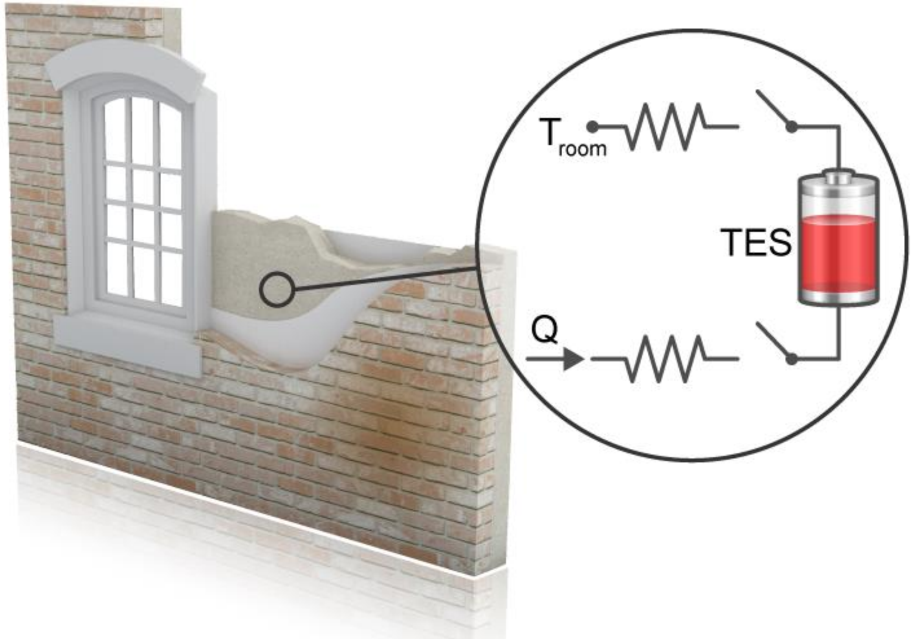
Solid State Tunable Thermal Energy Storage and Switches for Smart Building Envelopes



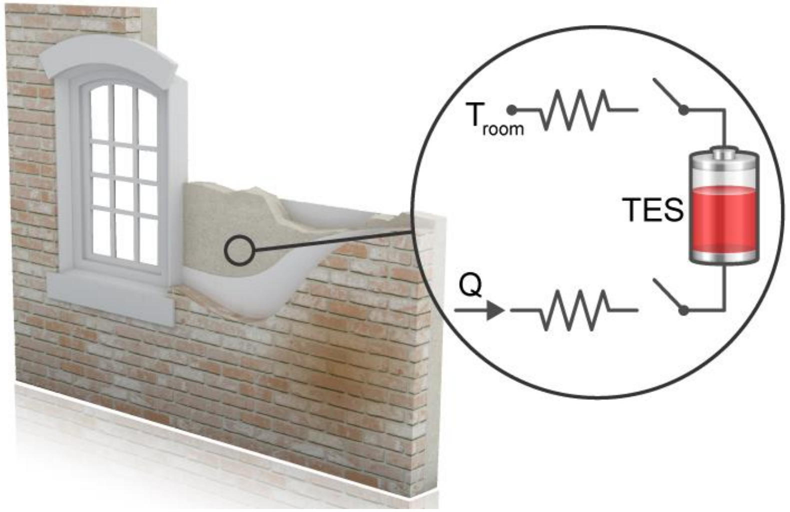
LBNL/UCB and NREL
PIs: Chris Dames & Ravi Prasher (LBNL) & Roderick Jackson (NREL)
WBS# 3.1.3.52

Project Summary

Objective: Large study of the dynamic tunable envelope, with new approaches to thermal storage as well as supercooling, thermal switches, improved metrologies, and high fidelity modeling.

Outcomes:

- Demonstrated tunability of PCM transition temperature by around 8 °C for all-season use.
- Designed and demonstrated the only thermal switch specifically for a building envelope, including switch ratio ~10:1, off-state k ~ 0.05 W/m-K, high cyclability (N=1000), and minimal parasitic energy consumption.
- Developed rational framework for more predictable supercooling.
- Identified root cause and provided user friendly solution to a long-standing issue in the SOA hot disk technique when applied to low-k porous insulation (errors previously were up to ~40%).
- Identified need for high throughput accurate thermal metrology, and developed and demonstrated a prototype with simultaneous multi-sample measurements and accuracy ~5%)
- Extensive simulations and modeling: Guided development of thermal switches target parameters (switch ratio and k_{Off}), envelope-related thermal load reduction 9 - 55% (heating) and 17-76% (cooling).



Team and Partners

Lawrence Berkeley National Lab (LBNL)

National Renewable Energy Laboratory (NREL)

University of California, Berkeley

Stats

Performance Period: Oct. 2018 - Sep. 2023:

DOE budget: $6,450k; Cost Share: N/A

Milestone 1: Integrated modeling of energy savings for realistic envelopes and climates.

Milestone 2: Thermal switch with performance suitable for building envelope

Milestone 3: Tunable PCM

Milestone 4: Overcame long-standing issue in hot-disk thermal conductivity measurement.

Team

PIs


Chris Dames, LBNL/UCB


Roderick Jackson, NREL


Ravi Prasher, LBNL/UCB

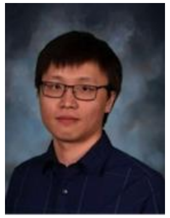
Tunable Solid-State Thermal Storage


Suman Kaur
LBNL

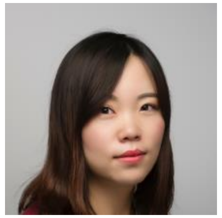

Youngsup
Song, LBNL


Drew Lilley
LBNL/UCB

Measurement Science (Metrology)


Qiye Zheng
LBNL


Ashwath Bhat
Berkeley

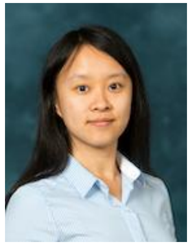

Shuang Cui
NREL

Electrochemistry


Gao Liu, LBNL


Jonathan Lau, LBNL

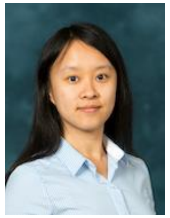
Thermal Switch


Ruijiao Miao,
LBNL


Sarah Chen,
LBNL/UCB


Menglong Hao,
LBNL

Multiscale Modeling


Ruijiao Miao


Ravi Prasher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LBNL / UCB


R. Jackson


Judith Vidal

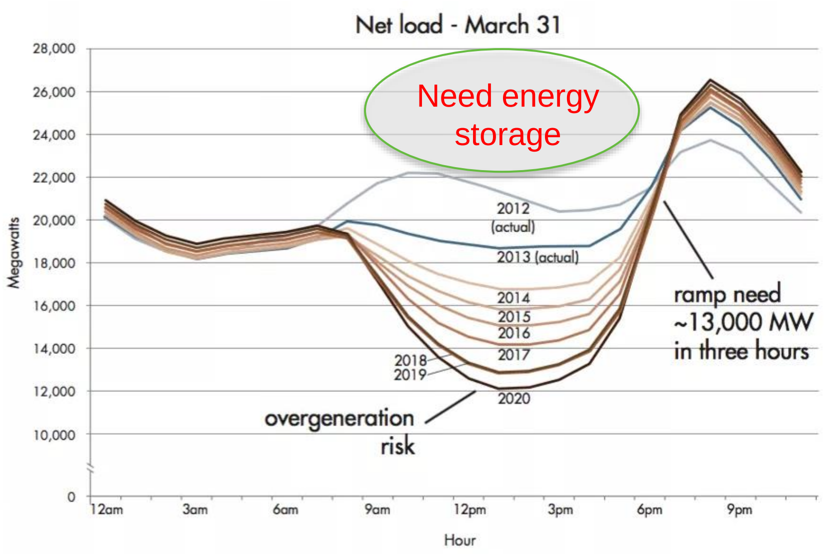

Ravi Kishore


Chuck Booten


Jason Woods

NREL

The Problem – Flexible Energy Storage is Needed

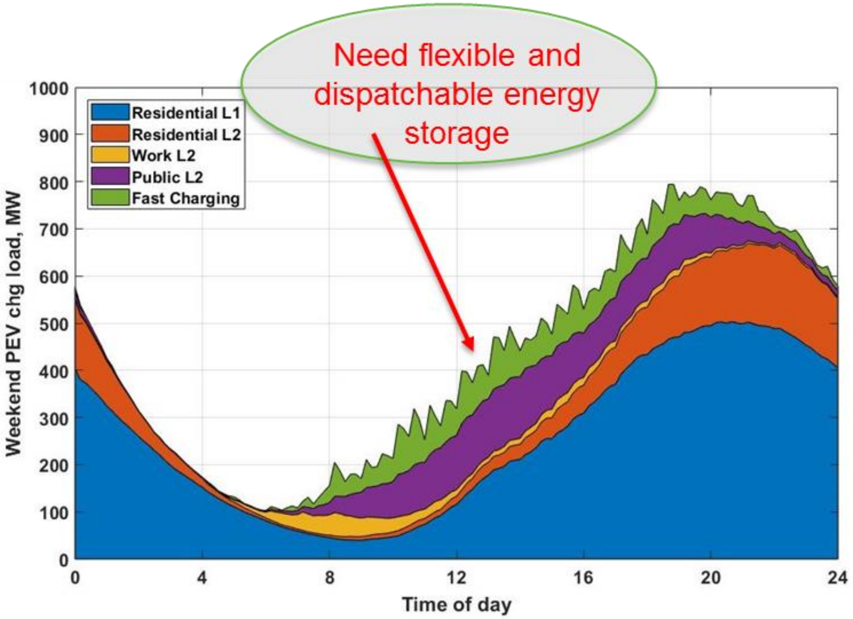


Need energy storage

Source: California ISO. "What the duck curve tells us about managing a green grid." (2016)

- Needed for balancing load and generation on the electricity grid match at a variety of timescales
- Storage provides ways to shift energy – helps to move variable generation to meet demand

Changes in electricity demand, such as electric vehicles, require flexible and dispatchable energy storage



Need flexible and dispatchable energy storage

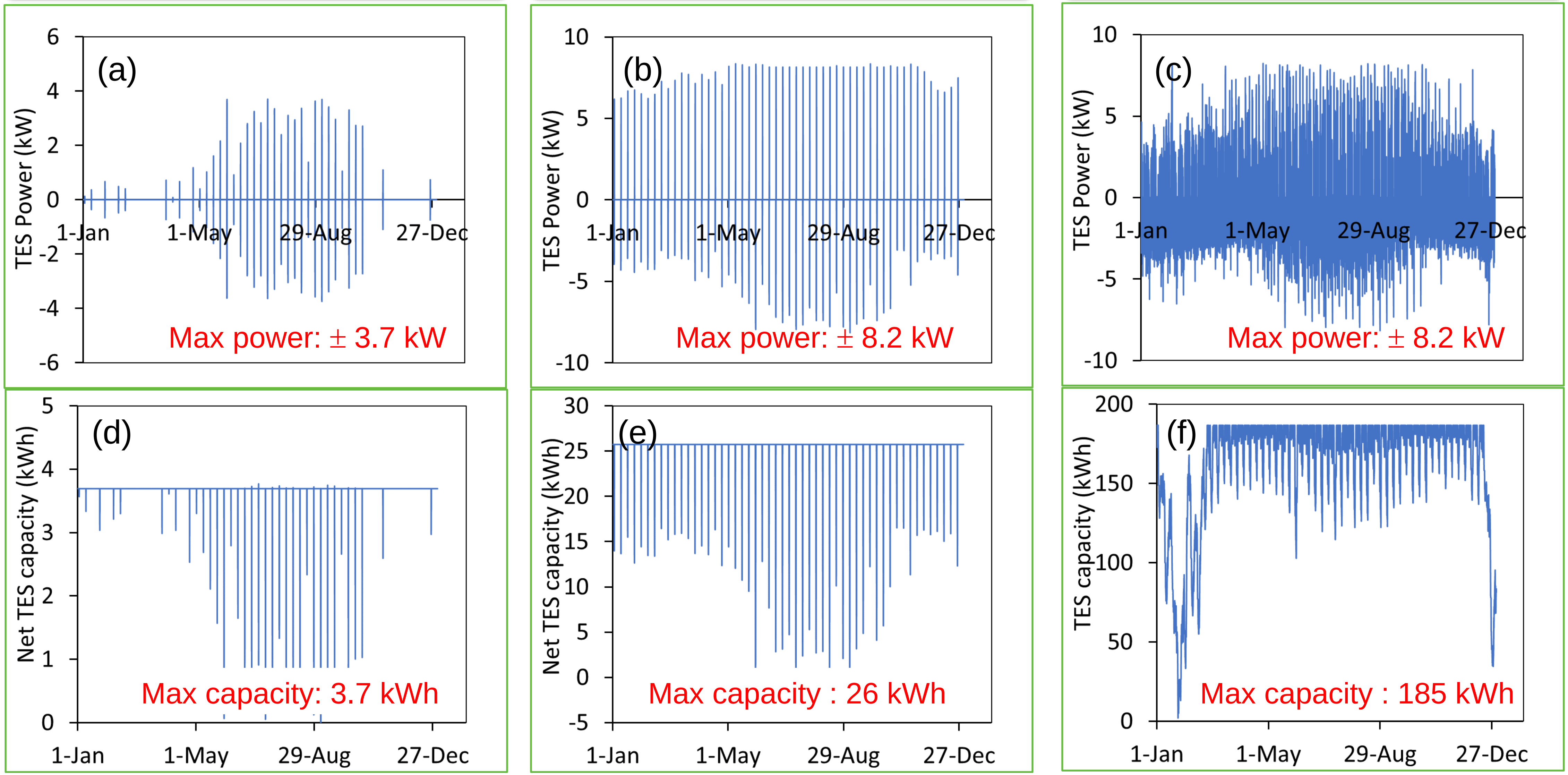
Source: Bedir, Abdulkadir, Noel Crisostomo, Jennifer Allen, Eric Wood, and Clément Rames. 2018. California Plug-In Electric Vehicle Infrastructure Projections: 2017-2025. California Energy Commission. Publication Number: CEC-600-2018-001

TES Power and Capacity Requirements (A single family home in Baltimore)

~8% peak elec. load reduction

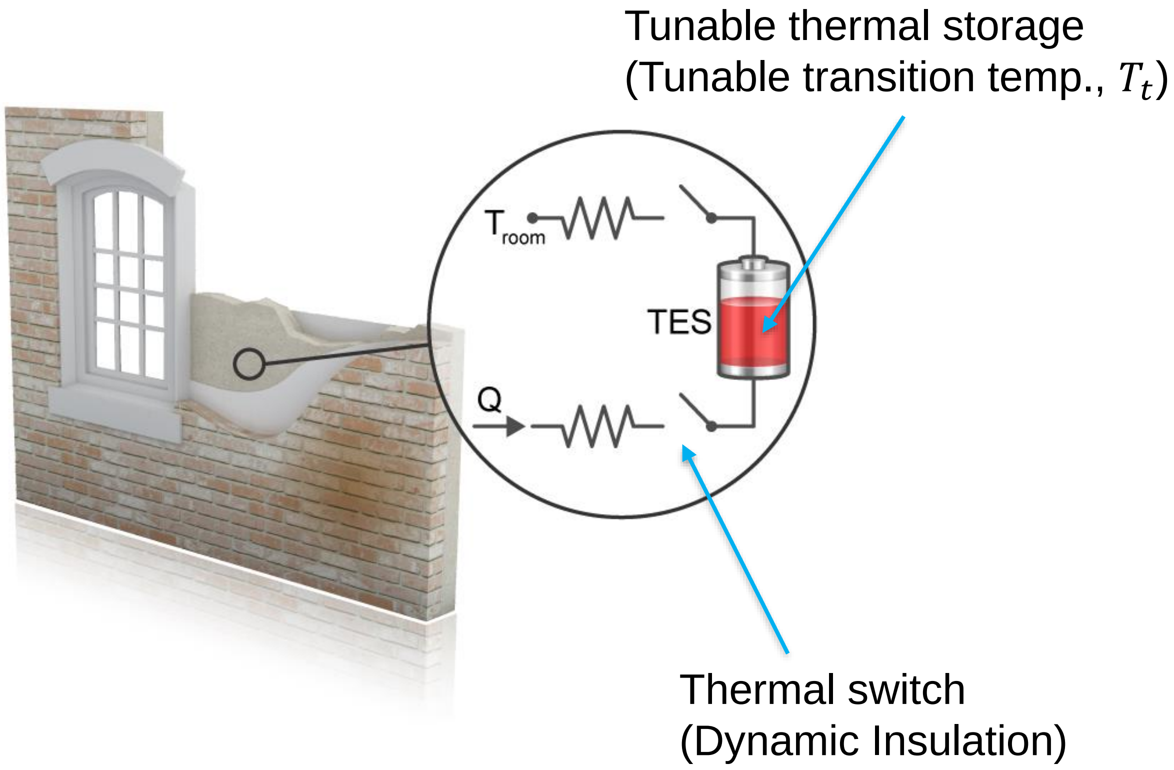
~40% peak elec. load reduction

~80% peak elec. load reduction



Approach – Thermal Switch and Storage

Use Case Example: Tunable thermal storage and switching integrated into the building envelope



Thermal Switch Requirements

Low $k_{Off} \lesssim 2k_{air} \approx 0.05\frac{W}{m \cdot K}$

Good switch ratio: $\frac{k_{On}}{k_{Off}} \gtrsim 10$

Voltage controlled

Cyclability 1000s +

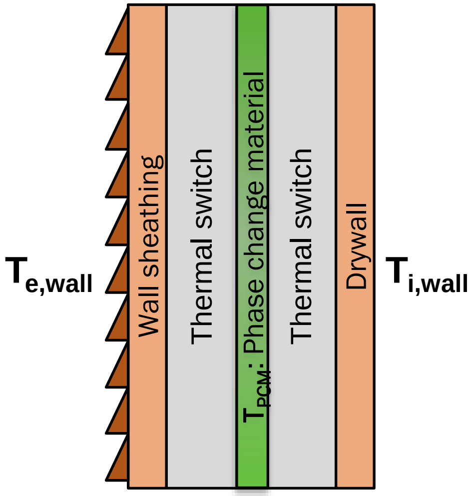
Thin package $\lesssim$ 60 mm

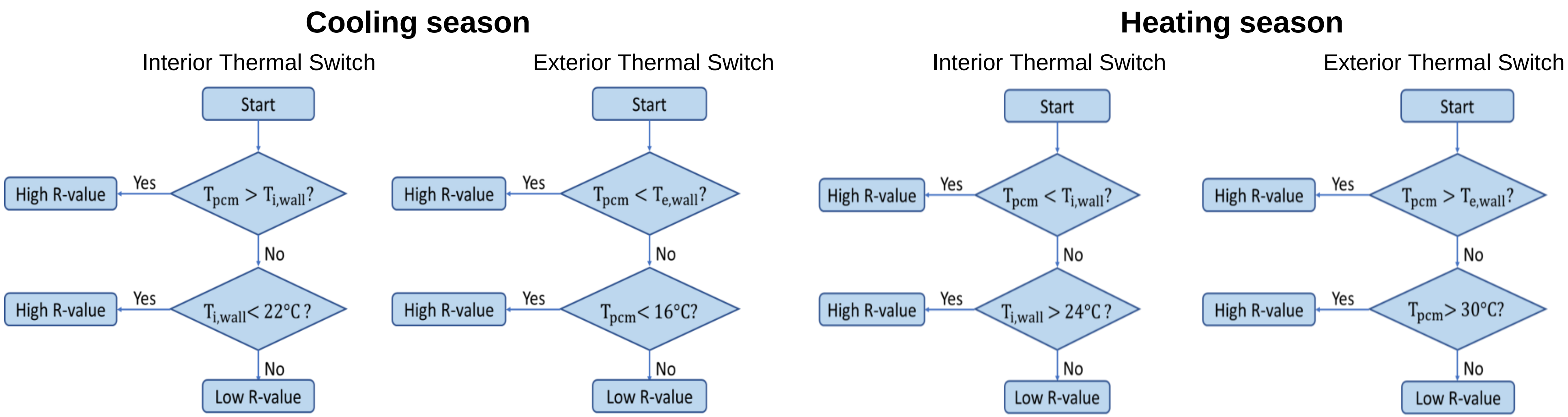
Ultra-low energy consumption

Low cost

(Applications not limited to building envelope.)

Optimizing Switch-Integrated Dynamic Wall





Cooling season

Interior Thermal Switch

Start
$T_{pcm} > T_{i,wall}$?
Yes
High R-value
No
$T_{i,wall} < 22°C$?
Yes
High R-value
No
Low R-value

Exterior Thermal Switch

Start
$T_{pcm} < T_{e,wall}$?
Yes
High R-value
No
$T_{pcm} < 16°C$?
Yes
High R-value
No
Low R-value

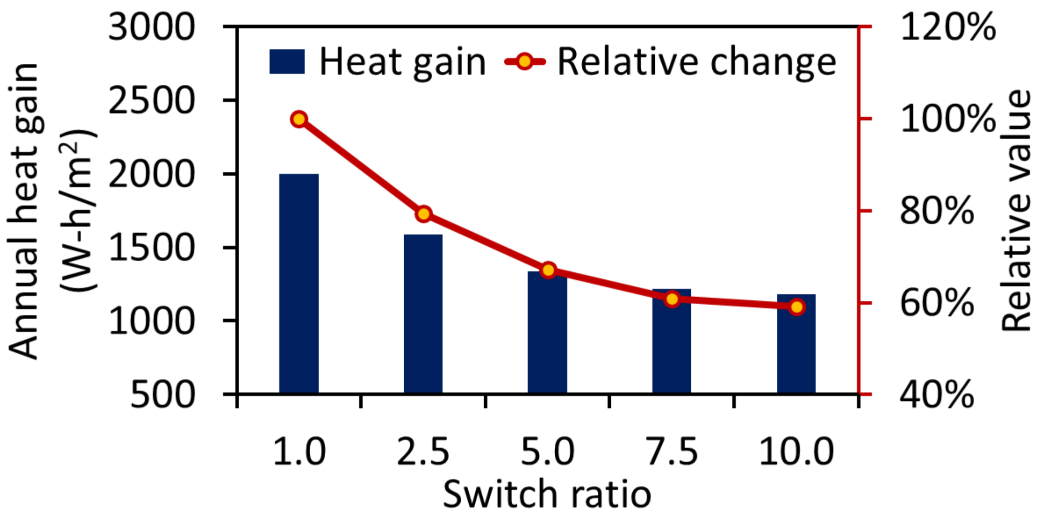
Heating season

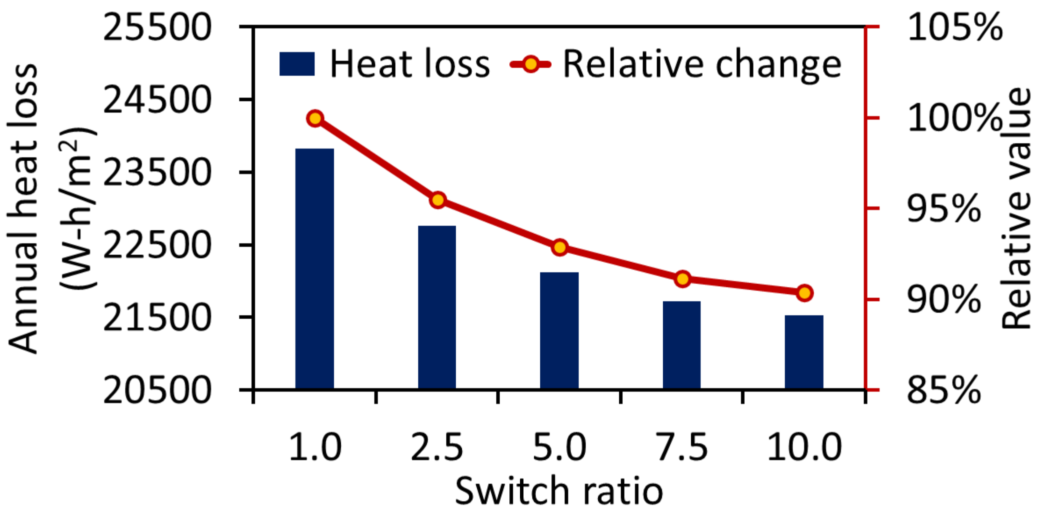
Interior Thermal Switch

Start
$T_{pcm} < T_{i,wall}$?
Yes
High R-value
No
$T_{i,wall} > 24°C$?
Yes
High R-value
No
Low R-value

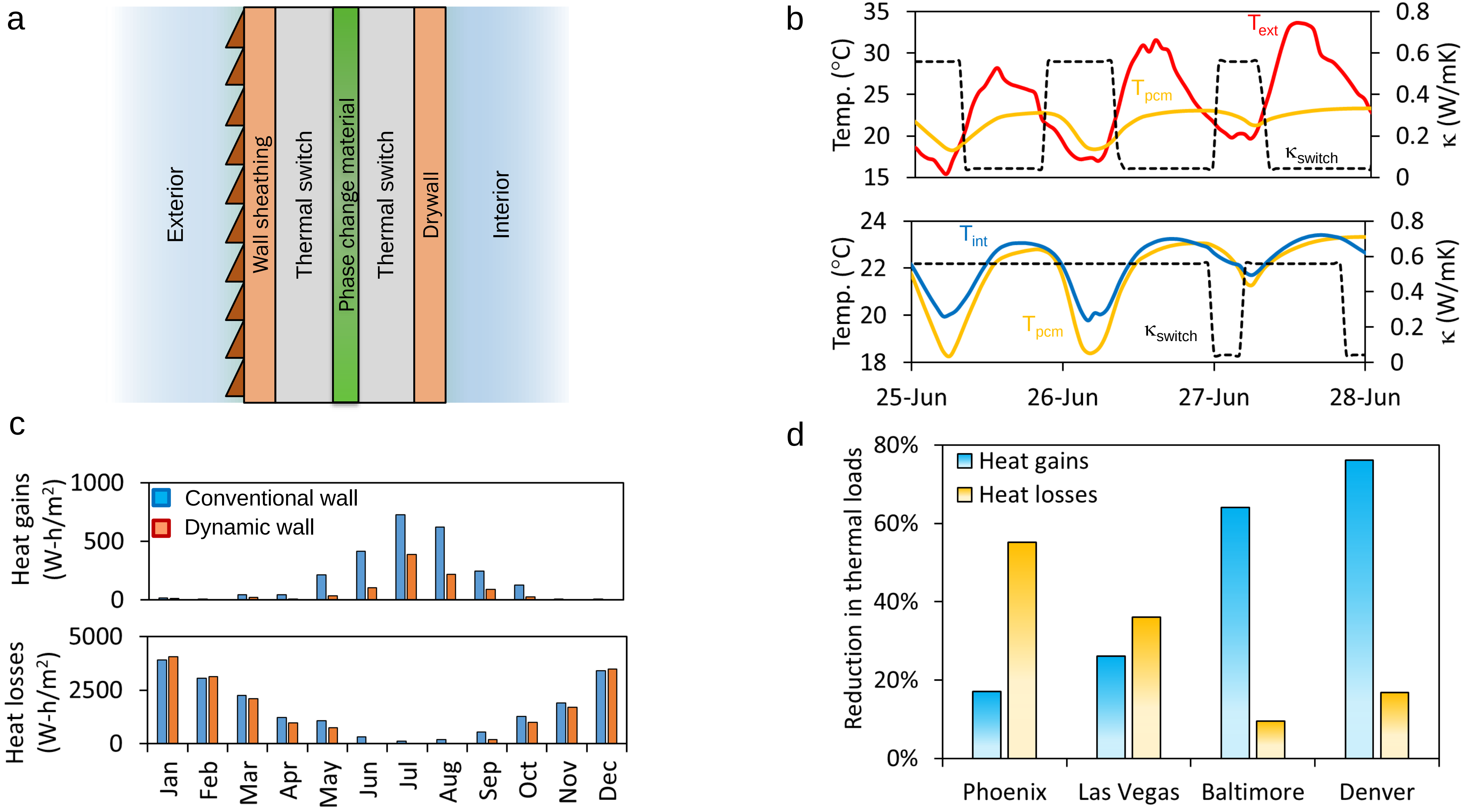
Exterior Thermal Switch

Start
$T_{pcm} > T_{e,wall}$?
Yes
High R-value
No
$T_{pcm} > 30°C$?
Yes
High R-value
No
Low R-value

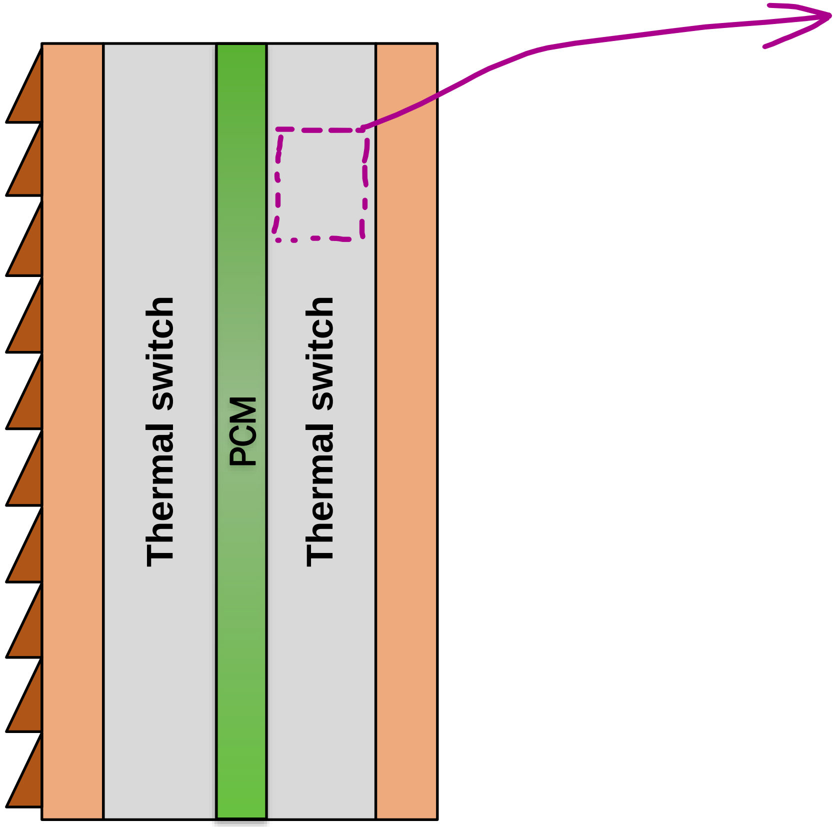




Impact – Thermal Switch and Storage



Approach & Progress: *Thermal Switches for Building Envelope*



Thermal Switch Requirements

Low $k_{Off} \lesssim 2k_{air} \approx 0.05\frac{W}{m \cdot K}$

Good switch ratio: $\frac{k_{On}}{k_{Off}} \gtrsim 10$

Voltage controlled

Cyclability 1000s +

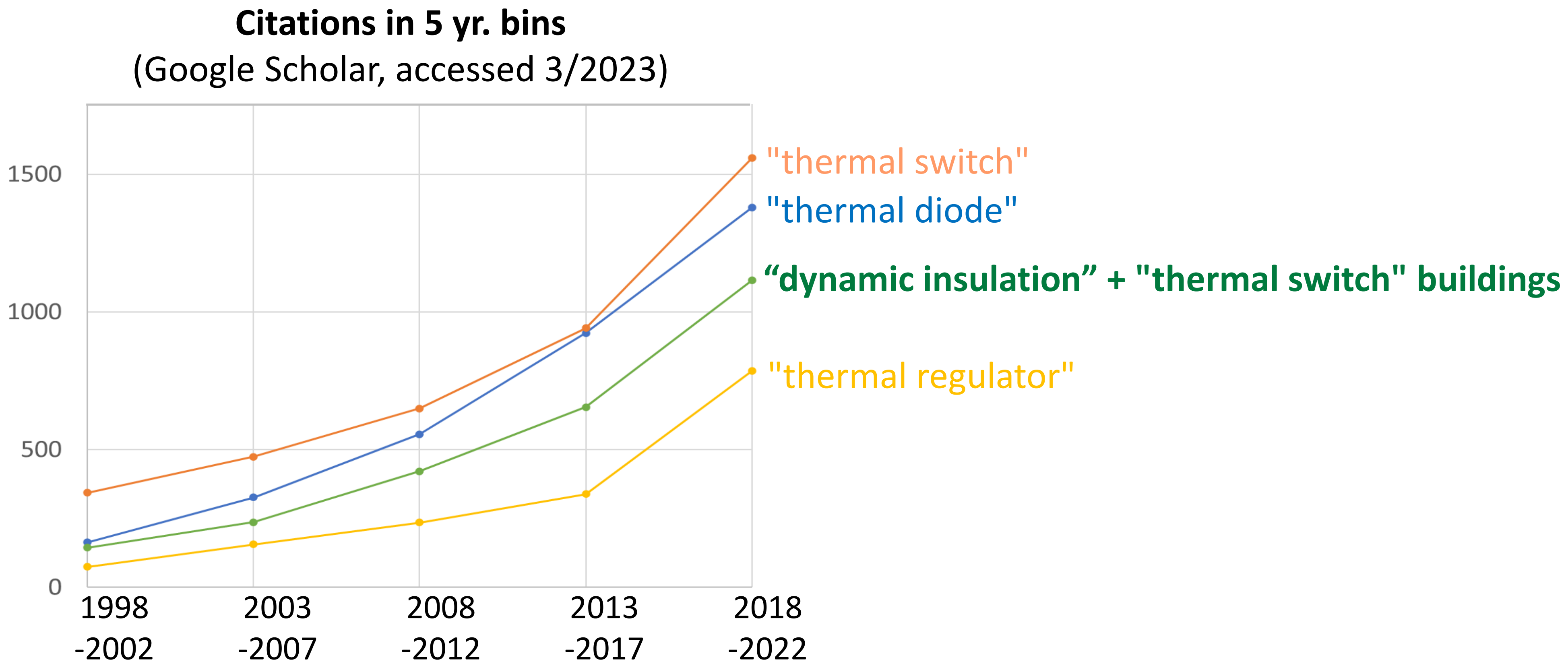
Thin package $\lesssim$ 60 mm

Ultra-low energy consumption

Low cost

Among 1000s of prior papers, to our knowledge *none* demonstrated these 2 key criteria.

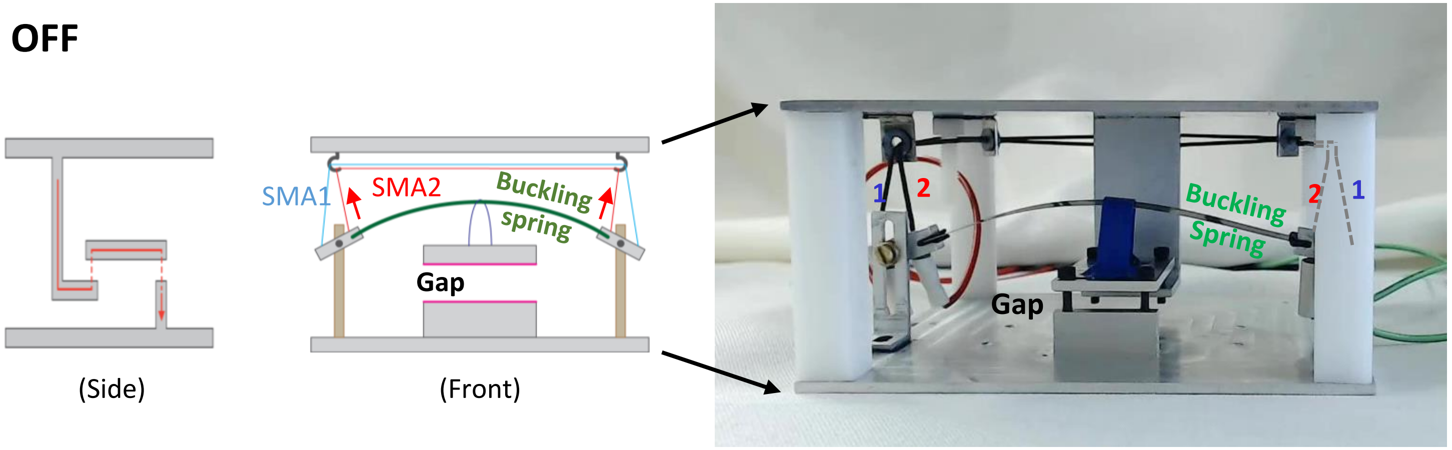
Approach & Progress: *Thermal Switches for Building Envelope*



Rapidly growing interest in active and nonlinear thermal components.

Approach & Progress: *Thermal Switches for Building Envelope*

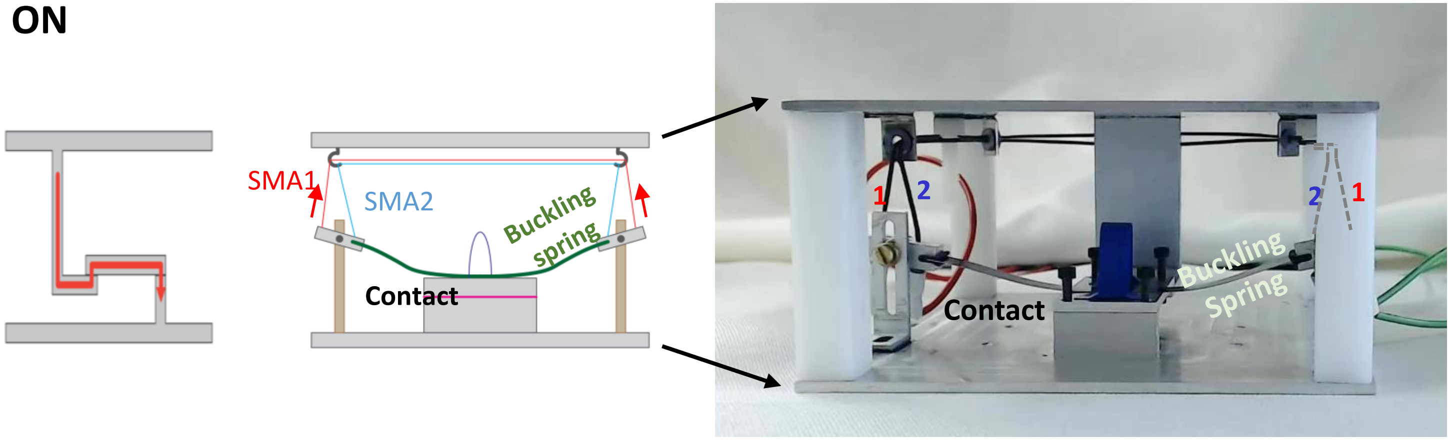
OFF



(Side)

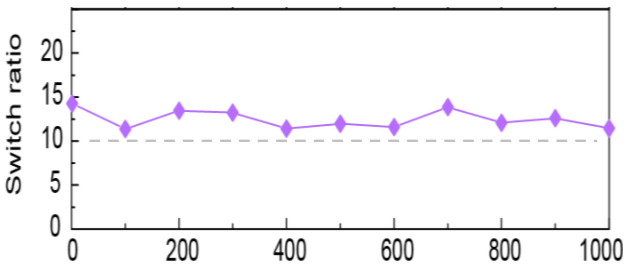
(Front)

ON



"Non-volatile": Requires *no* electricity to hold either ON or OFF

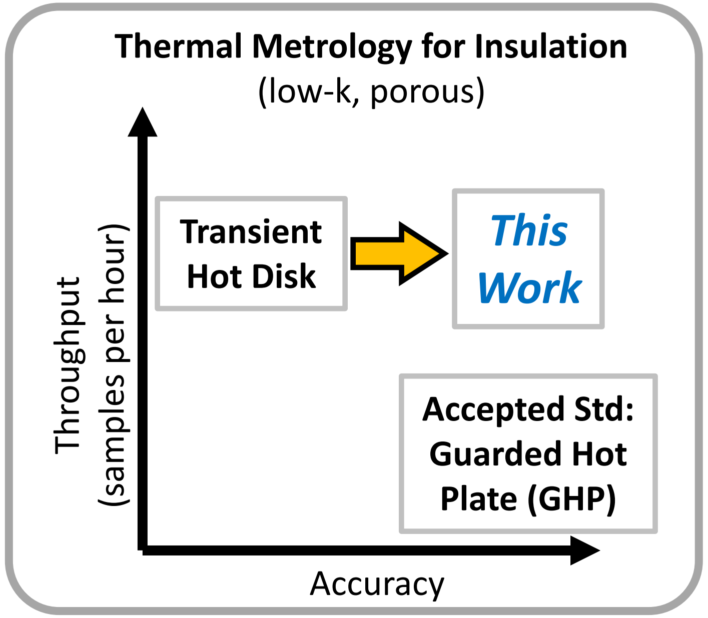
1000 cycles, Switch Ratio > 10



Thermal Switch Requirements

- ✓ Low $k_{off} \approx 0.05\frac{W}{m\cdot K} \lesssim 2k_{air}$
- ✓ Good switch ratio: $\frac{k_{on}}{k_{off}} \approx 12 \gtrsim 10$
- ✓ Voltage controlled
- ✓ Cyclability 1000s
- ✓ Thin package $\lesssim$ 60 mm
- ✓ Ultra-low energy consumption
- ✗ Low cost
  [Raw materials est. \$4,400 for 150m^2 wall area house (1,615 ft^2)]

Approach & Progress: *Thermal Metrology 1: Hot Disk*



Thermal Metrology for Insulation
(low-k, porous)

Throughput
(samples per hour)

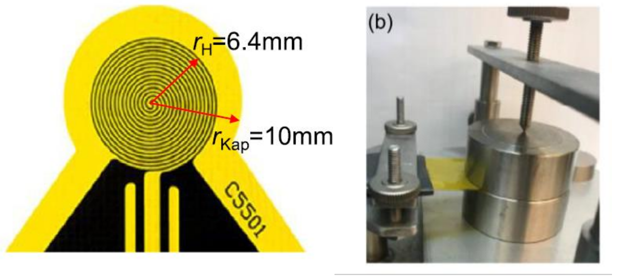
Transient Hot Disk

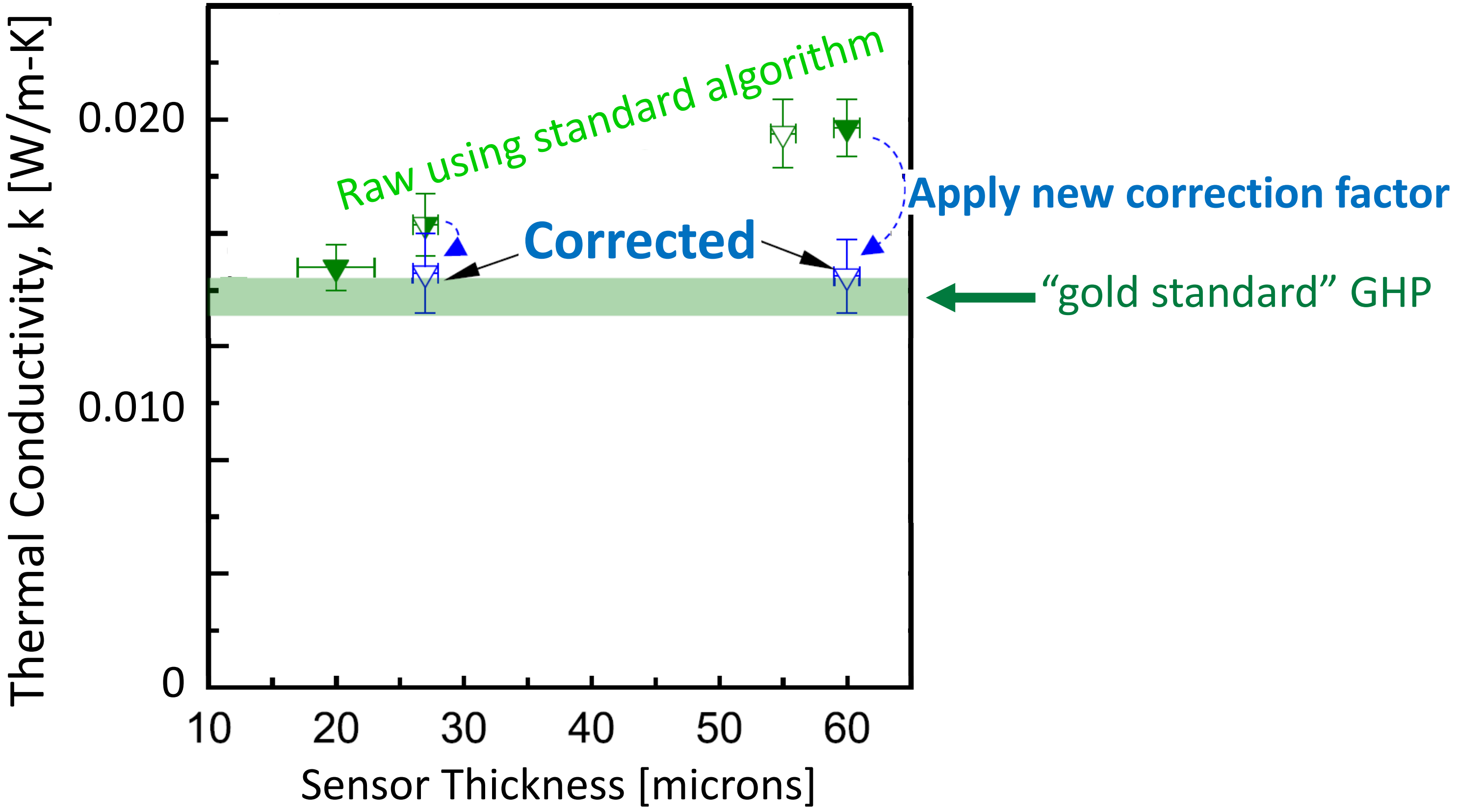
This Work

Accepted Std: Guarded Hot Plate (GHP)

Accuracy

Hot Disk TPS 2200 (Thermtest®)





Enables accurate Hot Disk measurement of aerogel, via two solutions:

(1) Thin down sensor, and use existing algorithm.

(2) Use existing sensor, and new correction factor.

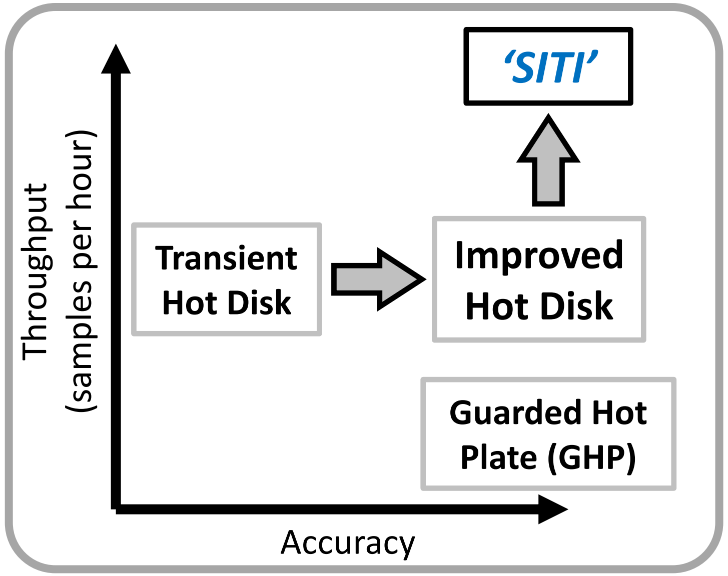
And have blind-tested on multiple low-*k* samples.

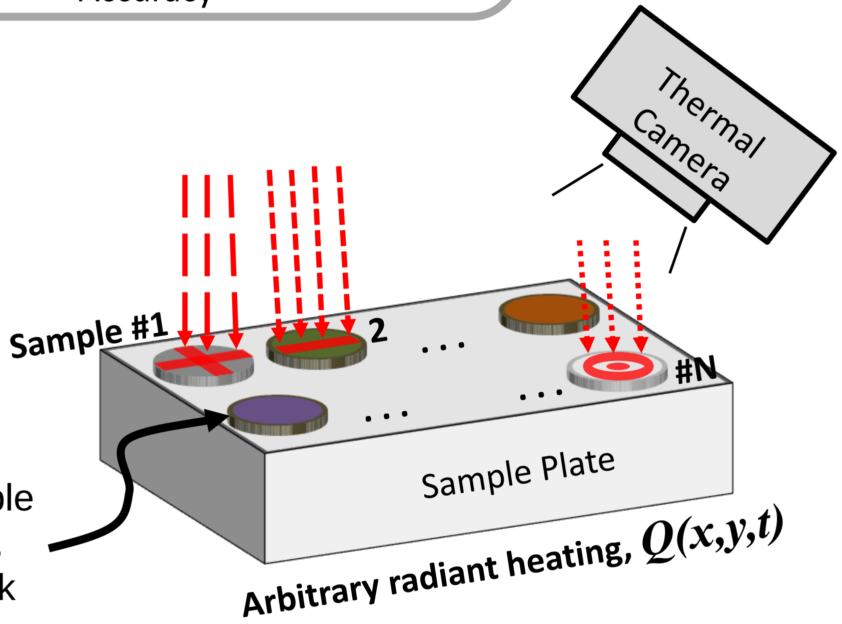
* Hot Disk is commercial State of Art (SOA) for insulation.

* GHP not appropriate for research because requires large (~4") samples.

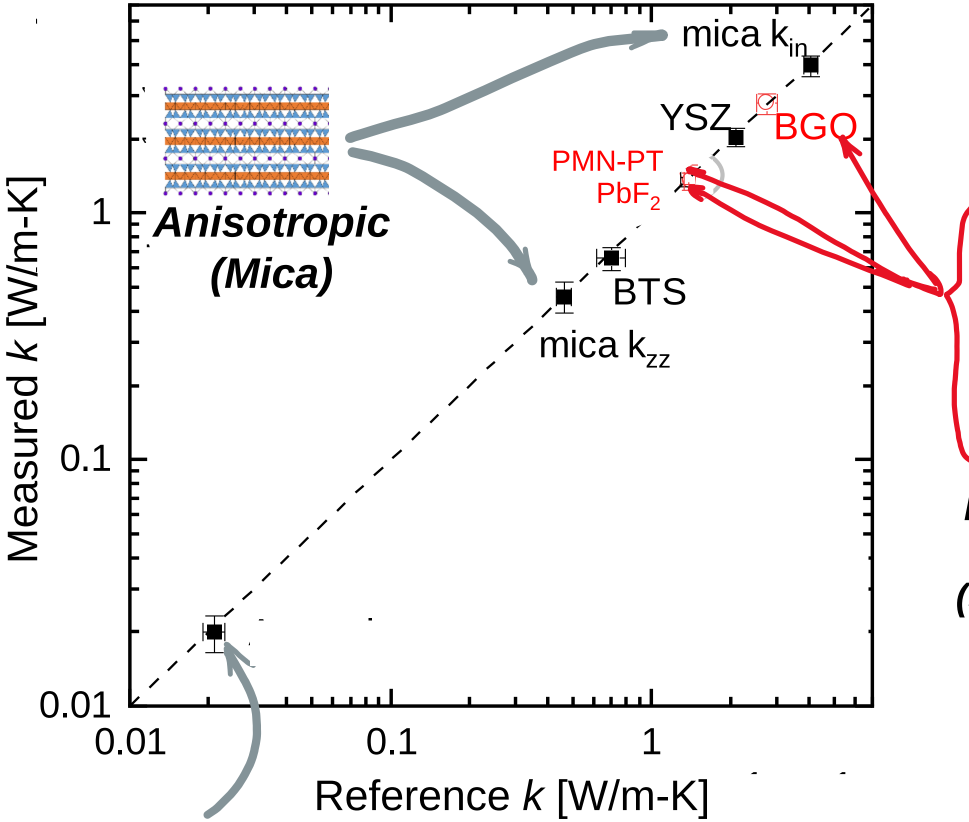
Zheng, Kaur, Dames, Prasher, IJHMT (2020) [24 pgs., 13 figs]

Approach & Progress: *Thermal Metrology 2: 'SITI'* *(SITI = Structured Illumination + Thermal Imaging)*

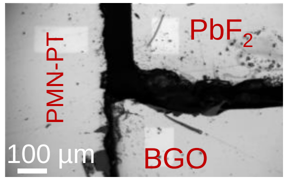




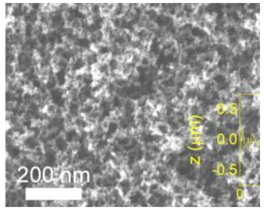
Typical sample
~3 mm dia.
x 1 mm thick



Anisotropic (Mica)



Parallelized 3 samples (simultaneous msmt)



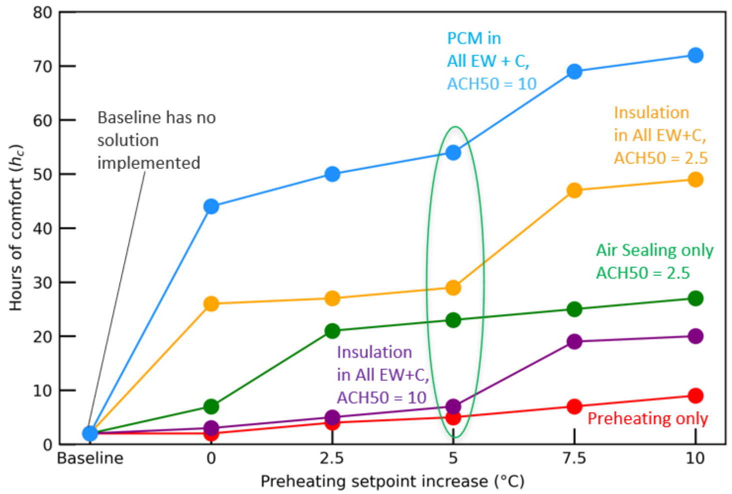
Rough & Porous: Aerogel

Zheng, Kaur, Prasher, Dames, et al. Appl. Phys. Rev. (2022) [>100 pgs. main + SI]

Future work

NREL

- Evaluate the thermal resilience using PCM – integrated dynamic envelopes in extreme weather events
- Evaluate the Carbon reduction potential from building thermal storage
- Experimentally characterize the retrofittable thermal switch for building envelope



LBNL / Berkeley

Thermal Switch: Exploring switching algorithms more broadly

Lumped approximation for speedup (expect 10x-100x vs. FEM or finite diffs)

Explore at least 1,000 different algorithms (stretch goal is 10,000)

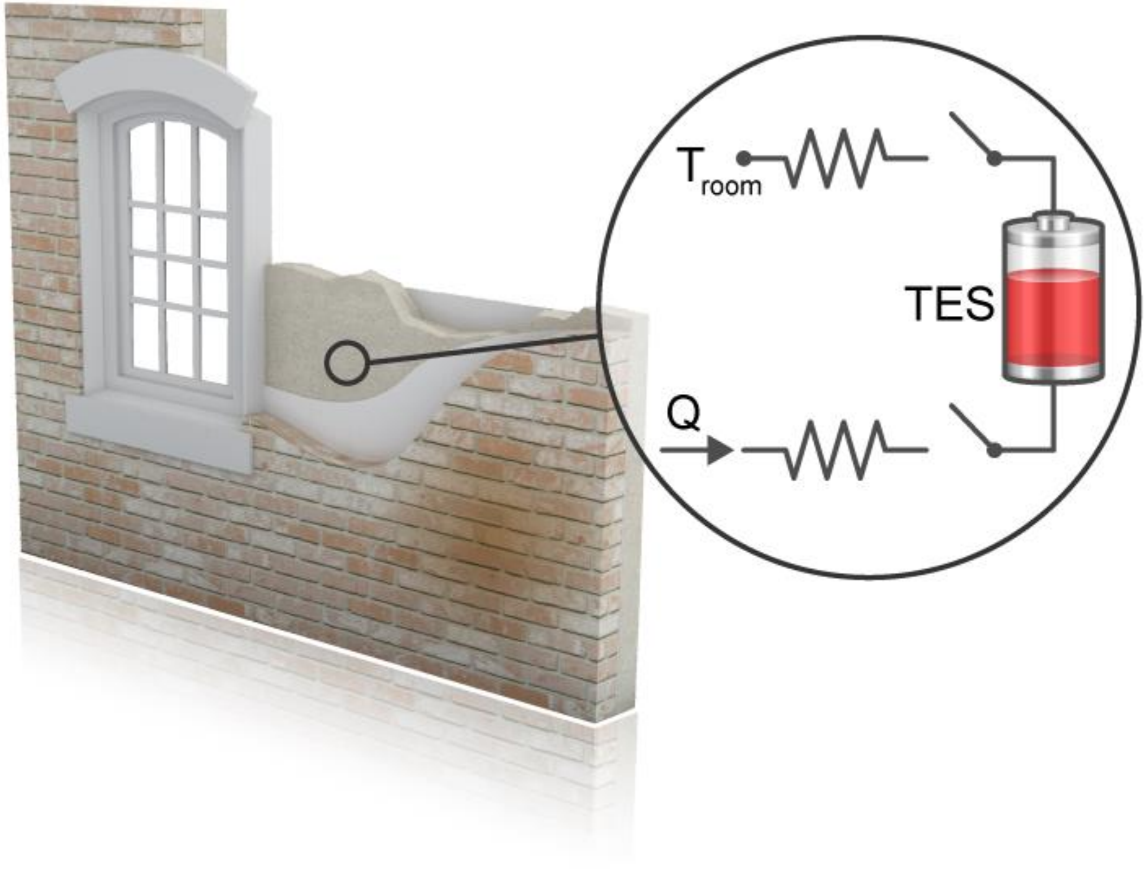
Share top ~5 algorithms back to NREL for high-fidelity simulation

Metrology: Next-Gen SITI

Order-of magnitude higher optical power

More samples in parallel; Higher throughput

Completely new concepts for heating patterns & fitting algorithms.



Thank You

LBNL/UCB and NREL

PIs: Chris Dames & Ravi Prasher (LBNL) & Roderick Jackson (NREL)

WBS# 3.1.3.52

REFERENCE SLIDES

Project Execution

	FY2021				FY2022				FY2023		
Planned budget											
Spent budget											
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
Past Work											
Solid-Solid Phase Change Materials: Refine design and synthesizes of Comb Branch Polymer (CMP) polymer (developed in FY 20) to further improve thermal energy storage density of solid to solid transition phase change material. Description: The current CMP with solid to solid phase change has transition temperature around 25°C with enthalpy of 80 J/g. The polymer structure will be redesigned/fine-tuned to further improve its energy density. (LBNL)	▨ ◆	◆									
Thermal Switch: Improve cyclability to > 1000 while keeping switch ratio r > 10 and Roff value > 2.5. (LBNL-UC)	▨	▨	◆								
Thermal Switch: During FY 20 we developed thermal switch (4x4 inch) and demonstrated switching ratio of around 20 but the Roff value was low, only 0.45 (high thermal conductivity). In FY 21 we aim to make version 2 thermal switch with improved properties. By modeling and selecting suitable thermal insulation strategy for SMA wire, reduce the energy cost to switch and maintain the working state, aiming at overall energy cost 1 W/m2. (LBNL-UC)	▨	▨	▨ ◆								
Optical Metrology: Apply the patterned optical heating and thermal imaging technique to measure at least 2 samples simultaneously, each of diameter no more than 5 mm. Analyze the experimental data with the analytical and numerical model we developed to obtain the thermal conductivity and heat capacity of the sample. (LBNL-UC)		▨	▨ ◆		◆ ◆						
Optical Metrology:Further improve the optical heating power and study thermal imaging in a larger field of view by a lower magnification objective lens. Complete and submit the manuscript of this research.(LBNL-UC)		▨	▨	▨							
			▨	▨							
Dynamic Tunability: Develop a prototype for dynamic tunable phase change material. The concept of dynamic tunable phase change material has been successfully demonstrated in FY 20 in coin cells (2032 coin cells: 2 cm in diameter). In Fy21, we aim to demonstrate dynamic tunability in a larger prototype specifically in pouch cell which has the dimension of 4.15 cm x 3.55 cm x 0.5 cm. (LBNL).			▨	▨ ◆		🟥◆					
Dynamic tunability: Determine cyclic performance (>50 cycles) of most promising developed shape-stabilized PCMs to demonstrate their long-term stability. (NREL)			▨	▨							
Modeling: NREL will quantify the performance of tunable- versus cascaded-PCMs with state-of-the-art performance. We will also evaluate the benefits of tunable PCM with low energy density (70-100 J/g) due to its increased utilization against static PCM with high energy density (200-280 J/g). The goal is to identify what, if any, performance advantages could be gained by developing/utilizing tunable PCMs over traditional materials. The use case will be embedding the PCMs in a lightweight construction wall.	▨ ◆										

EERE/BTO goals

The nation’s ambitious climate mitigation goals

Greenhouse gas emissions reductions

50-52% reduction by 2030 vs. 2005 levels

Net-zero emissions economy by 2050

Power system decarbonization

100% carbon pollution-free electricity by 2035

Energy justice

40% of benefits from federal climate and clean energy investments flow to disadvantaged communities

EERE/BTO’s vision for a net-zero U.S. building sector by 2050

Support rapid decarbonization of the U.S. building stock in line with economywide net-zero emissions by 2050 while centering equity and benefits to communities

Increase building energy efficiency

Reduce onsite energy use intensity in buildings 30% by 2035 and 45% by 2050, compared to 2005

Accelerate building electrification

Reduce onsite fossil -based CO_2 emissions in buildings 25% by 2035 and 75% by 2050, compared to 2005

Transform the grid edge at buildings

Increase building demand flexibility potential 3X by 2050, compared to 2020, to enable a net-zero grid, reduce grid edge infrastructure costs, and improve resilience.

Prioritize equity, affordability, and resilience

Ensure that 40% of the benefits of federal building decarbonization investments flow to disadvantaged communities

Reduce the cost of decarbonizing key building segments 50% by 2035 while also reducing consumer energy burdens

Increase the ability of communities to withstand stress from climate change, extreme weather, and grid disruptions