Advances In Thermal Energy Storage

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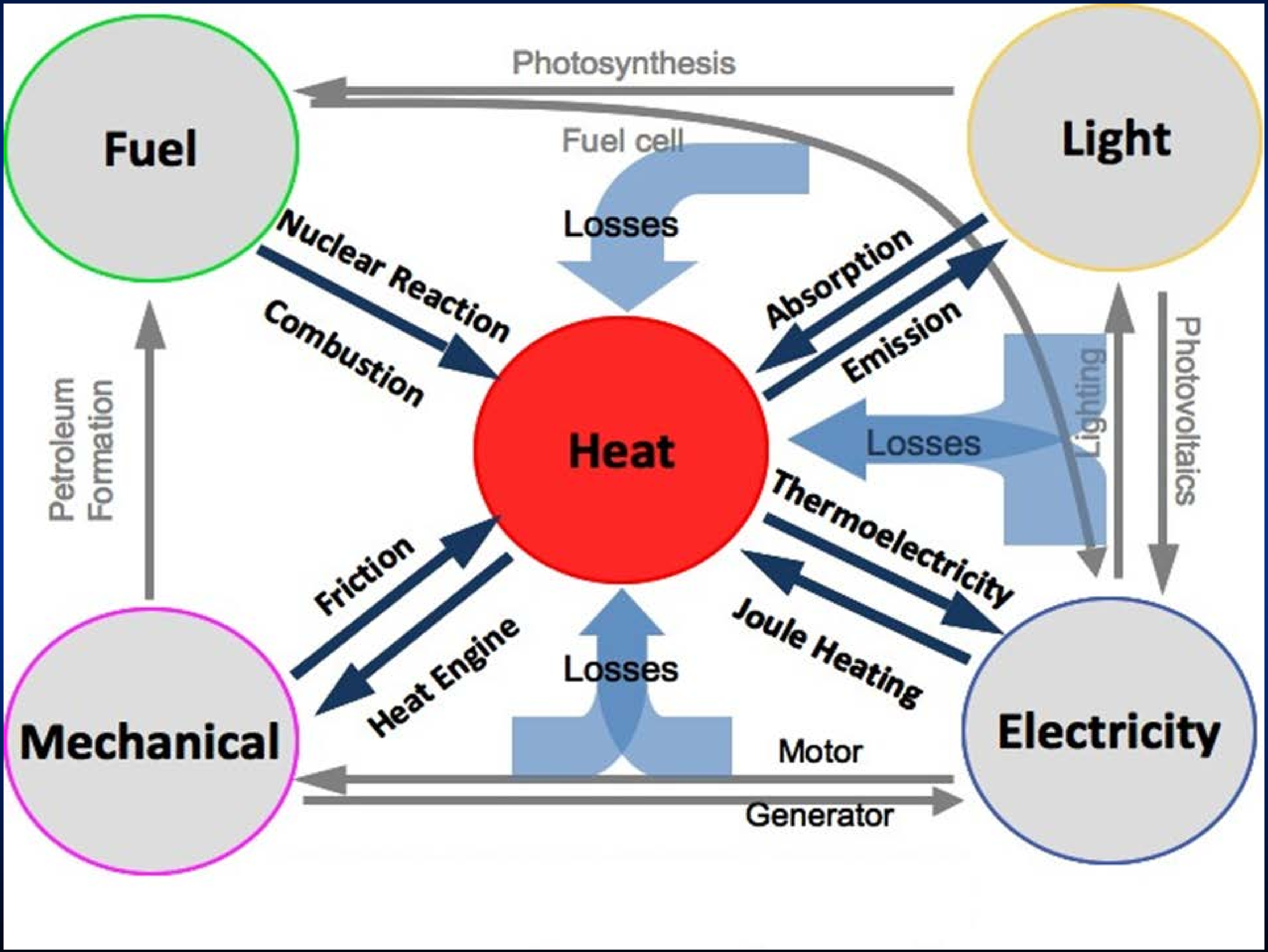
More than 90 % of Energy Budget involves Thermal Process



Thermal energy is the dominant component of our energy system

Energy Source → **Conversions** → **End-Use**

Biomass

Coal, Natural Gas & Petroleum

Nuclear

Renewable

Carbon Fuels

Hydrogen

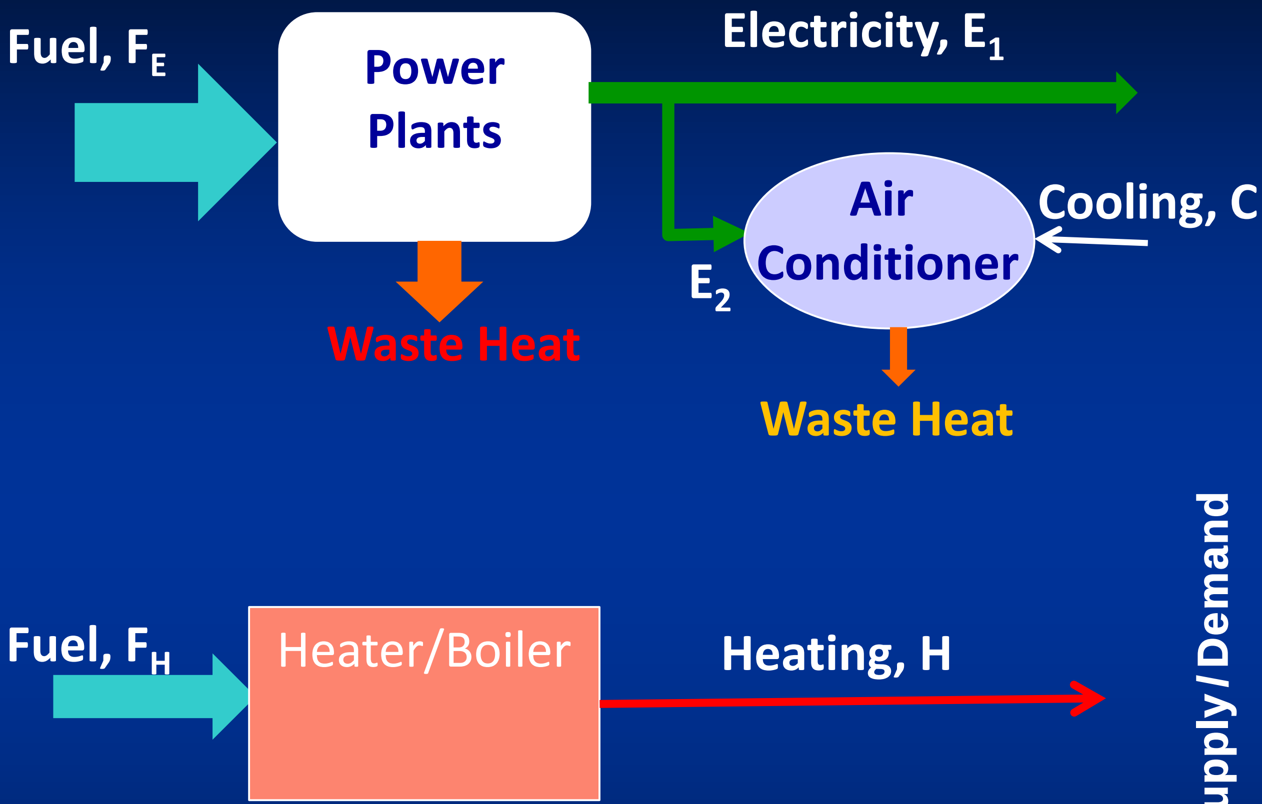
Electricity

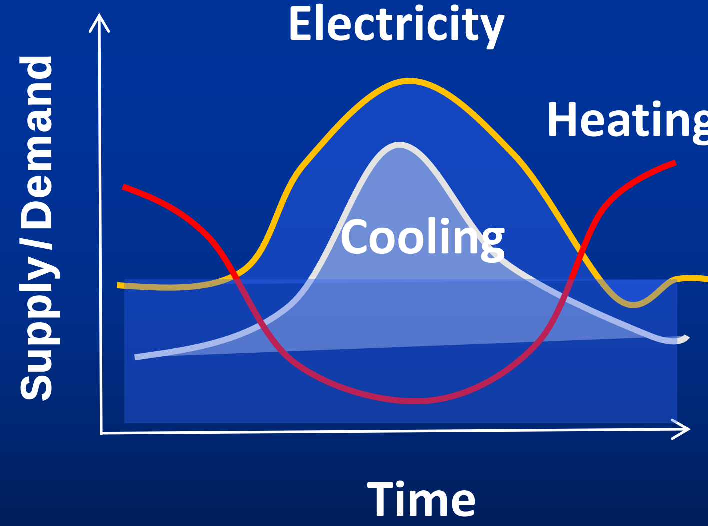
98 Quads

HEAT (59 Quads)

39 Quads

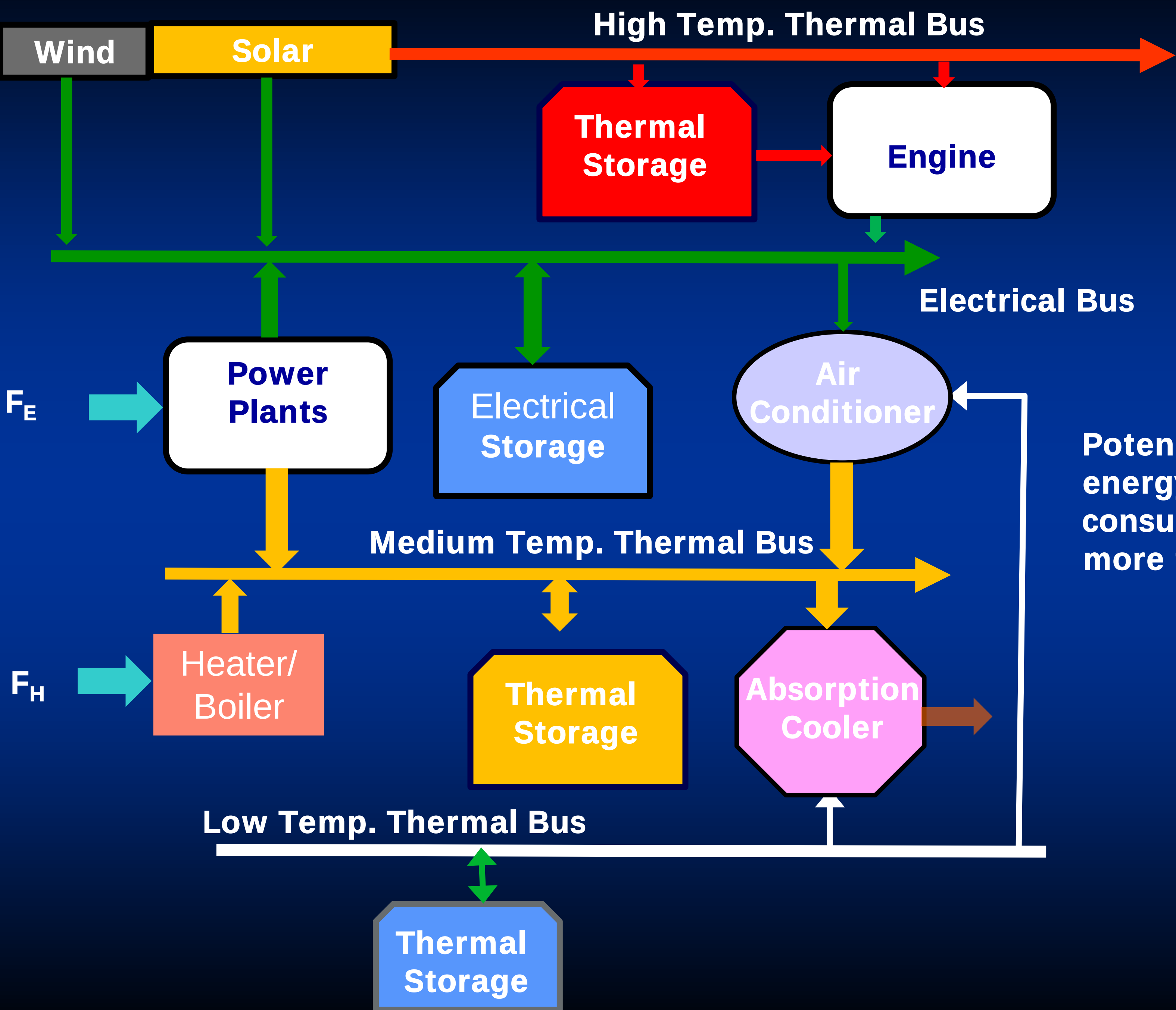
Current System Architecture





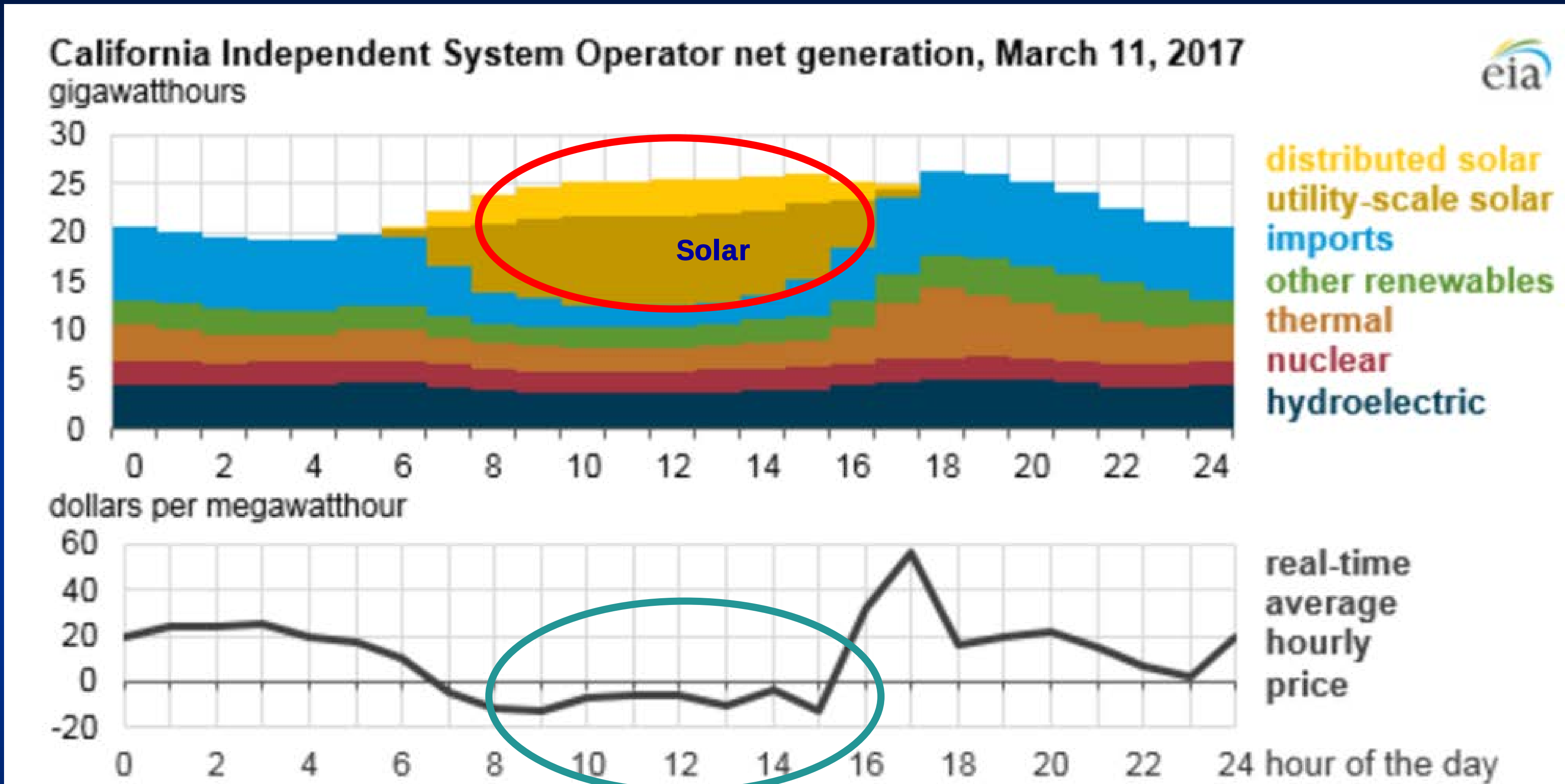
Rate of Fuel Use, $F = F_E + F_H$

Integrated Energy Supply Systems (Prasher & Majumdar, ARPA-E HEATS workshop)



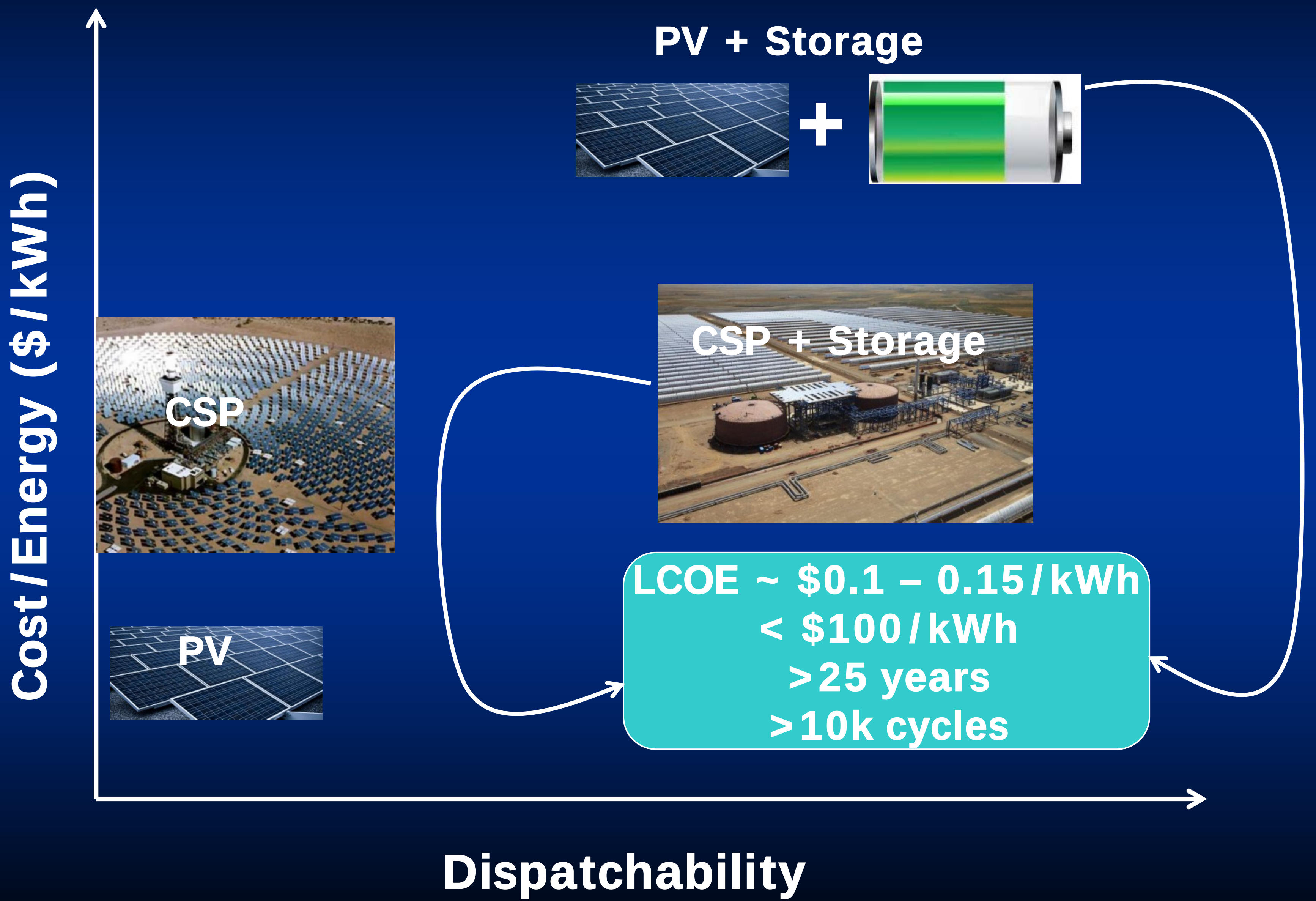
Potential to reduce energy consumption by more than 25%.

Solar Exceeds 50% in CA but Price drops Below Zero

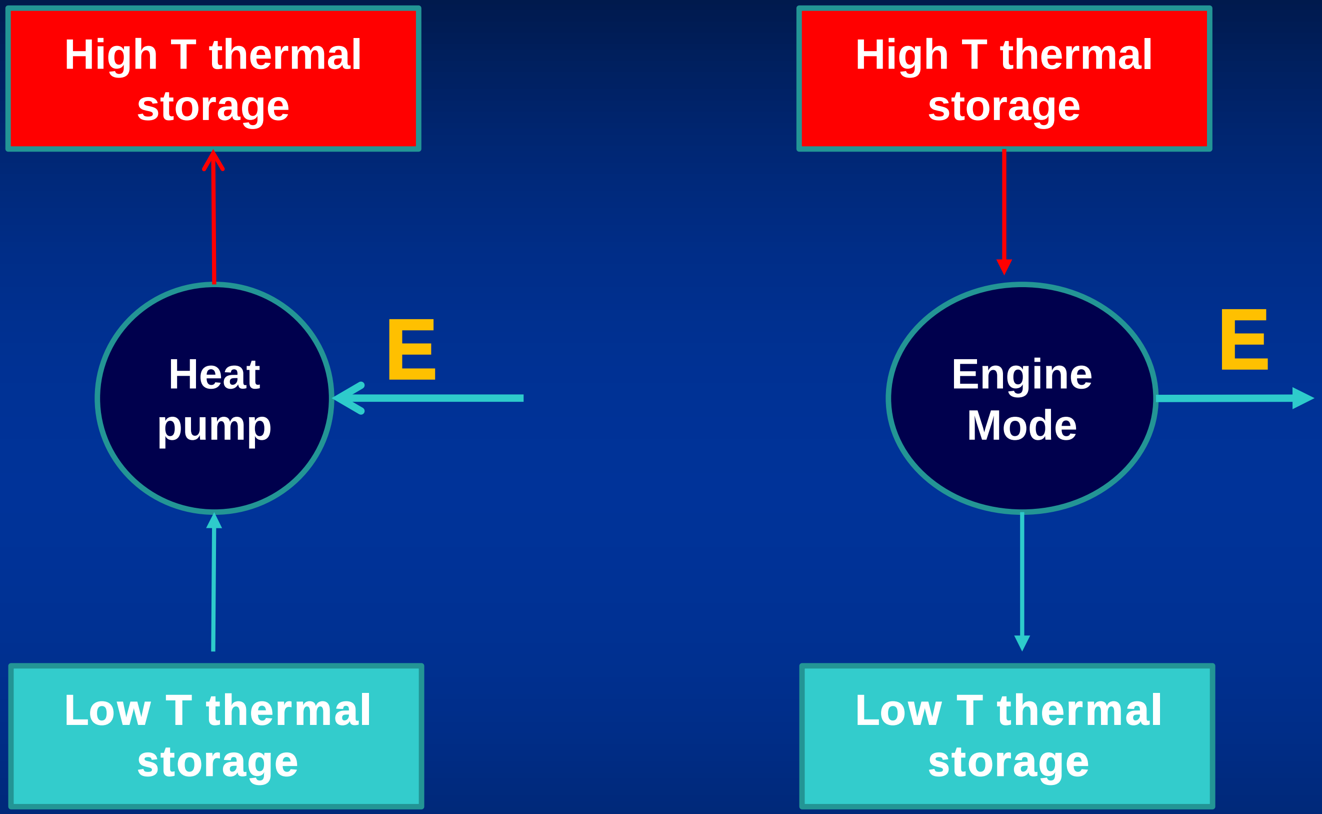


BERKELEY LAB

Dispatchable Renewable Power



Thermal Storage to Store Electricity

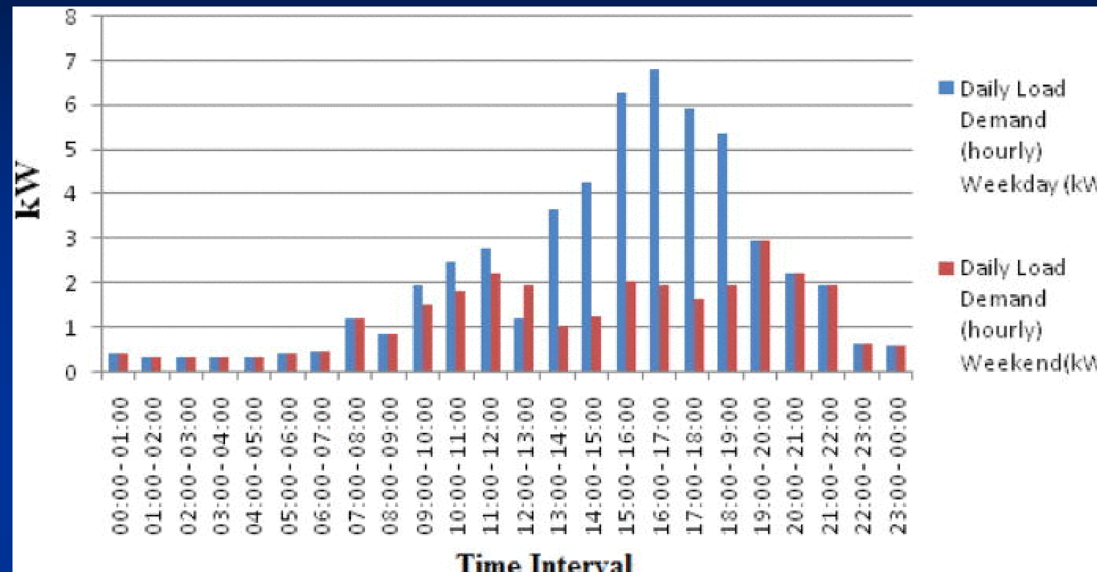


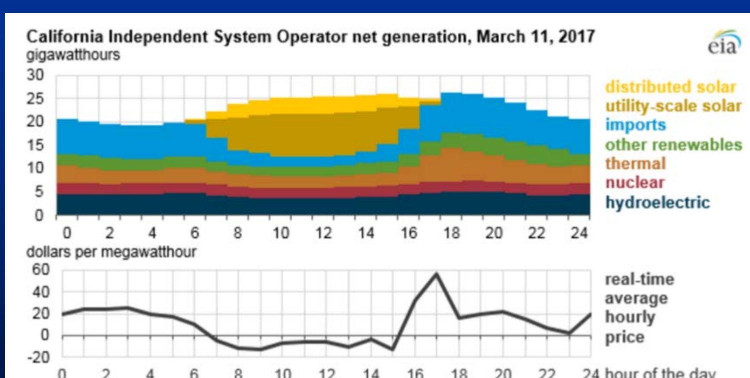
This can potentially enable electrical storage with cost of pumped hydro but geographically independent

References: 1) https://x.company/explorations/malta/ 2) Prof. Robert Laughlin, Nobel Laureate, Stanford University

Thermal Management Applications of Storage

Heating & Cooling is ~50% of Energy Consumption in Buildings

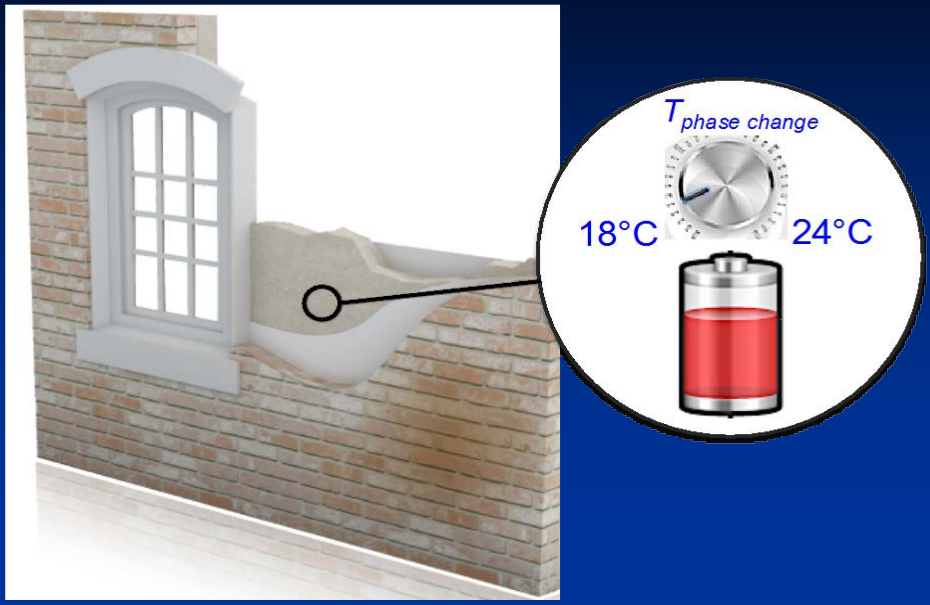




Building thermal loads are highly variable

Source: LBNL Environmental Energy Technologies Division, 2009

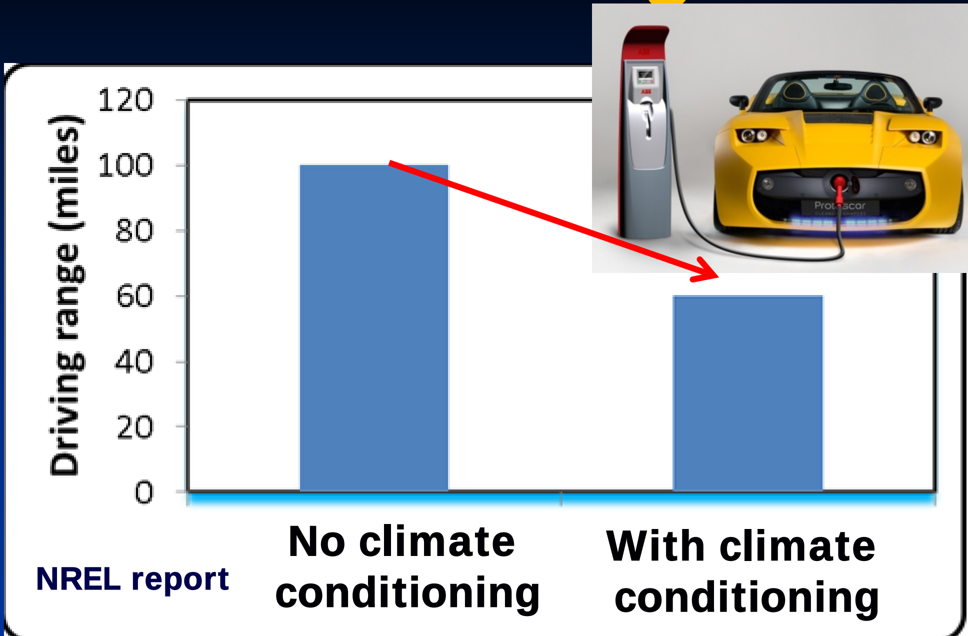
Thermal Storage In Building Walls

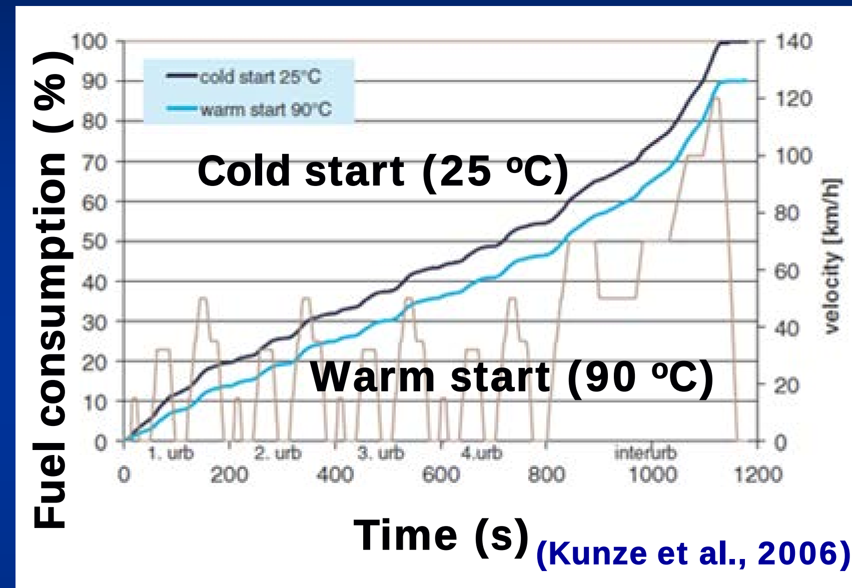


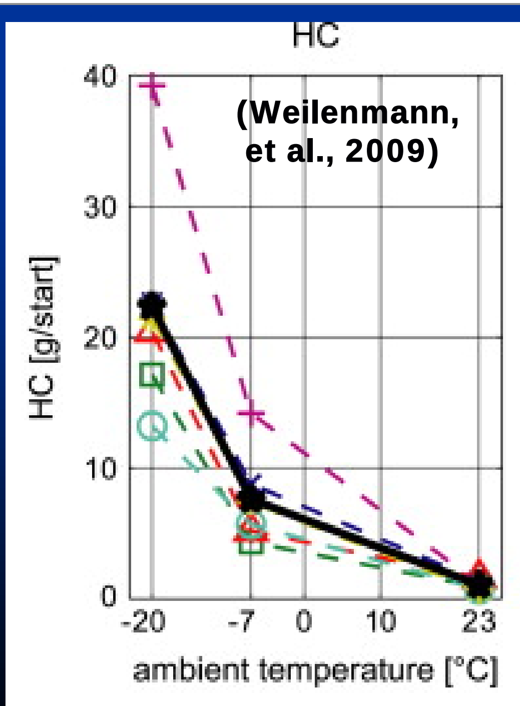
A typical 2000 ft^2 residential building can store an estimated 44 Ton-hours (~150kWh$_t$) of thermal energy. This is equivalent of 9 hours of storage assuming 5 ton of cooling.

Challenge: Tunable Transition Temperature

Thermal Management of Vehicles

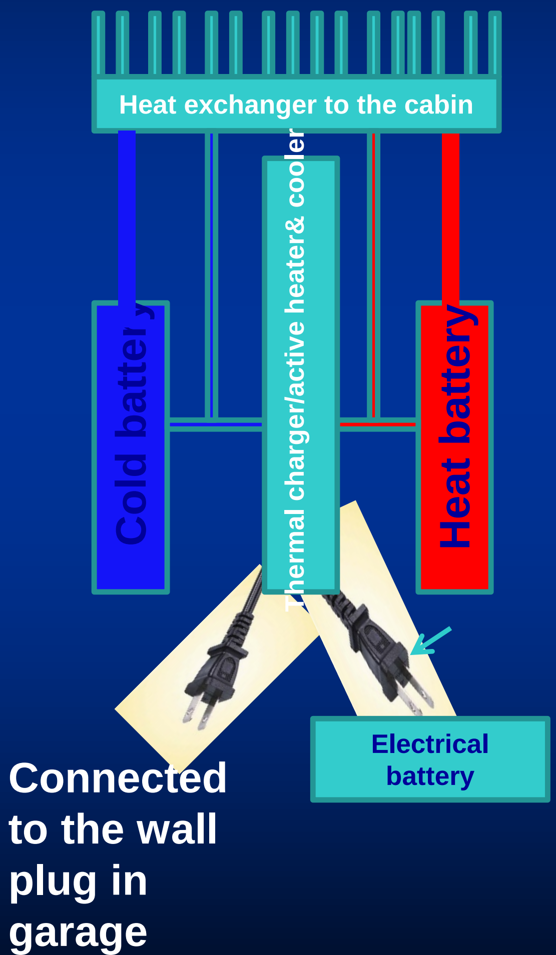


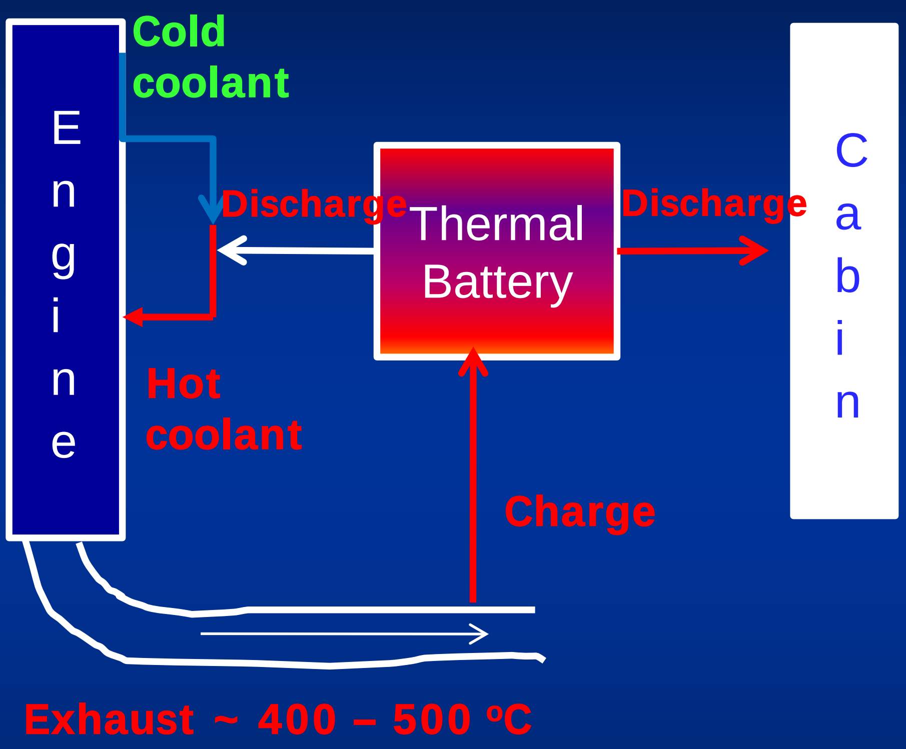




- Heating / cooling of cabin can reduce driving range of Electric Vehicles by 40 %
- Cold Start of IC vehicles increases fuel consumption and GHG emissions

Thermal Storage for ICV and EV





Science and Technology Challenge

- Reliable and cost effective thermal storage

- Long distance transmission of thermal energy

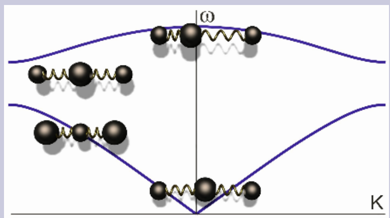
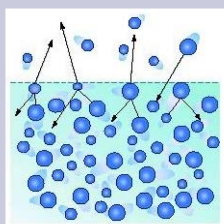
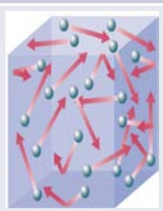
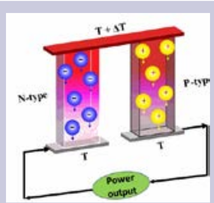
HEATER

Highly Efficient Advanced Thermal Energy Research

A U.S. Department of Energy initiative leveraging the expertise of the National Laboratories to achieve the full economic potential of U.S. thermal energy

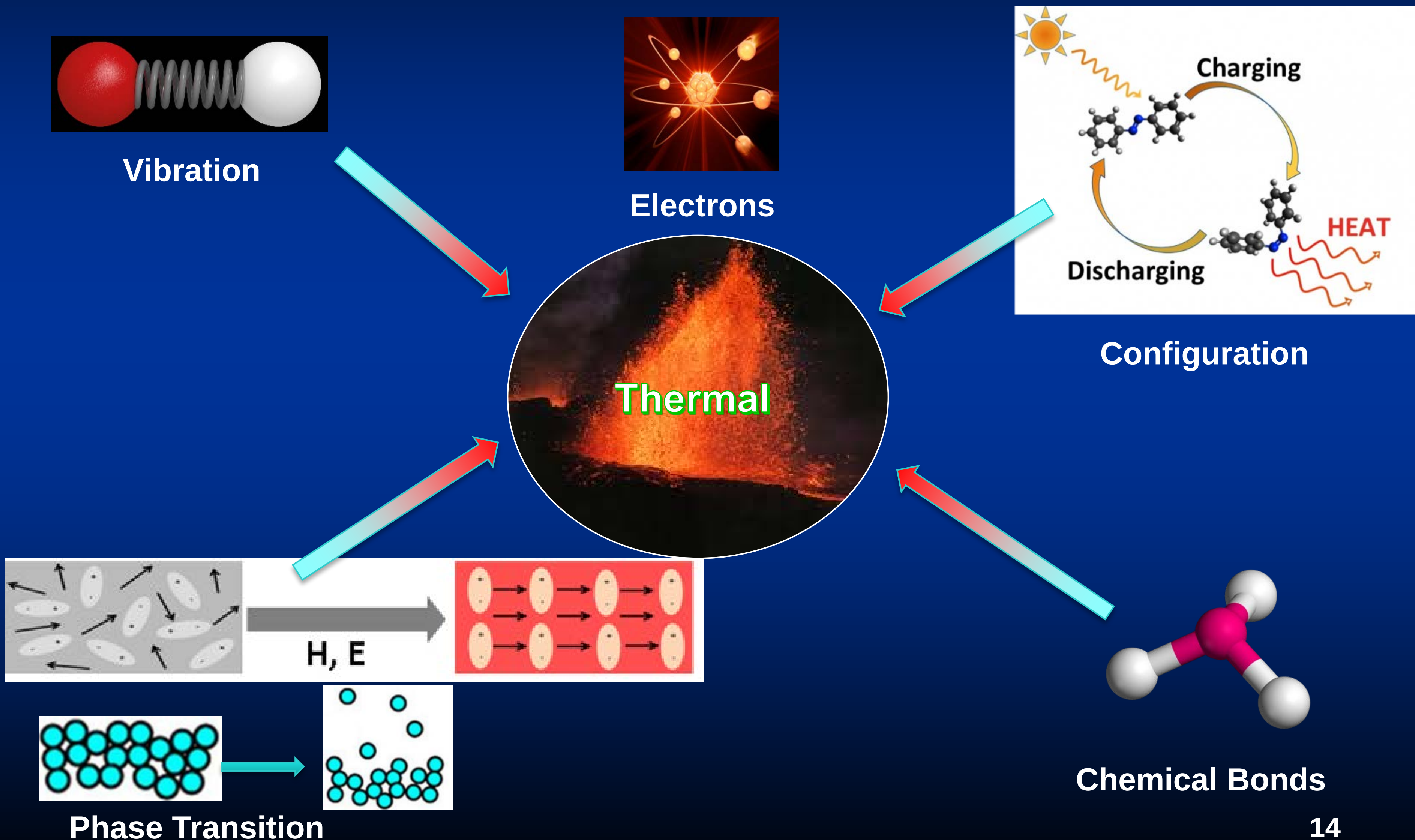
Aiming for Theoretical Limits

Thermal Energy Processes are atomic/molecular scale phenomena

	Data	**Theoretical limit**
Conduction 	High ~ 2kW/m^2-K (L = 1m)	~1 GW/m^2-K
	Low ~ 12 mW/m-K (50% of air)	None
Phase change heat transfer 	~5 - 10 MW/m^2	160 MW/m^2
Thermal Storage 	< 1 MJ/kg	None (Gasoline ~ 40 MJ/kg)
Heat to electricity (solid state) 	~15-20% of Carnot	Carnot

Prasher & Majumdar (to be published)

Harnessing molecular phenomena for thermal processes



Exploring the Limits of Thermal Conduction

10^{15}

Low

High

Electrical Conductivity

Ultra low?

Polymers

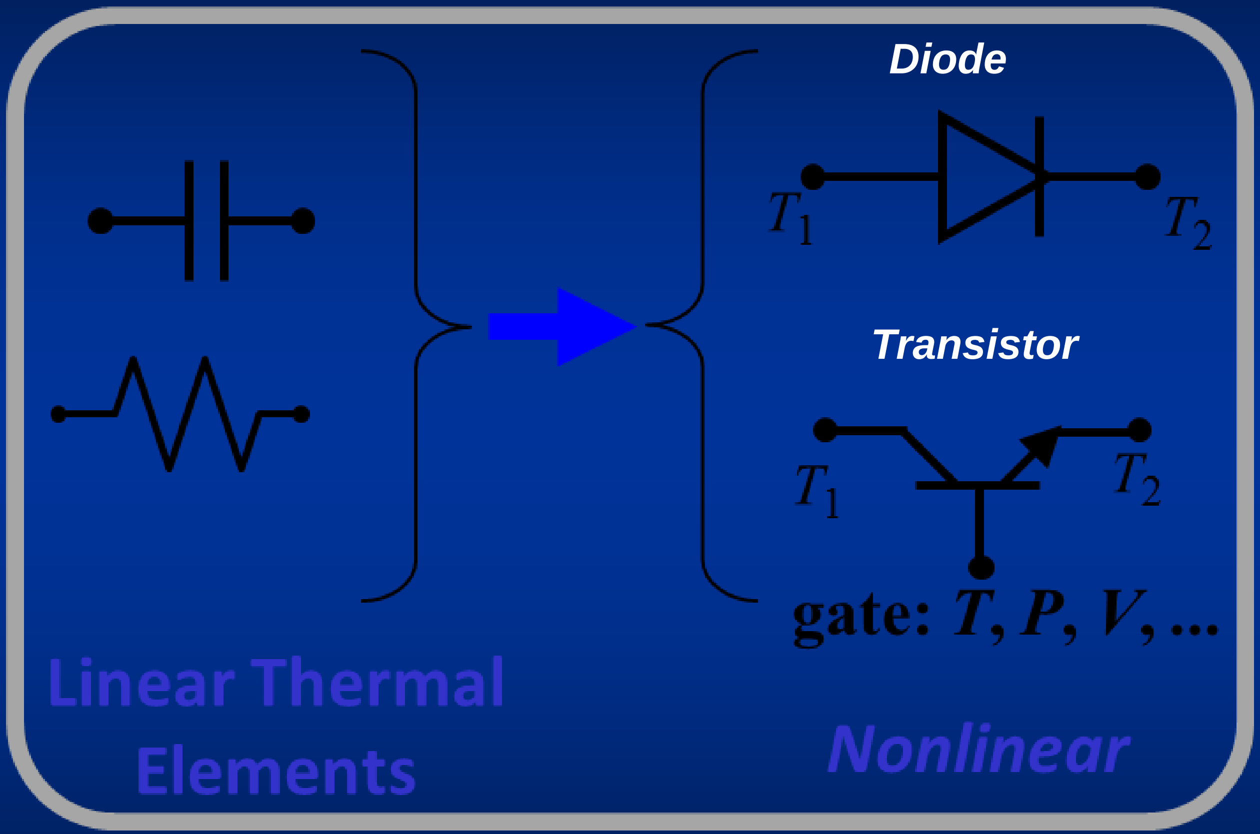
Diamond

Ultrahigh?

10^4 @300K

Phonon localization?	Correlated scattering & diffusion	Uncorrelated scattering & diffusion	Reduced Scattering & ballistic?

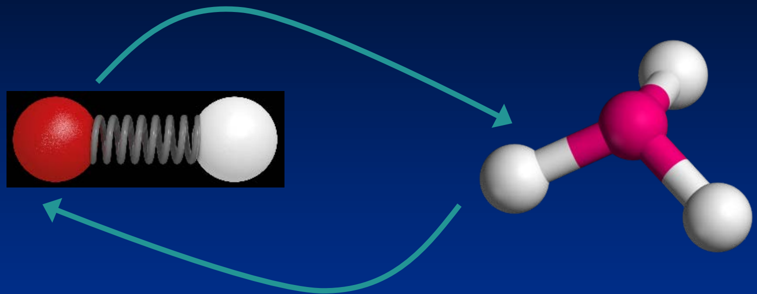
Nonlinear Thermal Transport: Enabled by Materials Science



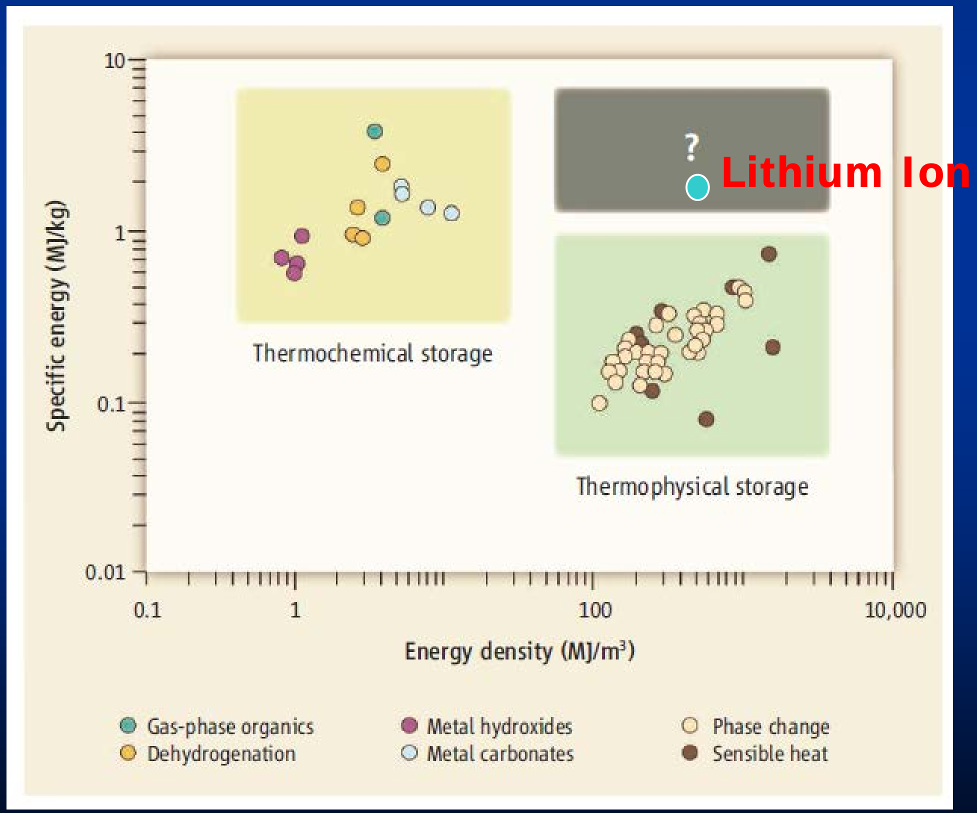
High contrast switch with minimal hysteresis

- **Phase transitions**
- **Intercalation**
- **Geometry**

Long Distance Thermal Transport and Storage: Phonons to Chemical Bonds



$A \leftrightarrow B + C$ $\Delta H = T\Delta S$



(Gur, Sawyer & Prasher, Science, 2012)

Chemistry Challenges

- Large entropy change in condensed state
- Tunable entropy change
- Tunable activation energy
- Large thermal effusivity

Other Challenges

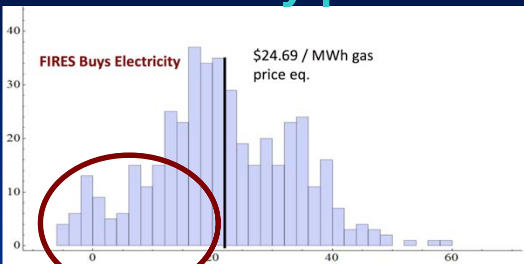
Most thermal storage based on: Solid / liquid phase change or sensible liquid heating

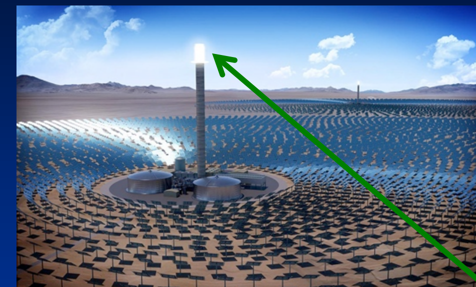
1) **Leakage**
2) **Thermal expansion**
3) **Corrosion**
4) **Low specific heat of liquids**

How about Solid State thermal storage?

Cheap Distributed High-*T* Storage

Electricity prices





Cheap electricity

(Electrically conducting; can be Joule heated)

Direct storage

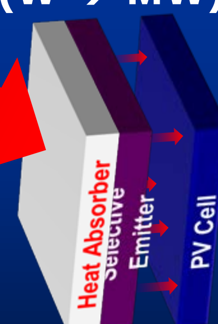
Heat

High-*T* Industrial Application

High-*T* optical coatings

Heat

(W → MW)

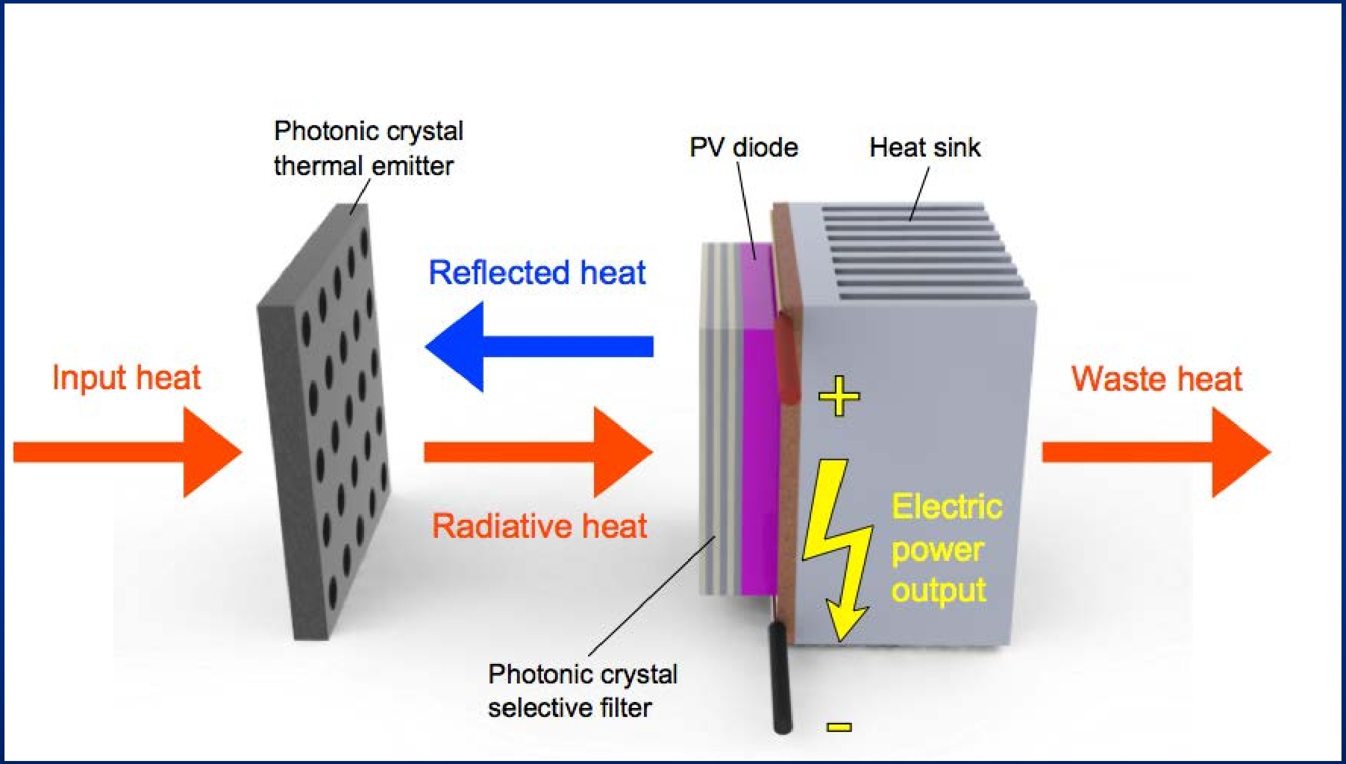


Electricity

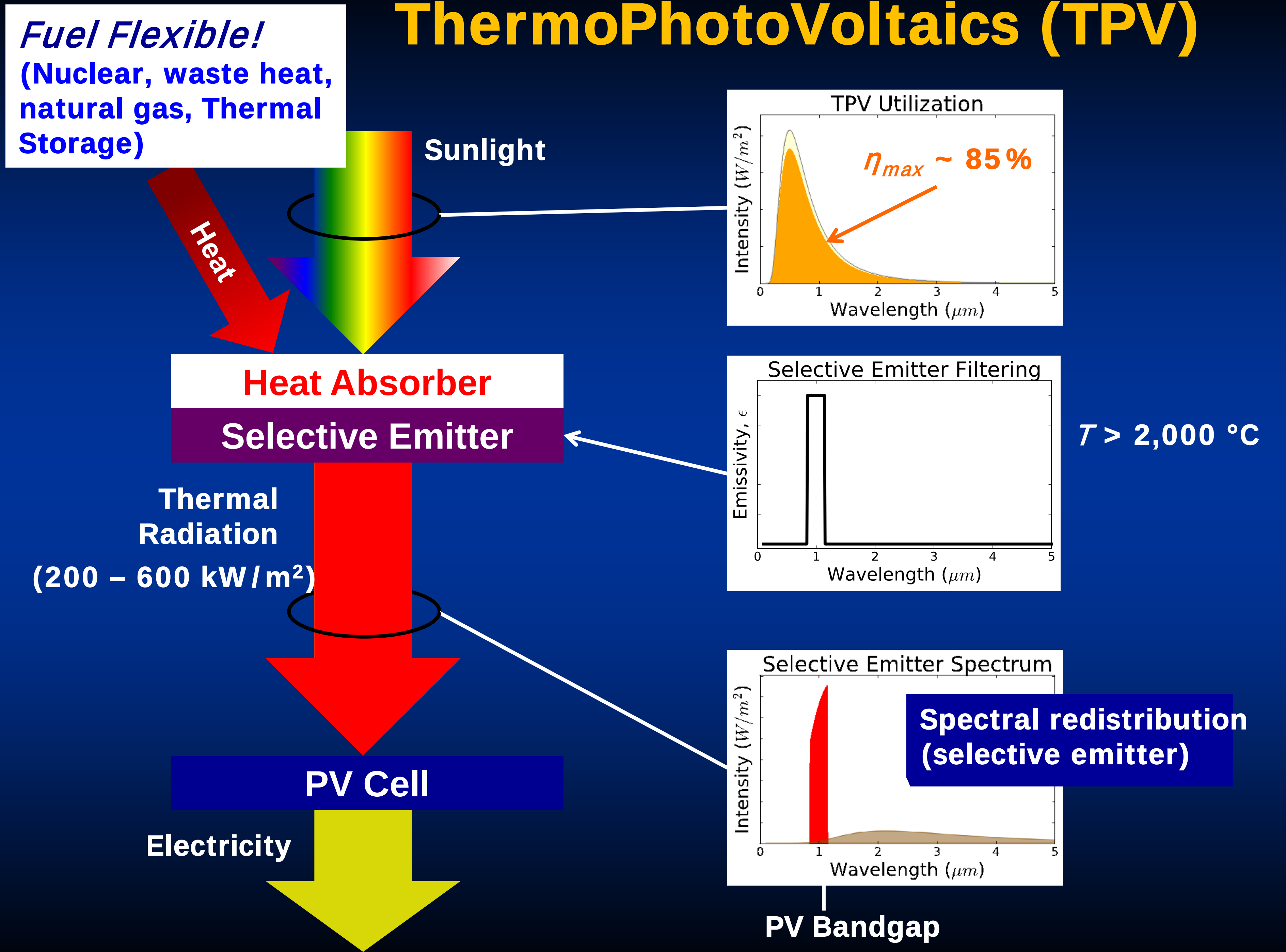
TPV

Higher *T* → higher energy density ~ 1 MWh_t / m^3
Cheaper than batteries, more versatile than pumped hydro etc.

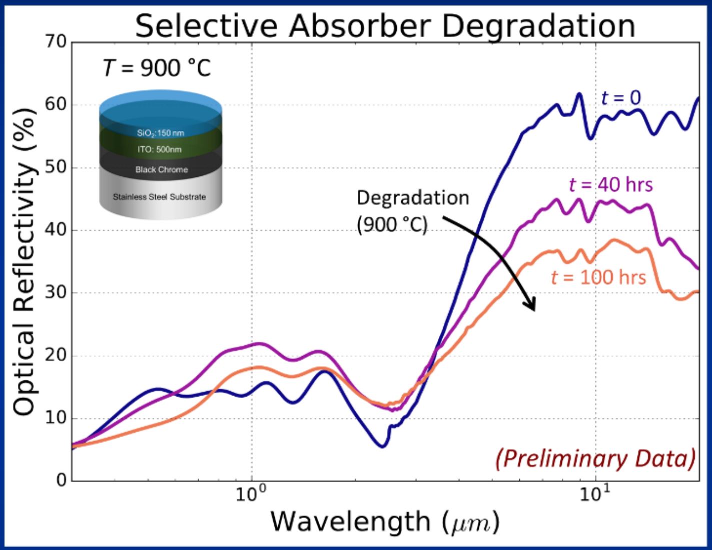
Thermo Photovoltaics (TPV)

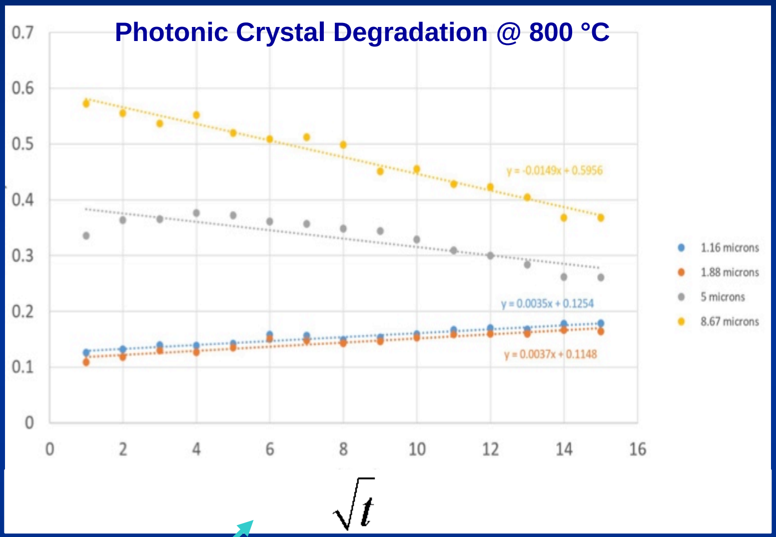


ThermoPhotoVoltaics (TPV)



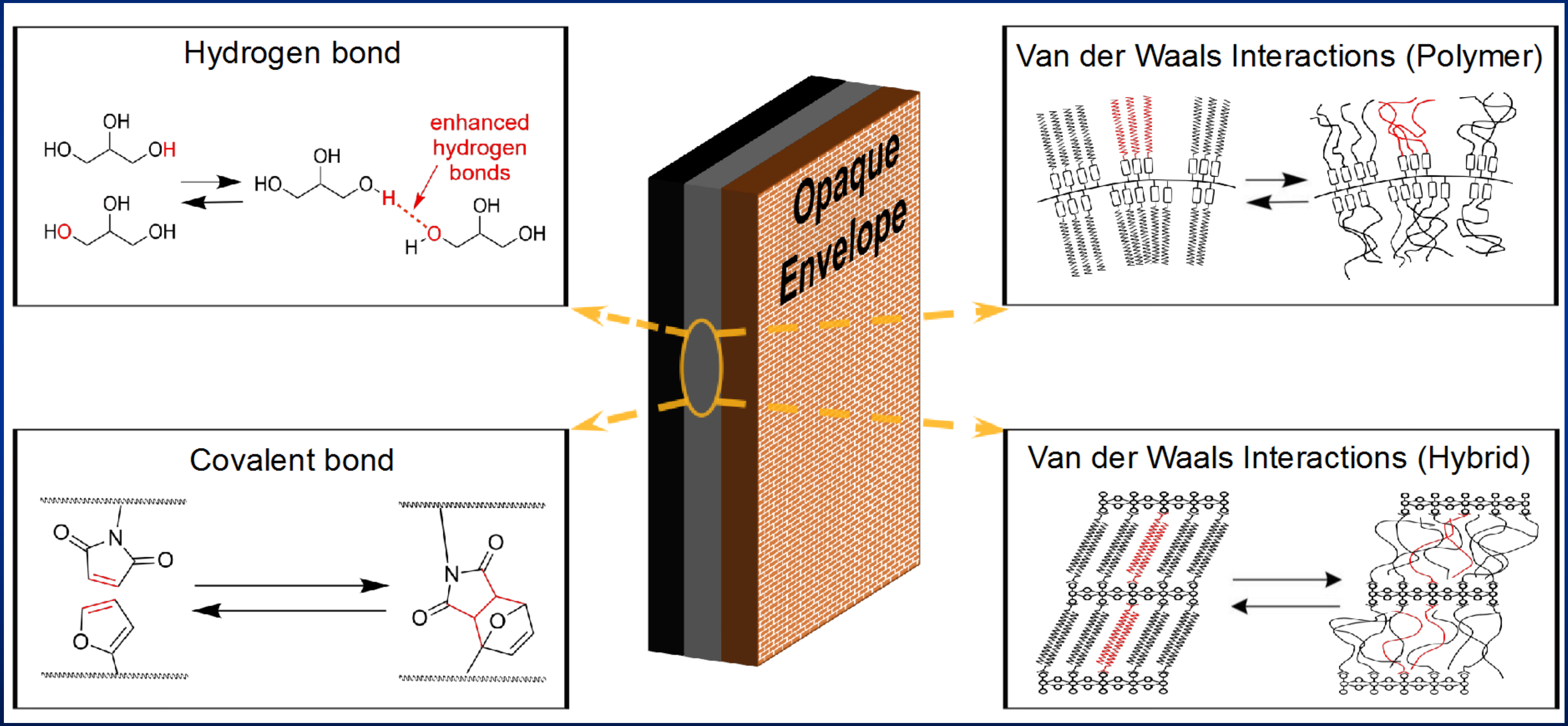
Challenges for High Temperature Emitters: Performance Degradation



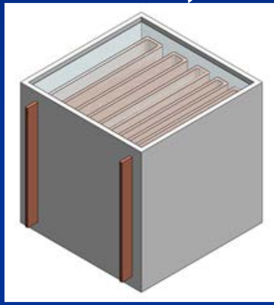


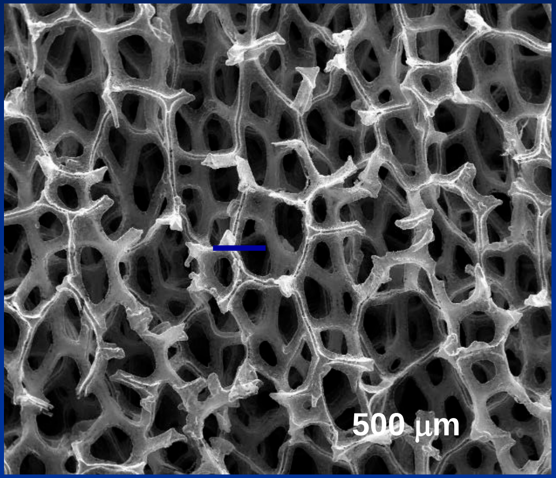
Diffusion driven

Solid State Low Temperature Thermal Storage

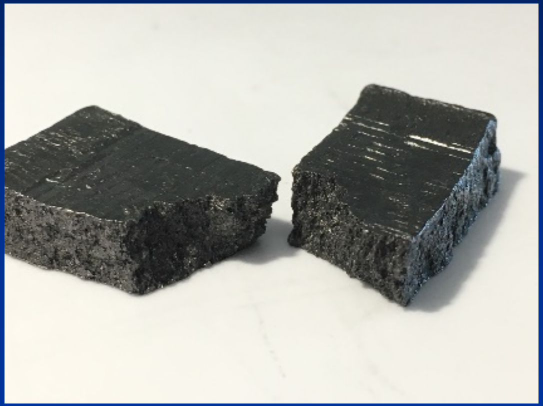


Cage Based Solid State Thermal Storage





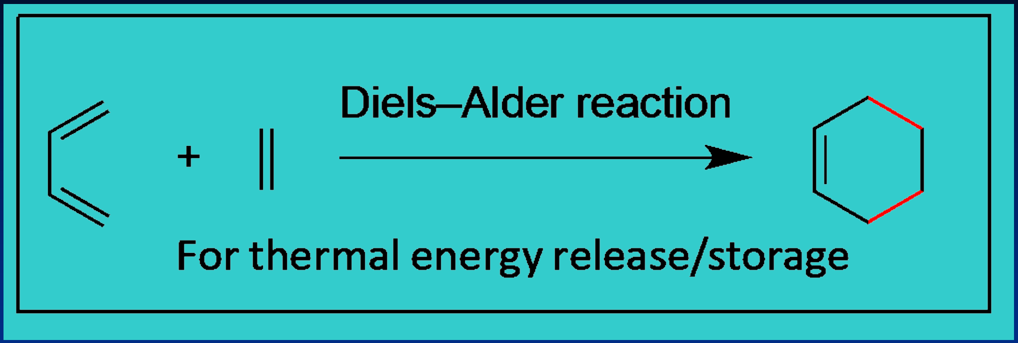
Li Shi, UT Austin

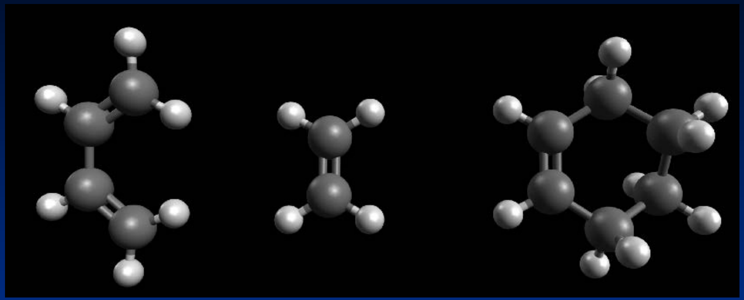


SL PCM caged in graphite matrix. Courtesy of "All Cell Technologies, LLC".

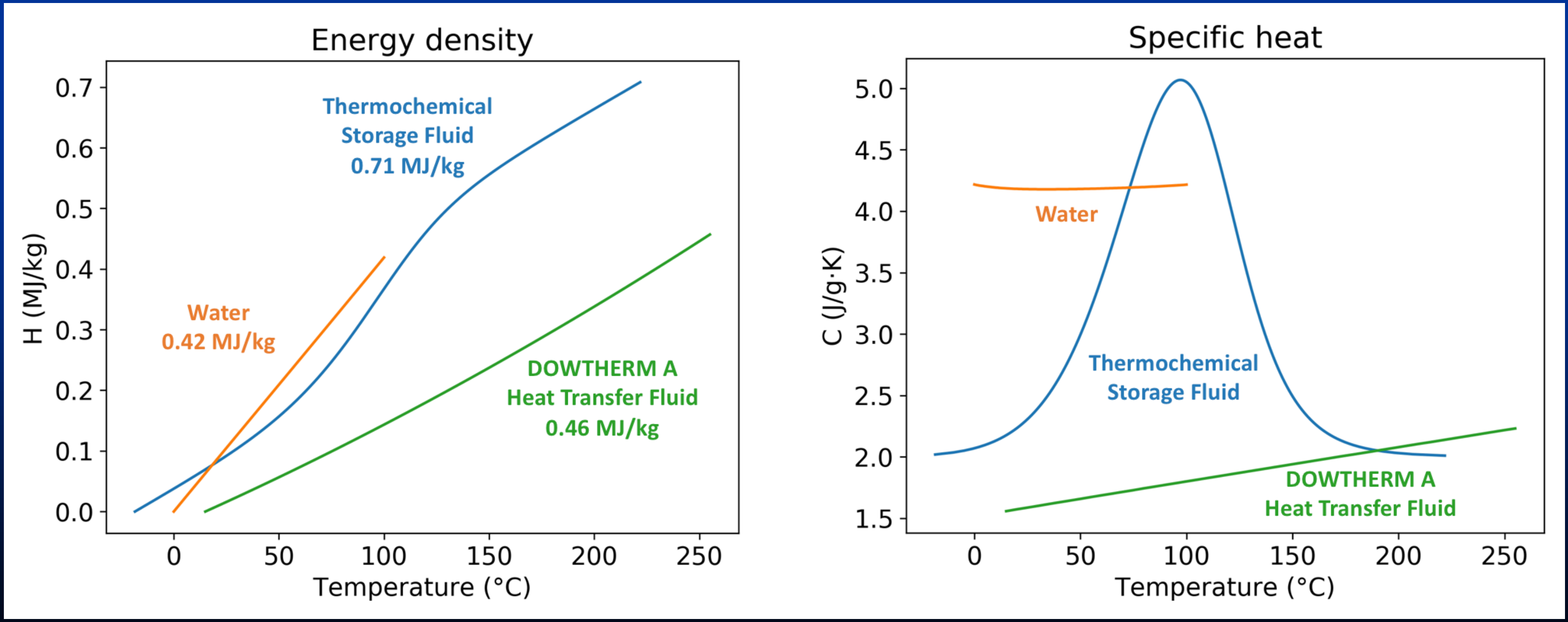
All Liquid Thermochemical Storage and Heat Transfer Fluid

Computational Chemistry for High Energy Density Storage

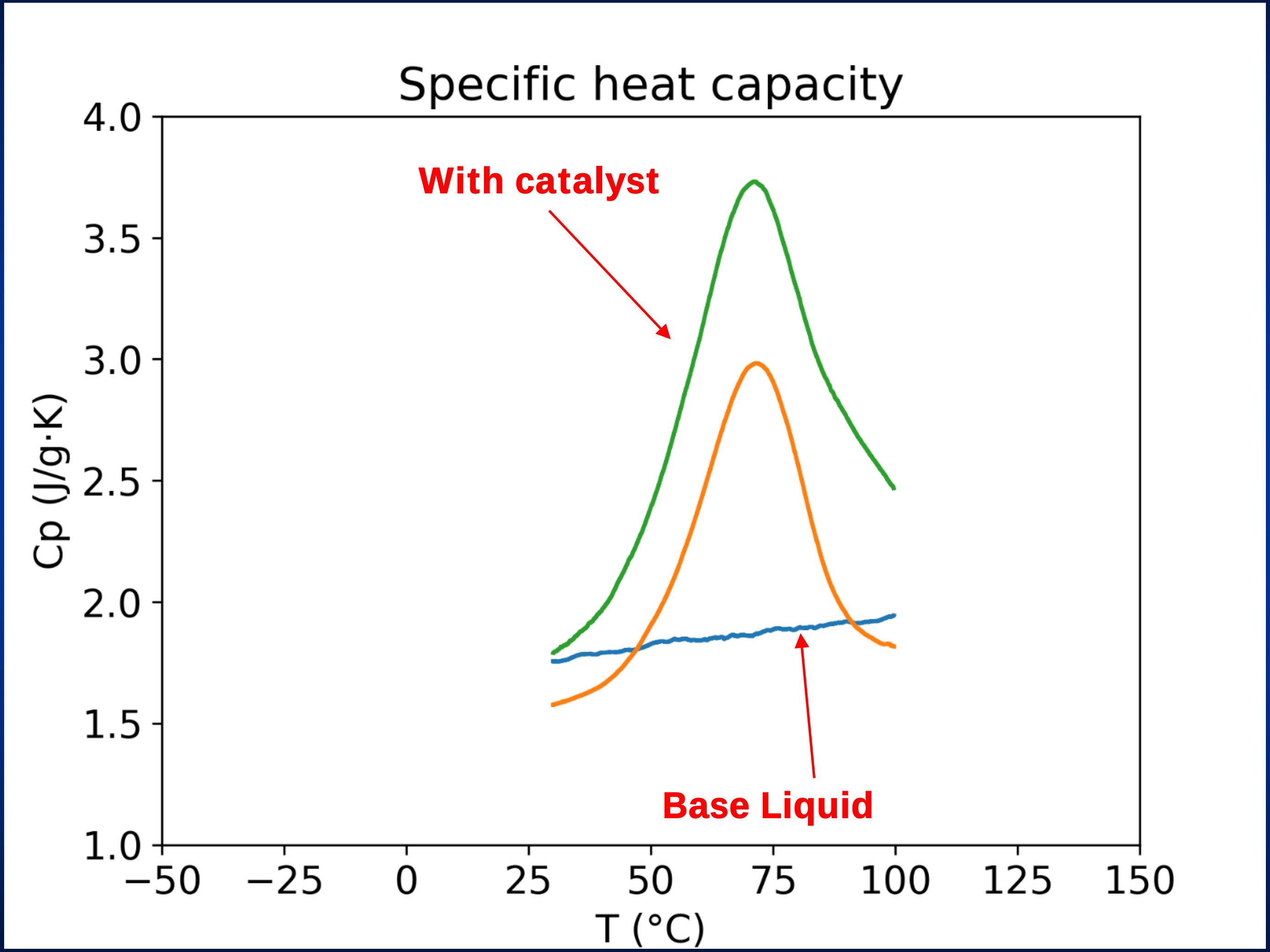




Condensed phase reversible chemical reaction

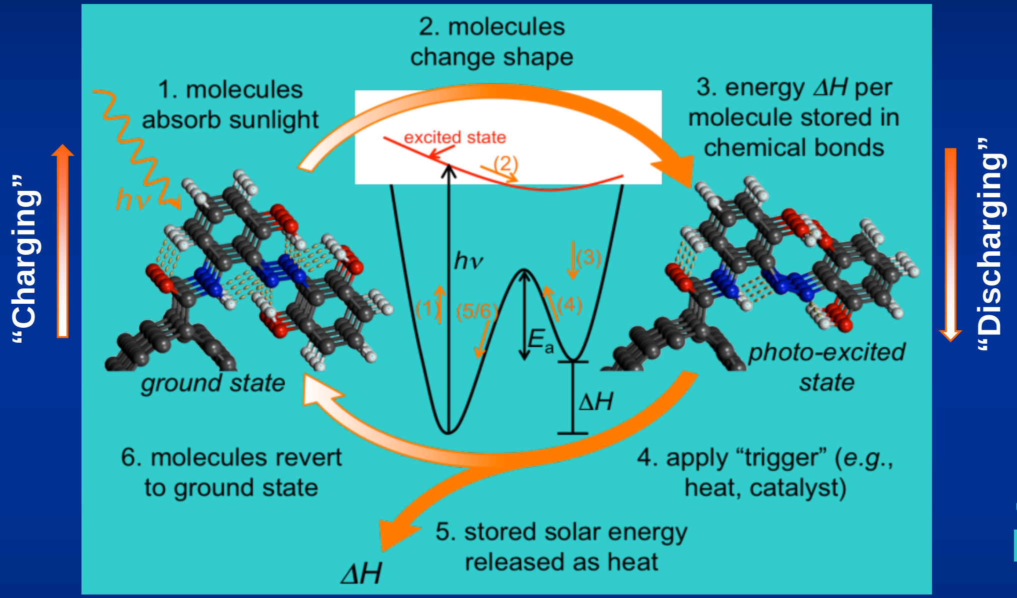


Preliminary Experimental Evidence



HYBRISOL: Hybrid Nanostructures for High-Energy-Density Solar Thermal Fuels

Grossman, MIT



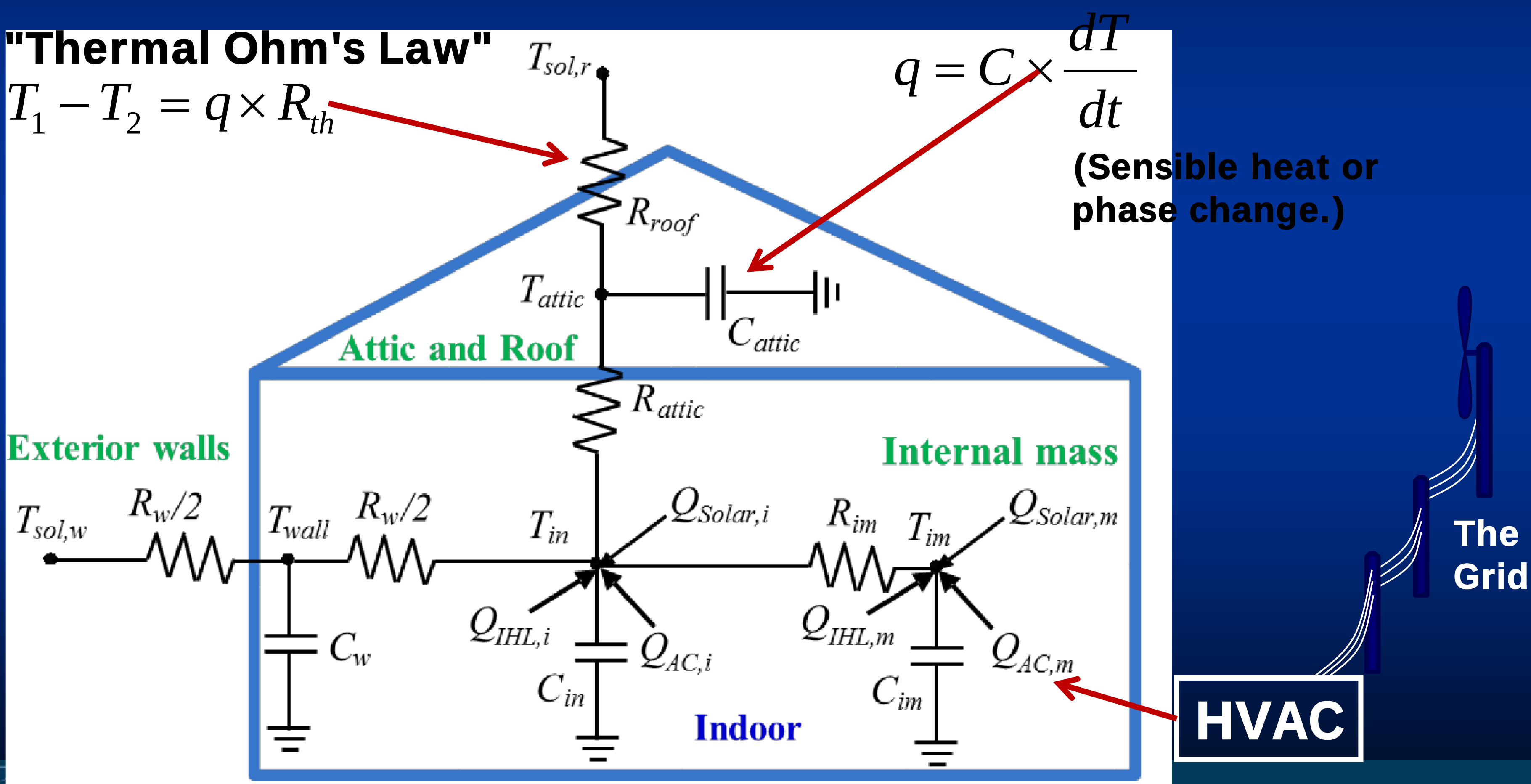
Transportable like a fuel…

…rechargeable like a battery.

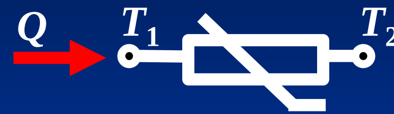
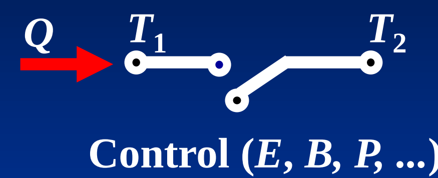
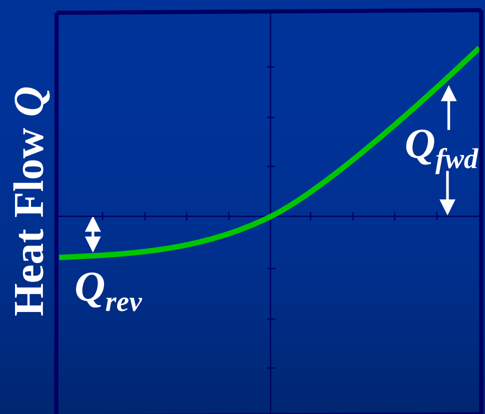
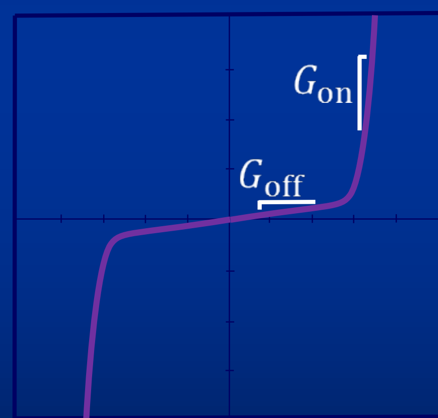
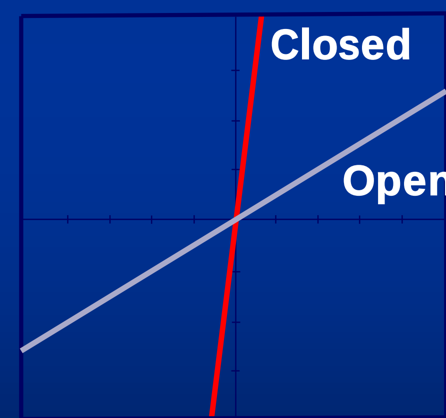
Energy density similar to a Li-Ion battery

Building thermal management still relies on *linear* thermal concepts, 100s of years old.

Thermal Storage

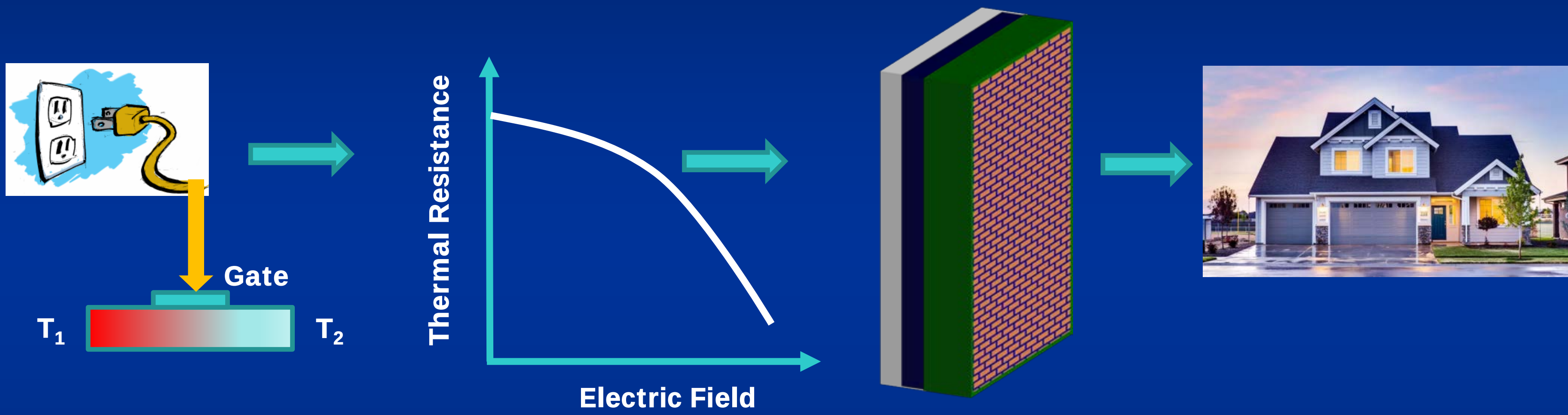


Nonlinear Thermal Elements

Diode	Regulator	Switch
		
Transfer Function: *Asymmetric*	**Transfer Function:** *Nonlinear*	**Transfer Function:** *Control-Dependent*
		
Thermal Bias $\Delta T = T_1 - T_2$ (T_{avg} fixed)	Thermal Bias $\Delta T = T_1 - T_2$ (T_{avg} fixed)	Thermal Bias $\Delta T = T_1 - T_2$ (T_{avg} fixed)

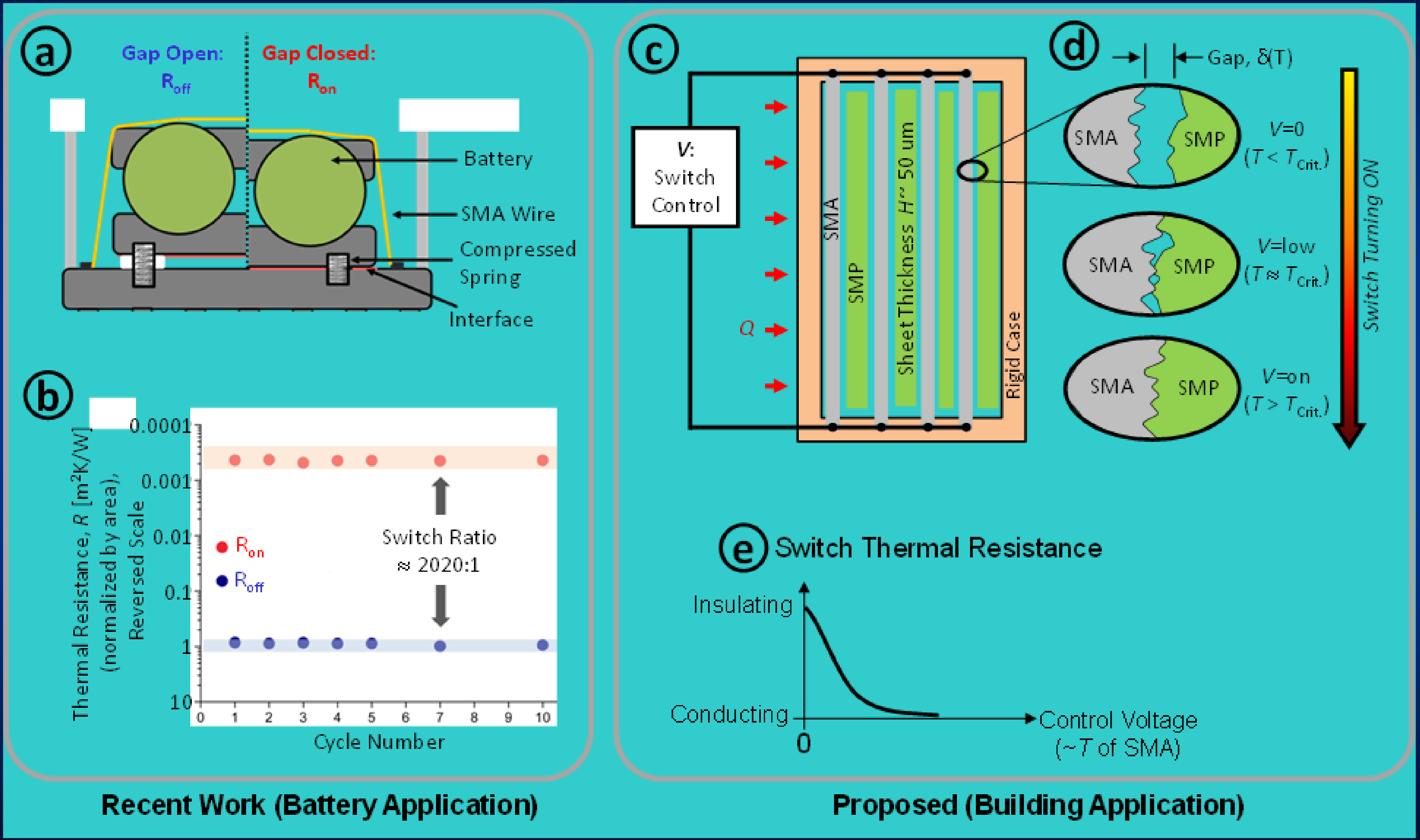
Dames *et al*. Review: "Thermal diodes, regulators, & switches: Physical mechanisms and potential applications" (2017).

GRID Interactive Thermo-Electric Transistor: Active Control of Thermal Resistance

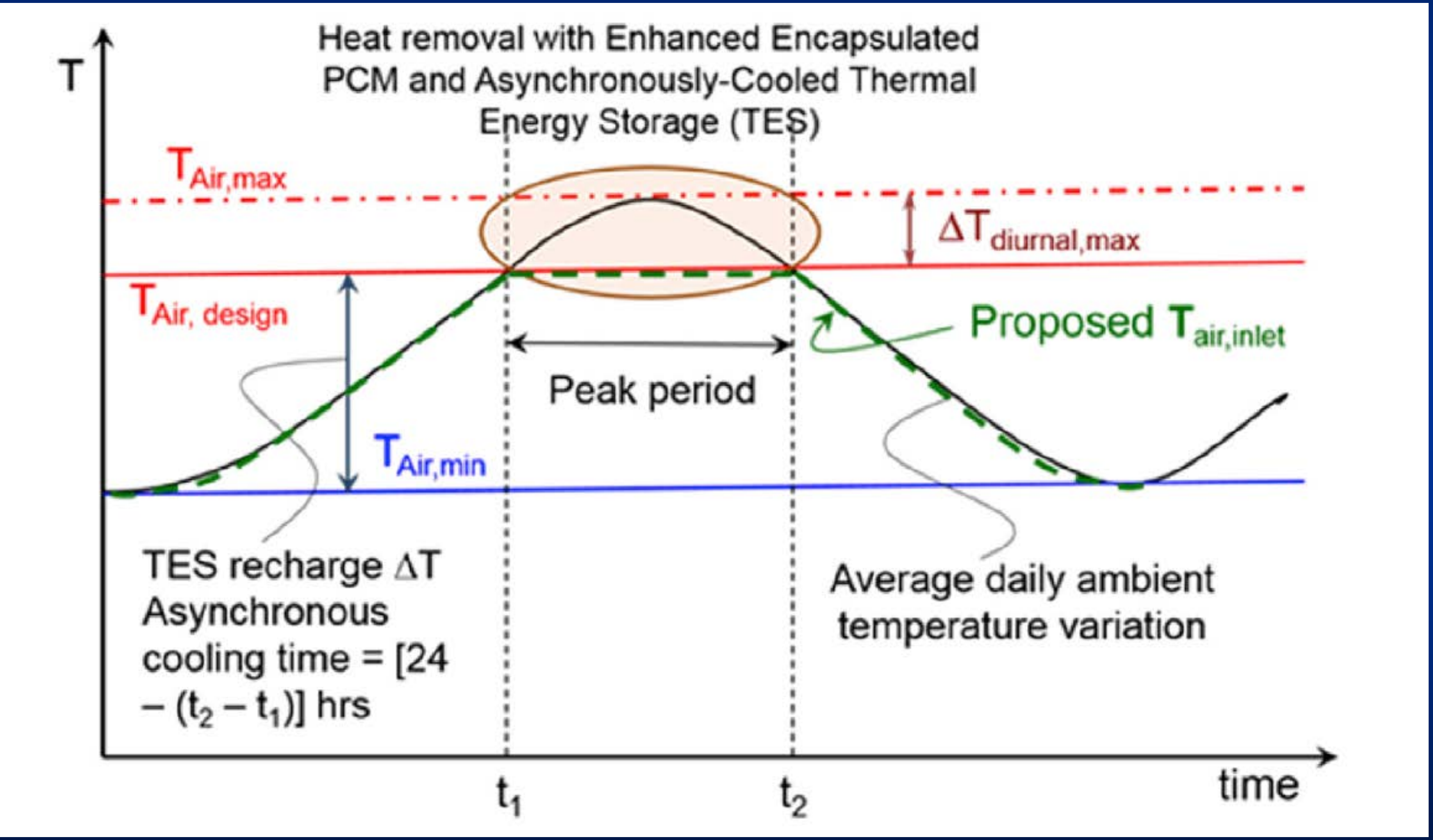


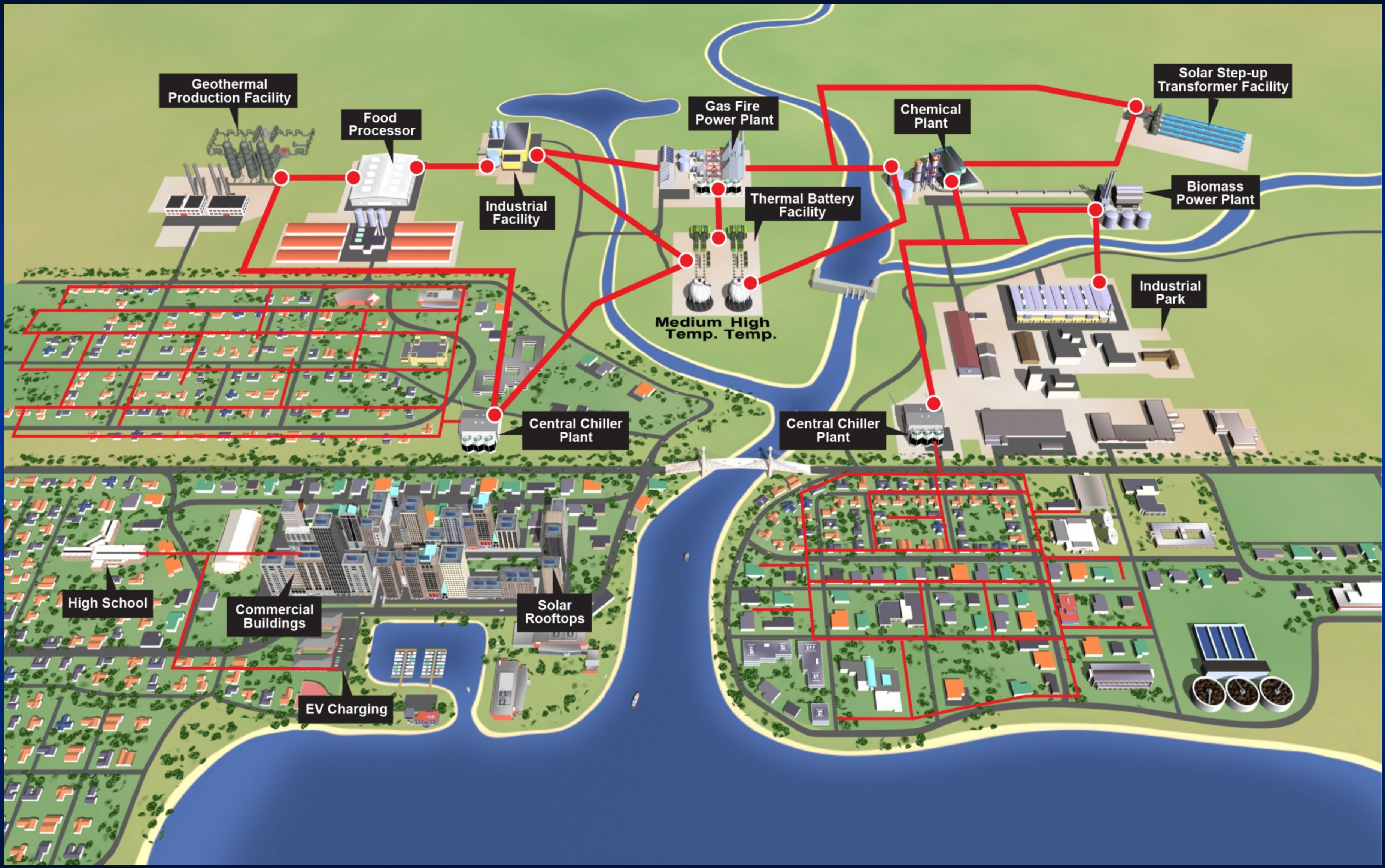
Dames *et al*. Review: "Thermal diodes, regulators, & switches: Physical mechanisms and potential applications" (2017).

Shape Memory Alloy Based Thermal Switch (Chris Dames, UC Berkeley)



Dry Cooling of Power Plants Using Thermal Storage





Geothermal Production Facility
Food Processor
Industrial Facility
Gas Fire Power Plant
Thermal Battery Facility
Medium Temp.
High Temp.
Chemical Plant
Solar Step-up Transformer Facility
Biomass Power Plant
Industrial Park
Central Chiller Plant
Central Chiller Plant
High School
Commercial Buildings
Solar Rooftops
EV Charging