Energy Storage in High Performance Buildings

Marc Rosenbaum (Energysmiths)

Curated by Mark Schow and Kurt Carlson

Northeast Sustainable Energy Association (NESEA)
March 28, 2023
Energy Storage in High Performance Buildings

<table>
<thead>
<tr>
<th>PV energy in and out of Battery, kWh, 95% efficiency</th>
<th>PV energy exported after Battery, kWh</th>
<th>Fraction of PV energy used on site</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10644</td>
<td>54%</td>
</tr>
</tbody>
</table>
Learning Objectives

Participants will be able to:

1) Describe the grid generation issues inherent in widespread use of renewable electricity

2) Describe the benefits of using energy storage, both thermal and electrical

3) Describe the types of thermal storage and identify suitable approaches for a particular project type

4) Describe the effects of increasing storage capacity and PV array size and how marginal benefits per additional increment decrease
Why Bother?

Grid Stability and Integration of Renewable Energy Sources

**SEASONAL LOAD PROFILES ON GRID**

General daily patterns / grid loads are predictable, variability is mostly based on space conditioning loads.

- **“Peaking Load”**
  - Natural gas “peaker plants”
  - Hydro

- **“Load Following”**
  - Natural gas CC
  - Some renewables

- **“Baseload”**
  - Coal
  - Nuclear
  - Some renewables

*Baseload power is mostly constrained to a constant output

Huge Thanks to Lisa White and PHIUS for these slides

Marc Rosenbaum, PE – Energysmiths – West Tisbury, MA
CA ISO Load

California ISO (CAISO) – July 26, 2022

Demand Trend

Day-ahead forecast  Hour-ahead forecast  Demand

http://www.caiso.com

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CA ISO Renewable Generation

California ISO (CAISO) – July 26, 2022

Renewables Trend

Solar  Wind  Geothermal  Biomass  Bio gas  Small hydro

Marc Rosenbaum, PE – Energysmiths – West Tisbury, MA
11 GW in 3 hours! (MA PV capacity ~3 GW)
Emissions Vary

Not all kWh’s (used and produced) are equal

Hourly Marginal Carbon Emissions will continue to be dynamic.

Price to meet peak grid loads will remain dynamic.

Source: WattTime

CHICAGO, IL - 2019
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

Guest Post: Why Is Net Metering Under Attack?

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

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Why Bother?

Resilience in Grid Outage Events

More than 100,000 remain without power in Massachusetts Thursday morning
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

Batteries added to ZNE house

27%

65%
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

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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

\[ \tau \] is the time to drop 63\% of the temperature differential.

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

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Thermal Capacity per °F change in temperature (BTU/°F)

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

Time to 50F from 70F Starting Temperature, Hours

- \( \tau = 96 \) for 2,000 sf house @ 6 BTU/°F
- \( \tau = 10 \) for 24,000 BTU/F
- \( \tau = 24,000 \) for 12,000 BTU/F

Time Constant \( \approx 2 \times \text{Hours} \)

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1 Week Heating Resilience

Thanks to Al Mitchell, Graham Wright, and PHIUS for this slide
A Taxonomy of Thermal Storage

Passive

Structurally integrated
Masonry
Wood/Plant
Phase Change
Water
Masonry

Freestanding

Active

Water (remote)
Hydronic
Air
Structurally integrated
Hydronic
Air
Remote
Rockbed
Pipes/ducts in soil
Masonry

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Passive Solar Design Handbooks

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

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Passive Freestanding

Water in fiberglass tubes – 1,100 BTU/°F

Phase Change pouches over metal ceiling panels

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

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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)
The material parameter that matters is *thermal effusivity* \( e \)

\[
e = \sqrt{k \cdot \rho \cdot Cp}
\]

The square root of thermal conductivity \( k \) times density \( \rho \) 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

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

*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

Marc Rosenbaum, PE – Energysmiths – West Tisbury, MA
Masonry floors, wood structure & decking

Kern Center Living Building – Bruner Cott

Marc Rosenbaum, PE – Energysmiths – West Tisbury, MA
Masonry floors, wood structure & decking

Winston Underground House – Don Metz Architect

Marc Rosenbaum, PE – Energysmiths – West Tisbury, MA
Cross-laminated Timber

ADIMAB – Sylvia Richards / Christopher Smith Architects

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Precast Concrete (or other masonry?)

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

Middlebury Bicentennial Hall – Payette Architects

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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
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

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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

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PEX tubing in topping slab over precast hollowcore plank

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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
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Fan-forced Rockbed
Fan-forced Water Containers

Active storage; passive release

45°F min. temp. at -7°F outdoors

Thermomass foundation

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Fan-forced Water Containers

Active storage; passive release

<table>
<thead>
<tr>
<th>Q, CFM</th>
<th>Q, ft³/sec</th>
<th>ΔP, psi</th>
<th>ΔP, inches of water</th>
<th>V, ft/min</th>
<th>V, ft/sec</th>
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<tbody>
<tr>
<td>70</td>
<td>1.17</td>
<td>0.0071</td>
<td>0.197</td>
<td>1245</td>
<td>20.7</td>
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<tr>
<td>g, ft/sec²</td>
<td>32.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>D, inch</td>
<td>0.25</td>
<td>0.0208</td>
<td>50</td>
<td></td>
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<tr>
<td>rho, lb/ft³</td>
<td>0.075</td>
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<tr>
<td>Cd</td>
<td>0.70</td>
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<tr>
<td>Number of holes</td>
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<td>A, ft²</td>
<td>0.056</td>
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</tbody>
</table>
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

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Active Annual Solar Thermal Water Storage

Swiss Federal Statistics Building

88,000 gallons

12,900 sf

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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

<table>
<thead>
<tr>
<th>Month</th>
<th>Day</th>
<th>Hour</th>
<th>Ambient Temp, F</th>
<th>Heat loss, BTU/hr</th>
<th>Heat pump COP</th>
<th>Heat pump usage, kWh</th>
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<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>28.4</td>
<td>39,865</td>
<td>3.0</td>
<td>3.9</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>28.4</td>
<td>39,865</td>
<td>3.0</td>
<td>3.9</td>
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<tr>
<td>1</td>
<td>1</td>
<td>2</td>
<td>28.4</td>
<td>39,865</td>
<td>3.0</td>
<td>3.9</td>
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<tr>
<td>1</td>
<td>1</td>
<td>3</td>
<td>26.6</td>
<td>41,677</td>
<td>3.0</td>
<td>4.1</td>
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<tr>
<td>1</td>
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<td>4</td>
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<td>41,677</td>
<td>3.0</td>
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<tr>
<td>1</td>
<td>1</td>
<td>6</td>
<td>26.6</td>
<td>41,677</td>
<td>3.0</td>
<td>4.1</td>
</tr>
</tbody>
</table>
## Model Inputs and Outputs

<table>
<thead>
<tr>
<th>Thermal storage capacity, kWh</th>
<th>98</th>
<th>Thermal storage capacity, gallons H2O</th>
<th>1000</th>
<th>Storage temp high limit</th>
<th>125</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV array 139, kW</td>
<td>19.0</td>
<td>PV array 319, kW</td>
<td>0.0</td>
<td>Roof area (PV W/sf)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Max roof area at 80% = 1824 sf</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Max</th>
<th>15.0</th>
<th>0.1</th>
<th>0.5</th>
<th>1.3</th>
<th>1.7</th>
<th>5.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>22925</td>
<td>702</td>
<td>702</td>
<td>6302</td>
<td>2118</td>
<td>13107</td>
</tr>
</tbody>
</table>

### Model starts September 1st

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Results: Ten Cases Modeled

<table>
<thead>
<tr>
<th>PV, kW</th>
<th>% load</th>
<th>Storage, gallons</th>
<th>PV Used, kWh</th>
<th>PV stored, kWh</th>
<th>PV exported, kWh</th>
<th>Grid imported, kWh</th>
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</thead>
<tbody>
<tr>
<td>19</td>
<td>100</td>
<td>0</td>
<td>7900</td>
<td>0</td>
<td>15025</td>
<td>15031</td>
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<td>19</td>
<td>100</td>
<td>1000</td>
<td>7900</td>
<td>4381</td>
<td>10644</td>
<td>10445</td>
</tr>
<tr>
<td>19</td>
<td>100</td>
<td>2000</td>
<td>7900</td>
<td>5020</td>
<td>10005</td>
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<td>5000</td>
<td>7900</td>
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<tr>
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<td>8629</td>
<td>0</td>
<td>30484</td>
<td>14302</td>
</tr>
<tr>
<td>32.4</td>
<td>171</td>
<td>1000</td>
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<td>5412</td>
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<tr>
<td>32.4</td>
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<td>7899</td>
<td>22585</td>
<td>6089</td>
</tr>
</tbody>
</table>

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The Winter Trough

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.

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

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Add Electric Batteries

<table>
<thead>
<tr>
<th>Thermal storage capacity, kWh</th>
<th>98</th>
<th>Thermal storage capacity, gallons H2O</th>
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<th>125</th>
<th># of Batteries</th>
<th>3</th>
</tr>
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<tbody>
<tr>
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<td>19.0</td>
<td>PV array 319, kW</td>
<td>0.0</td>
<td>Roof area PV W/sf</td>
<td>1055</td>
<td>Max roof area at 80% = 1824 sf</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Battery storage, kWh</td>
<td>40.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Charging efficiency</td>
<td>95%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Discharge efficiency</td>
<td>95%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

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An Off-grid House

Propane, Gallons/year vs. PV and Storage

Equivalent grid emissions, no PV

Gallons of Propane/year

kWh Storage

20 kW
30 kW

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Thank You!