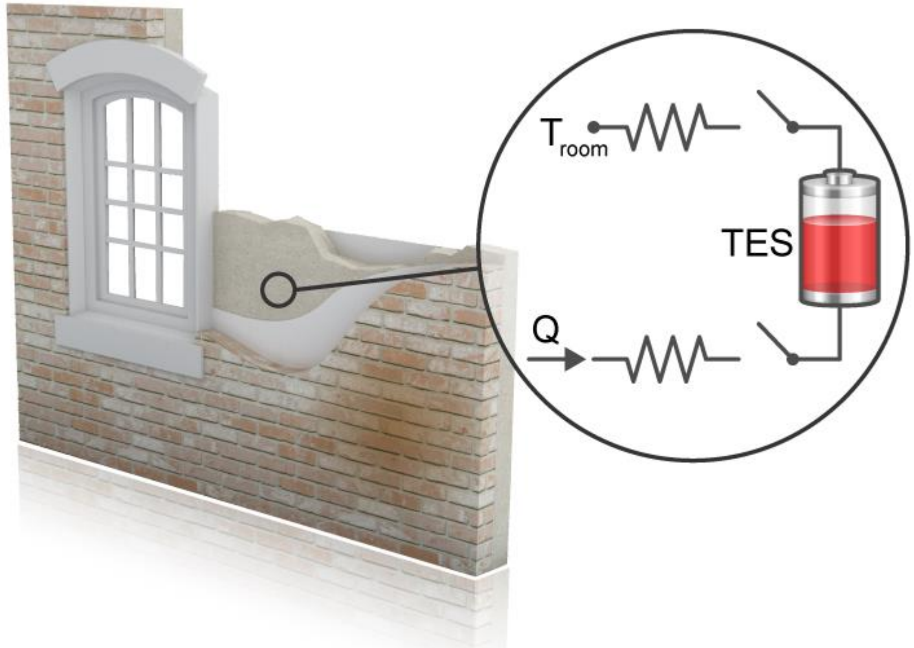
Solid State Tunable Thermal Energy Storage and Switches for Smart Building Envelopes



LBNL and NREL

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

Project Summary

Timeline:

Start date: Oct. 2018

Planned end date: Sep. 2021

Key Milestones

1. Milestone 1 (Sep. 2019): Select most promising potential use cases / applications for thermal switches and tunable thermal storage materials and perform multiscale modeling.
2. Milestone 2 (Sep. 2019): Thermal Storage: Demonstrate transition temperature (T_t) in 18-25C for solid-solid transitions with $\Delta H \sim 70\text{-}100$ J/g. Thermal switch: Demonstrate switch ratio of 2 - 5.

Budget:

Total Project $ to Date:

- DOE: $2,450,000
- Cost Share: N/A

Total Project $:

- DOE: $6,450,000
- Cost Share: N/A

Key Partners:

Lawrence Berkeley National Lab (LBNL)
National Renewable Energy Laboratory (NREL)
University of California, Berkeley
Georgia Institute of Technology
Stanford University

Project Outcome:

Enables **flexible** and **dispatchable thermal storage** by expanding traditional thermal storage R&D beyond energy density optimization to include *tunability* and *control*.

Applications (use cases) include dedicated thermal storage, equipment integrated thermal storage, and building envelope integration.

Team

PIs


Ravi Prasher, LBNL/UCB


Roderick Jackson, NREL

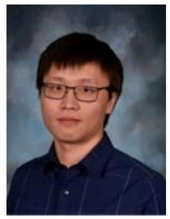

Chris Dames, LBNL/UCB

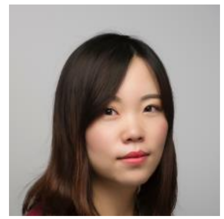
Tunable Solid-State Thermal Storage


Suman Kaur
LBNL


Drew Lilley
LBNL/UCB

Measurement Science (Metrology)


Qiye Zheng
LBNL

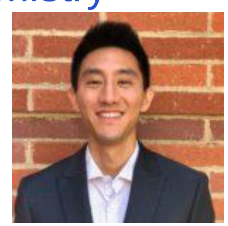

Shuang Cui
NREL



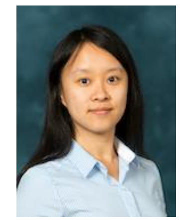
Sam Graham & Shannon Yee, Georgia Tech

Electrochemistry


Gao Liu, LBNL


Jonathan Lau, LBNL

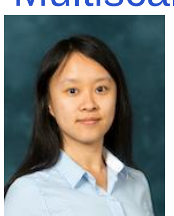
Thermal Switch

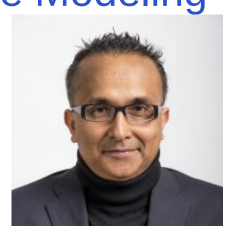


Ruijiao Miao &
Menglong Hao, LBNL


Arun Majumdar, Stanford

Multiscale Modeling


Ruijiao Miao


Ravi Prasher


Chris Dames

LBNL


R. Jackson


Judith Vidal

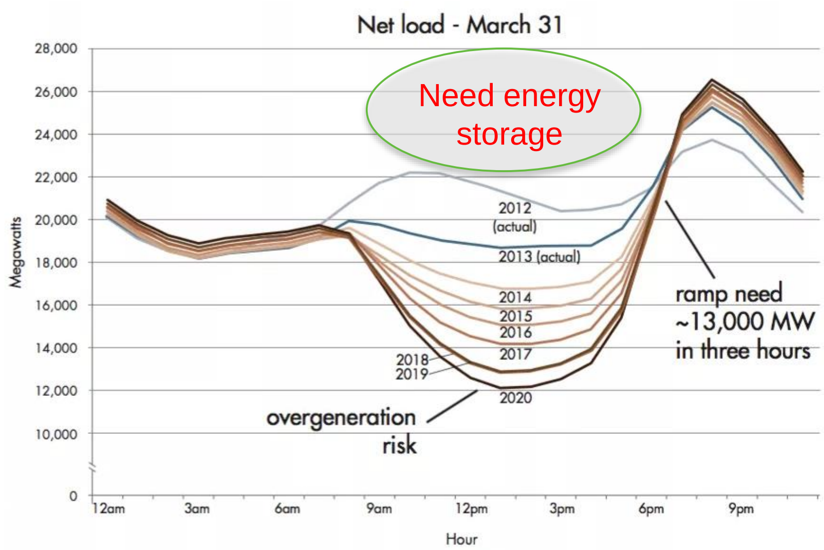

Ravi Kishore


Chuck Booten


Jason Woods

NREL

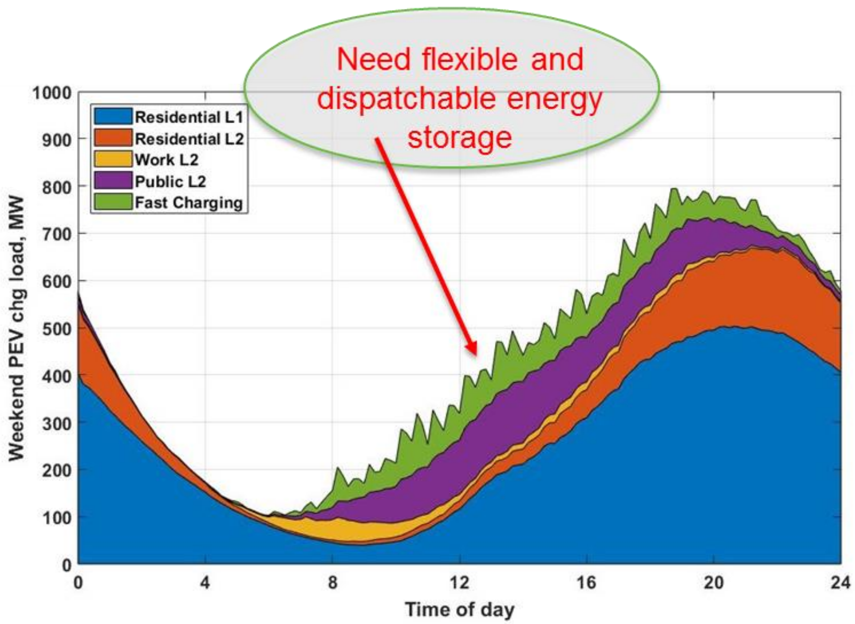
Challenge – Flexible Energy Storage is Needed



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

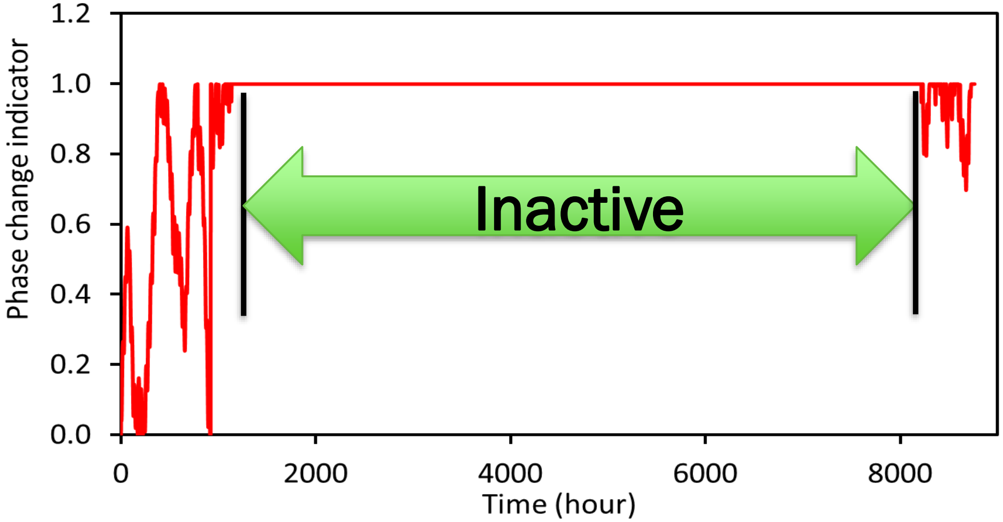
- Needed for balancing load and generation on the electricity grid match at a variety of timescales
- Storage provides ways to shift energy – helps to move variable generation to meet demand

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



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

Challenge – Traditional Approaches are NOT Flexible, Dispatchable, or Cost Effective



Simulation results illustrate that TES based on *static* PCM remains inactive for a major portion of the year (internal analysis)

	South Wall		East Wall	
	Fully Active	Partially Active	Fully Active	Partially Active
Percent of Days out of Year	0%	36%	8%	36%

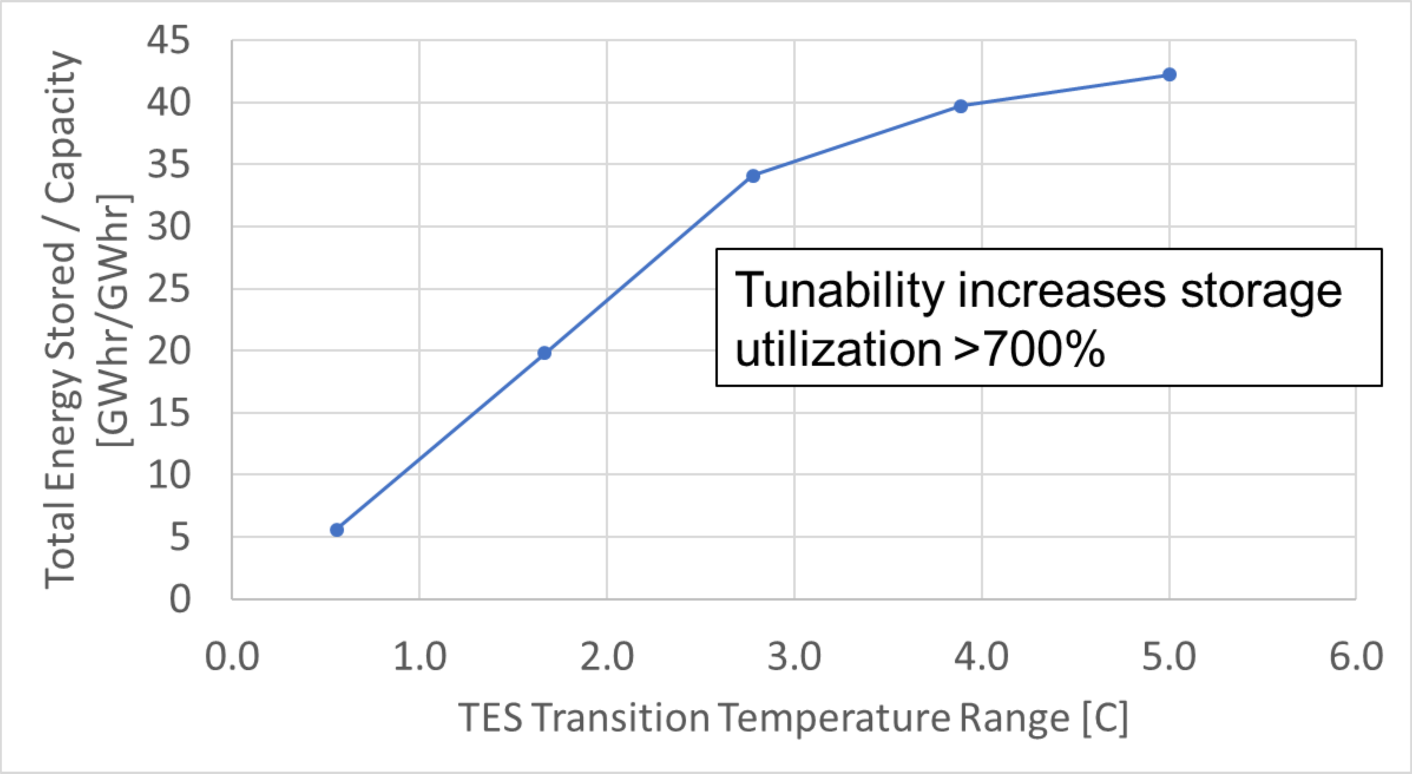
Source: Miller et al. 2012 ACEEE Summer Study on Energy Efficiency in Buildings

https://bma1915.com/projects/oak-ridge-national-laboratory-zero-energy-building-residence-alliance-zebra-homes/

Field tests have indicated limited PCM activity

Limited annual utilization ⇒ Limited energy efficiency opportunity

Approach – Thermal Control and Storage



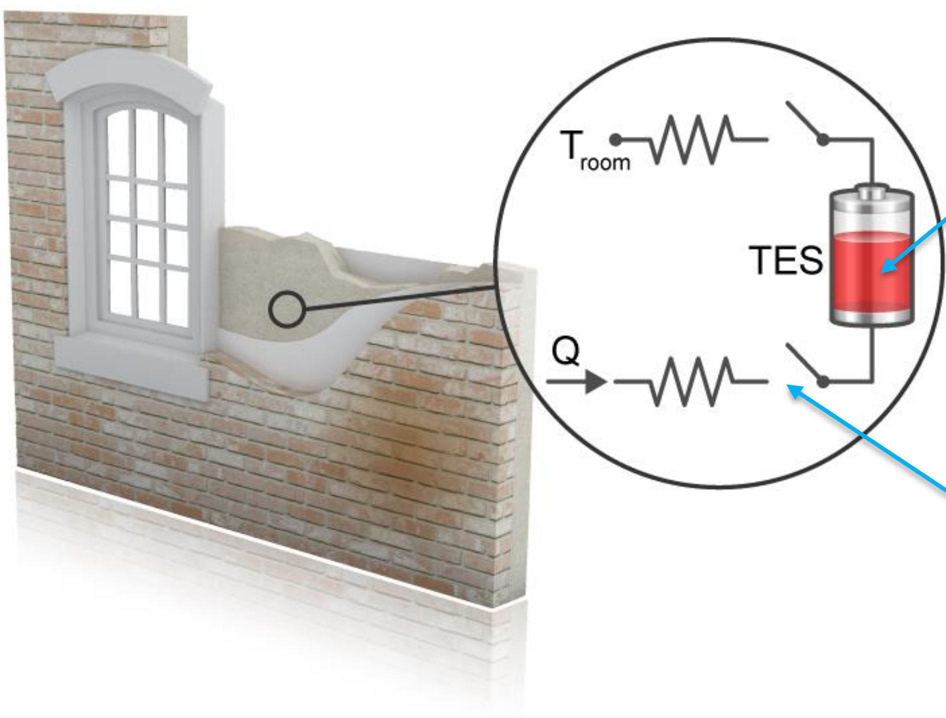
Tunable PCM can provide a substantial (e.g. 7x) improvement in energy storage utilization over the year.

Simulation Details:

- Physics-based envelope use case.
- Static PCM transition temperature 72-73 °F (22.2-22.8 °C).
- Annual simulations, nationally averaged.

Approach – Thermal Switch and Storage

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

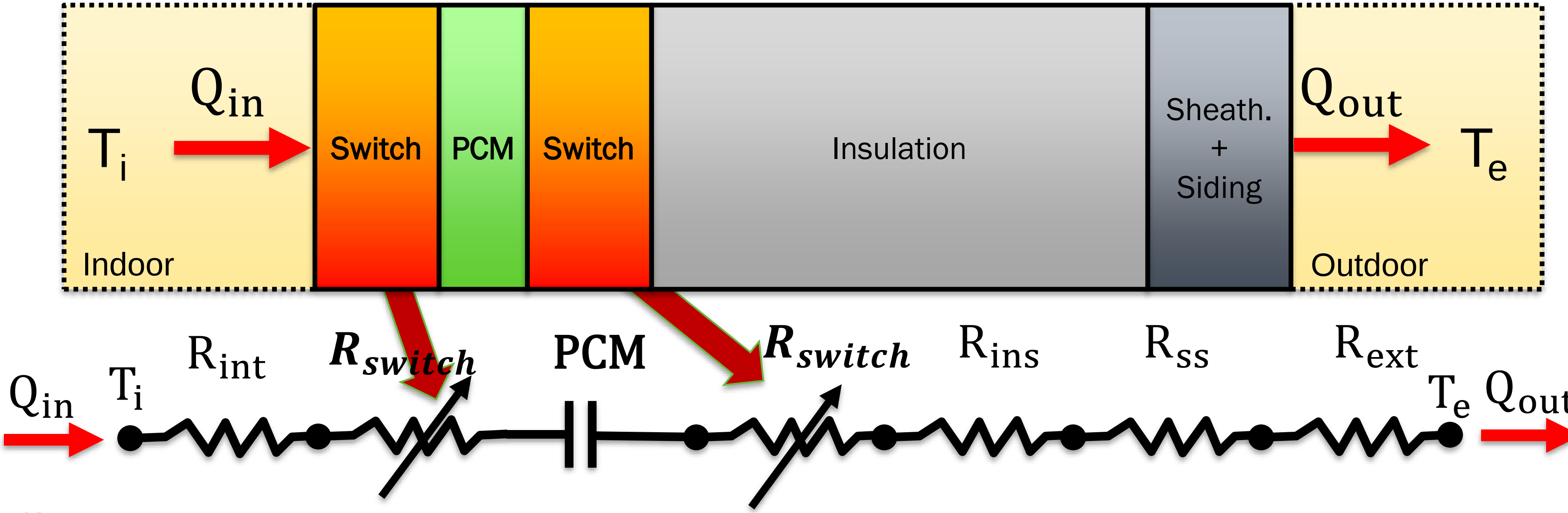


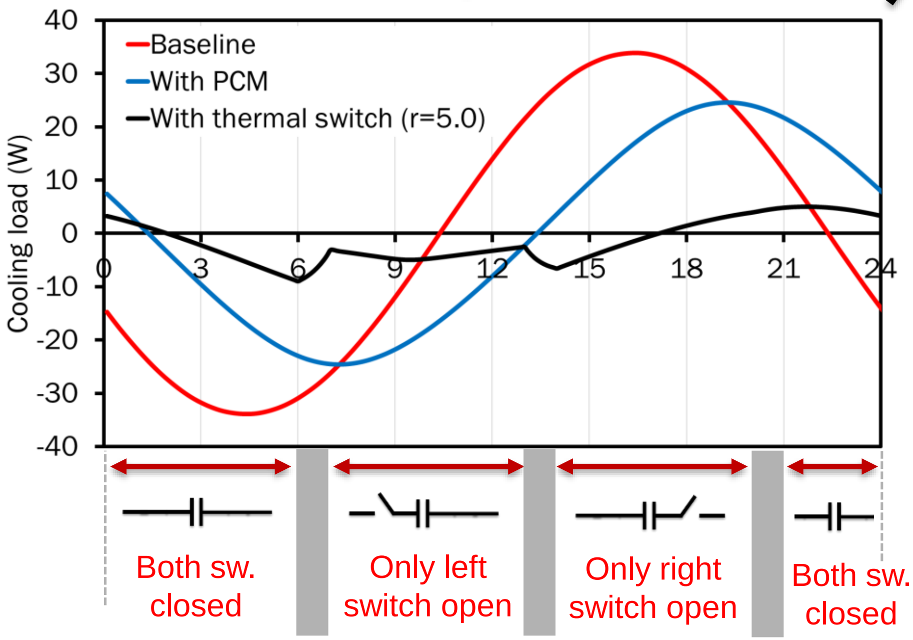
Tunable thermal storage (Tunable transition temp., T_t)

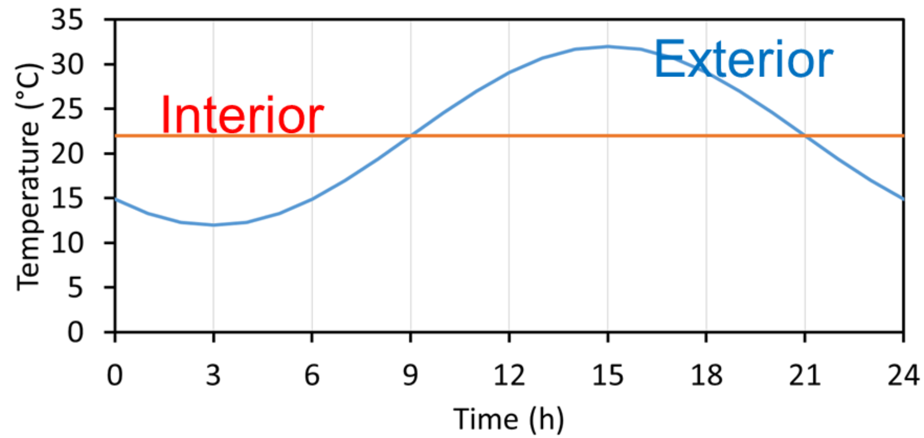
Thermal switch (Switch Ratio: $r = \frac{R_{off}}{R_{on}}$)

Note: Applications are not limited to the building envelope.

Approach – Thermal Switch and Storage







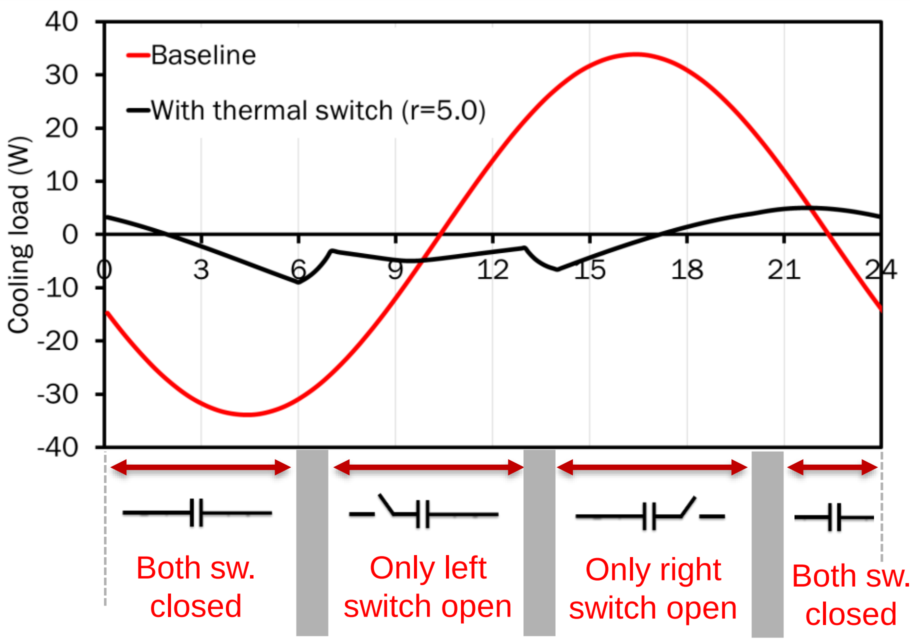
Simulation Details:

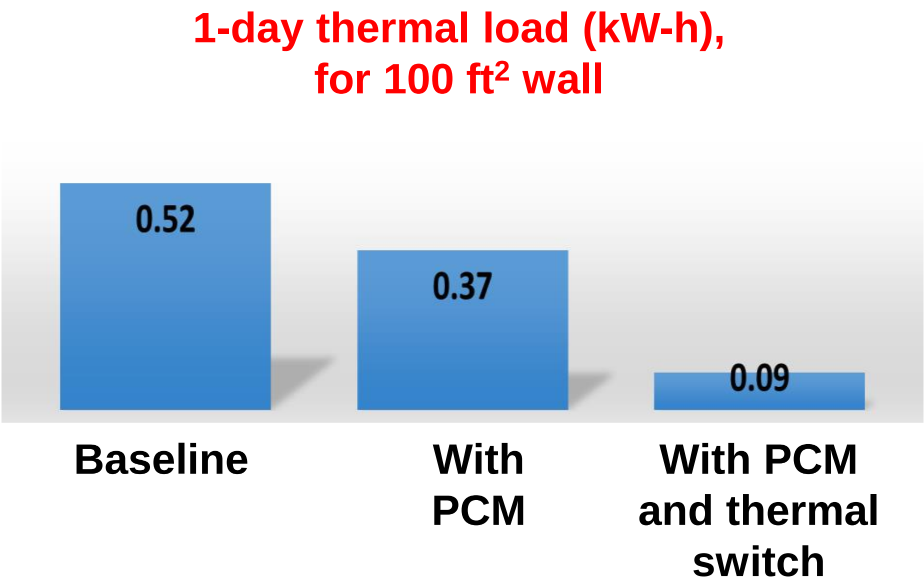
- Switch R_{on} = 1.4, R_{off} = 7.1. Thickness 1”.
- Traditional PCM (static).
- Original wall: $R_{ins}+R_{ss}$ = 14.5.

Approach – Thermal Switch and Storage

Thermal switches enable:

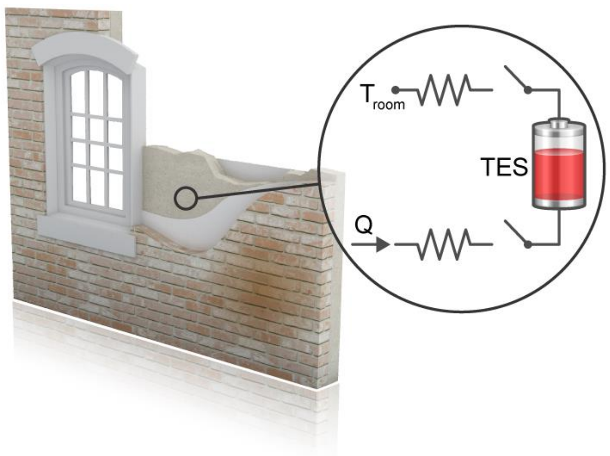
- Greater capacity to utilize diurnal temperature swings to maximize energy savings (e.g. 5x savings)
- **Ability to shape thermal demand (time shifting).**



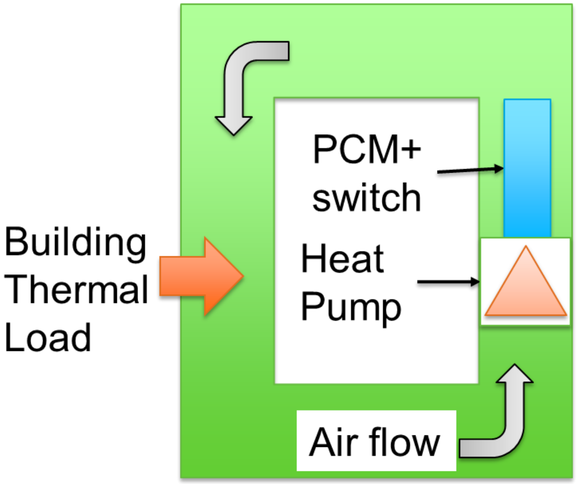


Approach – Multiple Use Cases and Applications

- **Low TRL research has multiple use cases and applications**
- Tunable PCM + switch can be integrated into multiple applications to control PCM charge/discharge during operation
- Broad range of transition temperatures facilitates both heating and cooling application



Envelope-integrated application



Equipment-integrated application

Approach & Progress: All-solid, Tunable PCM

Goal: Develop thermal energy storage (TES) materials that are:

- All solid state (encapsulation-free)
- Dynamically tunable

Approach:

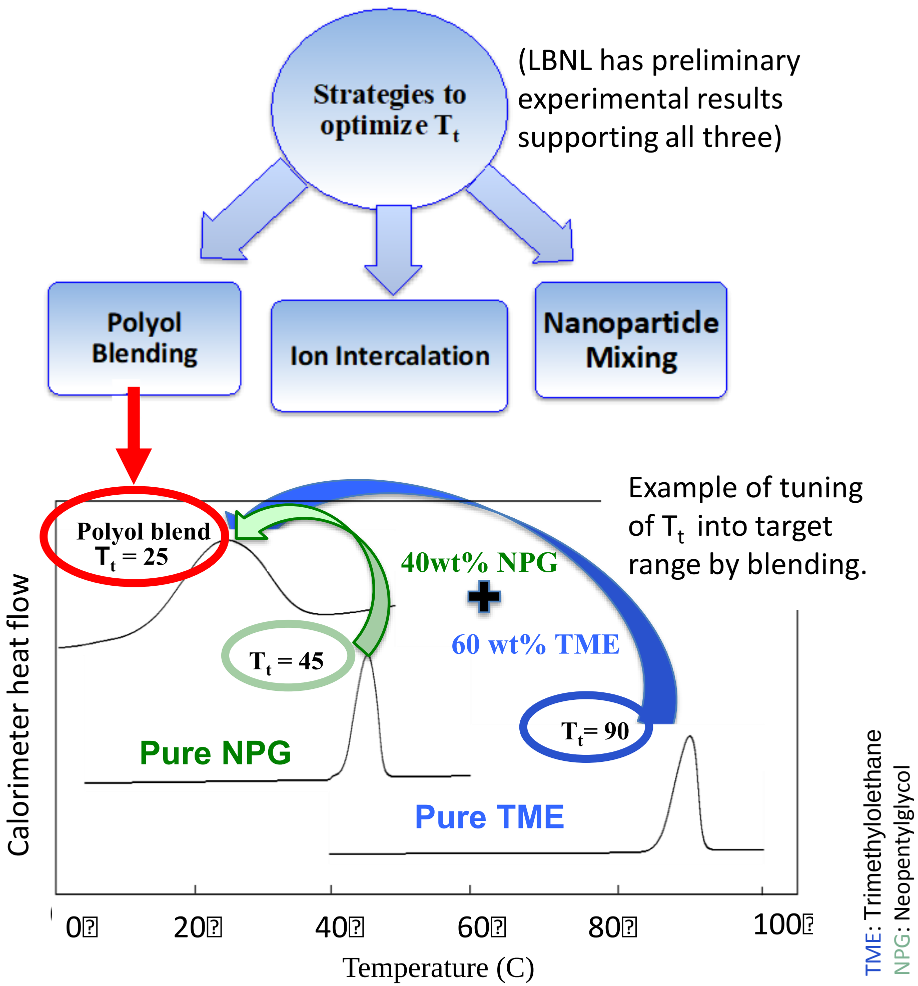
1) For all-solid state: Work with two classes of solid-solid PCMs to optimize their transition temperature (**T_t**) in 18 - 25 °C:
   a) Polyols
   b) Comb-branch Micro block Polymer (CMP)

2) For dynamic tunability:
   - Since both polyols and CMPs have polar molecules, voltage-driven tunability can be achieved by ion insertion and removal.
   - Leverages extensive knowledge from the electrochemical battery field.

Approach & Progress: All-solid, Tunable PCM

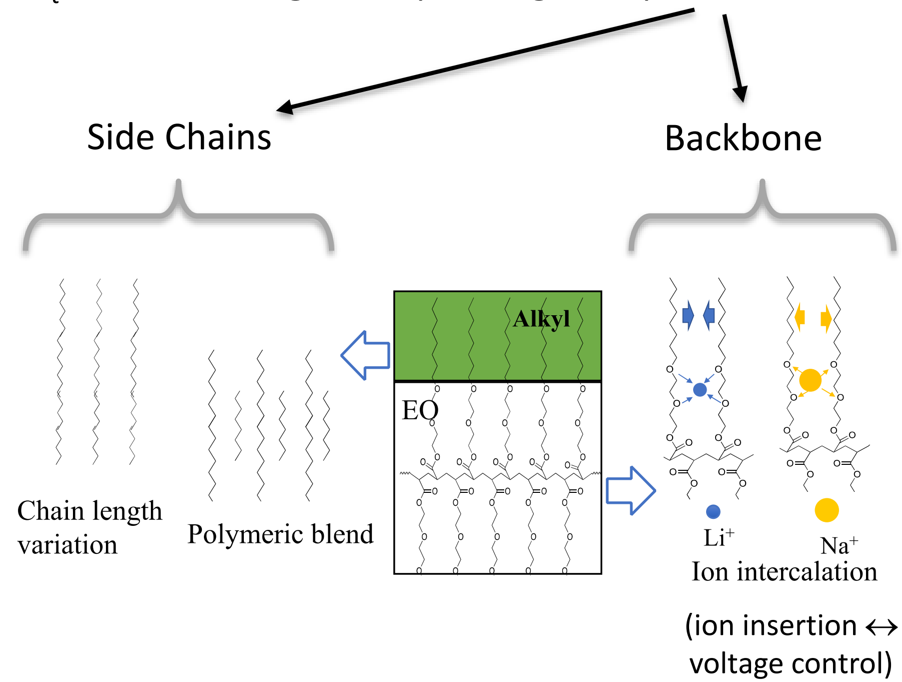
Polyols: solid-solid, phase change energy ΔH ~ 100 J/g. (Compare typ. solid-liquid PCMs, ΔH ~ 200 - 300 J/g.)

Potential Impact: 1 cm thick polyol on walls & ceiling of 2,000 ft^2 home → 44 Ton-hrs of thermal energy.



CMP: Solid-solid, phase change ΔH ~ 60 - 100 J/g.

- Extensive prior work for batteries at LBNL.
- As per published battery research, can optimize both T_t and ΔH through manipulating both phases:



Approach & Progress: Thermal Switches

Wehmeyer, ... Dames: "Thermal diodes, regulators, & switches: Physical mechanisms and potential applications" *Applied Physics Reviews* (2017). ~30 pages, 300 refs.

			Thermal Switches and Regulators	Thermal Diodes	
	Mechanism	Material system example	On/off ratio	Rectification Ratio	Refs.
Conduction	Solid-solid contact	Cu-Cu with TIM	>100 - 1,000	90	86,111
	Paraffin expansion	Encapsulated wax	100	-	99
	Liquid bridge switch	Mercury	200	-	86
	Electrostatic gating of k_{el} (Fig. 6)	Graphene (T=75 K)	5	-	126
Convection	Heat pipe diode	H_2O	-	>100	179
	Jumping droplets (Fig. 8)	H_2O	2	150	180,201
	Variable conductance heat pipe (Fig. 9)	N_2 gas and H_2O	80	-	189
	Gas gap switch (high vacuum, low T)	H_2	>500	-	190
	Electrowetting	H_2O on dielectric	2.5 - 15	-	194,195
	Electrical suppression of Leidenfrost	Isopropyl alcohol	20	-	198
Radiation	VO_2 emissivity across transition (Fig. 11)	VO_2	2-3	2	256
	Electrochromic (Fig. 12)	WO_3	2-10	-	257
	Liquid crystal regulators	Liquid crystals	2-5	-	268,269
	Near field (<200 nm gaps, UHV)	Au-Au surfaces	>100	-	280

Approach & Progress: Thermal Switches

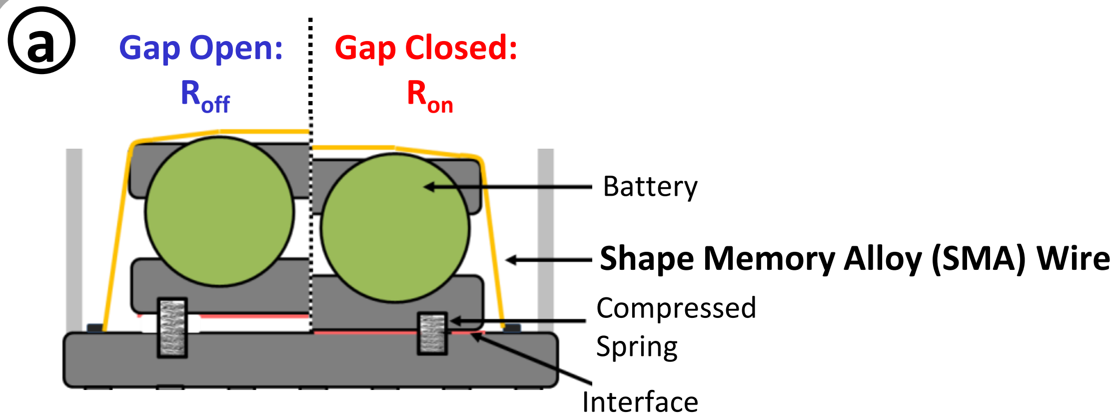
Building-Specific Requirements

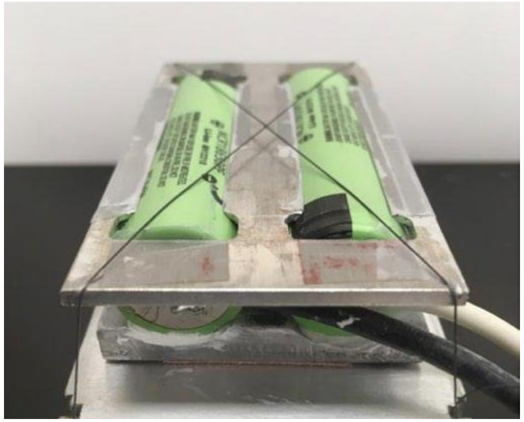
(Use-case dependent. All to be refined through iterative feedback with systems analysis.)

- Switch ratio $r = \frac{R_{off}}{R_{on}} \geq 10$.
- Large R_{off}.
- Switching *T* around 20 - 30 °C
- Voltage-controlled (integration, smart grid)
- Cyclability: 100s to 1000s of cycles.
- Thickness (if retrofit): ~1" or less.

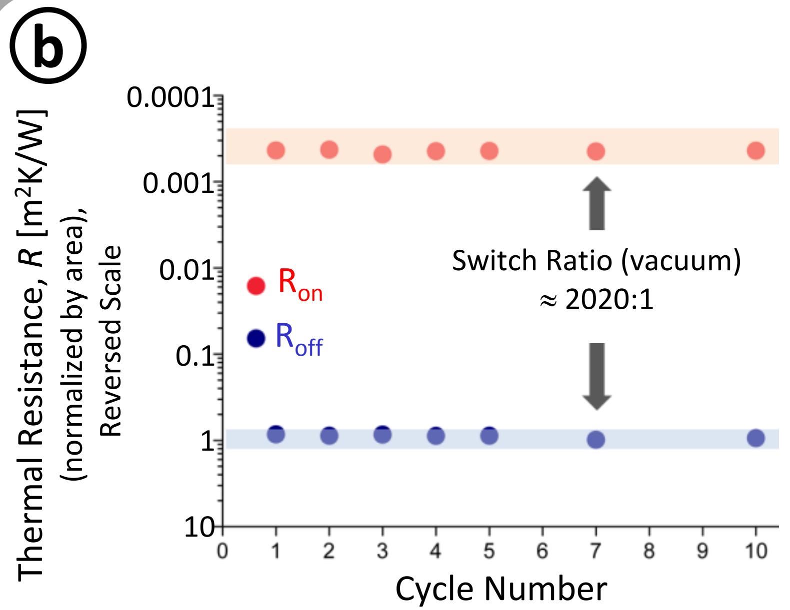
→ Best approach: Contact / Non-Contact

Approach & Progress: Thermal Switches





[Hao, ... Dames, "Efficient thermal management of Li-ion batteries with a passive interfacial thermal regulator based on a shape memory alloy" *Nature Energy* (2018)]



(a,b) Recent Work (Battery Application). Switch Ratio: ~2000:1 in vacuum, ~20:1 in air (1000 cycles).

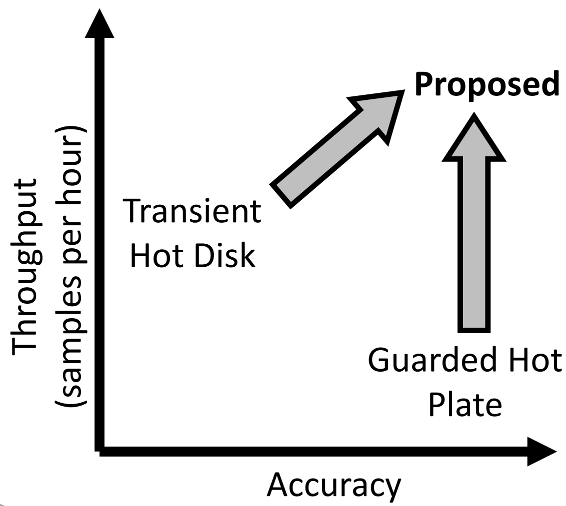
This Project:

We are pursuing 3 different concepts (all voltage-controlled, contact/non-contact):

- SMA based
- Ion insertion (adapt battery technology)
- Electroactive polymer (New team member: Arun Majumdar, Stanford)

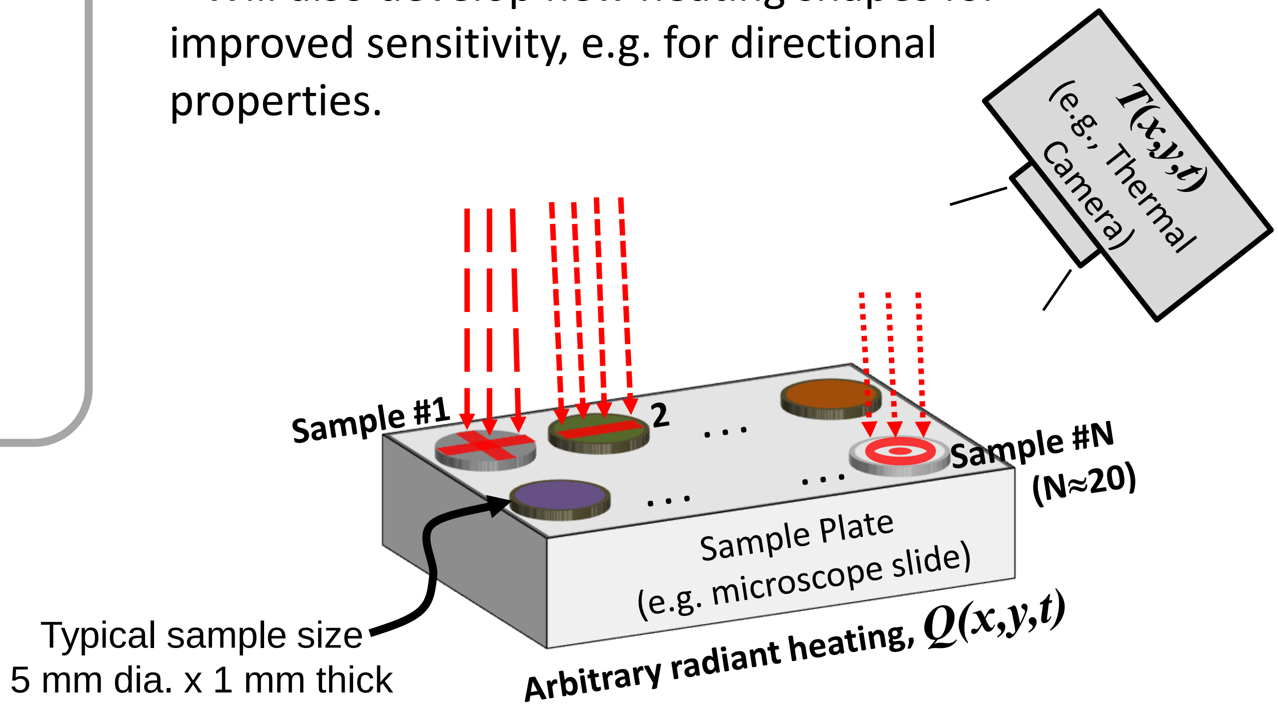
Approach & Progress: High-Throughput Metrology

Context: Thermal Metrology for Insulation
(low-k, porous)



Concept: All-optical heating and thermometry

- Enables "virtual" hot disk, 3ω, etc.
- Will also develop new heating shapes for improved sensitivity, e.g. for directional properties.

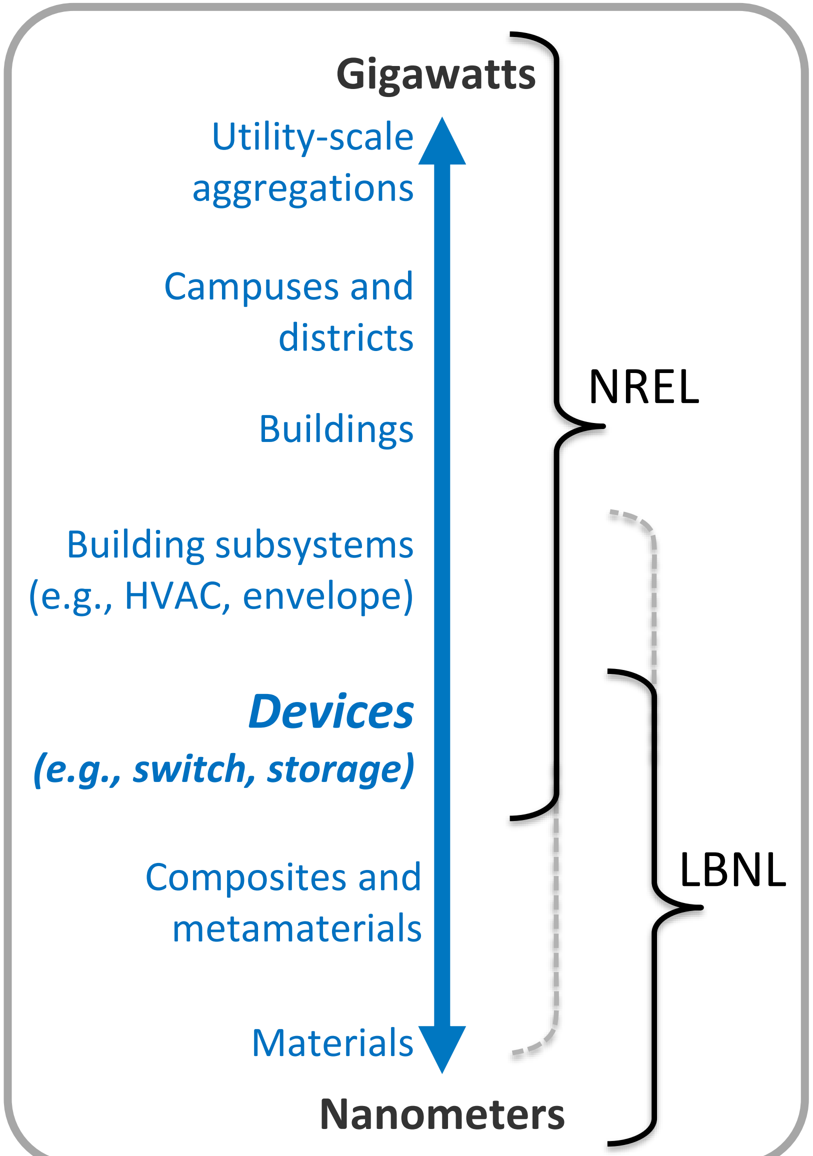


	Current SOA (Guarded Hot Plate)	Project Goals	Improvement Ratio
Sample Volume	Volume = 40 mL (~100 mm dia. x 5 mm thick)	Volume = 0.02 mL (~5 mm dia. x 1 mm thick)	> 1000 : 1
Throughput	~1 sample per 4 hrs	~20 samples per 20 mins	> 100 : 1

Approach & Progress: Multiscale Modeling

For each use case

e.g.
case1=envelope integrated
case2=equipment integr. storage
case3=standalone storage
...



Down-select most compelling use case

Prototype demo. & validation

Impact

- Enables **flexible** and **dispatchable thermal storage** by expanding traditional thermal storage R&D beyond energy density optimization to include *tunability* and *thermal switching*.
- Applications (use cases) include dedicated thermal storage, equipment integrated thermal storage, and building envelope integration.
  - Preliminary calculations for envelope integration indicate potential energy savings in the range of 5x (thermal switches) to 7x (tunable PCM).
- Develops an integrated platform of **materials science, measurement science**, and **integration science** for thermal storage R&D:
  - *Technical:* Thermal energy storage and control materials optimized for integration at the building scale.
  - *Core National Lab Competencies:* Capabilities accessible to the private sector for discovery, integration, and characterization of next generation thermal energy control and storage materials.
  - *Workforce development:* Partnerships with UC Berkeley, Stanford, and Georgia Tech enable a next generation of multi-discipline building scientists.

Stakeholder Engagement

- Project is early stage. First postdocs arrived in Dec. 2018 and Jan. 2019.
- Team has extensive range of expertise, from nanometers to GW. Includes NREL integration science experts at the building, district, and utility scale.
- Assumptions will be validated later in the project with external stakeholders to ensure we are on the right track.
- Plan to engage the broader scientific community through non-traditional buildings conferences like Materials Research Society (MRS).

Thank You

Roderick Jackson
NREL
Roderick.Jackson@nrel.gov

Ravi Prasher
LBNL / UC Berkeley
rsprasher@lbl.gov

Chris Dames
LBNL / UC Berkeley
cdames@berkeley.edu