Stor4Build
U.S. DEPARTMENT OF ENERGY

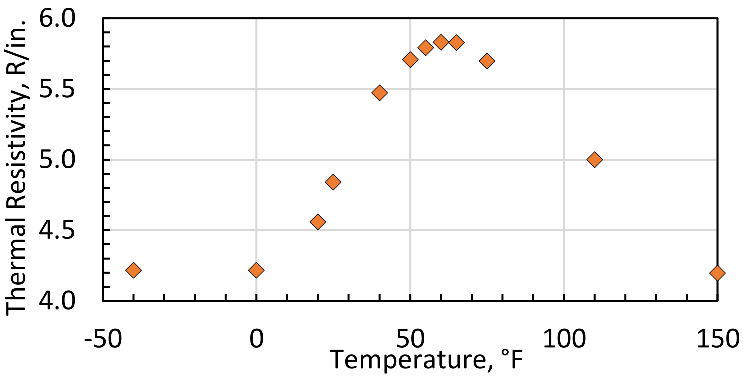
Active building envelope + TES to reduce energy use, peak demand, HVAC size and improve resiliency

Som Shrestha, PhD, BEMP
Senior R&D Staff, ORNL

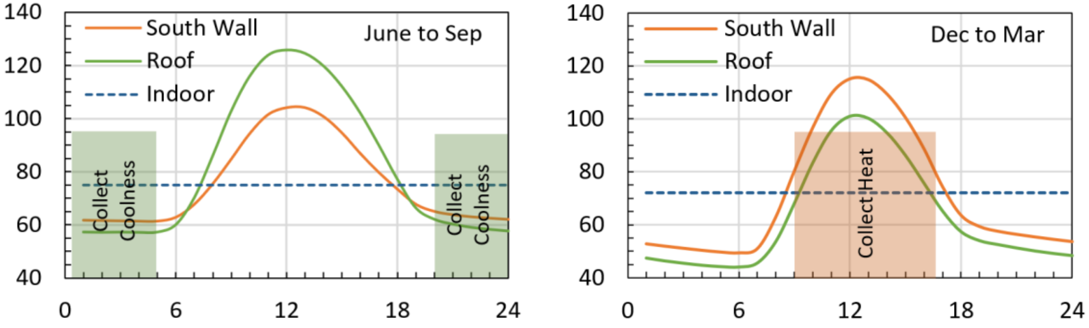
2024 Stor4Build Consortium Meeting

26 August 2024

- Heat transfer through opaque envelope ~ 25% of energy use in building.*
- Use of static insulation is not an optimum solution to cope with dynamic weather conditions!
- Active building envelope is needed to fully benefit from dynamic weather conditions.
- Mismatch between the time to collect thermal energy and thermal loads.



Some insulations lose thermal resistivity when the building heating and cooling loads are highest**



Hourly average exterior surface temperature for a building in LA

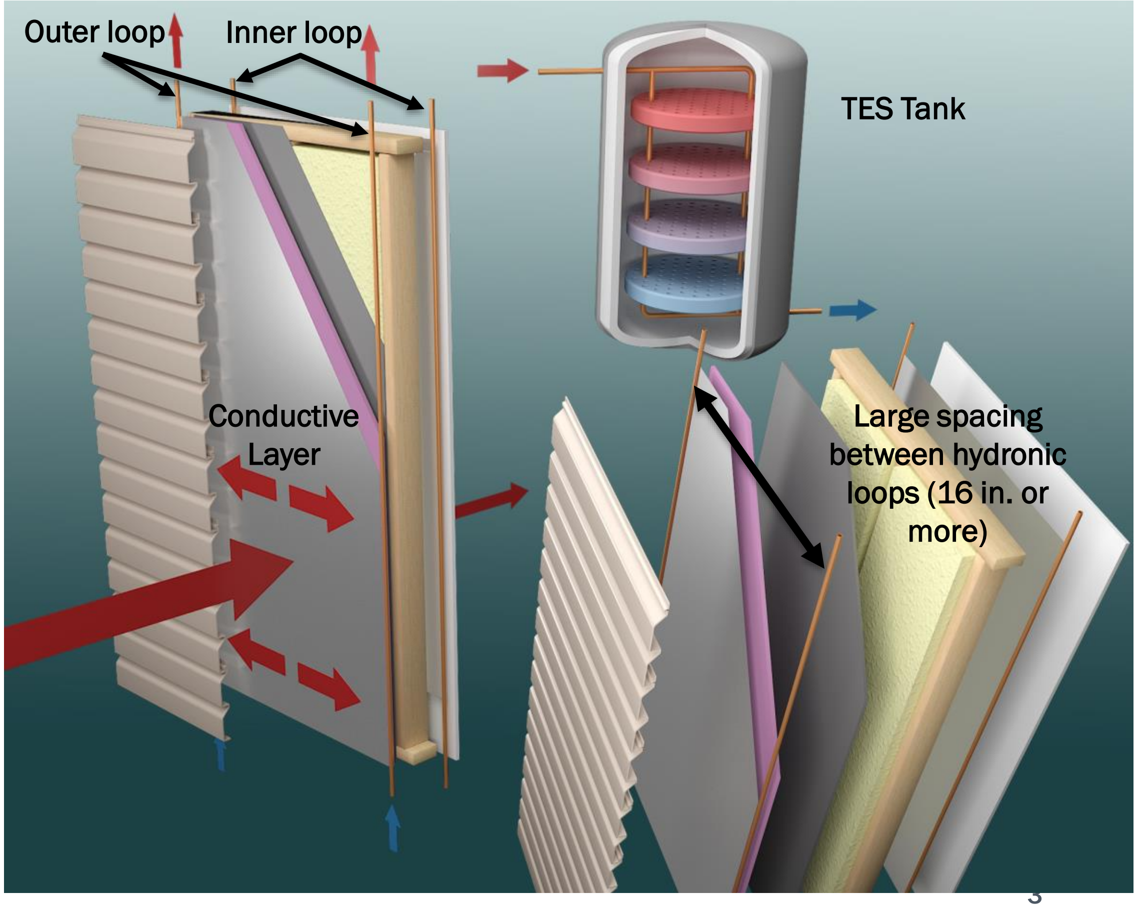
* DOE, Research and Development Opportunities Report for Opaque Building Envelopes

** Shrestha S. et al., IIBEC Interface June 2021

Thermally Anisotropic Building Envelope (TABE)

Active building envelope with one or more thin conductive layers connected to hydronic loops

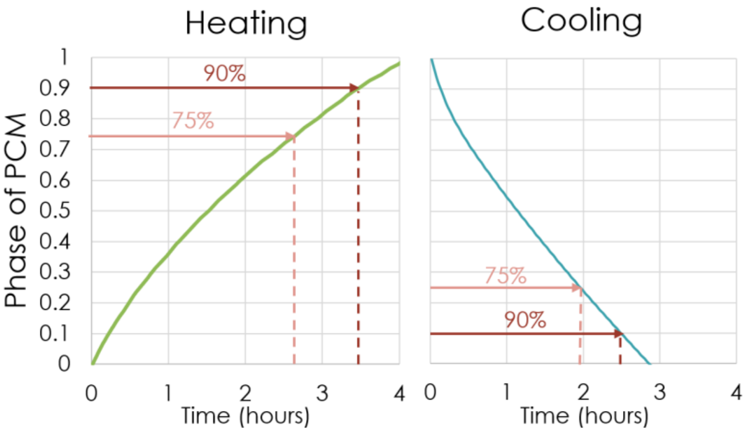
- TABE/ hydronic loops can be on
  - ✓ Exterior side of envelope
  - ✓ Interior side of envelope
  - ✓ Partition walls, ceiling, slab
- Hydronic loops connect to
  - ✓ TES system
    - ✓ Geothermal loop
    - ✓ Between the outer and inner loops – equivalent to active insulation
    - ✓ Appliances
- Use off-the-self materials



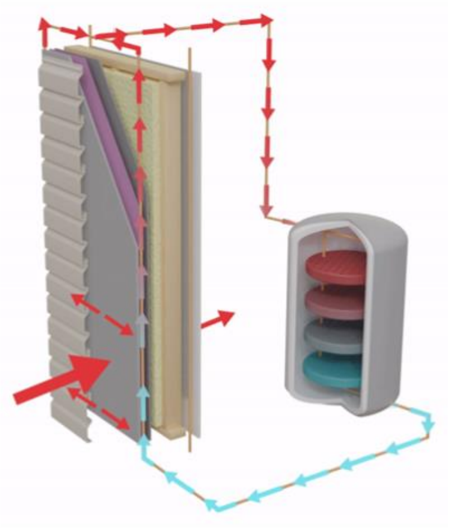
Developing TES for TABE

- High-performance
  - Discharge 90% in 4 hours
  - Utilize 90% of the storage volume with PCM
  - $\Delta T < 10°F$
- Long term stability:
  - Material 10000 cycles
  - System 200 cycles completed
- Suitable to integrate with TABE

Custom-designed heat exchanger

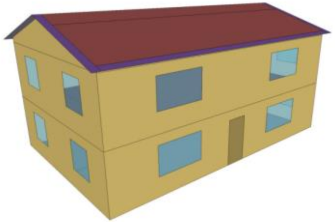


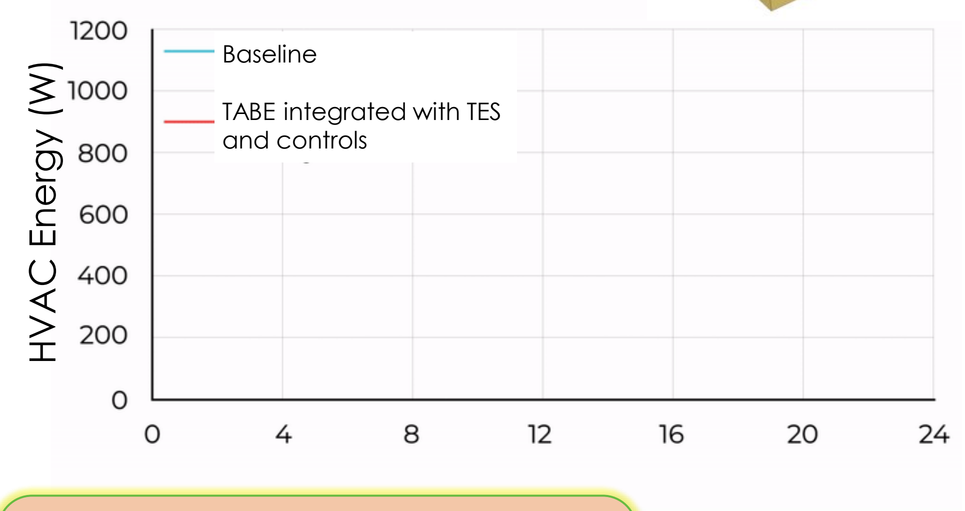
Example simulation result



Collect the coolness at night and use it in the day

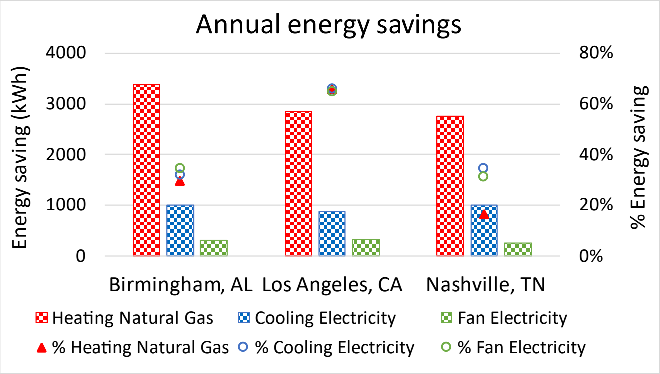
- DOE residential prototype building: 2 story, 2400 ft^2
- Los Angeles weather
- Summer: June to Sep
- Hourly average values

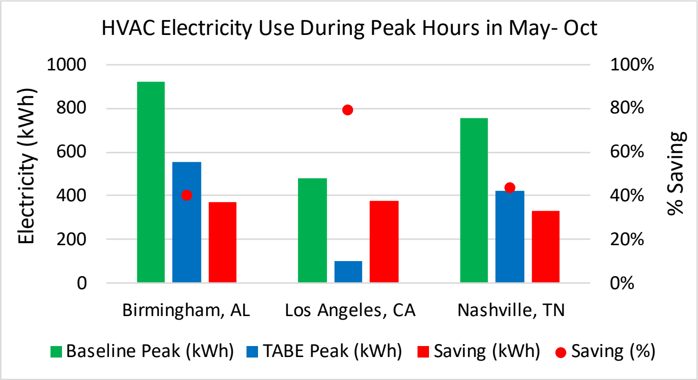


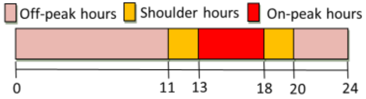


TABE+TES can reduce:
- Energy use
- Peak demand
- HVAC size

TES + TABE energy and peak demand savings potential

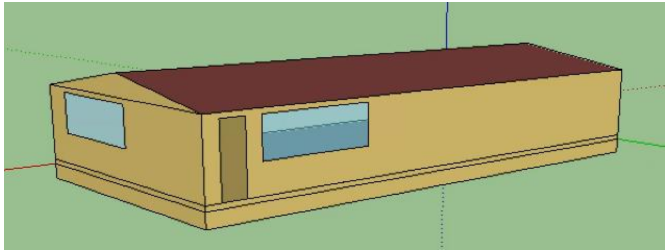






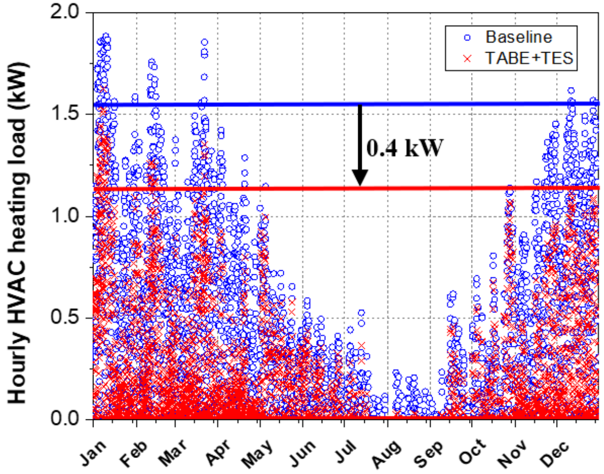
High energy and peak demand savings potential from a single technology.

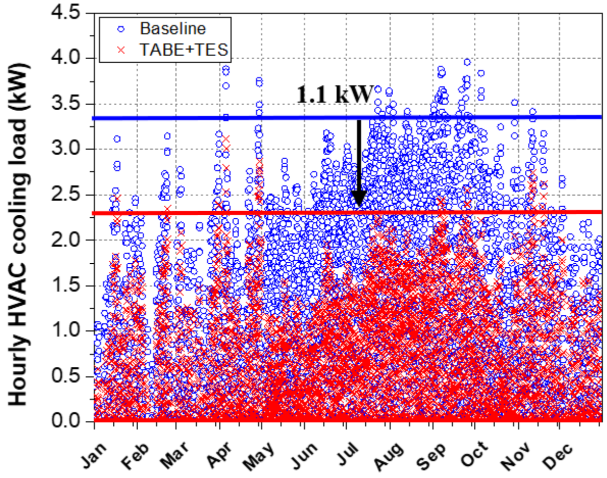
HVAC size reduction potential



- Prototype manufactured house 925 ft^2
- Ducted split system for cooling and an electrical furnace for heating
- TABE roof and wall panels
- 35-gallon TES (5.6 kWh)

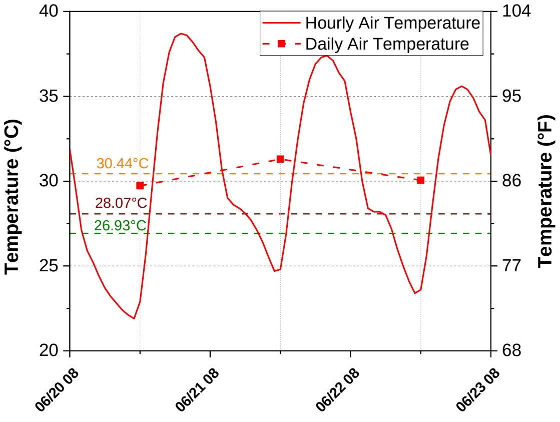
- HVAC size to meet 99.5% of hourly peak cooling and heating loads.
- 25% reduction in heating.
- 32% reduction in cooling.

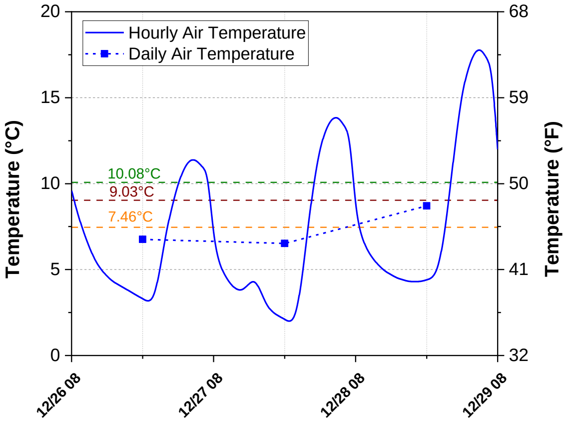


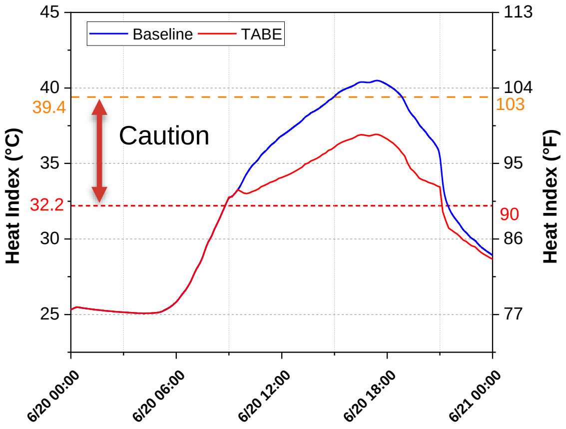


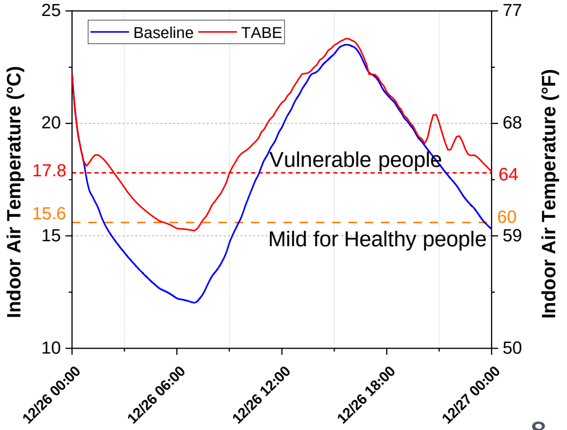
Improve building thermal resiliency

- TABE+TES can significantly reduce the exposure to unsafe temperatures during heat wave and cold snap that coincidence with power outage.









Manufacturability

TES

5-Gal HX

35-Gal HX

Custom-designed HX fabricated in a HX manufacturing plant

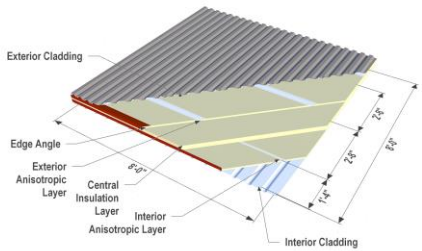
TABE

8 x 8 ft. TABE wall from MCA

Incorporating TABE into metal panels

Completed

Assembly test at lab



Ongoing

Assembly test at a NET Facility

Natural Exposure Test facility at Charleston, SC

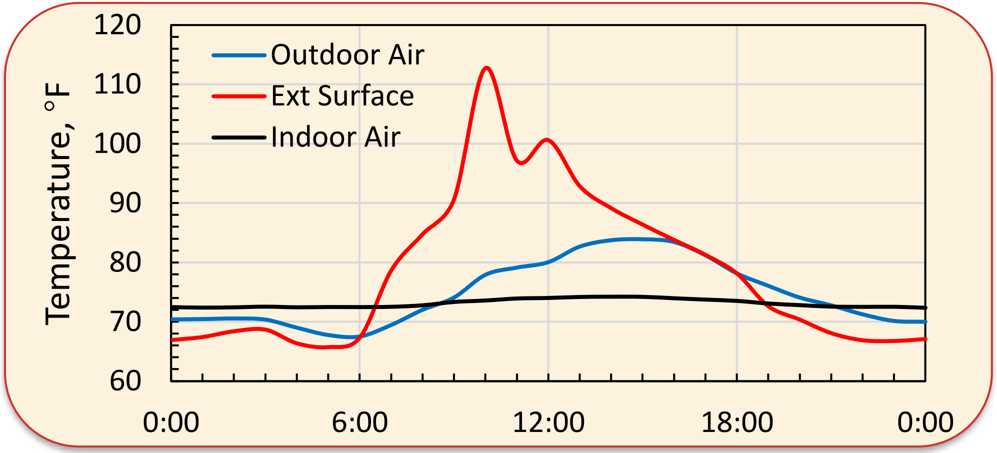
Planned

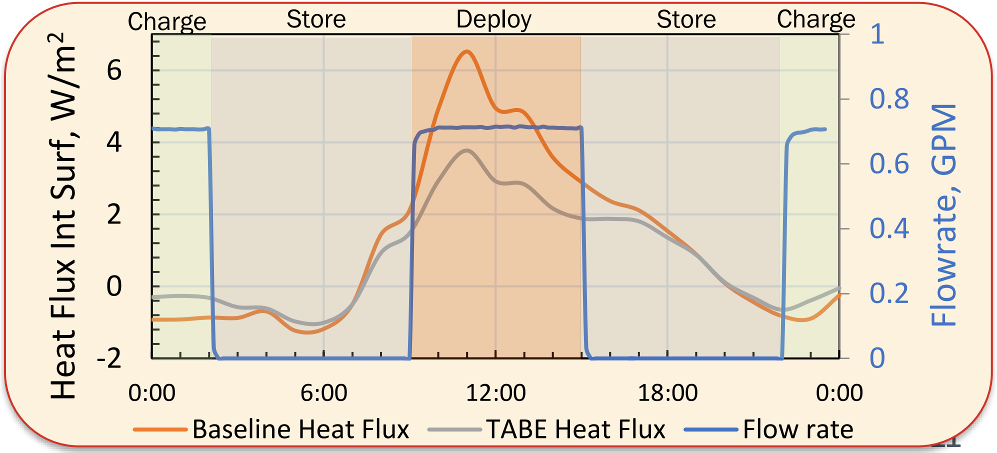
Whole building test at Tennessee State University

Assembly test at a NET Facility

- South-East facing wall
- 34% reduction in heat gain from wall
- 42% reduction in peak heat gain from wall
- Control yet to optimize

August 22, 2024





Risks and mitigation plans

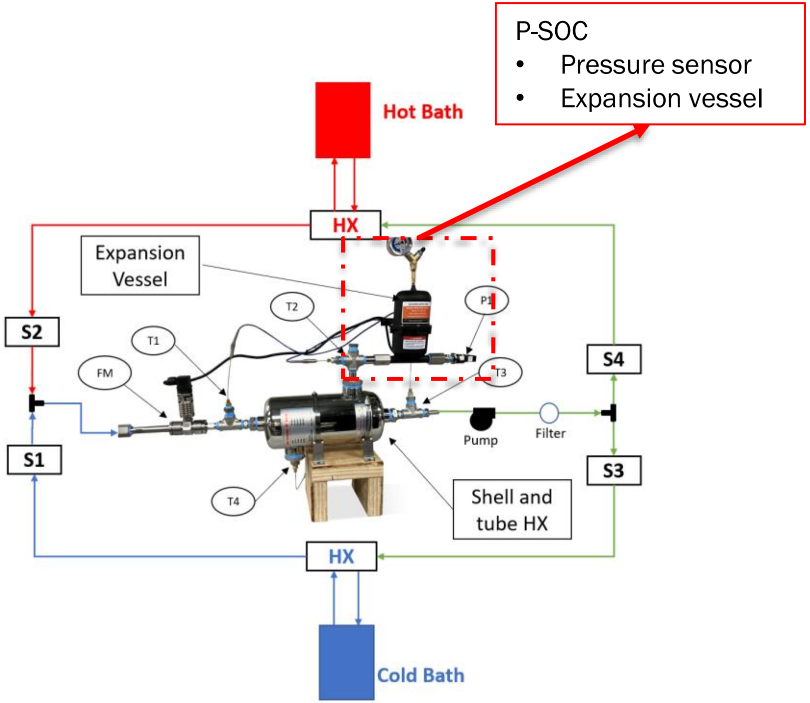
Risk	Mitigation
Manual assembly of TABE can be labor-intensive.	Panelized construction at manufacturing plant that requires minimum modifications.
Condensation in TABE panel.	Fluid temperature regulated at below dewpoint.
Leak from hydronic loops.	PEX tubes are becoming more reliable and common for indoor plumbing. Use moisture sensors.
Cost, energy density, thermal properties, and long-term performance of PCMs and TES systems.	Joint effort between research institutions and industry.

Pressure based PCM state of charge sensor (P-SOC)

SOC determines energy available in TES.

Current Methods

1. Multiple point temperature measurements in TES.
2. Energy balance (flow meter and temperature sensors in heat transfer fluid inlet and outlet of TES)
3. Pressure based liquid measurement in ice storage.



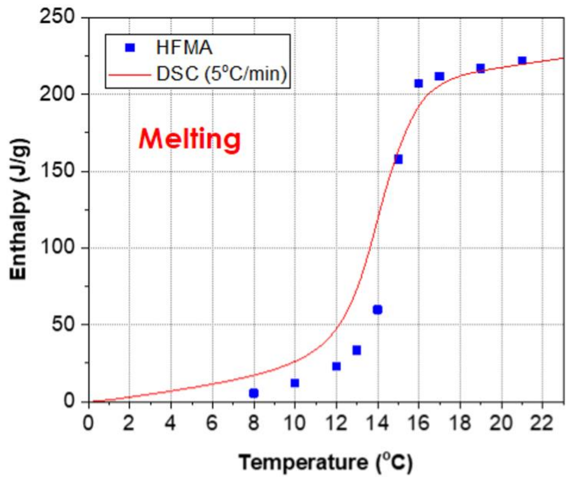
P-SOC improvements to current methods

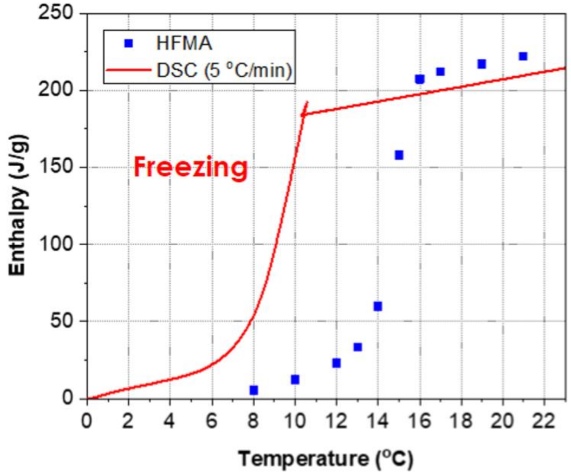
- Vs. 1: P-SOC **is global instead of a local measurement** and higher accuracy than temperature measurements.
- Vs. 2: P-SOC is **10 times less expensive** than a high accuracy flow meter and has **low uncertainty** over time or due to ambient conditions.
- Vs. 3: P-SOC is more versatile (ongoing study).

- Low-cost, scalable, global, and high accuracy SOC sensor under development
- Non-provisional patent Appl. No: 18/208,551

PCM property evaluation: DSC vs. HFMA test

- Organic PCM PT15
- Differential Scanning Calorimeter – commonly used method
- Heat Flow Meter Apparatus: ASTM C1484, large sample, slow temperature change
- Subcooling does not match
- Hermetically sealed sample holders can cause pressure swing and affect onset of phase change.





Publications and Patents

- Published
  - *Thermally anisotropic composites for improving energy efficiency of building envelopes*. Energies, 2019, 12(19), 3783.
  - Thermally anisotropic composites for heat redirection and thermal management in building envelopes. Buildings XIV International Conference
  - A machine learning-assisted framework to control thermally anisotropic building envelopes in residential buildings. Buildings XV International Conference.
  - *Machine learning–assisted prediction of heat fluxes through thermally anisotropic building envelopes*. Building and Environment, 2023.
  - Thermally Anisotropic Building Envelope Integration into Panelized Metal Construction: Laboratory Evaluation and Numerical Study. ASHRAE Winter Conference 2024.
  - Novel PCM-based fin and tube heat exchanger system for building heating and cooling applications. ASHRAE Winter Conference 2024.
  - Experimental Investigation and Performance Characterization of PCM Integrated Finned Tube Heat Exchanger for Building Heating and Cooling Applications. Purdue Conference 2024.
  - Pressure Sensor for State of Charge Measurements in Latent Thermal Energy Storage (P-SOC). Purdue Conference 2024.
  - Pushing the envelope - moving dynamic building envelope thermal energy storage systems mainstream. 2024 ACEEE Summer Study.
  - Energy burden aware and thermal resilience informed thermal energy storage system planning for disadvantaged communities. 2024 ACEEE Summer Study.

Publications and Patents

- Patent application and invention disclosures
  - Thermally anisotropic composites for thermal management in building environments. U.S. Patent Publication No. 20200326085
  - Solid-state thermal switch Panel for Thermal Storage. Non-Provisional Patent Application - 157379.11801
  - State of charge sensor for phase change material thermal energy storage. Non-Provisional Patent Application - 18/208,551
  - Heat Exchanger for low conductivity PCMs. Non-Provisional Patent Application - 18/614,115
- Under review
  - Thermally anisotropic building envelope: field evaluations and finite element model calibration. IBPSA Journal.
  - Design and optimization of low-cost fin-tube PCM heat exchanger for building thermal energy storage. International Communications in Heat and Mass Transfer.
  - Coupling thermal energy storage with thermally anisotropic building envelope for building demand side management under various US climate conditions. Energy and Buildings.

DOE Decarbonization Blueprint Alignment

Cross-Cutting Goals

- **Equity:** *Equitable access to efficient homes for disadvantaged communities. Field demonstration in a historically black university.*
- **Resilience:** Improve resiliency by using stored thermal energy during grid failure.

Strategic Objectives

- **Increase Building EE and Onsite Emissions Reduction:** *Reduce energy use, peak demand, and HVAC size.*
- **Transform the Grid Edge:** Support utility grid by minimizing building's peak energy demand and provide load flexibility.

Team

- ✓ Som Shrestha
- ✓ Diana Hun
- ✓ Andre Desjarlais
- ✓ Daniel Howard
- ✓ Zhenglai Shen
- ✓ Joe Rendall
- ✓ Achutha Tamraparni
- ✓ Kaushik Biswas
- ✓ Jerald Atchley
- ✓ Tony Gehl
- ✓ Amit Rai
- ✓ Robert Zabcik
- ✓ Jeff Henry

METAL CONSTRUCTION ASSOCIATION

The team is thankful to Sven Mumme for his valuable guidance.

Multidisciplinary team with an industry partner to ensure success

Summary

- Developed and demonstrated technical feasibility of an active building envelope system (TABE) to fully benefit from dynamic weather conditions.
- Demonstrated high energy and power density TES to integrate with active building envelope that
  - Utilizes 90% of storage volume for PCM, allowing **high energy density**
  - Charge or discharge 75% of stored latent energy in 3 hours and 90% in 4 hours with $\Delta T < 10^{\circ}F$, ensuring **high power density** and **suitable to reduce peak electricity demand.**
- Demonstrated long term stability: PCM >10,000 cycles, TES system >200 cycles.
- Studies show TABE + TES can **reduce 30% HVAC energy and 50% peak electricity demand.**
- TABE + TES can also reduce HVAC size and improve building's thermal resiliency.
- Planning whole-house field validation at a HBCU.

Please contact us for collaborations.

shresthass@ornl.gov

Stor4Build
U.S. DEPARTMENT OF ENERGY

Integrating Thermal Switches and Storage for an Active Envelope

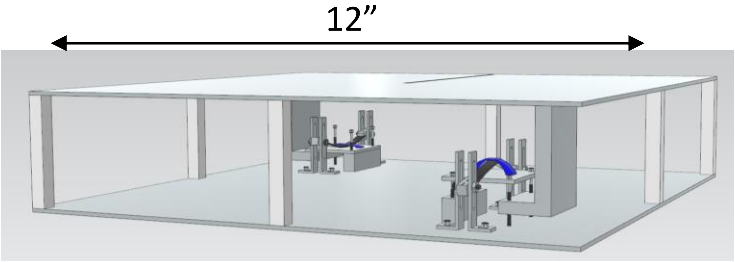
Chris Dames, UC Berkeley

26 Aug 2024

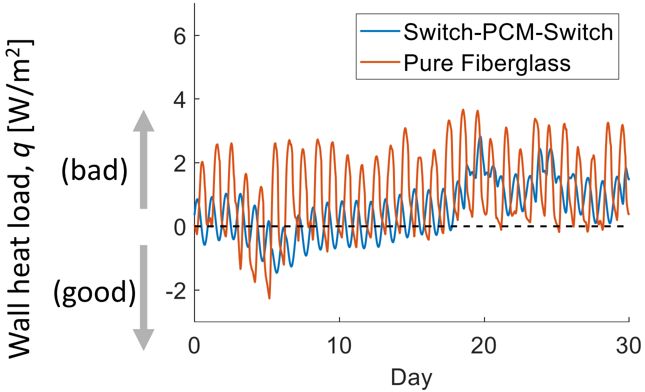
Stor4Build Annual Meeting

Topics

(1) Experimentation

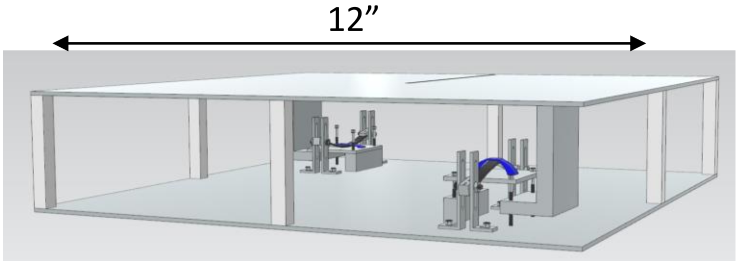


(2) Switching Algorithms



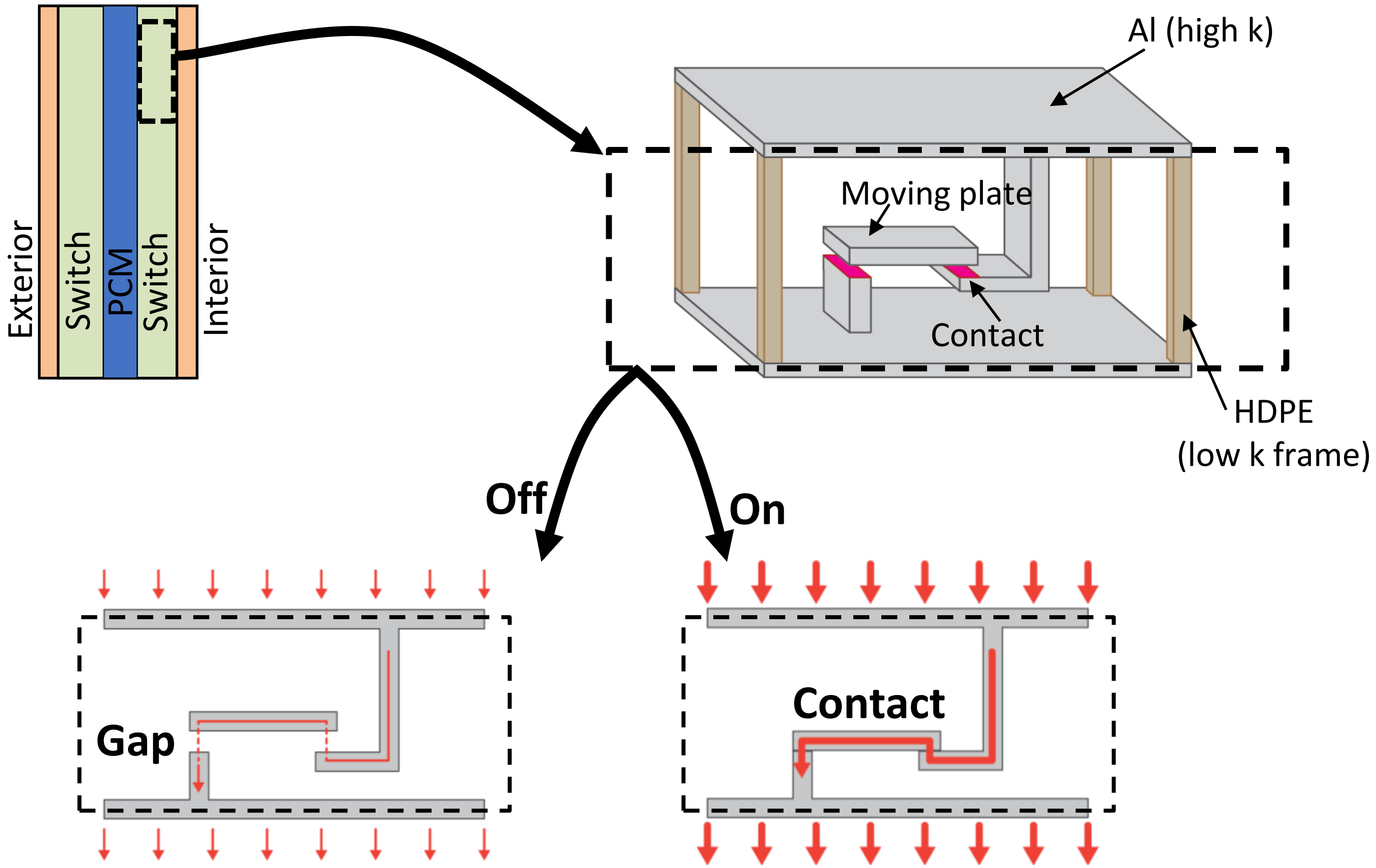
Topics

(1) Experimentation

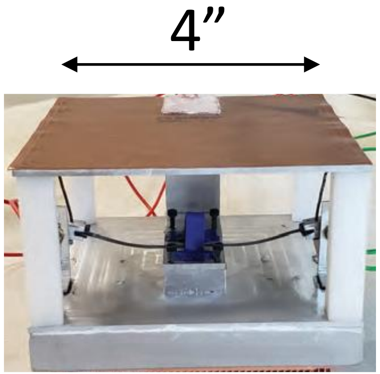


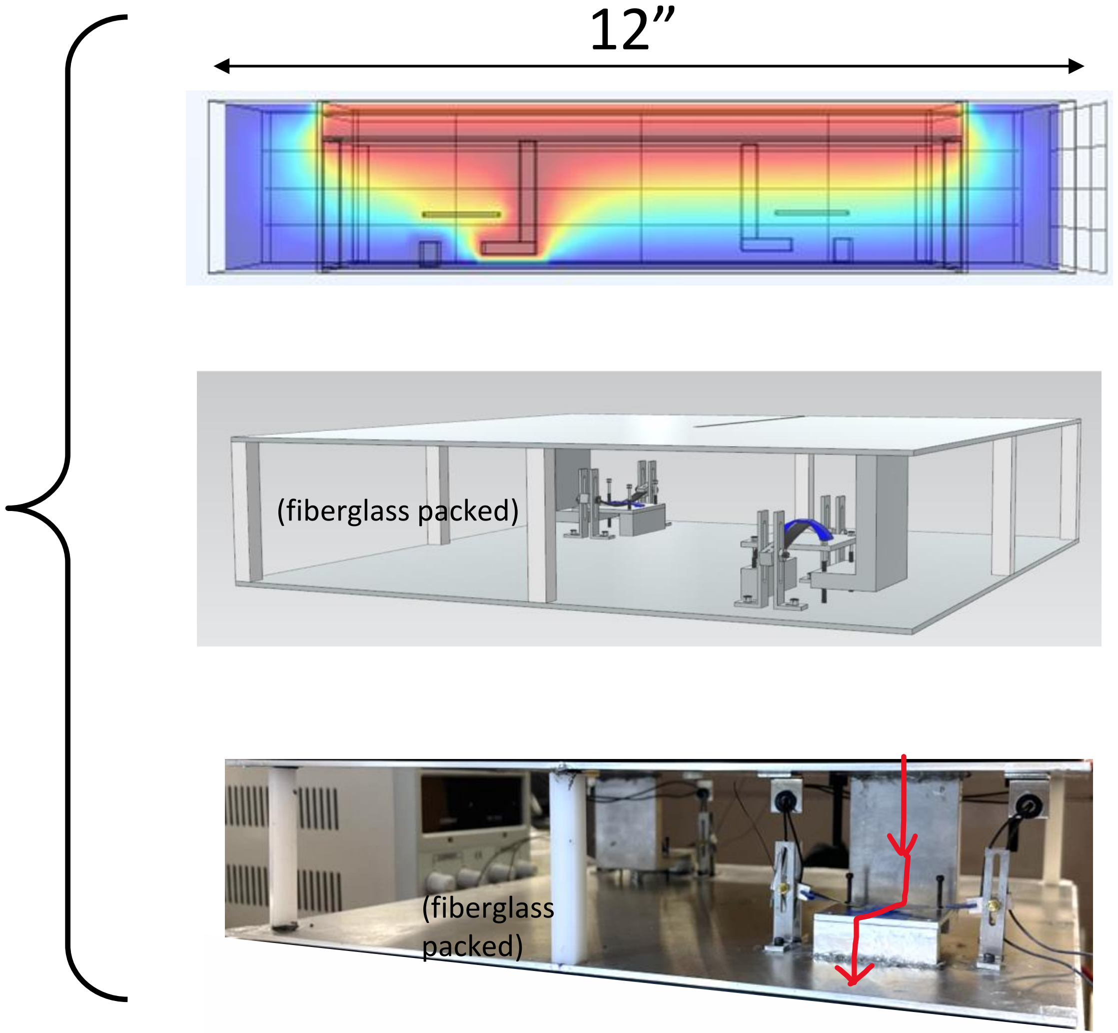
(2) Switching Algorithms

Approach: Contact thermal switch

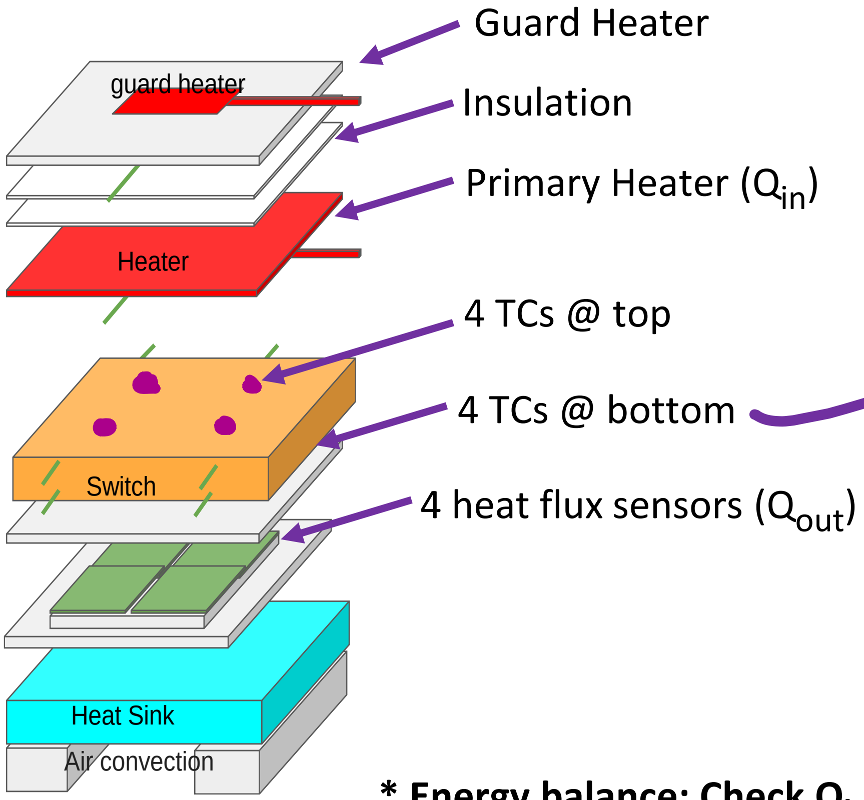


Scale-up

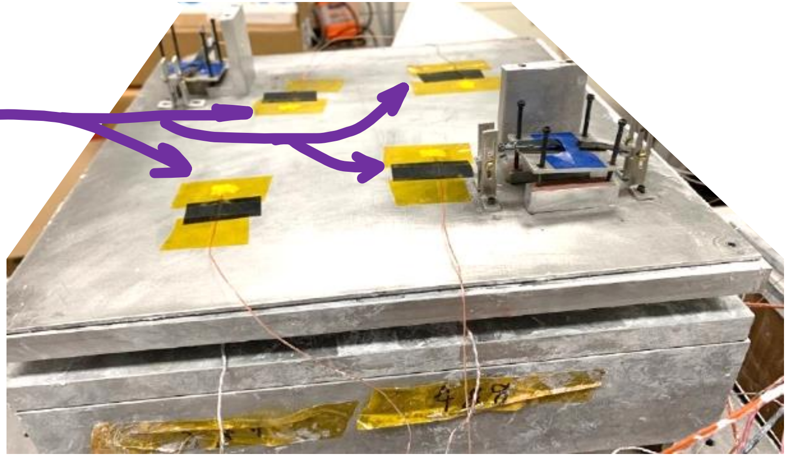




Gen3: Changes and lessons learned



Switch opened up:
View of bottom plate



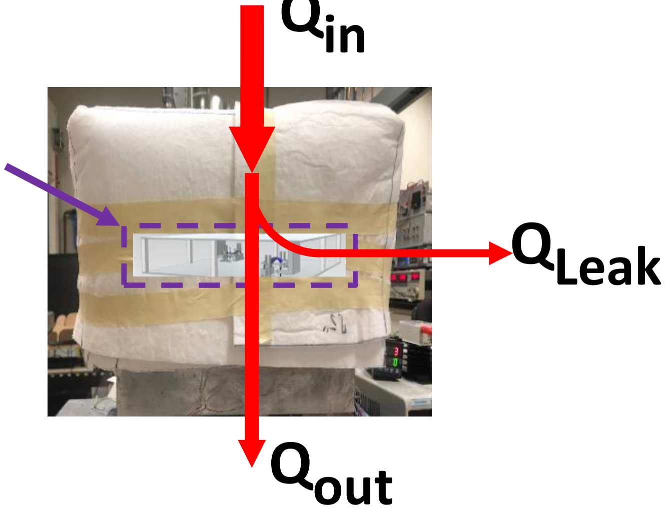
*** Energy balance: Check Q_{in} vs. Q_{out}.**

*** Reduce parasitic losses: Insulation + Guard heating**

*** Spatial nonuniformities: Multiple sensors for T(x,y) and q(x,y).**

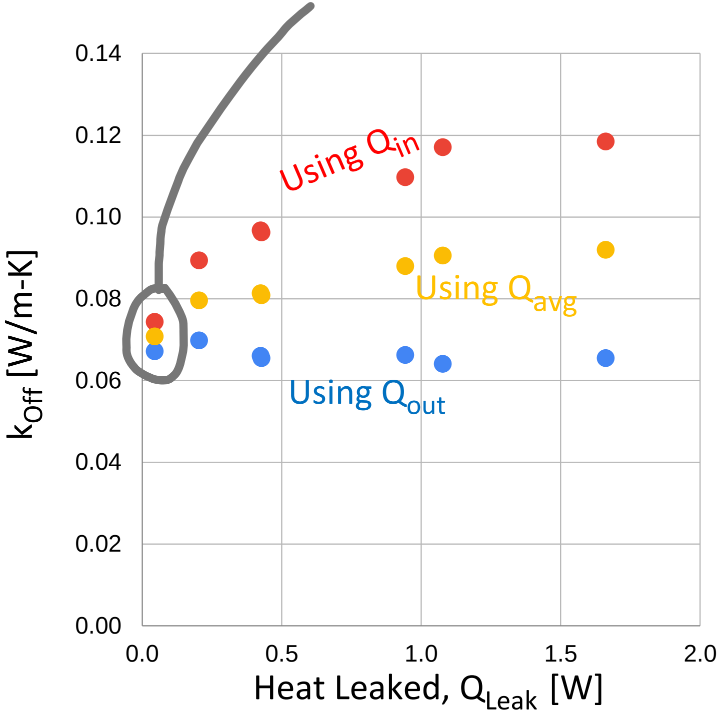
Example results for k_{Off}

switch inside

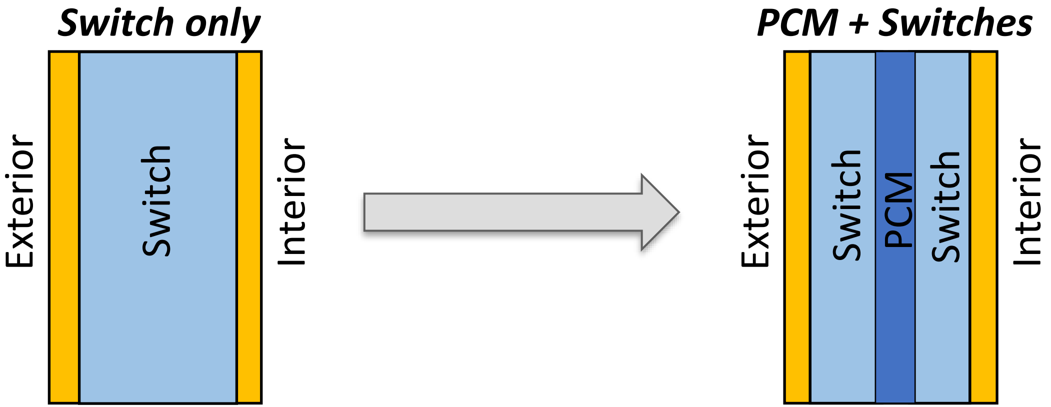


Converged:

k_{Off} = 0.071 W/m-K ± 10%



Next steps: Integration and Dynamical Testing

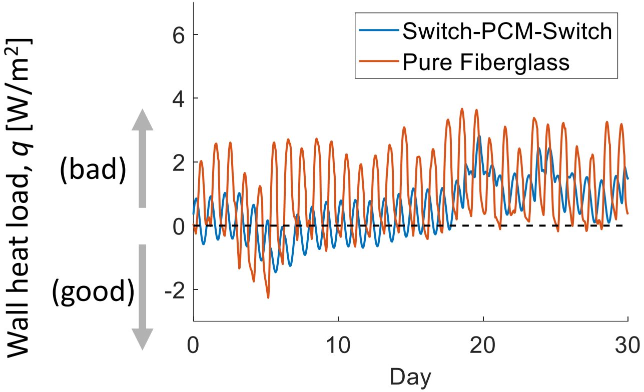


$T_{Ext}(t)$?	Constant	Sine wave
$T_{Int}(t)$?	Constant	Allow to vary ± 1 °C
Switch state?	Static (on or off)	Dynamic (what algorithm?)
$Q_{Ext}(t)$, $Q_{Int}(t)$?	Constant, and should match	Dynamic, and won't match

Topics

(1) Experimentation

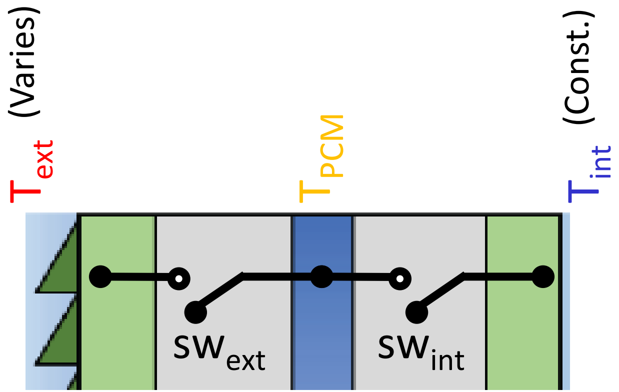
(2) Switching Algorithms



Algorithms

So far: Close a thermal switch when its exterior *T* is helpful.

("In summertime, grab free cooling whenever you can.")



Ravi Kishore, NREL

Questions:

(a) Can we verify whether this intuitive algorithm is optimal?

(b) What if T_{int} can vary slightly, e.g. 22 ± 1°C?

(c) What if electricity has time-of-day (ToD) pricing?

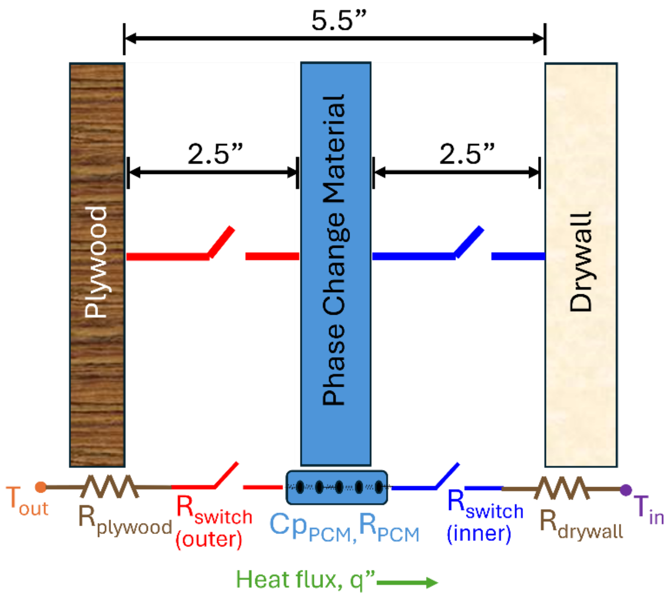
Approach:
Exhaustive search of over 300,000 algorithms

Scale of search:

- Allow each switch to turn on and off at any hour of the day.
- Requires $N \approx (24)^4 \approx 330{,}000$ permutations.
- Impractical for FEM: e.g. 6 yrs of computing time at 10 mins per sim.

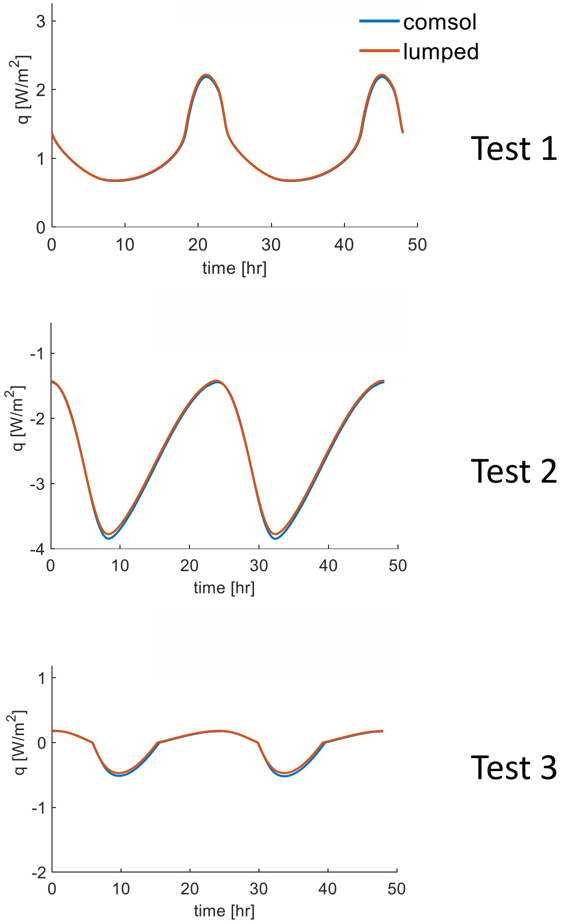
→ Develop lightweight numerical model.

Lumped model



* Runtime <0.5 sec. per scenario.
* Speedup > 10,000x vs. COMSOL

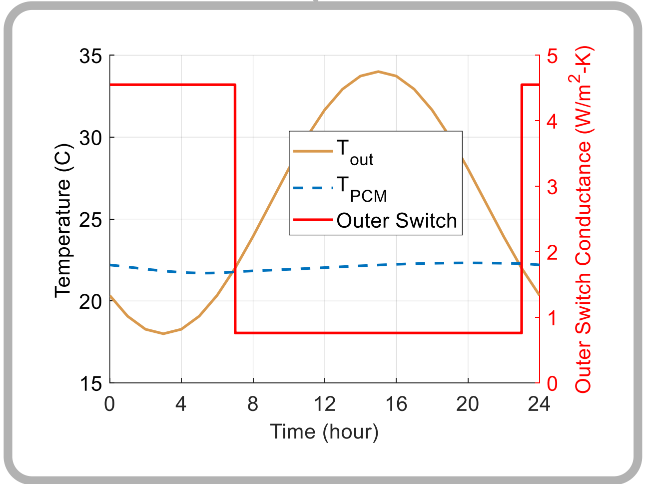
Confirm matches FEM well

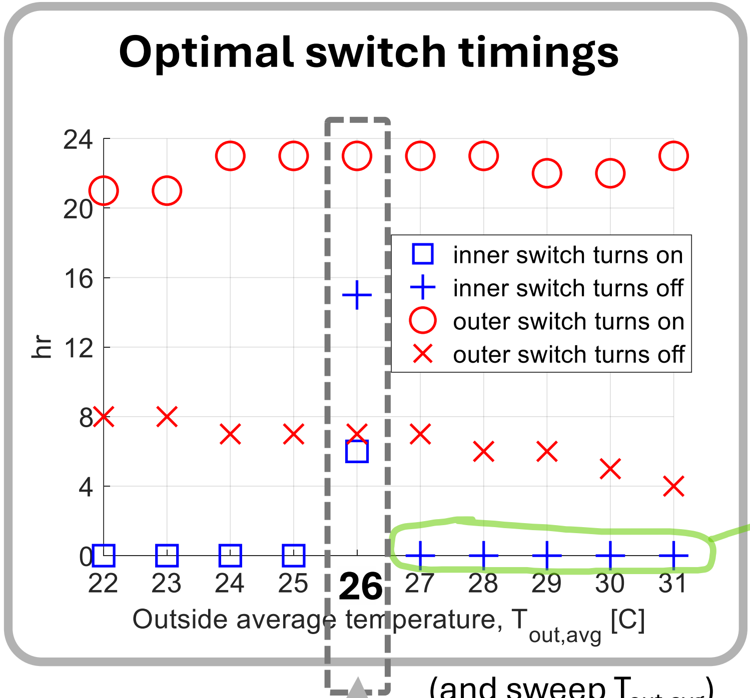


Results Ex: If maximizing free cooling in the summer.

$$T_{out}(t) = T_{out,avg} + \Delta T_{out} sin(\omega t + \phi)$$

Example for $T_{out,avg}$=26 °C





(and sweep $T_{out,avg}$)

(ΔT_{out} =8 °C, T_{in}=22 °C)

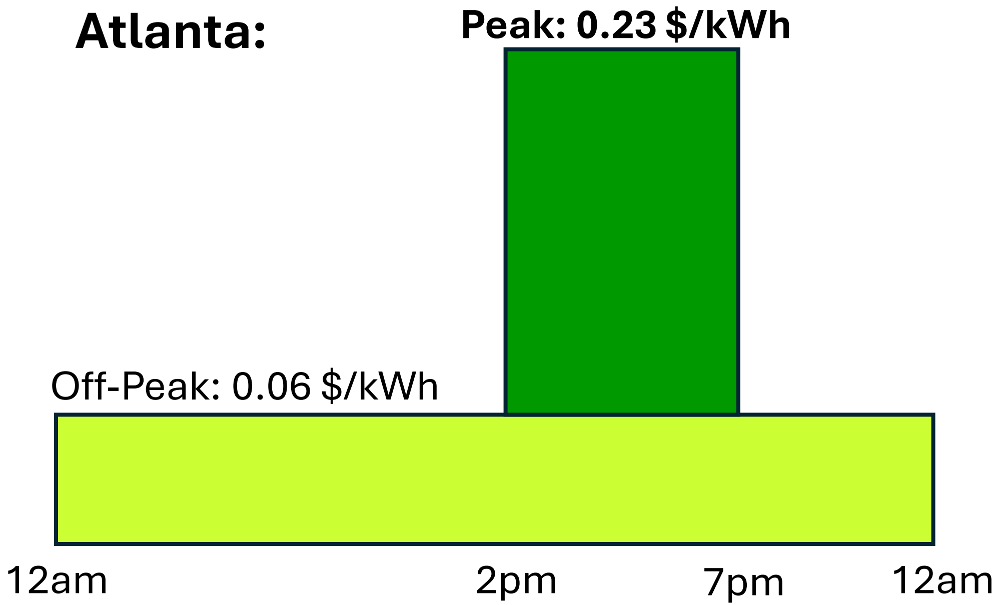
Findings

(1) Optimal timings match Kishore's algorithm *every time*!

(2) The inner switch stays locked off...(!)

(3)... may replace it w/ fiberglass.

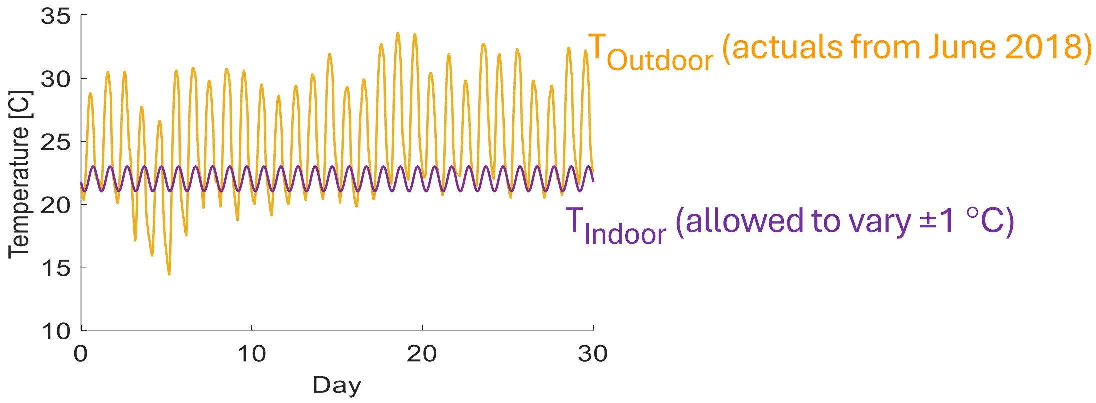
Time of Day Pricing



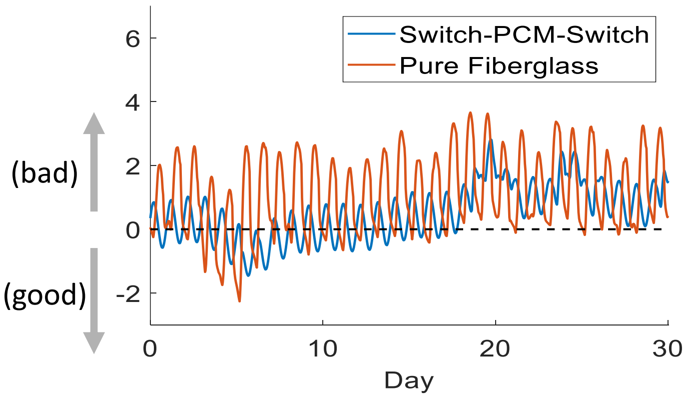
Three examples

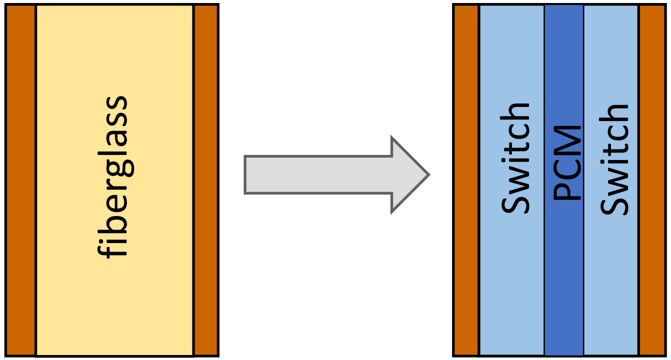
	Ratio Peak / OffPeak	Duration of Peak
Denver	2.5	4 hrs
Atlanta	3.8	5 hrs
Oklahoma City	4.9	5 hrs

Time of Day Pricing Ex: Atlanta in June



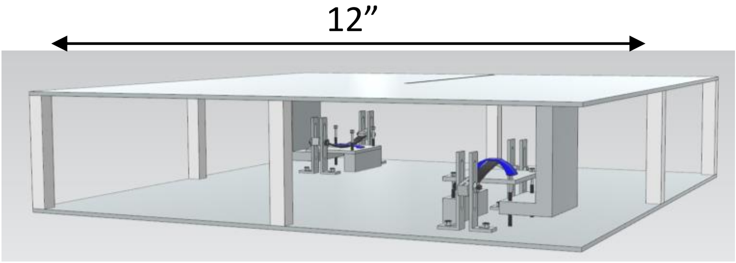
Heat load through inner wall, *q* [W/m²]





61% cost savings

Summary

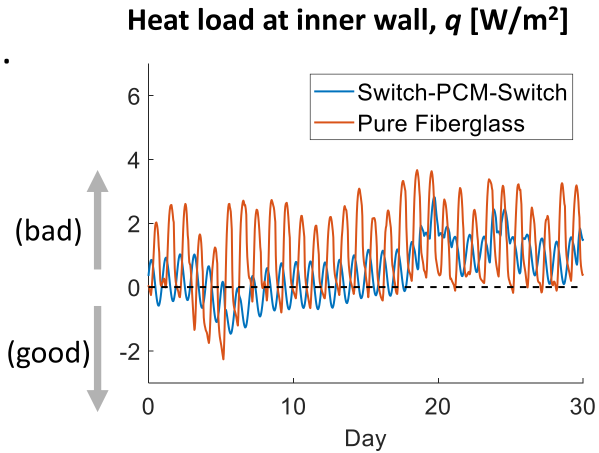


(1) Experimentation

* Scale up to 12”
* Heat leakage, energy balance, and spatial nonuniformities
* TIM, thermal contact, alignment
* Next: Dynamical testing of Switch-PCM integration and algorithms

(2) Algorithms

* For constant pricing: verified Kishore’s switching algorithm is optimal.
* May forego the inner switch: Replace by static fiberglass?
* For Time of Day pricing: Some precooling is optimal.



Dynamic building envelopes with retrofittable thermal switches and thermal storage systems

Ravi Anant Kishore, Senior Research Engineer, NREL

26 Aug 2024

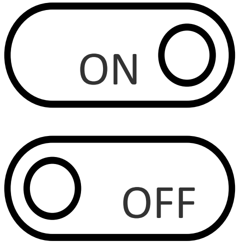
Stor4Build Annual Meeting

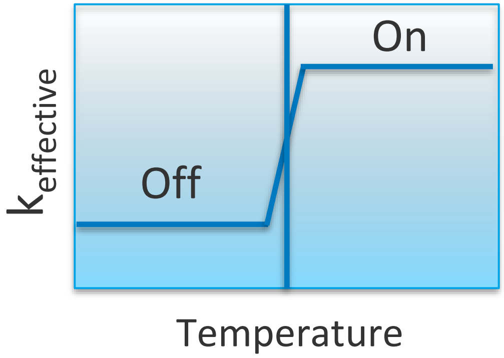
This Presentation Includes Unpublished and/or Preliminary Data

- Data, results, conclusions, and interpretations presented have not been reviewed by technical experts outside NREL
- Does not constitute a comprehensive treatment of the issues discussed or specific advice to inform decisions
- Do <u>not</u> photograph slides marked with preliminary information.
- Do <u>not</u> discuss presented preliminary analysis results outside of this meeting.
- Marked slides <u>not</u> for public use - do <u>not</u> distribute, quote, or cite.

Project objective

To demonstrate the feasibility of plug-and-play thermal switches that selectively open and close two thermally conductive surfaces in form of retrofittable plugs.





What is a thermal switch?

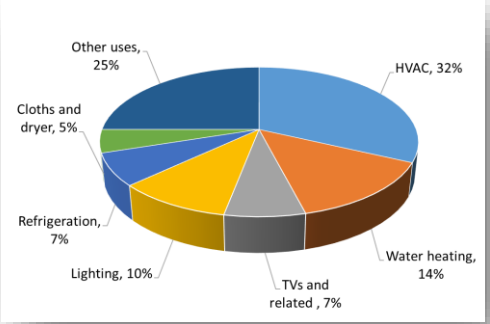
Analogous to an electrical switch, a thermal switch:

- allows heat flow, when the switch is "on"
- stops or lessens heat flow when it is "off"

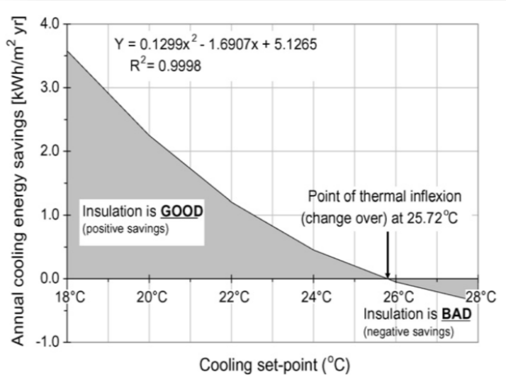
Thermal switches makes envelopes dynamic:

- Low thermal conductivity, when outdoor conditions are unfavorable (too hot or cold)
- High thermal conductivity, when outdoor condition is favorable

Why dynamic envelopes?



Source: Residential Energy Consumption Survey (www.eia.gov/consumption/residential/index.php)



Masoso & Grobler, Energy and Buildings 40.10 (2008): 1889-1894.

- HVAC accounts for 30-40% of total energy consumed in buildings
- Simple solution to a complex problem:
  - ➢ increase insulation R-value
- Insulation above a certain value can be detrimental:
  - reduces free ambient cooling/heating
  - traps internal heat gains
- Dynamic envelope is crucial for highly insulated TES-integrated envelopes

Limitations, concerns, and challenges

Technical

- High switching ratio
  R_{off}/ R_{off} > 5
- $R_{off} \approx R_{insulation}$

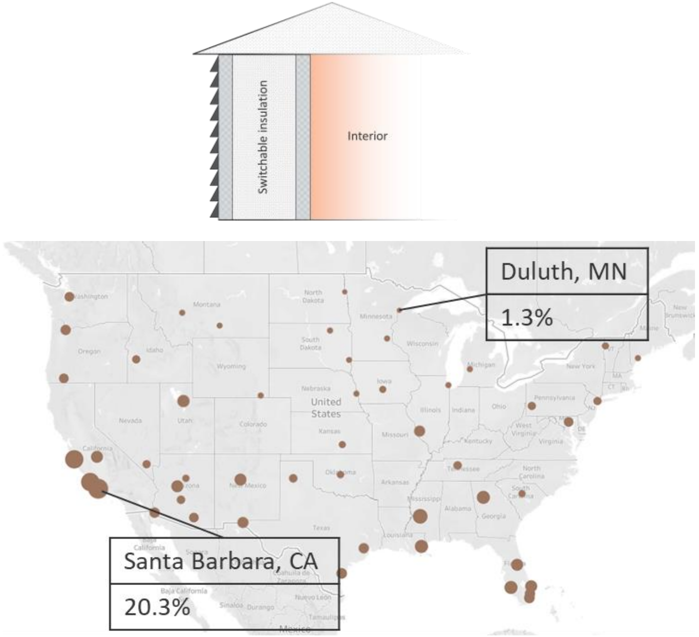
Deployment

- Retrofit-ablity
- Replacing existing insulations
- External excitation
  - Fan
  - Mechanical
  - Electricity

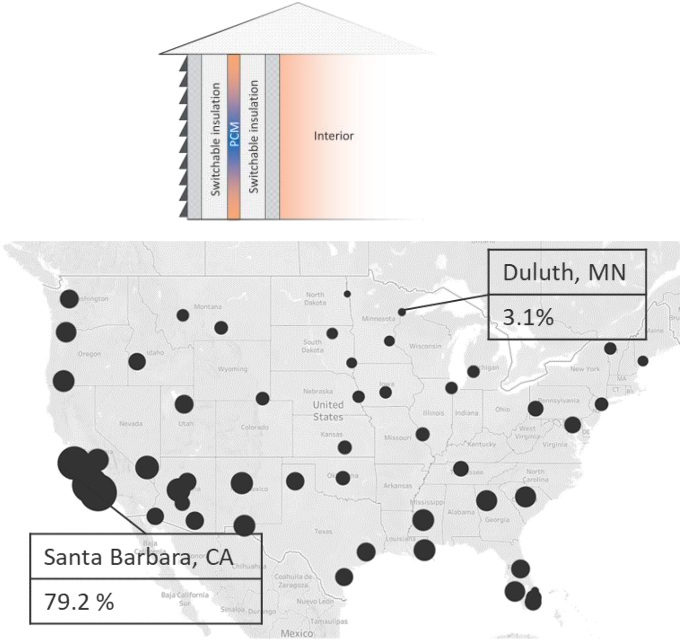
Techno-economics

- Cost
  - Material
  - Labor
  - Operational
  - Maintenance
- Pay-back period
- Reliability & durability

HVAC energy savings in single-family homes



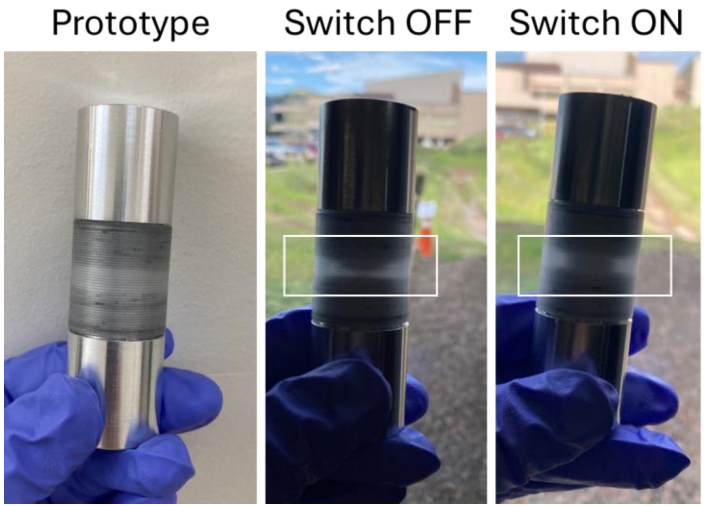
Switchable insulation only

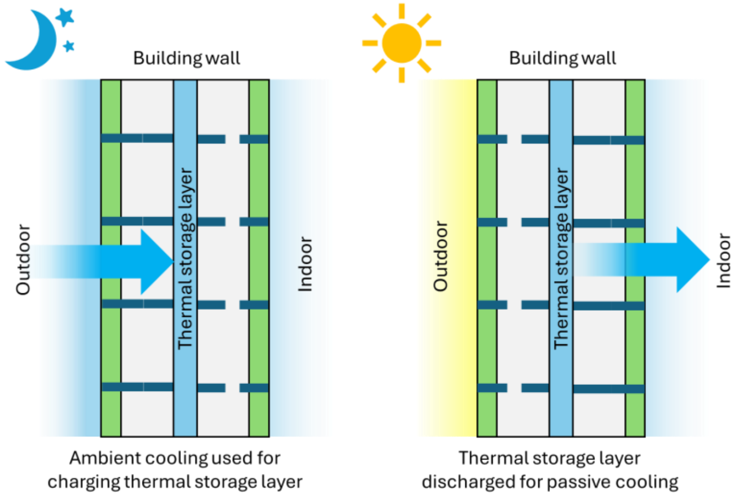


Switchable insulation + PCM

Unpublished/Preliminary Information

Retrofittable thermal switches



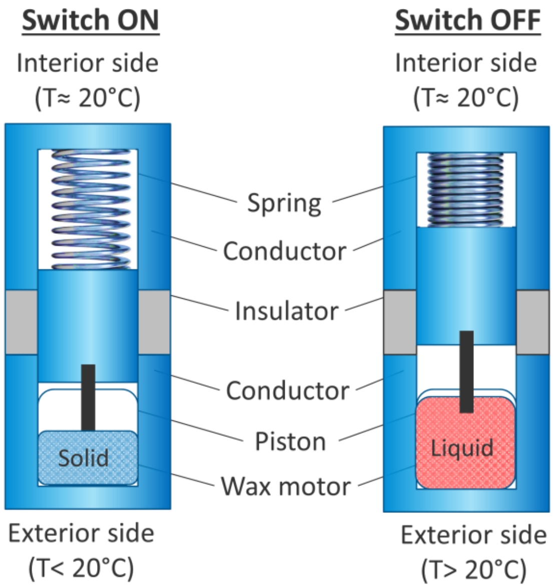


Design goals:

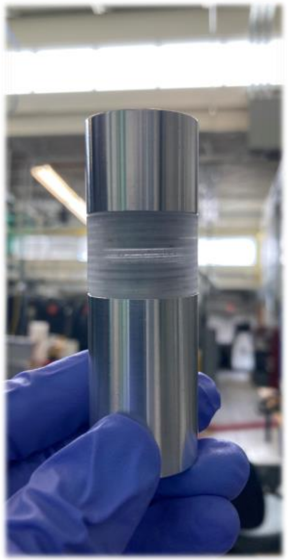
- Constructed using readily available materials
- Simple installation: drilling, plugging, and sealing
- Passive operation, needs no external power

St

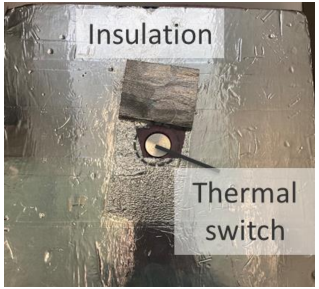
Working principle

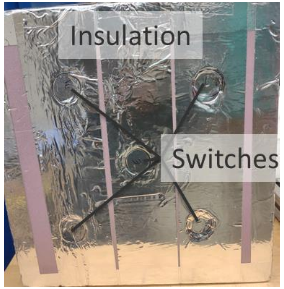


Prototype



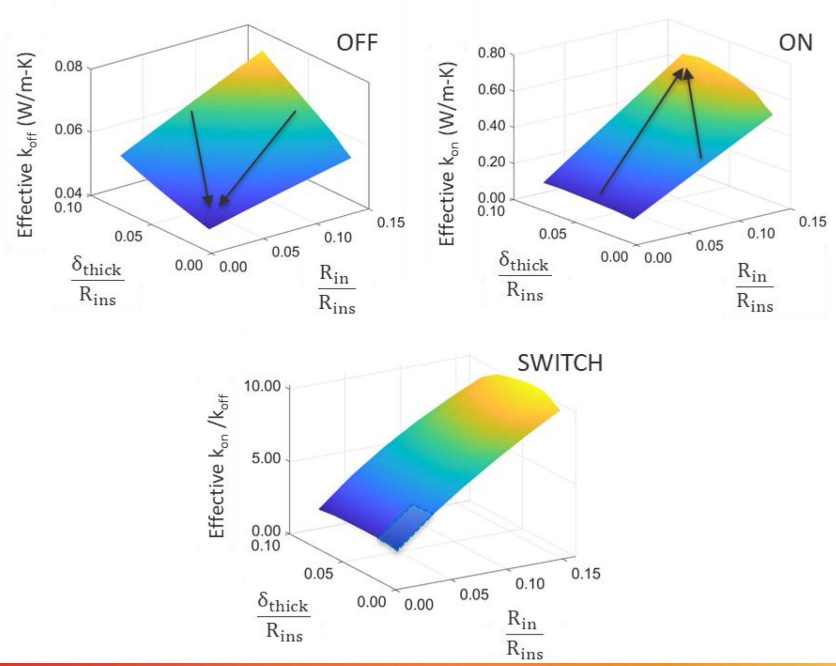
Installation

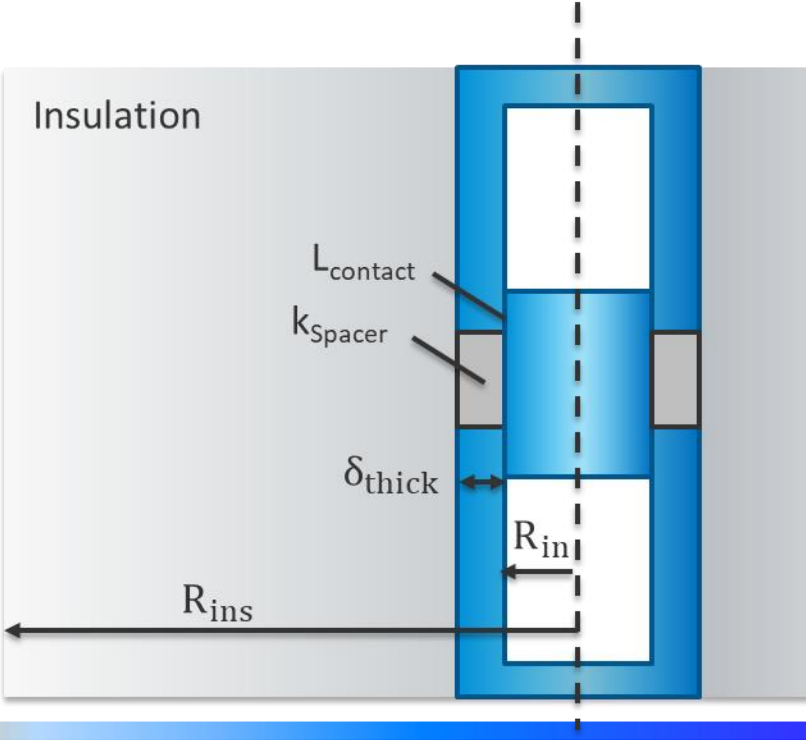




U.S. Patent : US 2022/0326722 A1

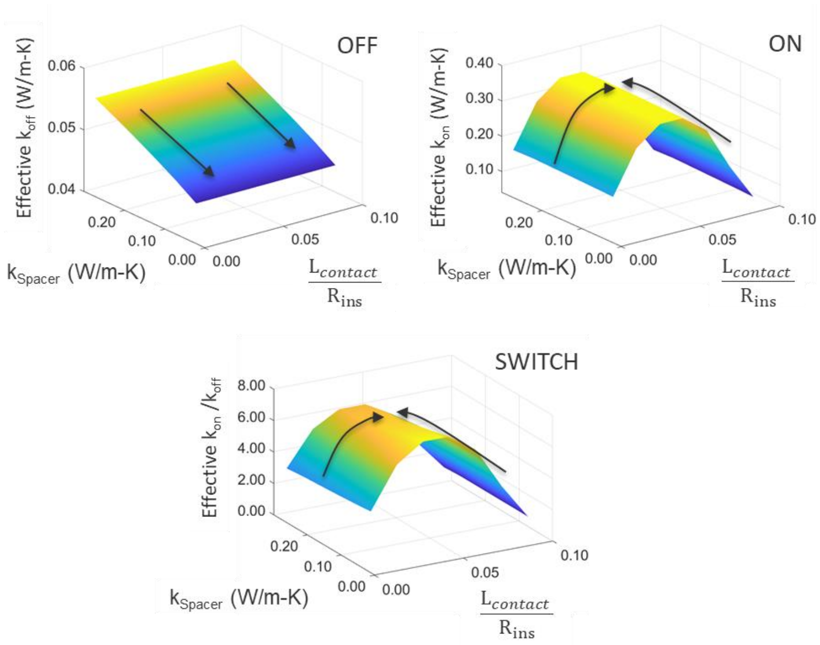
Performance optimization

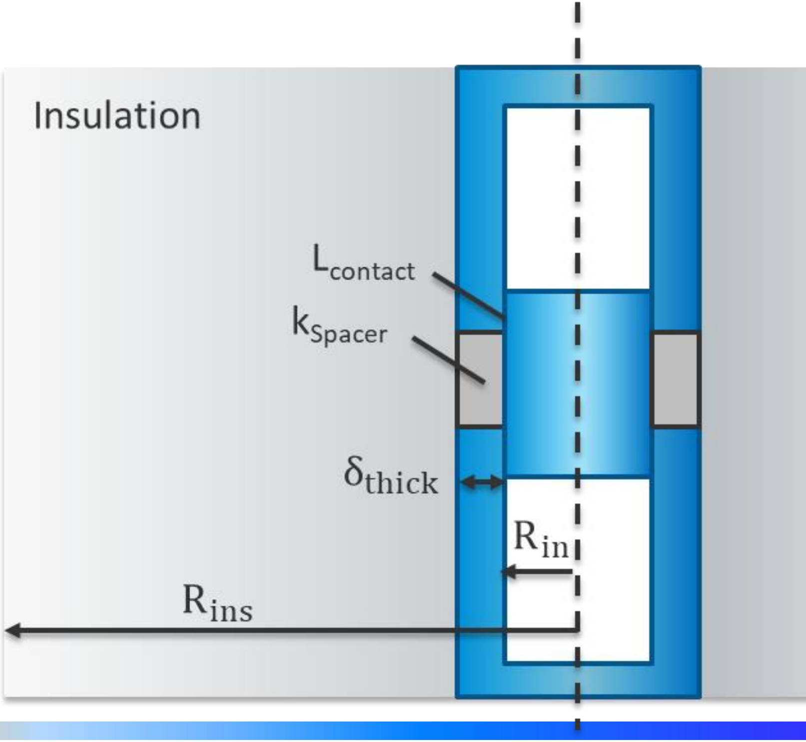




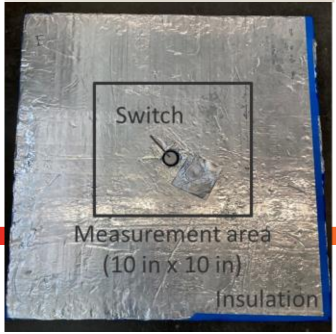
Unpublished/Preliminary Information

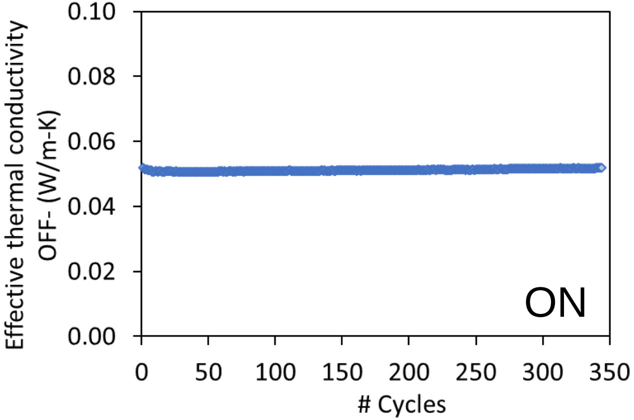
Performance optimization

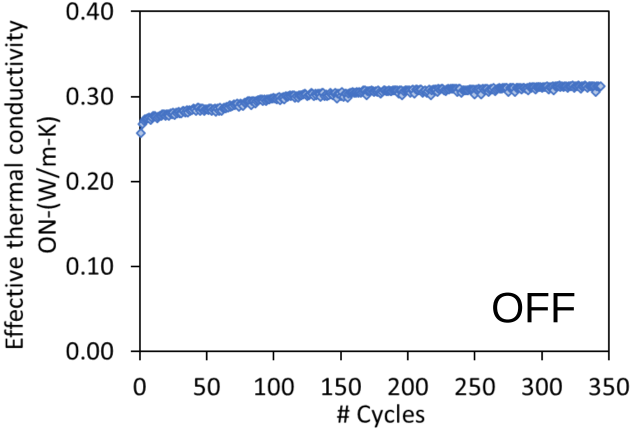


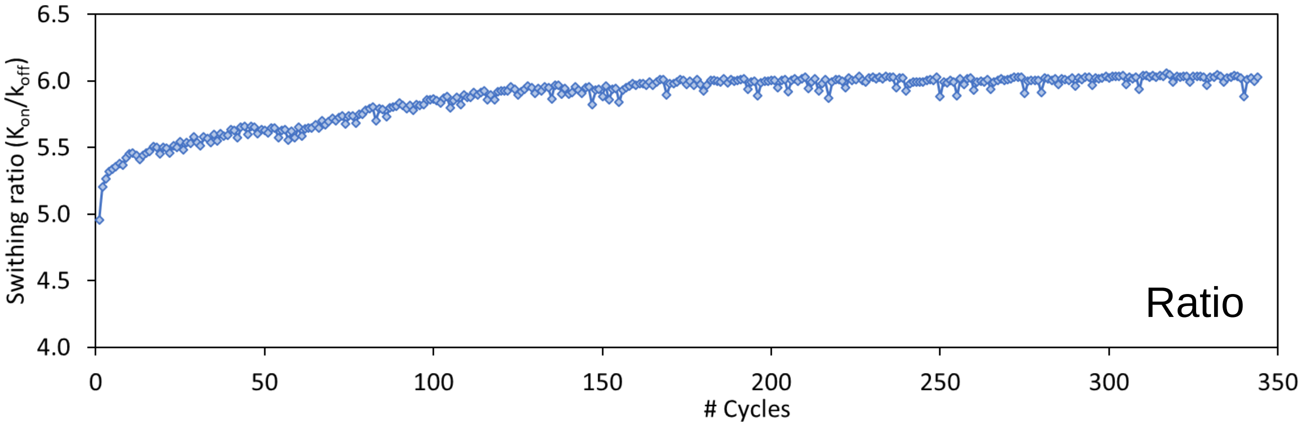


Experiments & cyclability test





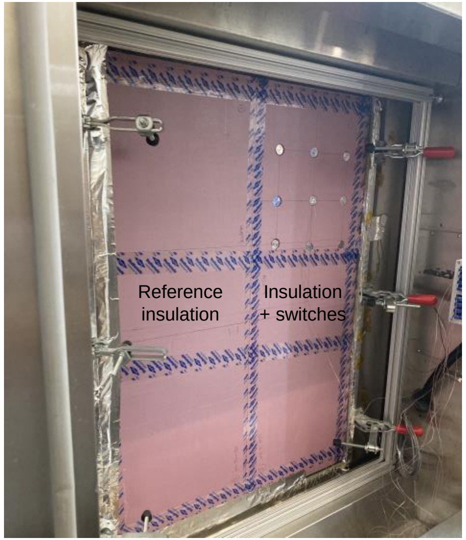




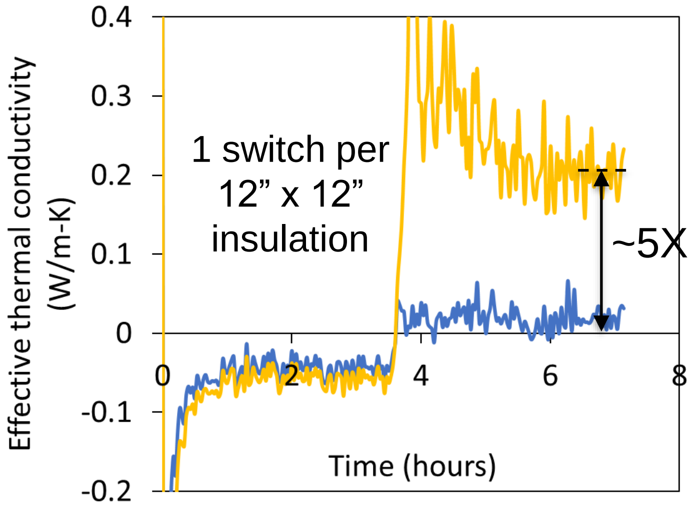
Unpublished/Preliminary Information

Scalability test

Differential Thermal Cycling Unit



Test in progress



Preliminary results

Unpublished/Preliminary Information

Ongoing/Future work

- Continued cyclability and scalability tests
- Third party validation
- Field pilot in collaboration with an industry partner
- Identify a technology transition pathway

Conclusions

- Dynamic envelopes are challenging but it is high-risk high-reward
- HVAC energy savings up to 80% is predicted in some climates
- Building manufacturing and construction industries are largely unfamiliar
  - significant supply chain issues, including cost and deployment
- Our retrofittable switch design minimizes disruptions and facilitates installation using simple processes
- The proposed solution is passive (no external energy needed) with few slow-moving parts and produces no noise
- Actively seeking manufacturing/deployment partners – Please feel free to connect ☺

References

- Kishore, R. A., et al. U.S. Patent : US 2022/0326722 A1. Thermal Diode and Thermal Switch for Bi-Directional Heat Transfer in Building Envelopes
- Kommandur, S. and Kishore, R. A, Contact-Based Passive Thermal Switch with a High Rectification Ratio. ACS Engineering Au, 2022.
- Kishore, R. A., Booten, C., & Bianchi, M. V. (2023). Techno-Economic Analysis of Dynamic Building Envelopes Comprising Phase Change Materials and Switchable Insulations (No. NREL/CP-5500-82623). National Renewable Energy Lab.(NREL), Golden, CO (United States).
- Kishore, R. A., Bianchi, M. V., Booten, C., Vidal, J., & Jackson, R. (2021). Enhancing building energy performance by effectively using phase change material and dynamic insulation in walls. Applied Energy, 283, 116306.
- Kishore, R. A., Bianchi, M. V., Booten, C., Vidal, J., & Jackson, R. (2020). Optimizing PCM-integrated walls for potential energy savings in US Buildings. Energy and Buildings, 226, 110355.

Acknowledgments

- Zhiying Xiao, NREL
- Chuck Booten, NREL
- Sajith Wijesuriya, NREL
- Som S. Shrestha, ORNL
- Bandana Kar, U.S. DOE BTO
- Sven Mumme, U.S. DOE BTO

Thank you & QA

NREL/PR-5500-91045

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Building Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

Relation to the U.S. Buildings Decarbonization Blueprint's goal

- **Energy efficiency**: Thermal switches and dynamic envelopes can provide significant HVAC energy savings by utilizing ambient cooling and heating.
- **Grid edge**: Thermal switches enhance PCM utilization and provide control over charging and discharging process.

Additionally

- **Equity and Affordability**: The technology supports underrepresented and disadvantaged communities by reducing their energy-related cost burdens and enhancing occupants' comfort
- **Resilience**: Our passive thermal management solution enhances thermal resilience in buildings, for instance, by providing cooling during nighttime and overheating protection during daytime