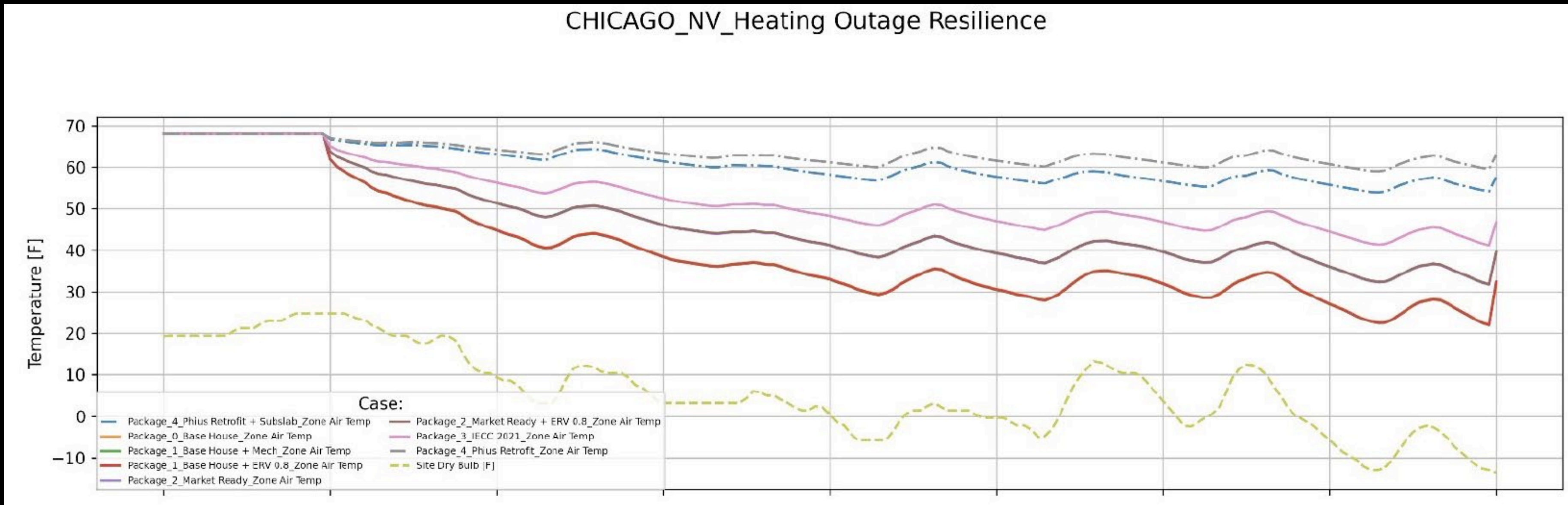
Therefore, a range of time constant of light frame houses would be 10-50 hours

A 2018 paper (John et al) analyzed data from over 10,000 Ecobee thermostats and estimated that a majority of time constants were in the 15-55 hour range

Time Constant and Cool Down

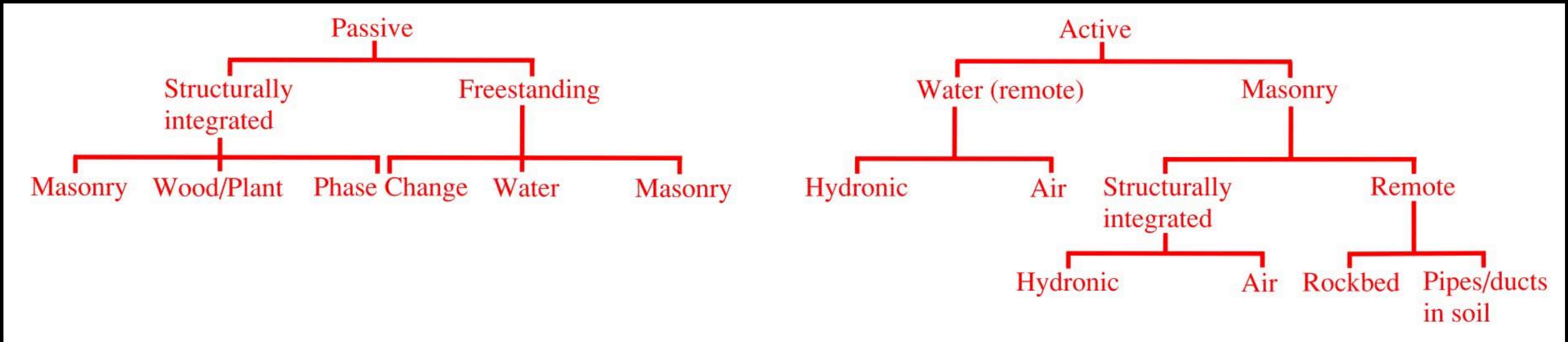


1 Week Heating Resilience

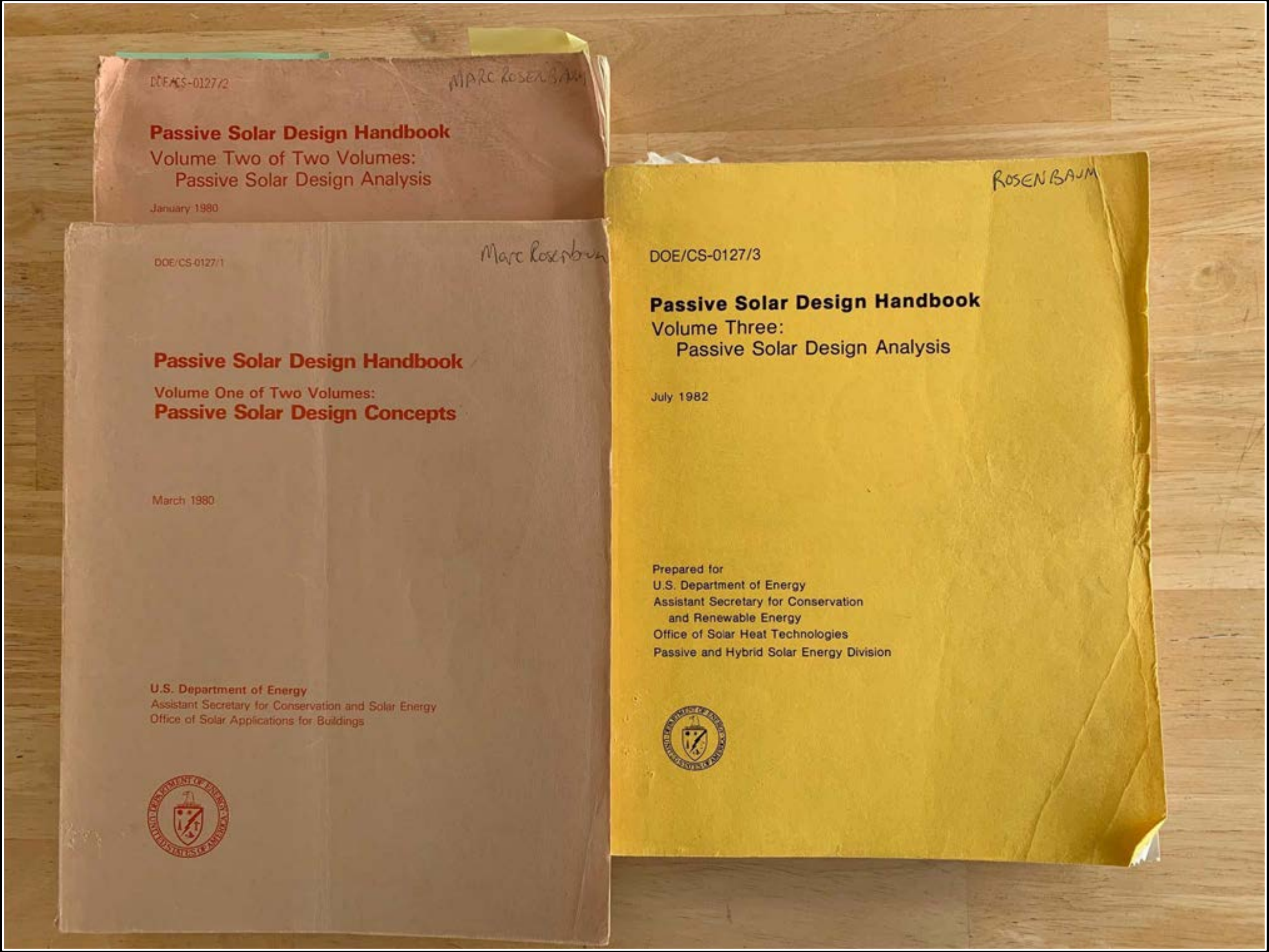


Thanks to Al Mitchell, Graham Wright, and PHIUS for this slide

A Taxonomy of Thermal Storage



Passive Solar Design Handbooks

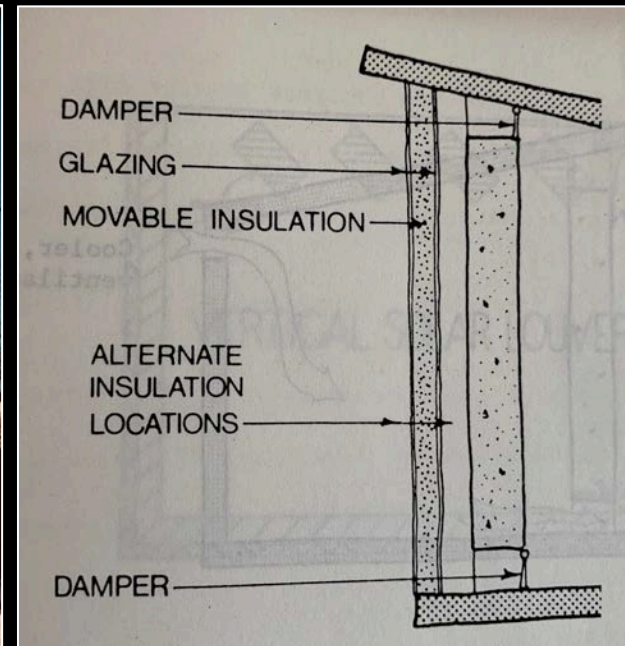


https://www.osti.gov/servlets/purl/5672634

Passive Freestanding

Photos courtesy of Amanda Nickerson and E. Lord – Society for the Protection of New Hampshire Forests Conservation Center – Banwell Architects

Passive Structurally Integrated



Doug Kelbaugh's Trombe (mass) wall house in Princeton NJ
15" concrete with black selective surface
Mass walls delay the solar heat delivery (best when unvented)

Passive Thermal Storage

The material parameter that matters is *thermal effusivity e*

$$e = \sqrt{k*\rho*Cp}$$

Thermal effusivity is a measure of a material's ability to exchange thermal energy with its environment.

The square root of thermal conductivity (k) times density (ρ) times specific heat (*Cp)*. Density times specific heat is volumetric heat capacity - how much heat a material holds per degree of temperature change (BTU/ft^3-°F).

So, how much energy can penetrate into the surface of a material is dependent on both how well it conducts heat, and how much heat it can hold.

Thermal Effusivity of Materials

Material	Density, lb/ft3	Conductivity, BTU/hr-ft-˚F	Specific heat, BTU/lb-˚F	Heat capacity, BTU/ft3-˚F	Thermal effusivity, BTU/ft-˚F-√hr
Cast iron	450	28	0.12	54	38.9
Concrete	150	1.16	0.19	28	5.69
Gypsum plaster	81	0.29	0.26	21	2.47
Softwood	27	0.067	0.76	20	1.17
Drywall	50	0.093	0.26	13	1.1
Fiberglass batt	0.8	0.025	0.16	0.12	0.06

Thin layers of materials like plaster and wood can store usable amounts of heat when applied over lots of area

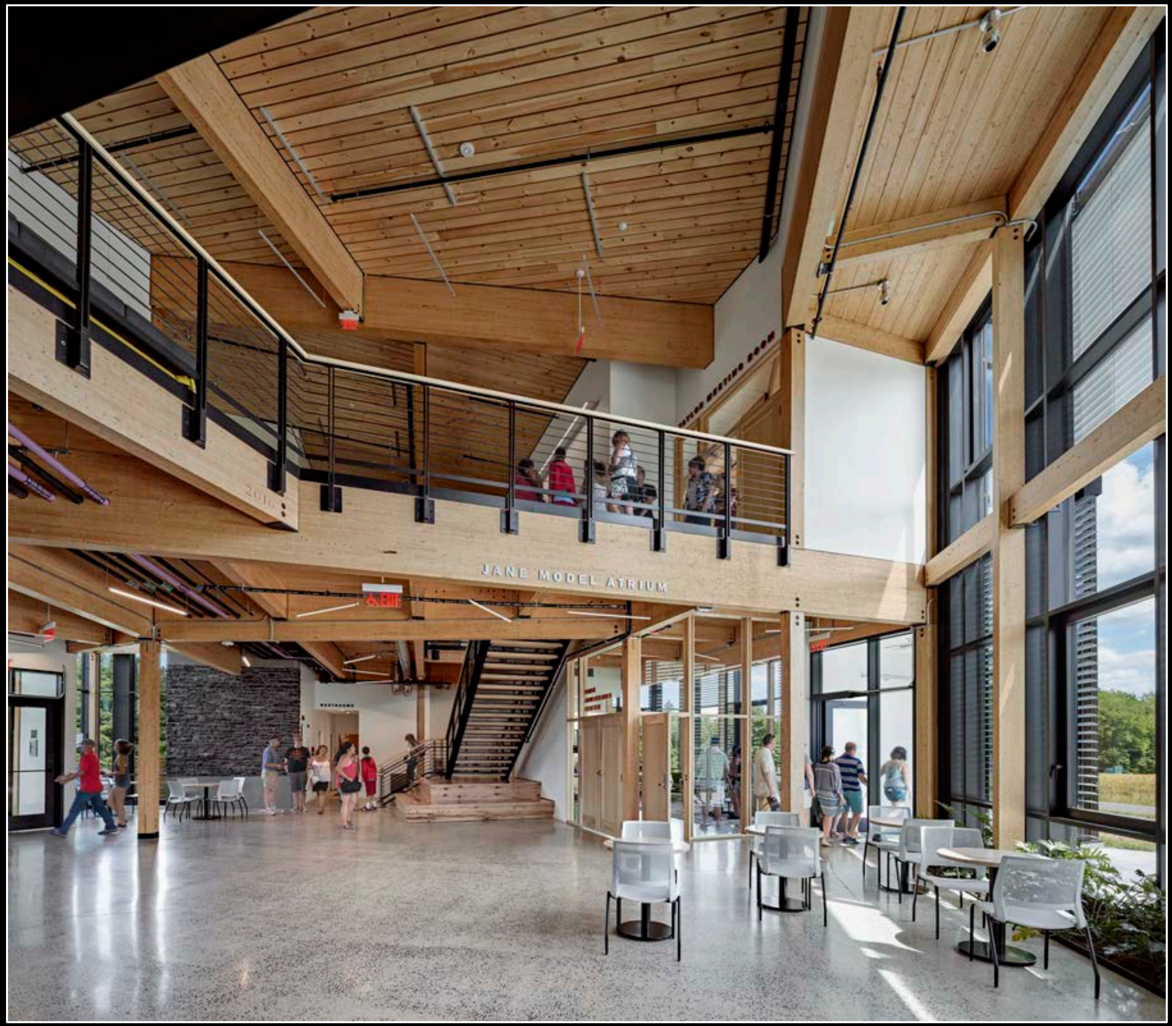
Direct Gain Passive Guidelines

- Up to 7-8% net S glazing/floor area needs no additional storage
- Above that, 5-6 sf of *directly sunlit* thermal storage per 1 sf additional sf of glazing
- Or, 40 sf of indirect (convective) thermal mass connected to the space (here, thin is OK)

Plaster and wood

Straw Bale and Timber - New Frameworks Natural Building

Masonry floors, wood structure & decking



Kern Center Living Building Hampshire College – Bruner Cott

Masonry floors, wood structure & decking


Winston Underground House – Don Metz Architect

Cross-laminated Timber

ADIMAB – Sylvia Richards / Christopher Smith Architects

Precast Concrete (or other masonry?)

Hillside Center for Sustainable Living
Hall & Moskow (developers) Moskow Linn Architects

Middlebury Bicentennial Hall – Payette Architects

Precast Concrete

- Precast concrete on steel beams
- Absorbs daily heat (no A/C)
- Shape reflects uplighting down
- Shape reflects sound onto sound absorption panels

Wessex Water – Bath, England
Bennetts Architects
Buro Happold Engineers
Integration of design team from conceptual stage

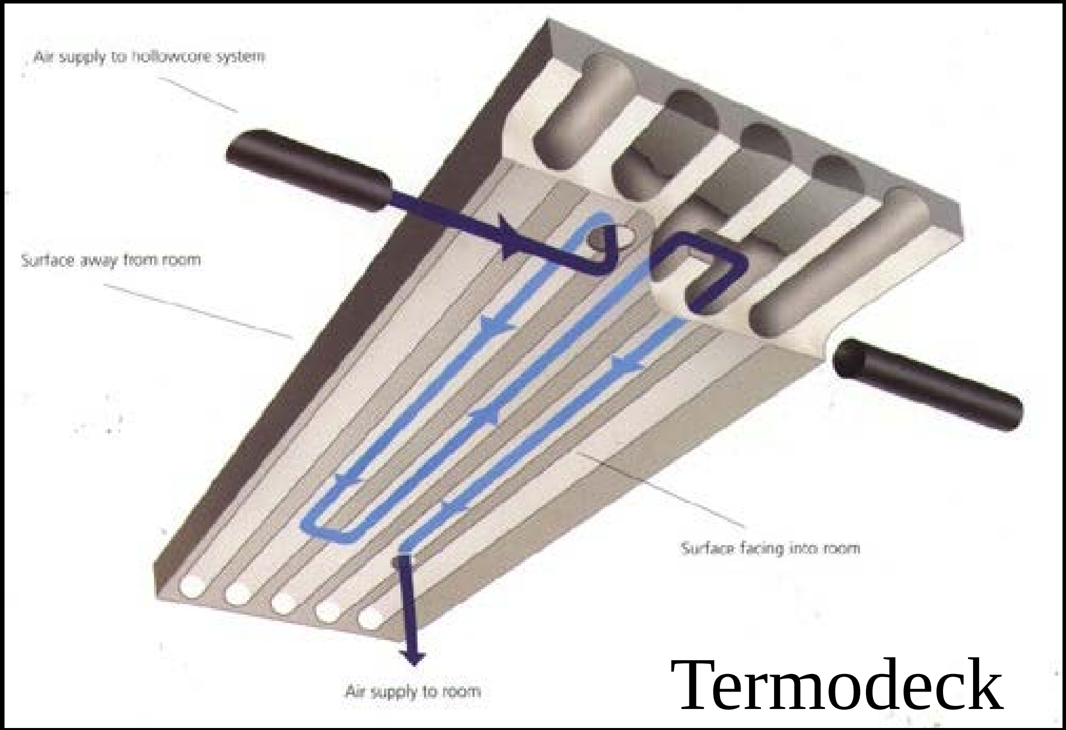
NERDS

Active Thermal Storage

- Storage is (usually) remote
- Storage is dispatchable according to need
- Much higher ΔT is possible
- Power is needed to charge/discharge (not always both)

Masonry Structurally Integrated - Air

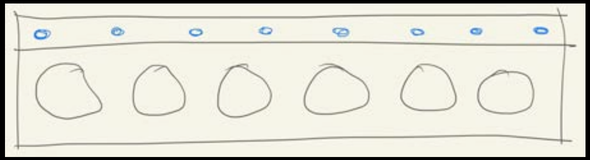
Elizabeth Fry Building



Termodeck

- Hollowcore precast planks
- Ventilation air delivered in space conditioning air
- 35,000 sf building, 5 zones
- CMU walls add passive mass
- Highest occupant satisfaction in PROBE Study

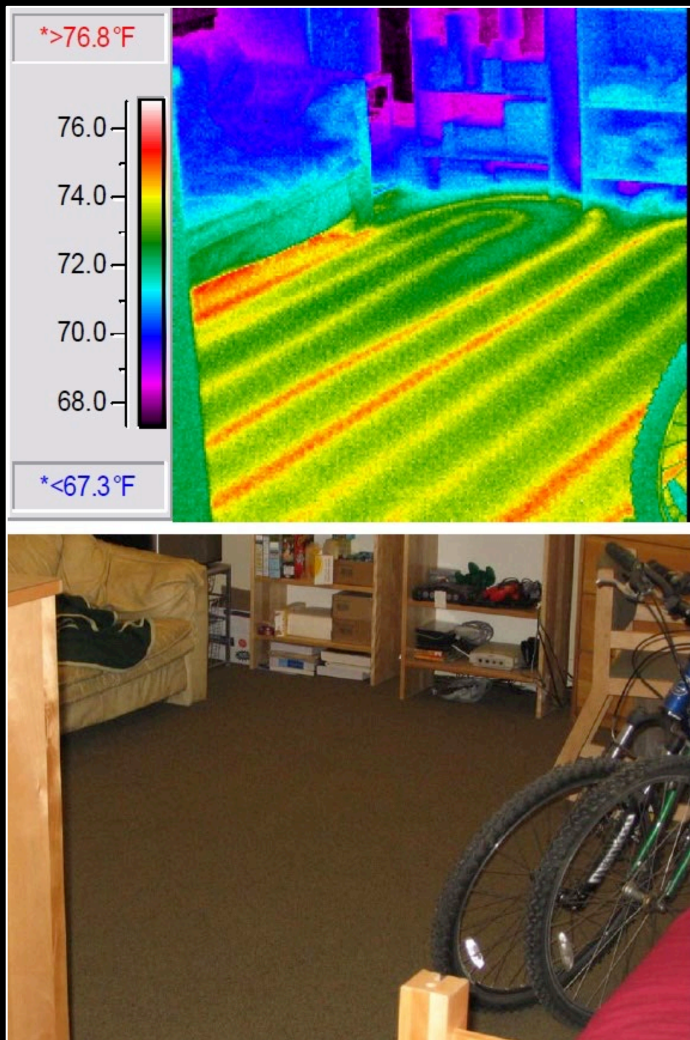
Masonry Structurally Integrated - Hydronic

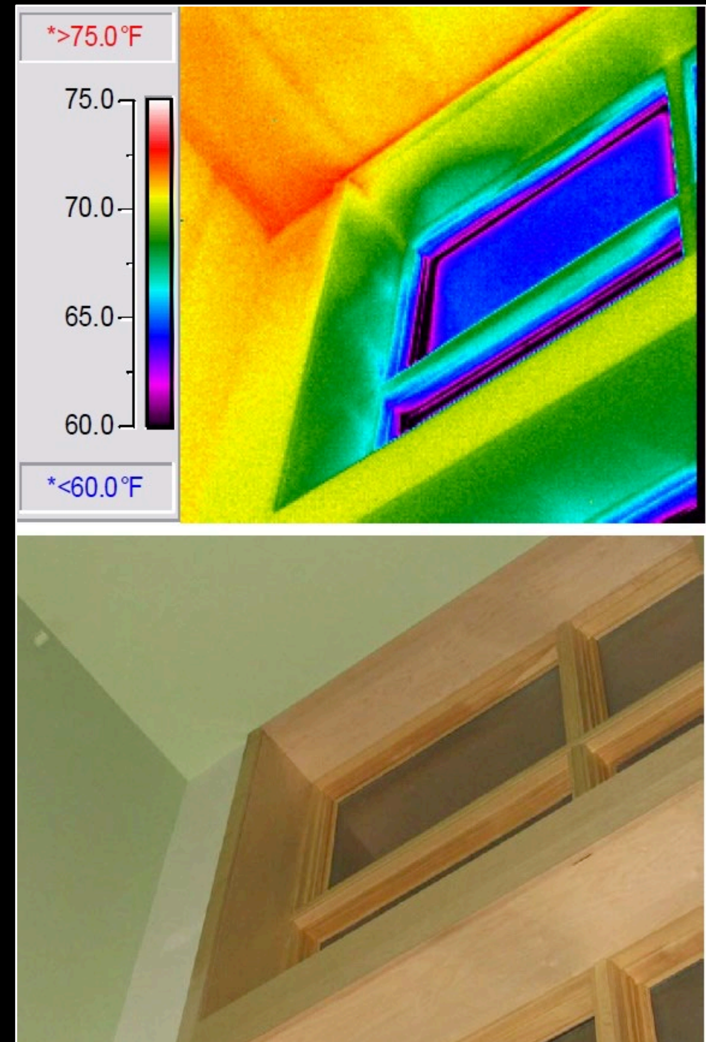


- PEX tubing in topping slab over precast hollowcore plank
- Both floor and ceilings are thermally active
- Floor dominates in heating; ceilings dominate in cooling
- Latent load removed in ventilation air

Dartmouth McLaughlin Dorms – Moore Rubell Yudell / Bruner Cott
Dan Nall – mechanical engineer

Masonry Structurally Integrated - Hydronic



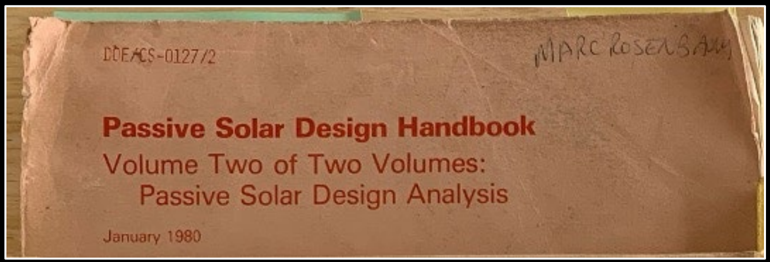


PEX tubing in topping slab over precast hollowcore plank

Fan-forced Rockbed

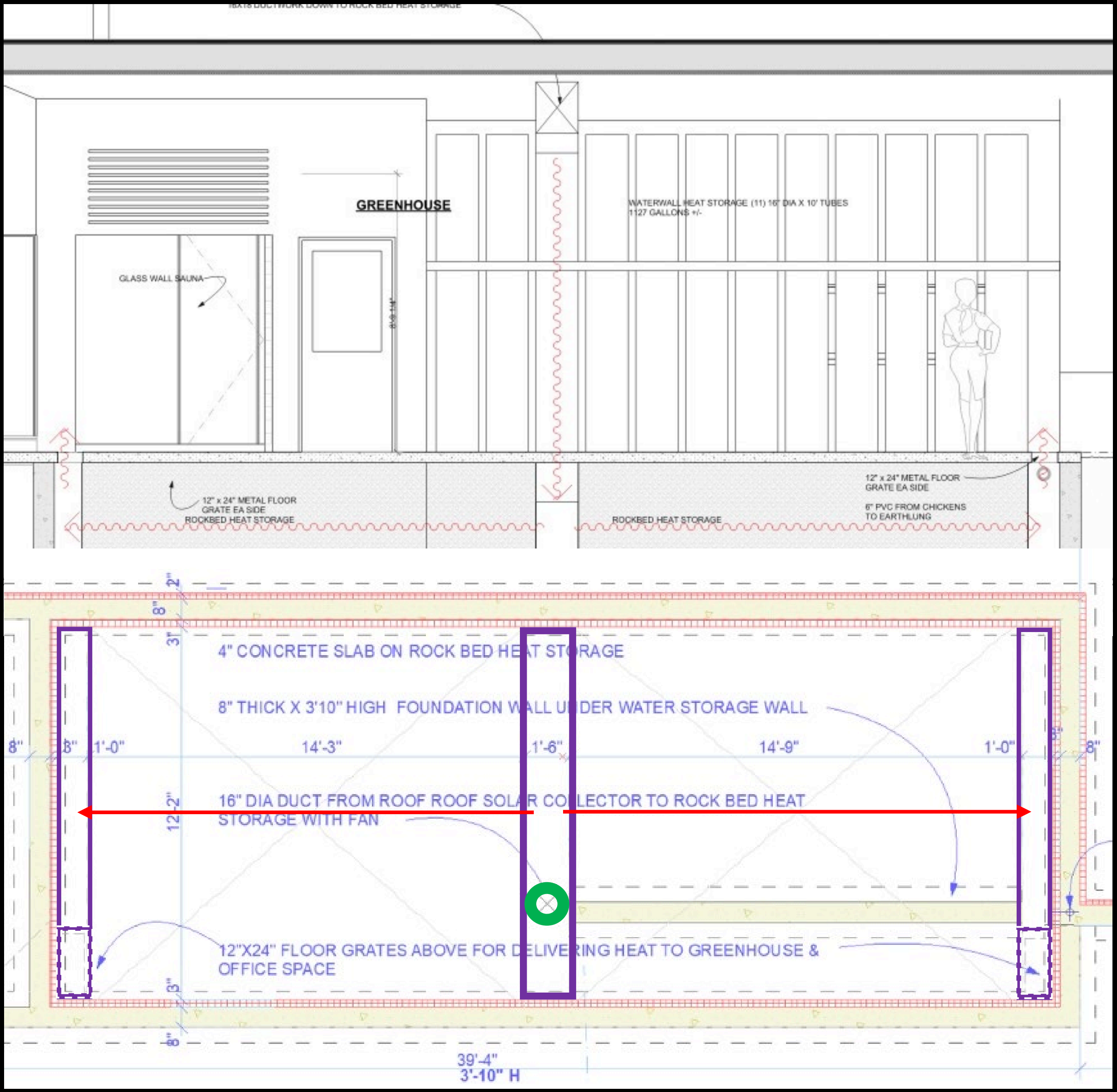
Active storage; passive release

Solar attic above greenhouse charges the air up to 110˚F for more energy stored per CFM in this VT house



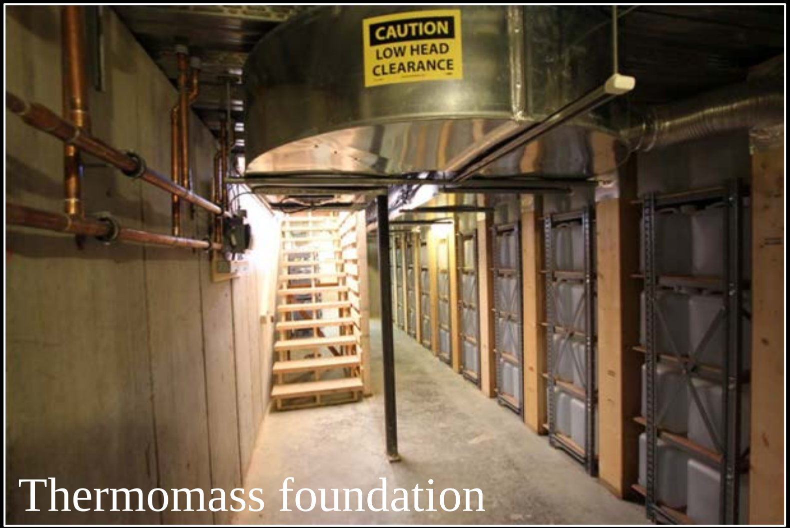
Natick Community Greenhouse – Jon Romig Architect

Fan-forced Rockbed



Fan-forced Water Containers

Active storage; passive release



Thermomass foundation

45˚F min. temp. at -7˚F outdoors

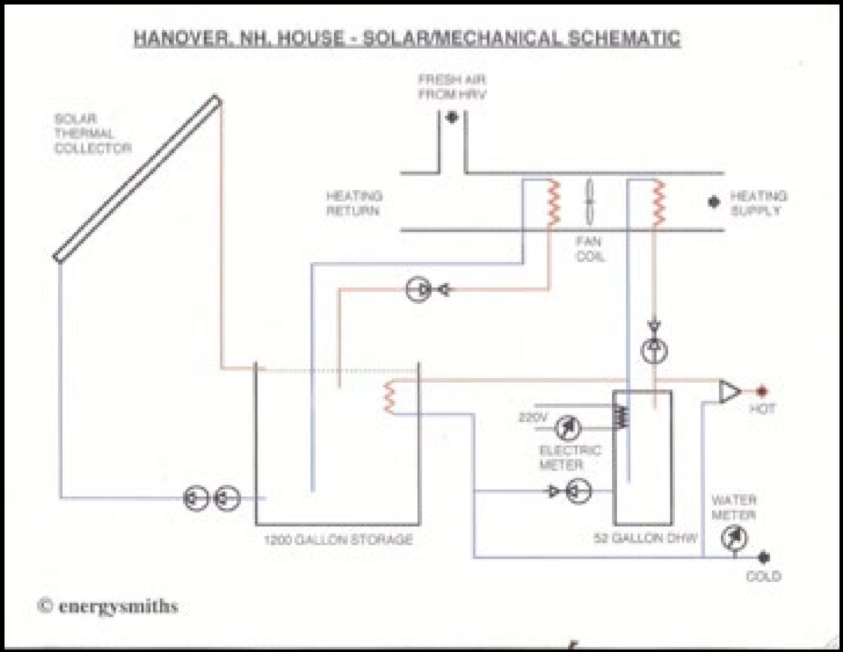
Marc Rosenbaum, PE – Energysmiths – West Tisbury, MA

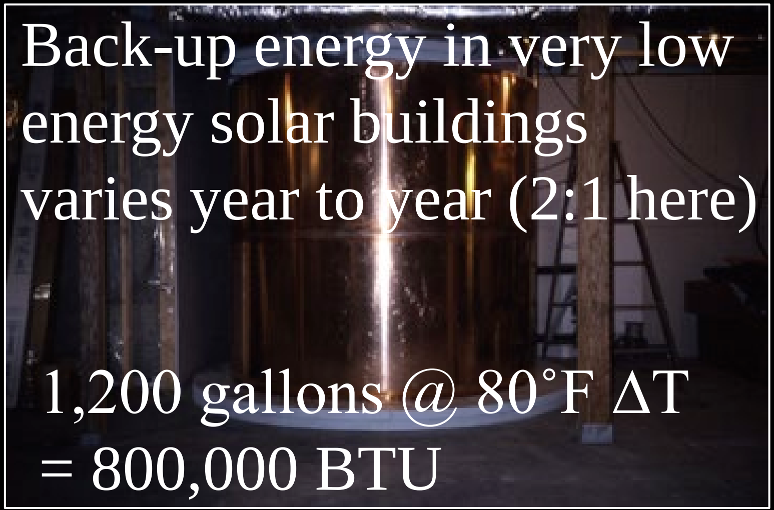
Fan-forced Water Containers

Active storage; passive release

Q, CFM	70	Q, ft3/sec	1.17	ΔP, psi	0.0071
g, ft/sec2	32.2			ΔP, inches of water	0.197
D, inch	0.25	D, ft	0.0208	ΔP, Pascals	50
rho, lb/ft3	0.075			V, ft/min	1245
Cd	0.70			V, ft/sec	20.7
Number of holes	165	A, ft2	0.056		

Active Solar Thermal Water Storage



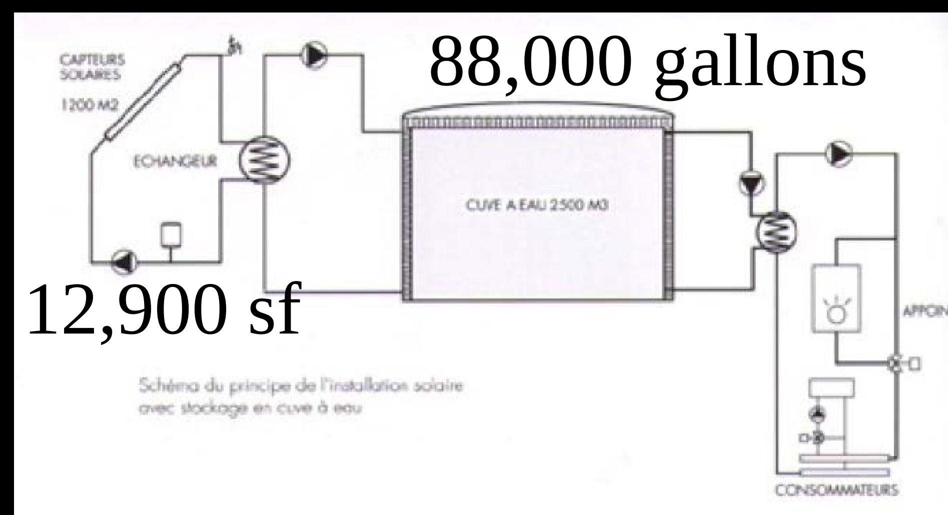


Back-up energy in very low energy solar buildings varies year to year (2:1 here)

1,200 gallons @ 80˚F ΔT = 800,000 BTU

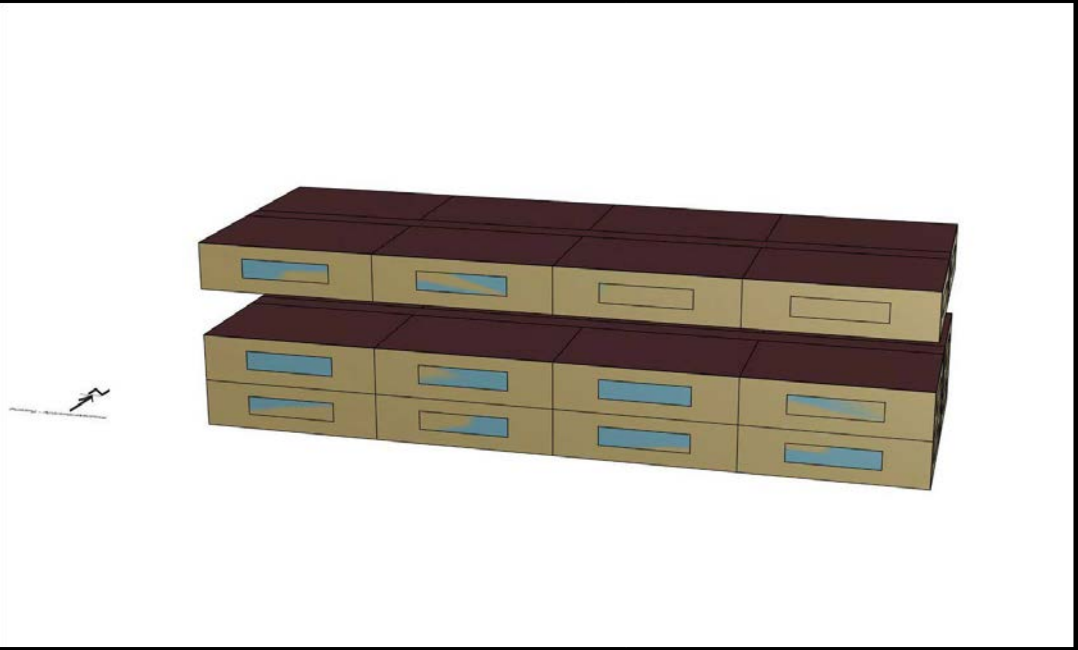
Active Annual Solar Thermal Water Storage

Swiss Federal Statistics Building



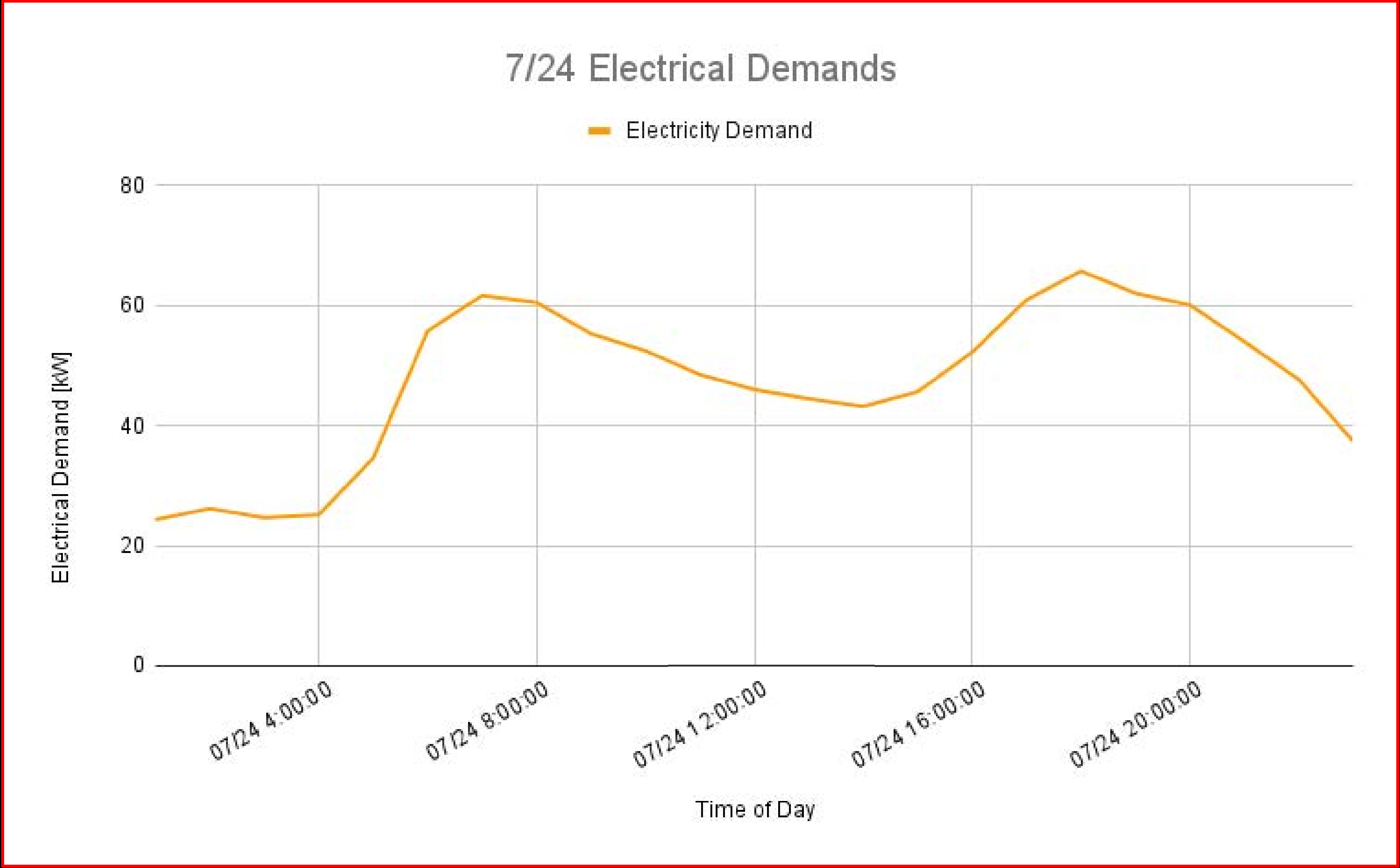
Ice Storage Case Study

- Prototypical Multifamily
- 23,300 sf
- 32 Units
- Phius Enclosure Spec

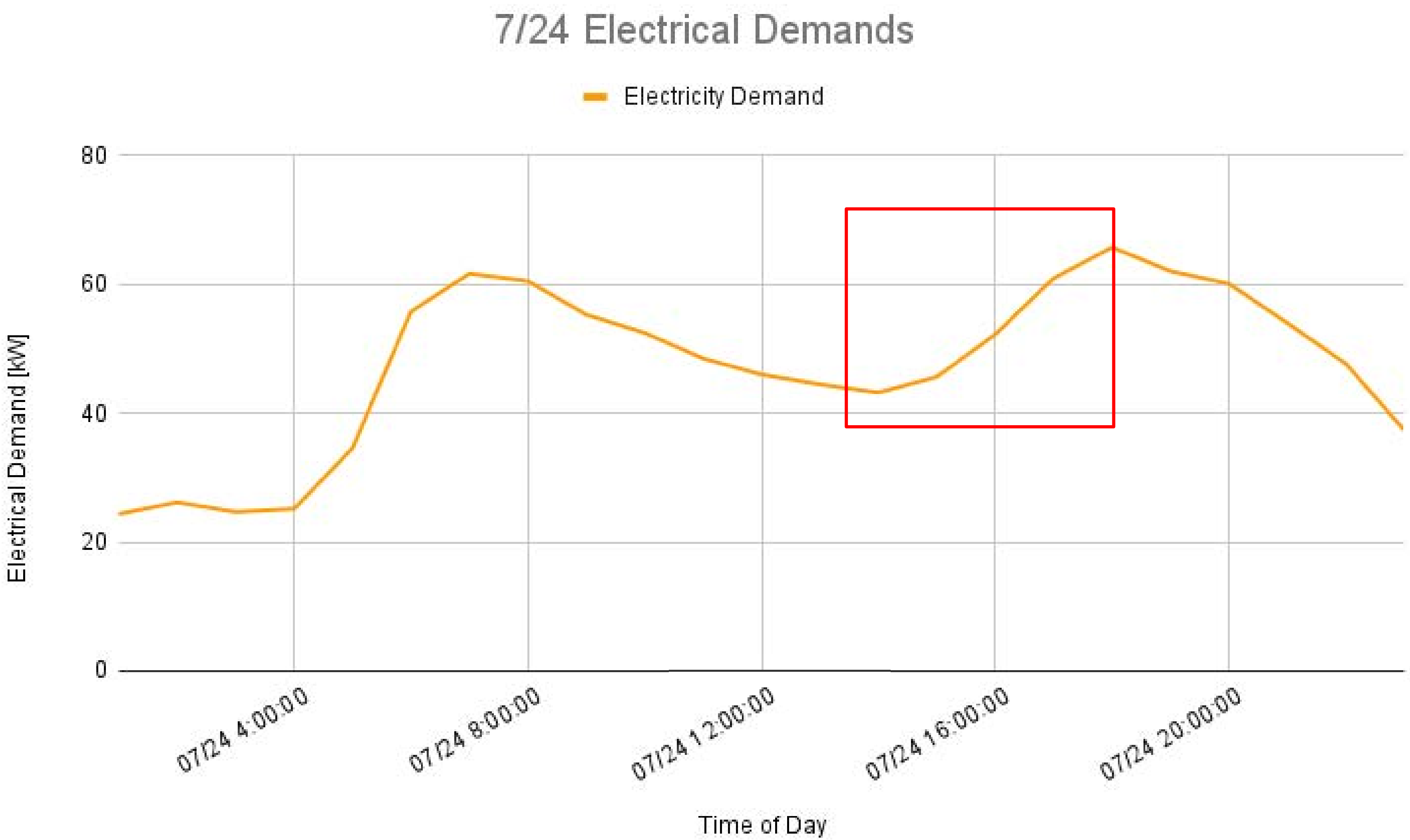


Thanks to Al Mitchell and PHIUS for these slides

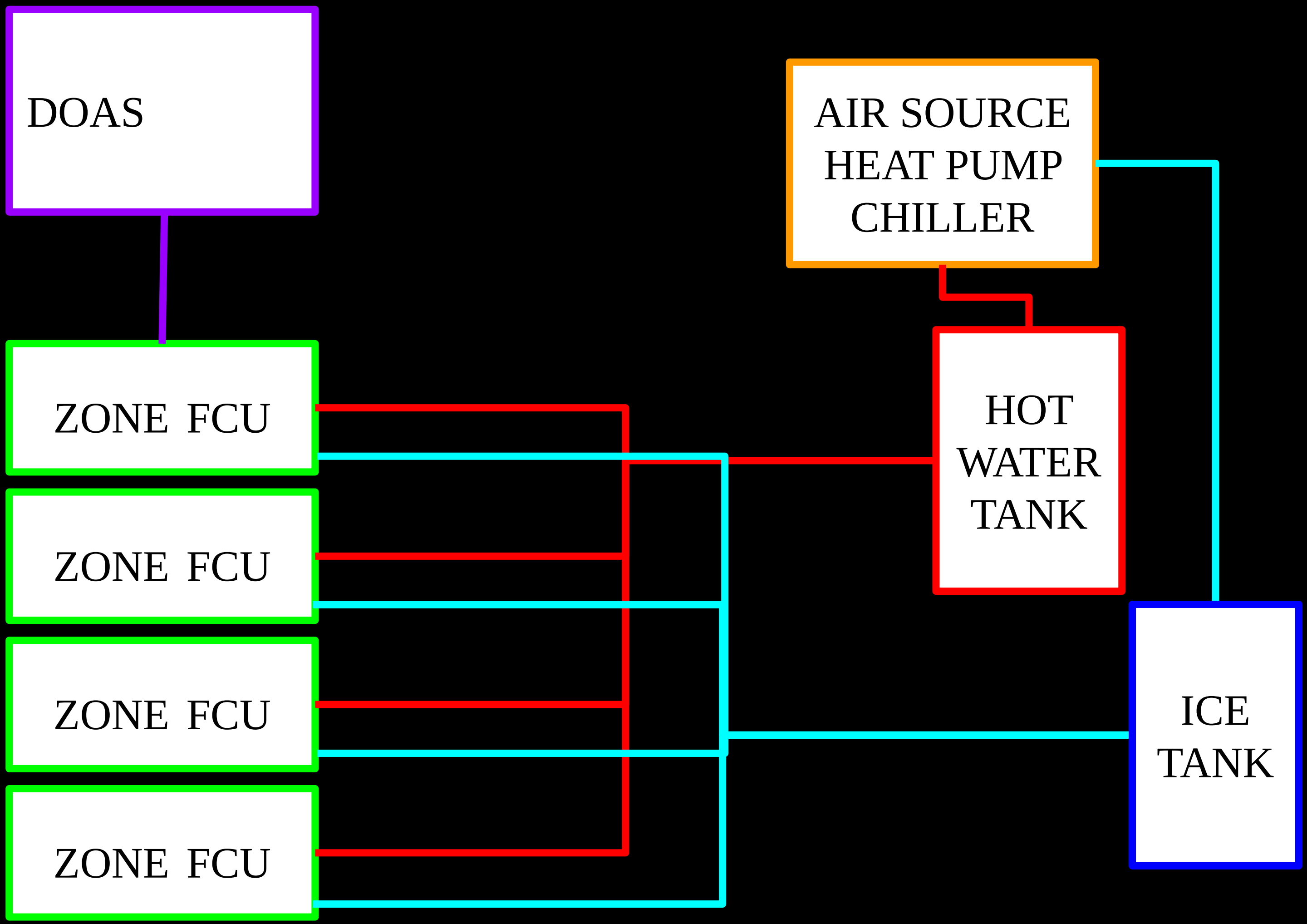
Ice Storage Case Study



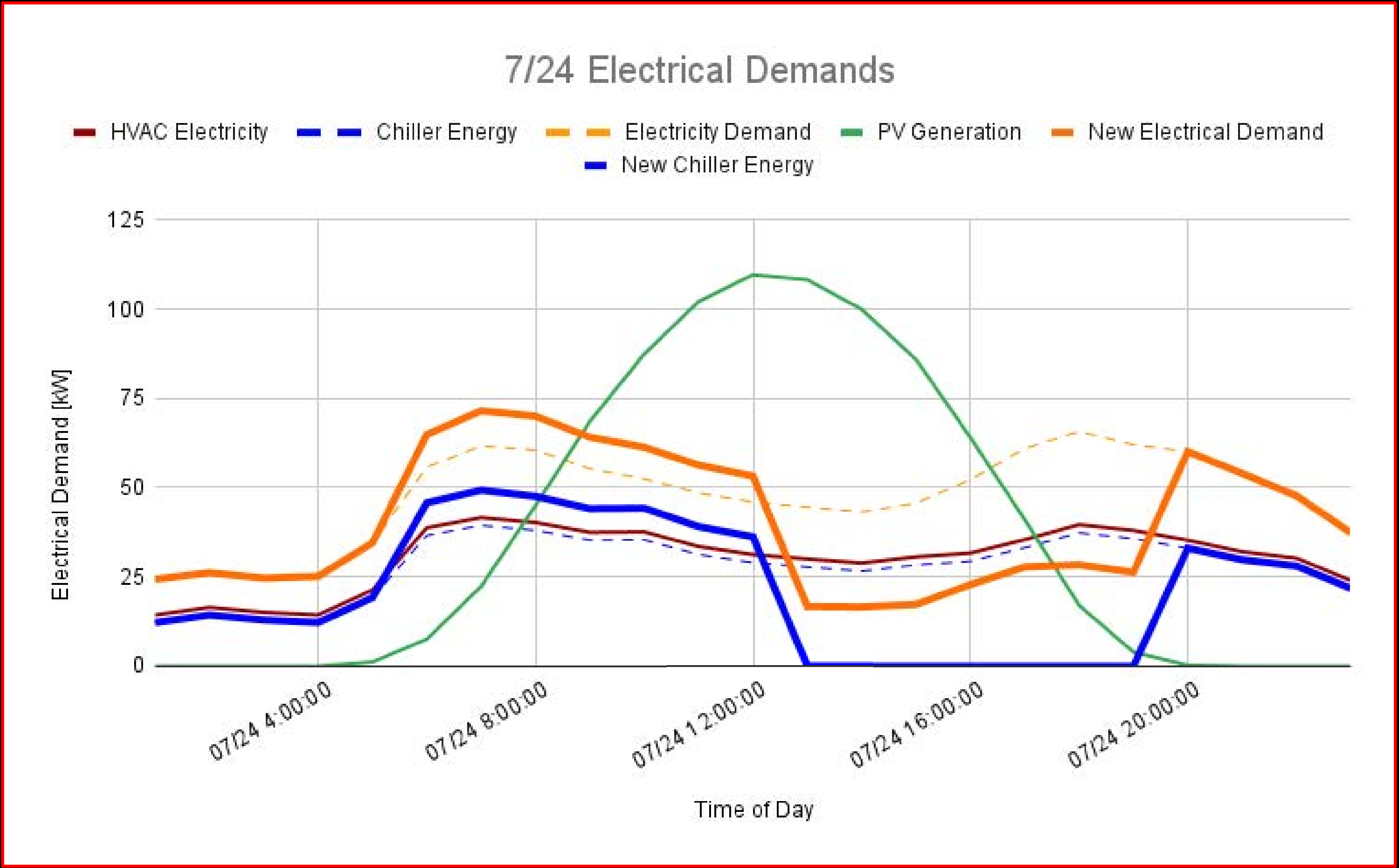
Ice Storage Case Study



Ice Storage Case Study



Ice Storage Case Study



PV/A-WHP w/ Thermal Water Storage

- 4,500 sf footprint airplane hangar with office space
- Owner wanted maximum onsite consumption of solar energy
- Non-optimal solar orientation and tilt
- A-WHP and hydronic radiant floor slab
- “Brick in a box” Excel hourly model to inform sizing of storage and PV
- Hourly model of PV gain and outdoor temp from PV Watts
- Hourly heating; cooling; DHW; EV; plug and lighting loads
- A-WHP COP vs. outdoor temp varied from manufacturer’s data

UA, BTU/hr/F	1,007	Setpoint, F	68			
Month	Day	Hour	Ambient Temp, F	Heat loss, BTU/hr	Heat pump COP	Heat pump usage, kWh
1	1	0	28.4	39,865	3.0	3.9
1	1	1	28.4	39,865	3.0	3.9
1	1	2	28.4	39,865	3.0	3.9
1	1	3	26.6	41,677	3.0	4.1
1	1	4	26.6	41,677	3.0	4.1
1	1	5	26.6	41,677	3.0	4.1
1	1	6	26.6	41,677	3.0	4.1

Model Inputs and Outputs

Thermal storage capacity, kWH	98	Thermal storage capacity, gallons H2O	1000		Storage temp high limit	125
					Storage temp low limit	85
				Roof area	PV W/sf	
PV array 139, kW	19.0			1055	18	Max roof area at 80% = 1824 sf
PV array 319, kW	0.0			0	18	

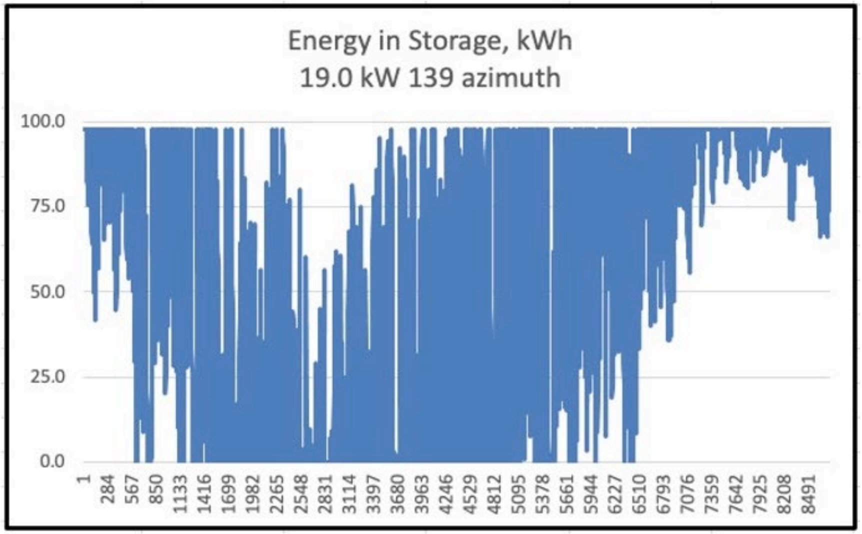
		PV generated, kWh	DHW, kWh	Cooling, kWh	P/L/A, kWh	EV, kWh	Heating, kWh			Total non-heating used, kWh	Grid energy imported serving non-heating, kWh	Total load, kWh	Non-heating use served directly by PV, kWh	Heating loads served directly by PV, kWh	Grid energy into heating, kWh	Total imported grid energy, kWh	PV energy into thermal storage, kWh	PV energy exported, kWh	PV generation/load	Fraction of PV energy used on site	
		22925	702	702	6302	2118	13107			9824	5204	22931	4620	3280	5241	10445	4381	10644	100%	54%	
	Max	15.0	0.1	0.5	1.3	1.7	5.7			2.7	13.8	14.9	4.6	14.9	12.7	14.9	5.7	10.7	51.1	13.0	
	Total	22925	702	702	6302	2118	13107			9824	18305	47237	3280	35032	17239	17793	5241	4381	17237	10644	
Date/Time		PV, kWh	DHW, kWh	Cooling, kWh	P/L/A, kWh	EV, kWh	Heating, kWh			Use except heating, kWh	Surplus PV after Use except heating, kWh	Heating load, kWh	Surplus PV applied to heating load, kWh	Remaining heating load, kWh	Heat extracted from storage, kWh	Remaining heat load, kWh	Grid energy into heating, kWh	Surplus PV applied to thermal storage, kWh	Energy added to storage, kWh	Surplus PV exported to the grid, kWh	Energy in Thermal Storage, kWh
9/1/2014 0:00		0.0	0.06	0.09	0.35	0.00	0.00	0.00	0.00	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7
9/1/2014 1:00		0.0	0.06	0.20	0.35	0.00	0.00	0.00	0.00	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7
9/1/2014 2:00		0.0	0.06	0.20	0.35	0.00	0.00	0.00	0.00	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7
9/1/2014 3:00		0.0	0.06	0.14	0.35	0.00	0.00	0.00	0.00	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7
9/1/2014 4:00		0.0	0.06	0.09	0.35	0.00	0.00	0.00	0.00	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7
9/1/2014 5:00		0.6	0.12	0.09	0.35	0.00	0.00	0.00	0.00	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7
9/1/2014 6:00		3.5	0.12	0.09	0.53	0.00	0.00	0.00	0.00	0.7	2.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.8	97.7
9/1/2014 7:00		6.6	0.12	0.09	0.88	0.00	0.00	0.00	0.00	1.1	5.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.5	97.7
9/1/2014 8:00		9.2	0.12	0.09	0.88	0.00	0.00	0.00	0.00	1.1	8.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.1	97.7
9/1/2014 9:00		10.9	0.12	0.09	0.88	0.00	0.00	0.00	0.00	1.1	9.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.8	97.7
9/1/2014 10:00		11.8	0.06	0.09	1.23	0.00	0.00	0.00	0.00	1.4	10.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.4	97.7
9/1/2014 11:00		12.3	0.06	0.14	1.23	0.00	0.00	0.00	0.00	1.4	10.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.9	97.7
9/1/2014 12:00		7.6	0.06	0.14	1.23	0.00	0.00	0.00	0.00	1.4	6.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.2	97.7
9/1/2014 13:00		8.0	0.06	0.19	1.23	0.00	0.00	0.00	0.00	1.5	6.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.5	97.7
9/1/2014 14:00		6.1	0.06	0.19	1.23	0.00	0.00	0.00	0.00	1.5	4.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.6	97.7
9/1/2014 15:00		5.4	0.06	0.19	1.23	0.00	0.00	0.00	0.00	1.5	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	97.7
9/1/2014 16:00		2.4	0.06	0.23	1.23	0.00	0.00	0.00	0.00	1.5	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	97.7
9/1/2014 17:00		0.5	0.12	0.28	0.88	0.00	0.00	0.00	0.00	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7
9/1/2014 18:00		0.0	0.12	0.33	0.88	0.00	0.00	0.00	0.00	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7
9/1/2014 19:00		0.0	0.12	0.37	0.53	1.16	0.00	0.00	0.00	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7
9/1/2014 20:00		0.0	0.12	0.37	0.35	1.74	0.00	0.00	0.00	2.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7
9/1/2014 21:00		0.0	0.12	0.37	0.35	1.74	0.00	0.00	0.00	2.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7
9/1/2014 22:00		0.0	0.06	0.37	0.35	1.16	0.00	0.00	0.00	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7
9/1/2014 23:00		0.0	0.06	0.28	0.35	0.00	0.00	0.00	0.00	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7

Model starts September 1st

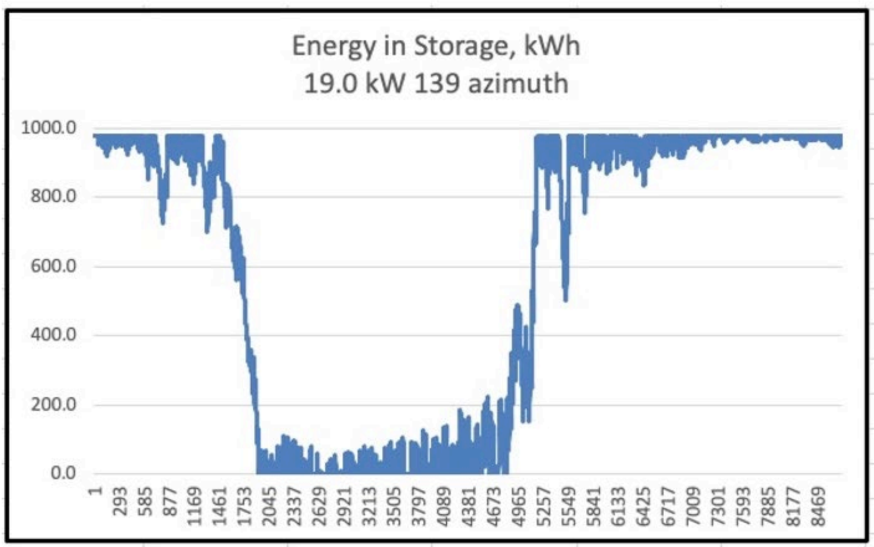
Results: Ten Cases Modeled

PV, kW	% load	Storage, gallons	PV Used, kWh	PV stored, kWh	PV exported, kWh	Grid imported, kWh
19	100	0	7900	0	15025	15031
19	100	1000	7900	4381	10644	10445
19	100	2000	7900	5020	10005	9768
19	100	5000	7900	5276	9749	9491
19	100	10000	7900	5384	9641	9355
32.4	171	0	8629	0	30484	14302
32.4	171	1000	8629	5412	25072	8718
32.4	171	2000	8629	7131	23353	6907
32.4	171	5000	8629	7750	22734	6252
32.4	171	10000	8629	7899	22585	6089

The Winter Trough



1,000 Gallons (98 kWh) of Thermal Storage



10,000 Gallons (978 kWh) of Thermal Storage

Note that the vertical axis, kWh in storage, is *ten times higher* in the 10,000 gallon case.

Solar availability and high heating loads always produce the winter trough. The same result occurred on the solar thermal house in Hanover, NH – the tank dropped from peak temperature to minimum temperature for 6-8 weeks then bounces back up.

Add Electric Batteries

Thermal storage capacity, kWH	98	Thermal storage capacity, gallons H2O	1000			Storage temp high limit	125	# of Batteries	3
						Storage temp low limit	85	kWh/Battery	13.5
				Roof area	PV W/sf			Battery storage, kWh	40.5
PV array 139, kW	19.0			1055	18	Max roof area at 80% = 1824 sf		Charging efficiency	95%
PV array 319, kW	0.0			0	18			Discharge efficiency	95%

		PV generated, kWh	DHW, kWh	Cooling, kWh	P/L/A, kWh	EV, kWh	Heating, kWh			Total non-heating used, kWh	Grid energy imported serving non-heating, kWh	Total load, kWh	Non-heating use served directly by PV, kWh	Heating loads served directly by PV, kWh	Grid energy into heating, kWh	Total imported grid energy, kWh	PV energy into thermal storage, kWh	PV energy exported, kWh	PV generation/ load	Fraction of PV energy used on site	PV energy in and out of Battery, kWh, 95% efficiency	PV energy exported after Battery, kWh		
		22925	702	702	6302	2118	13107			9824	5204	22931	4620	3280	5241	10445	4381	10644	100%	79%	5756	4888		
	Max	15.0	0.1	0.5	1.3	1.7	5.7			2.7	13.8	14.9	4.6	14.9	12.7	14.9	5.7	10.7	51.1	13.0				
	Total	22925	702	702	6302	2118	13107			9824	18305	47237	3280	35032	17239	17793	5241	4381	17237	10644				
Date/Time		PV, kWh	DHW, kWh	Cooling, kWh	P/L/A, kWh	EV, kWh	Heating, kWh			Use except heating, kWh	Surplus PV after Use except heating, kWh	Heating load, kWh	Surplus PV applied to heating load, kWh	Remaining heating load, kWh	Heat extracted from storage, kWh	Remaining heat load, kWh	Grid energy into heating, kWh	Surplus PV applied to thermal storage, kWh	Energy added to storage, kWh	Surplus PV exported to the grid, kWh	Energy in Thermal Storage, kWh		Surplus PV stored in batteries, kWh	
9/1/2014 0:00		0.0	0.06	0.09	0.35	0.00	0.00	0.00	0.00	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7			
9/1/2014 1:00		0.0	0.06	0.20	0.35	0.00	0.00	0.00	0.00	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7			
9/1/2014 2:00		0.0	0.06	0.20	0.35	0.00	0.00	0.00	0.00	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7			
9/1/2014 3:00		0.0	0.06	0.14	0.35	0.00	0.00	0.00	0.00	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7			
9/1/2014 4:00		0.0	0.06	0.09	0.35	0.00	0.00	0.00	0.00	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7			
9/1/2014 5:00		0.6	0.12	0.09	0.35	0.00	0.00	0.00	0.00	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7			
9/1/2014 6:00		3.5	0.12	0.09	0.53	0.00	0.00	0.00	0.00	0.7	2.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.8	97.7			
9/1/2014 7:00		6.6	0.12	0.09	0.88	0.00	0.00	0.00	0.00	1.1	5.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.5	97.7			
9/1/2014 8:00		9.2	0.12	0.09	0.88	0.00	0.00	0.00	0.00	1.1	8.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.1	97.7			
9/1/2014 9:00		10.9	0.12	0.09	0.88	0.00	0.00	0.00	0.00	1.1	9.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.8	97.7			
9/1/2014 10:00		11.8	0.06	0.09	1.23	0.00	0.00	0.00	0.00	1.4	10.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.4	97.7			
9/1/2014 11:00		12.3	0.06	0.14	1.23	0.00	0.00	0.00	0.00	1.4	10.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.9	97.7			
9/1/2014 12:00		7.6	0.06	0.14	1.23	0.00	0.00	0.00	0.00	1.4	6.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.2	97.7			
9/1/2014 13:00		8.0	0.06	0.19	1.23	0.00	0.00	0.00	0.00	1.5	6.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.5	97.7			
9/1/2014 14:00		6.1	0.06	0.19	1.23	0.00	0.00	0.00	0.00	1.5	4.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.6	97.7			
9/1/2014 15:00		5.4	0.06	0.19	1.23	0.00	0.00	0.00	0.00	1.5	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	97.7			
9/1/2014 16:00		2.4	0.06	0.23	1.23	0.00	0.00	0.00	0.00	1.5	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	97.7			
9/1/2014 17:00		0.5	0.12	0.28	0.88	0.00	0.00	0.00	0.00	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7			
9/1/2014 18:00		0.0	0.12	0.33	0.88	0.00	0.00	0.00	0.00	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7			
9/1/2014 19:00		0.0	0.12	0.37	0.53	1.16	0.00	0.00	0.00	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7			
9/1/2014 20:00		0.0	0.12	0.37	0.35	1.74	0.00	0.00	0.00	2.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7			
9/1/2014 21:00		0.0	0.12	0.37	0.35	1.74	0.00	0.00	0.00	2.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7			
9/1/2014 22:00		0.0	0.06	0.37	0.35	1.16	0.00	0.00	0.00	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7			
9/1/2014 23:00		0.0	0.06	0.28	0.35	0.00	0.00	0.00	0.00	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.7		69.6	32.4

This is a simplified model on the battery side, likely over-estimates the energy stored

Marc Rosenbaum, PE – Energysmiths – West Tisbury, MA

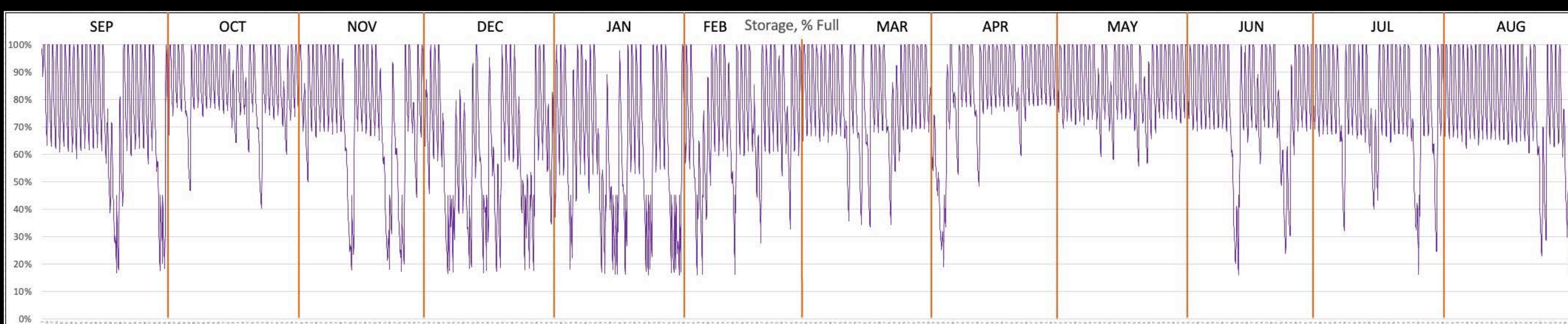
An Off-grid House

- 4,400 sf house on Martha's Vineyard with a heated pool
- 32.4 kW PV; 138 kWh battery storage; propane generator
- Hourly model to optimize systems
- Systems design by Brice Delhougne Energylogik

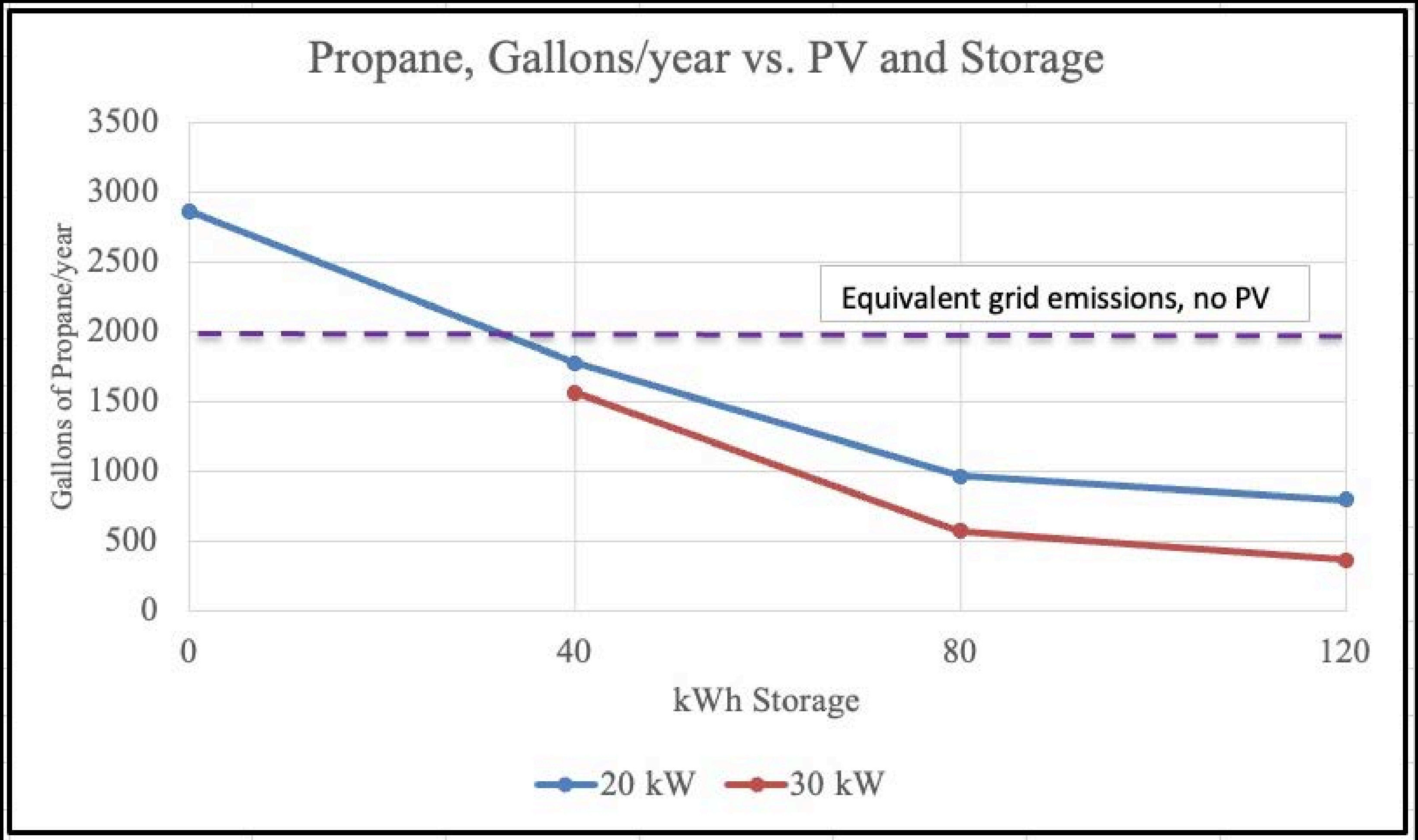
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Used	2607	2201	1983	1565	2166	2433	2701	2756	2582	1560	1808	2344	26707
PV generated	2711	3254	4008	4068	4345	4173	4222	4340	3996	3445	2588	2349	43500
Generator	681	136	0	44	0	45	45	45	137	0	136	446	1716
Propane, gals	110	22	0	7	0	7	7	7	22	0	22	72	276

Storage capacity, kWh	138		
Discharge limit	0.15	Generator charge limit	0.45
Useful storage capacity, kWh	117.3		
Charging efficiency	0.95	PV array	32.4
Discharging efficiency	0.95	MA Grid CO2 lbs/MWh	947

PV Cost, $1,000	Storage Cost, $1,000	Total Cost, $1,000	Heat, kWh	DHW, kWh	Cooling, kWh	P/L/A, kWh	EV, kWh	Misc., kWh	Pool, kWh	Pool pump, kWh	Total used, kWh	PV generated, kWh	Served directly by PV, kWh	Load not served by PV, kWh	Potential stored PV, kWh	Stored PV, kWh	Used from Storage, kWh	Generator, kWh	% of load served by PV - no Net Metering	% of load served by PV - w/Net Metering	PV generated / load	Propane, gallons	CO2 Emissions of propane, pounds	No PV -CO2 emissions, pounds, MA Grid @ 947lbs / MWh
162	166	328	5153	2537	1698	11556	2118	353	1150	2142	26707	43500	9695	17012	32115	16265	15295	1716	94%	100%	163%	276	3512	25291
	43500	43500	5153	2537	1698	11556	2118	353	1150	2142	26707	17012		60	890581	33805	32115		1716	1573				
Date/Time	PV, Wh	Adjusted PV, kWh	Heat, kWh	DHW, kWh	Cooling, kWh	P/L/A, kWh	EV, kWh	Misc., kWh	Pool, kWh	Pool Pump, kWh	Use, kWh	Net load after PV, kWh	Energy in Storage, kWh	Net load after PV and Storage, kWh	Energy in Storage after Load, kWh	Surplus PV, kWh	Potential stored PV, kWh	Energy in Storage after PV and Load, kWh	Generator Energy, kWh	Generator Energy Stored, kWh	Final Energy in Storage, kWh	Storage, % Full		Total Daily Use, kWh



An Off-grid House



Thank You!