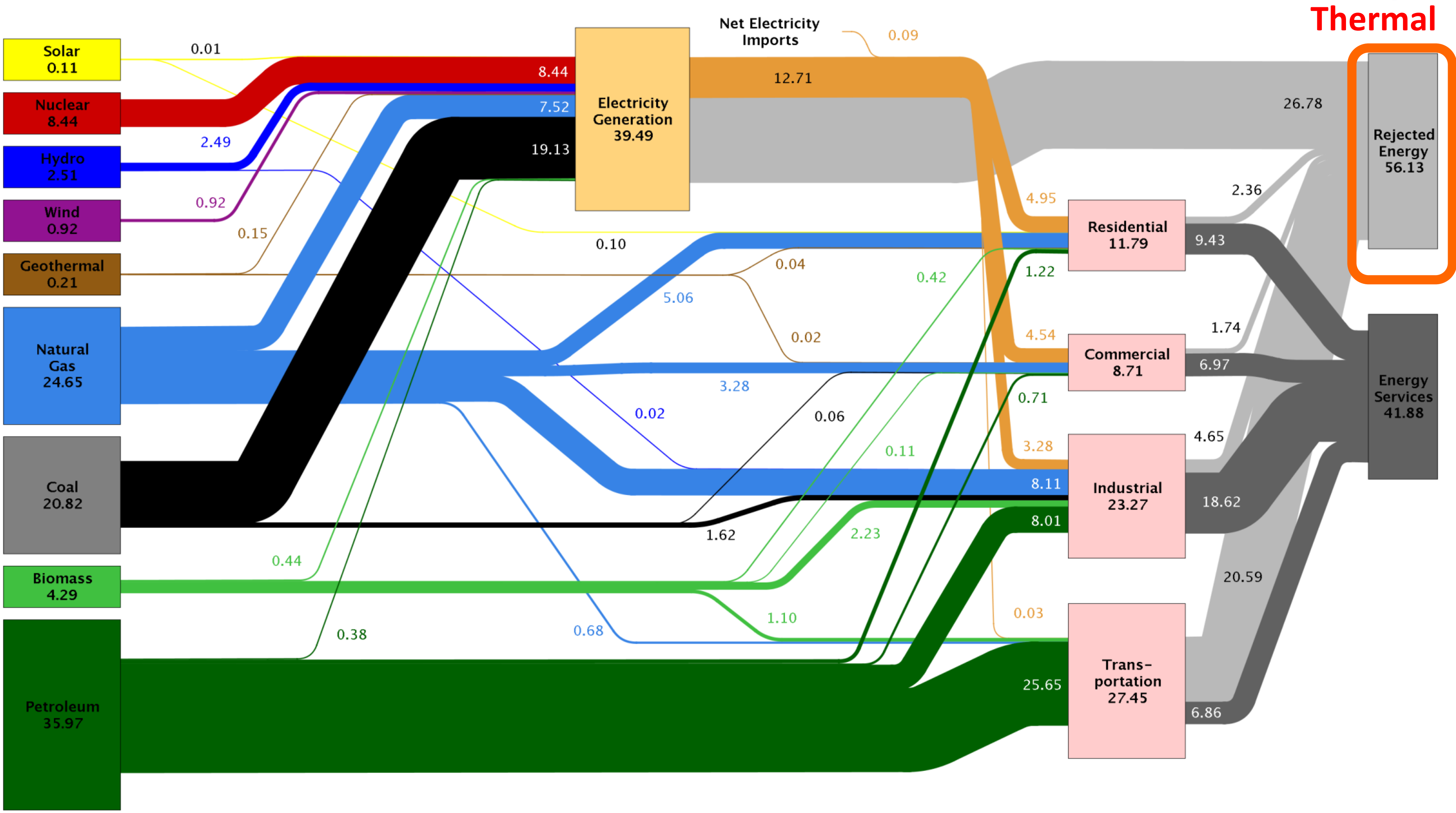
Thermal Storage: Challenges and Opportunities

Ravi Prasher
Sheetak Inc., Austin, Texas

Estimated U.S. Energy Use in 2010: ~98.0 Quads

Lawrence Livermore National Laboratory

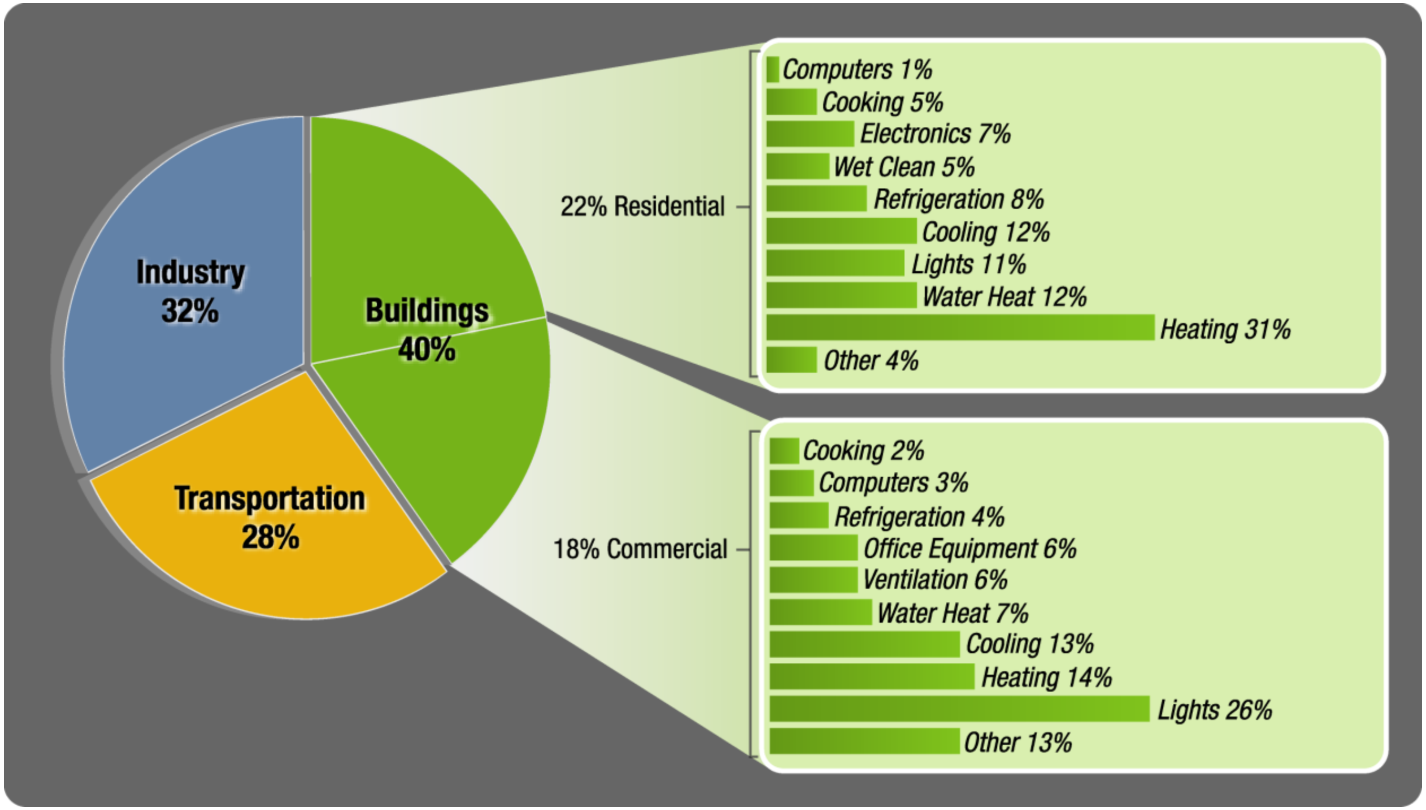


Source: LLNL 2011. Data is based on DOE/EIA-0384(2010), October 2011. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports flows for hydro, wind, solar and geothermal in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." (see EIA report for explanation of change to geothermal in 2010). The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 80% for the residential, commercial and industrial sectors, and as 25% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Residential and Commercial Buildings

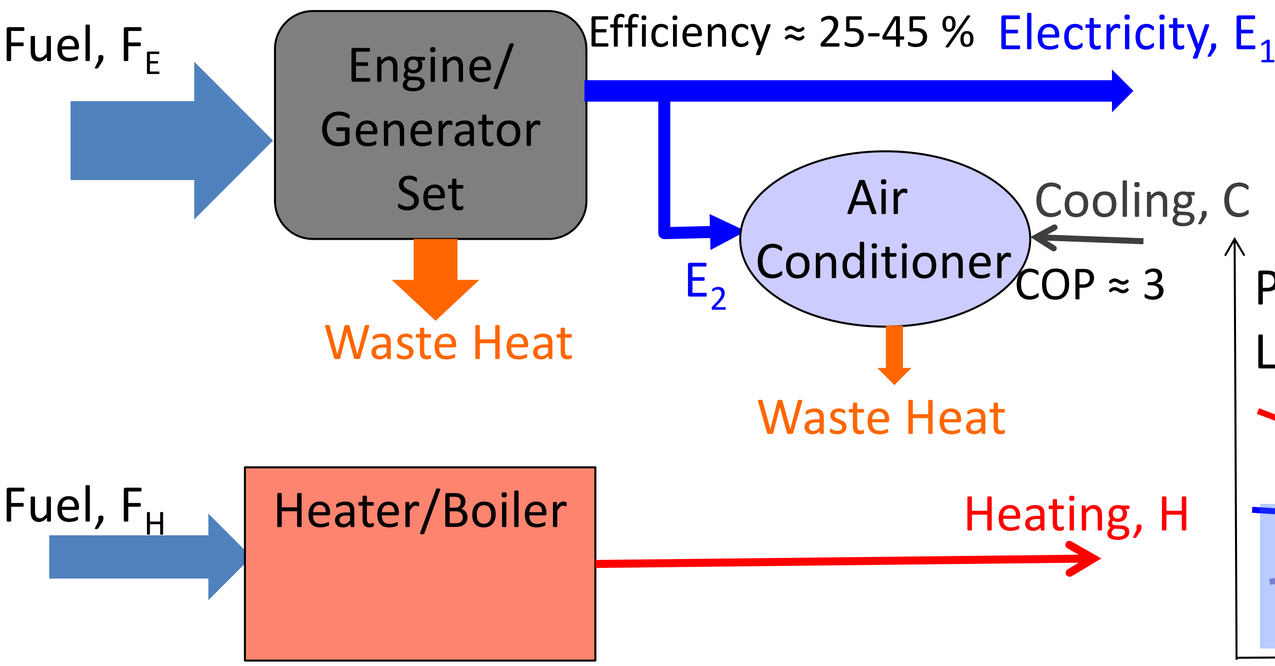
Buildings use 72% of the U.S. electricity and 55% of the its natural gas

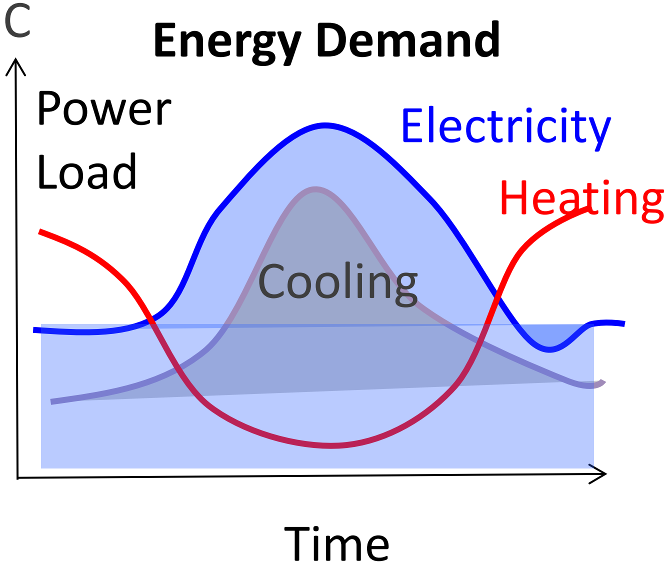
Heating & cooling is ~50% of energy consumption



Source: LBNL Environmental Energy Technologies Division, 2009

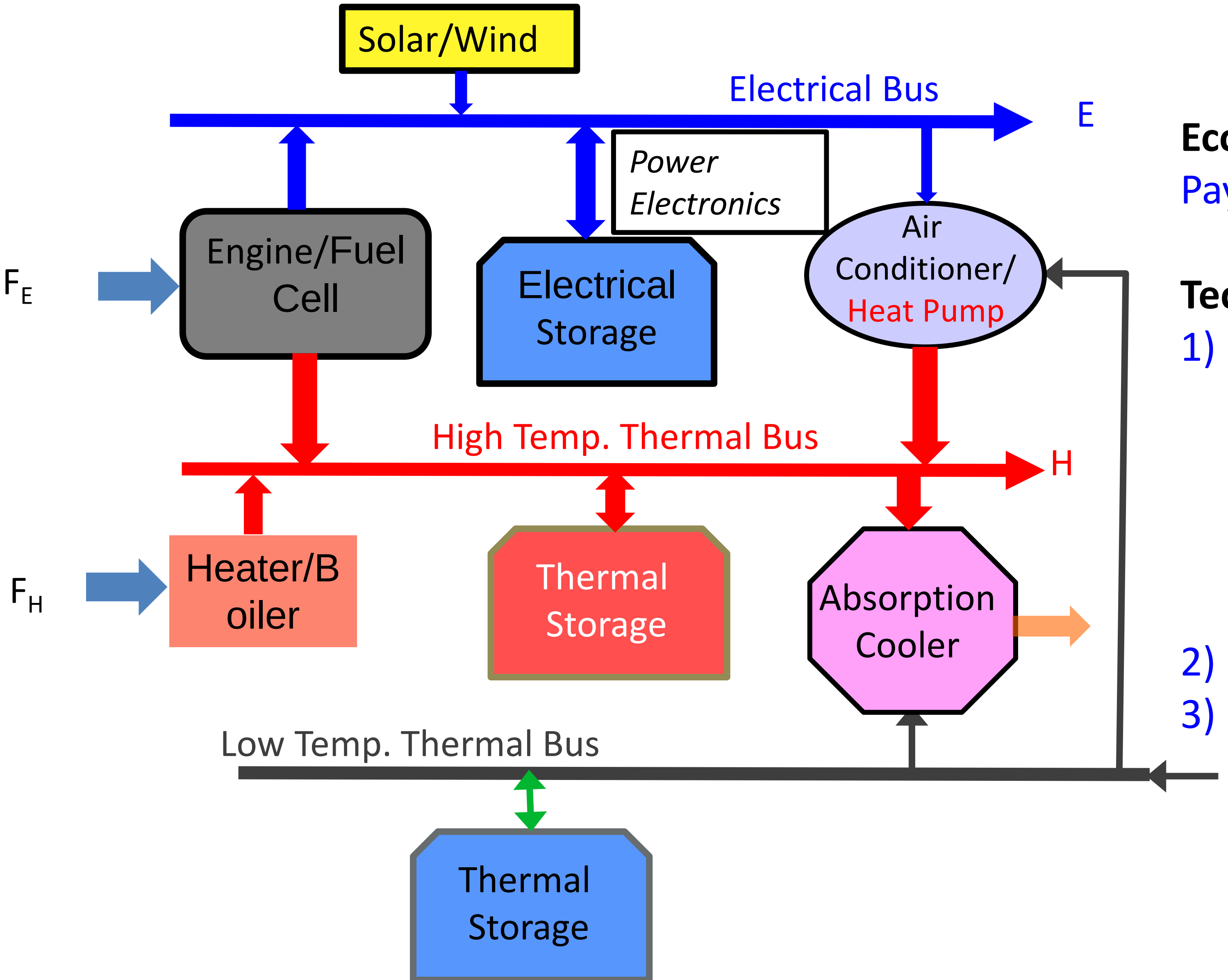
Current System Architecture





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

Integrated Energy Supply Systems



Economic Goal:
Payback in 4-5 years

Technical Challenges:

1) Operating System (Software) & Sensors-Actuators (Hardware) for Optimal Operation
2) Thermal storage
3) Integration

National Impact of Integrated Energy Supply Systems – Ideal Scenarios

	Today	Heat Coming from Integrated Systems	Heat & Air Conditioning Coming from Integrated Systems
Buildings Site Electrical Load (Quads)	9	9	7.5
Building Site Heat Load(Quads)	10	18	17
Primary Energy Consumption (Quads)	9 x 3.2 +10 = **38.8**	**27**	**24.5**
Primary Energy Saved (Quads)		**11.8 (30%)**	**14.3 (37%)**

US Primary Energy Consumption (Annual) ≈ 100 Quads

Assumptions: 33% efficient engine, Electrical COP ~3, Thermal COP ~0.7

Thermal Storage Issues for CHP

Conventional Gas Appliance

>1000 °C

Combustion

<100 °C

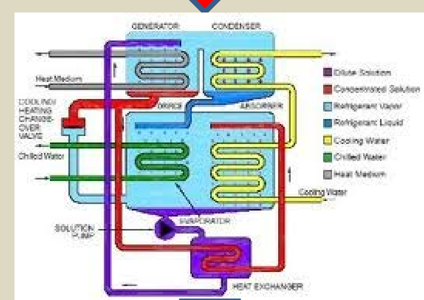
Gas Appliances

Heated Fluid

Heat exchanger cost is minimal

Exhaust ~ 500 °C

Thermal Storage
Low or high
temperature?



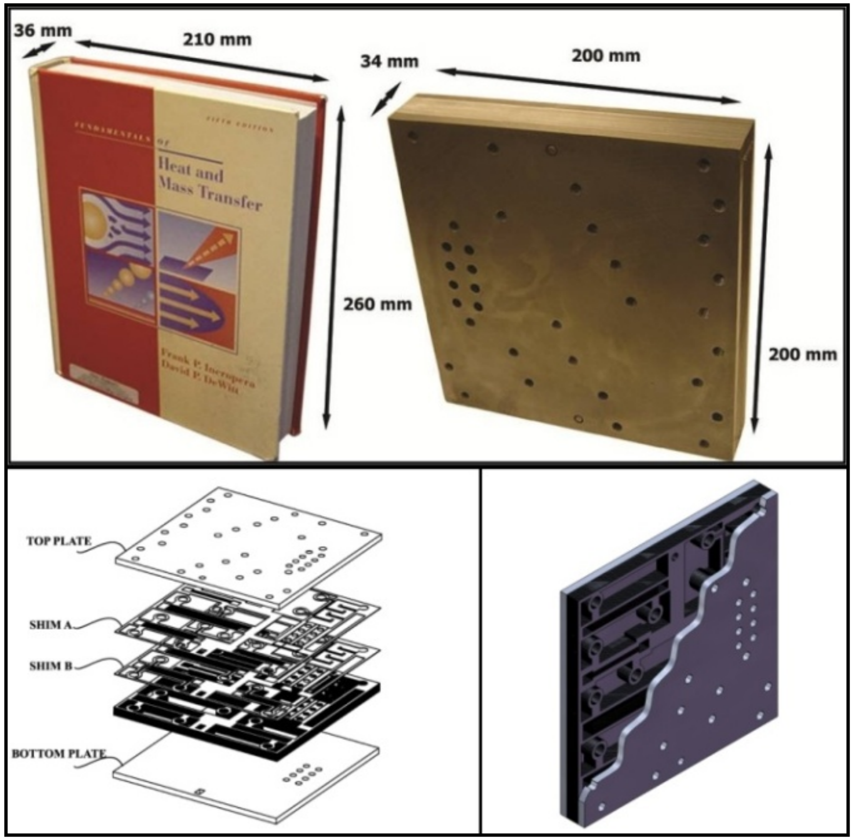
Heat on demand < 100 °C

Cold Thermal Storage

Cooling on demand

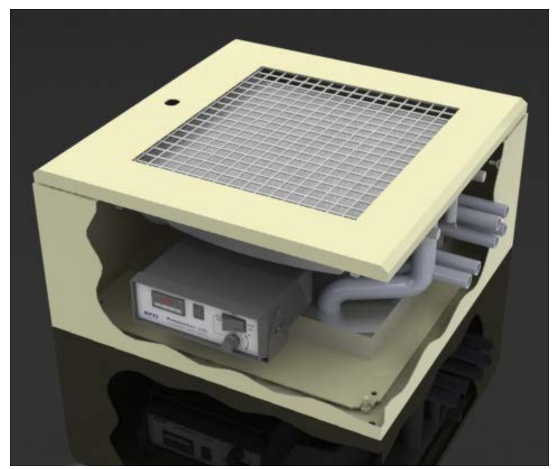
Modular Thermal Hub For Building Cooling Heating, and Water Heating

Srinivas Garimella/Georgia Institute of Technology



Technology Impact

- Significant size reductions ~ 3x
- High COPs: integration of AC/Heating/Water heating
- Monolithic packaging offers small fluid charge, flexible placement, reduced labor



Ultracompact Integrated Space-Conditioning and Water Heating at $COP_{eq} \rightarrow 8$

Thermal Storage Issues for CHP

Cost:

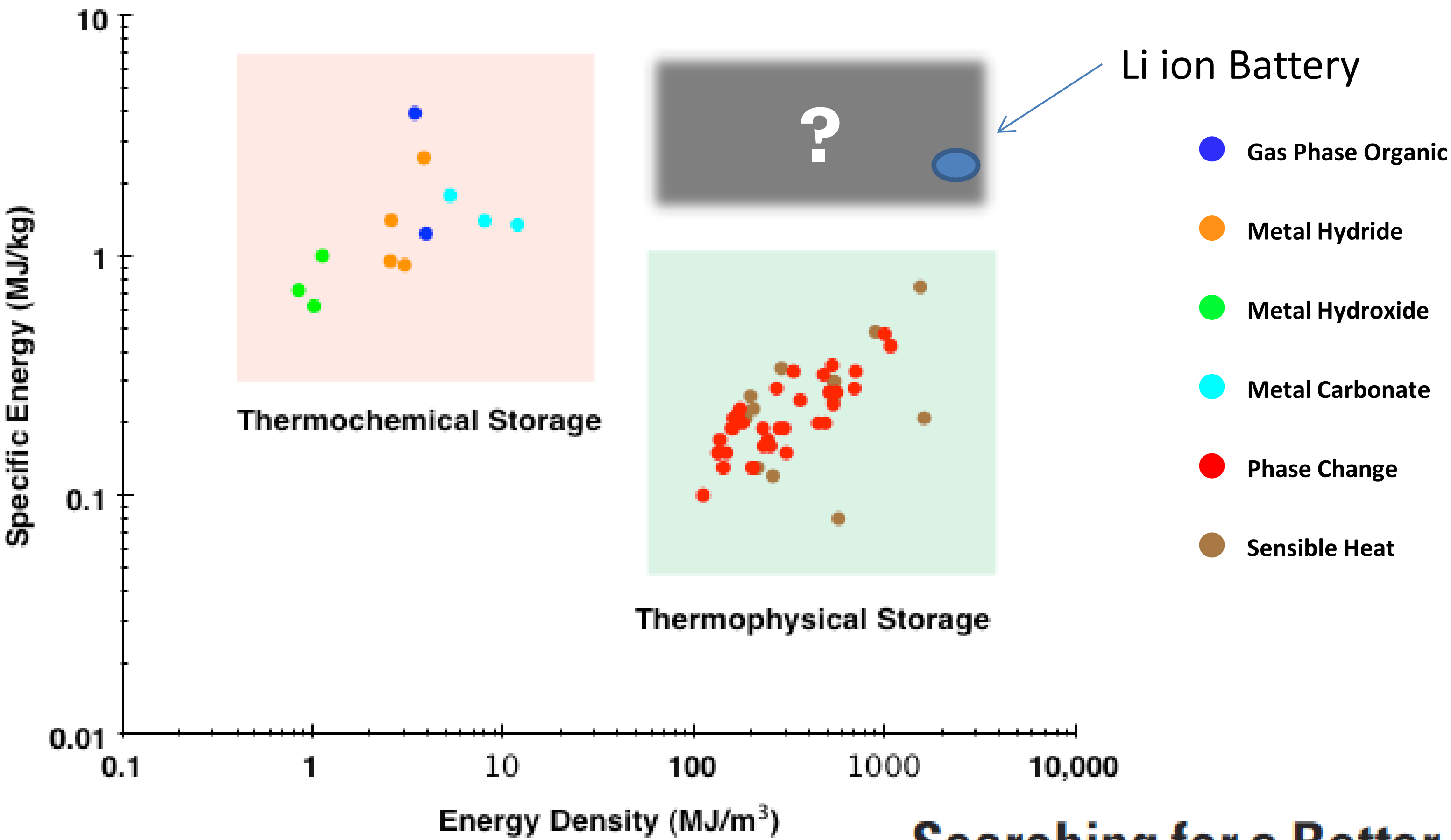
- **Cost of storage = Thermal storage cost + Rate of heat delivery cost (heat exchangers)**
- **Heat exchanger cost** $\propto 1/\Delta T$

Physical Volume and Mass:

•1 therm of NG ~ 400 kG of water
(20 - 80 °C) or PCM
•Average Therms/day in winter ~ 5- 10

Thermal Storage: Science + Engineering

Scientific Challenge: New Materials



Searching for a Better Thermal Battery

Ilan Gur,[1,2] Karma Sawyer,[1] Ravi Prasher[1,2]

23 MARCH 2012 VOL 335 SCIENCE www.sciencemag.org

Key Parameters for Thermal Storage

- **Storage Time**: Minutes to months; Insulation free(?)
- **Discharge Time**: Minutes to hours; Heat exchangers systems
- **Energy Density**: High energy density by mass and volume (kWhr/kg, kWhr/L)
- **Low and High**: Both low temperature (273-320 K) and high temperature (≈1000 K) - minimize exergy loss and control heat transfer rates
- **Cost**: $/kWhr, $/kW, **Cost of delivered energy $\propto$ 1/N**

High Energy Advanced Thermal Storage (HEATS) at ARPA-E

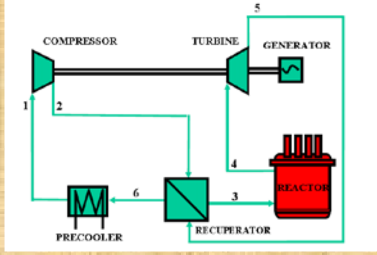
Modular thermal storage

Building and EV Thermal Management

Energy density
~ 2 – 3X of state-of-the-art

Increase EV range by ~ 40%

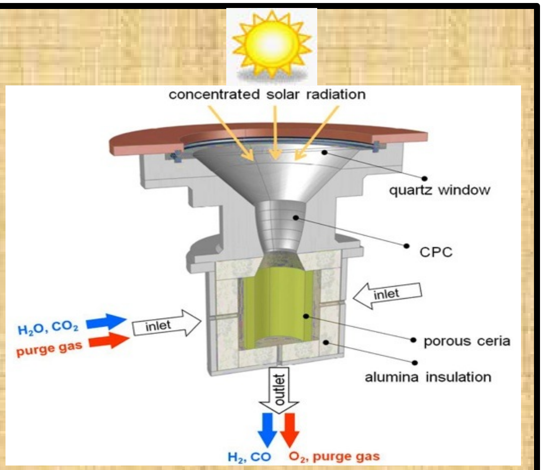
Base Load Solar and Peaking High-Temp Nuclear



Grid Level Storage Using Heat Pumps

~10X reduction in cost

Utility scale thermal storage



Thermofuel: Sunlight to heat to fuel

Sunlight to fuel conversion efficiency > 10X of photosynthesis (Biofuels)

Chemical thermal storage

Scale

<100 °C

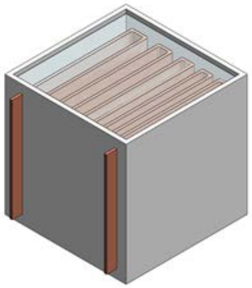
>600 °C

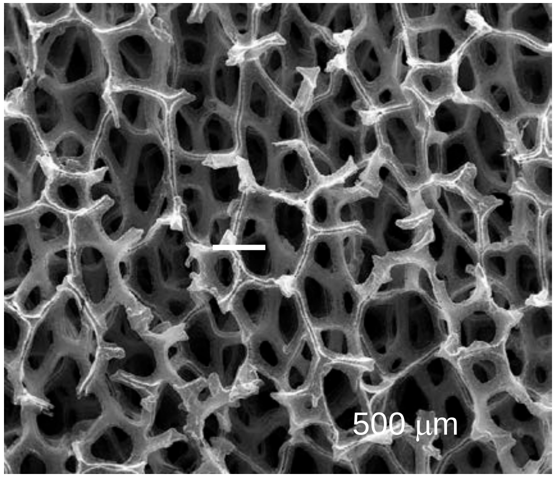
800-1500 °C

Temperature

Thermal Batteries for Electric Vehicle

Li Shi/ The University of Texas at Austin



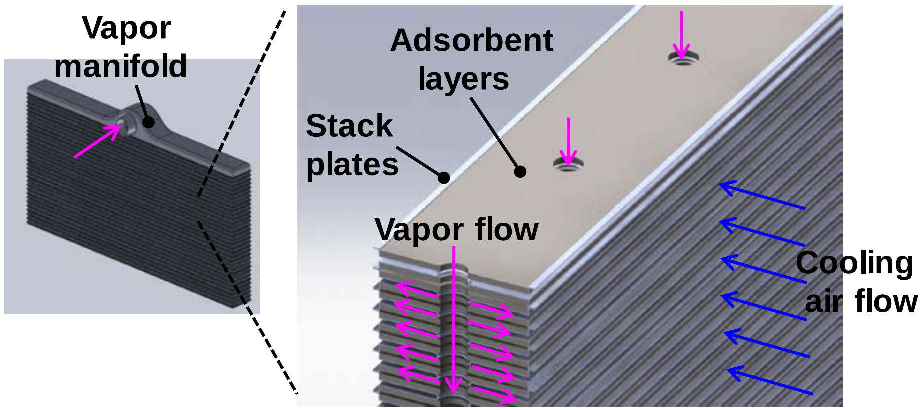


Sugar derivatives-graphene foam composites with heat of fusion 2-3 x of state of the art and thermal conductivity > 10 – 20 x of state of the art

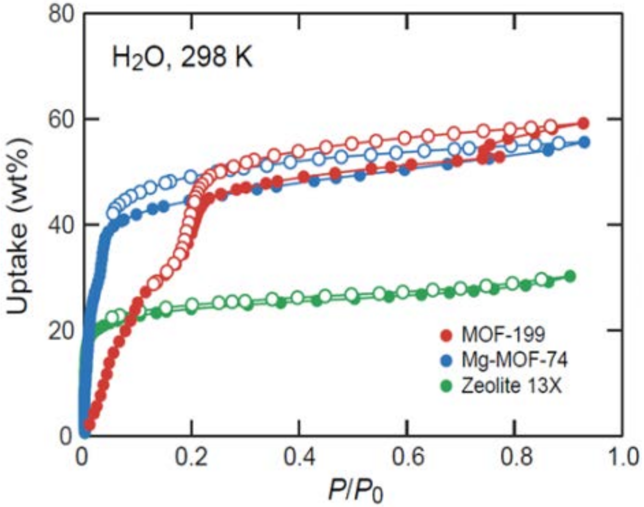
Advanced Thermo-Adsorptive Battery (ATB) Climate Control System

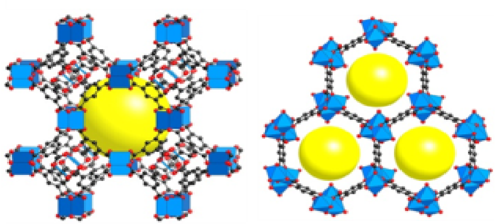
Prof. Evelyn Wang / MIT

Illustration of Key Technical Concepts



ATB Adsorbent Stack Design

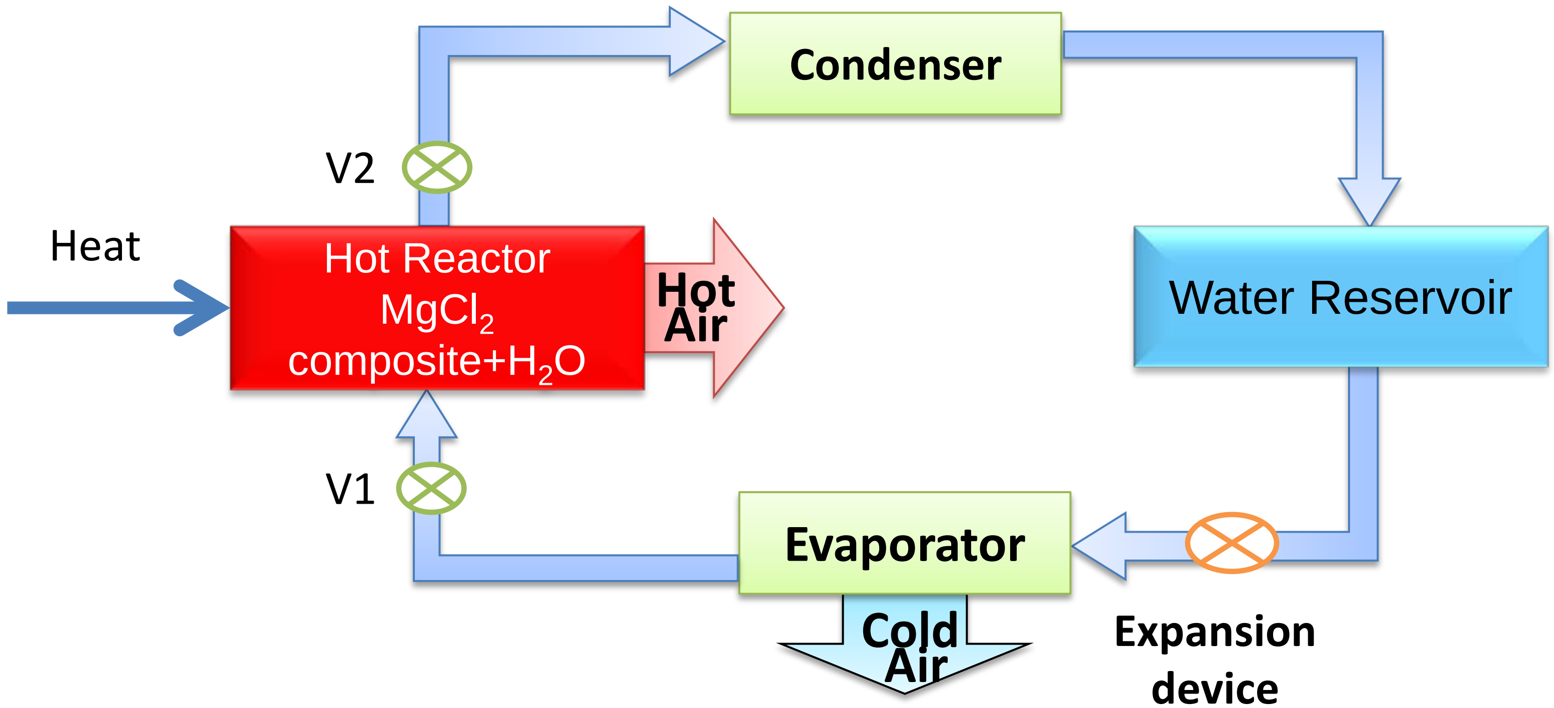




MOF-199 Mg-MOF-74

- High capacity adsorption materials (MOFs)

Sheetak's Thermal Storage



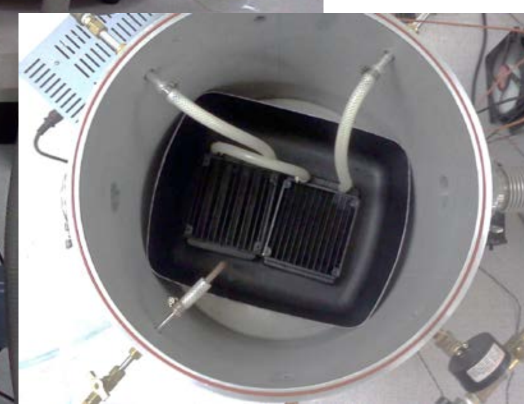
- Hot and cold storage integrated into a simple elegant system
- Heating by exothermic hydration of $MgCl_2$/other salts
- Cooling by water expansion – 7x energy density of ice

Thermal Storage Test Bed

Condenser Chamber

Hot Reactor Chamber

Evaporator Chamber



Solar Combine Heat and Power (S-CHP)

T_{sun} = 5500 °C

Heat

T_{water} < 100 °C
Exergy loss

Electricity

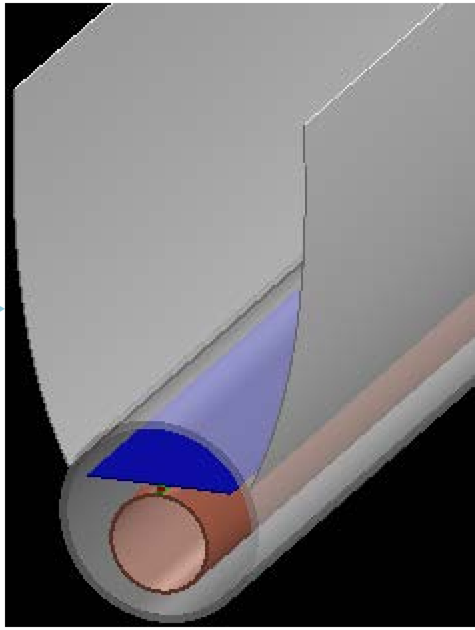
~ 15% efficiency
Energy loss

Combined Heat & Electricity

Very expensive & complex

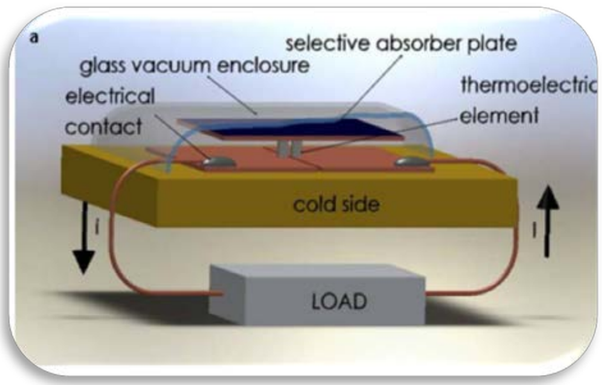
S-CHP Using Thermolectric Generator (TEG)

Heat + Electricity

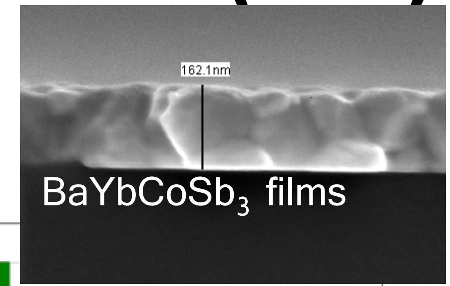


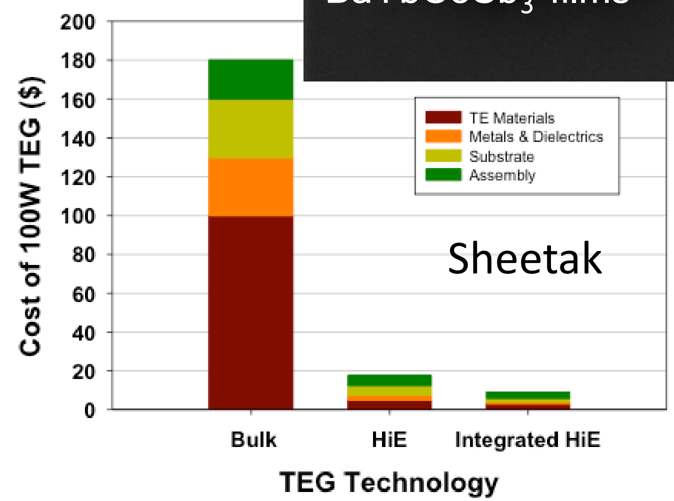
Thermoelectric Generator Integrated Solar Water Heater

S-CHP Using Thermolectric Generator (TEG)



GMZ & MIT

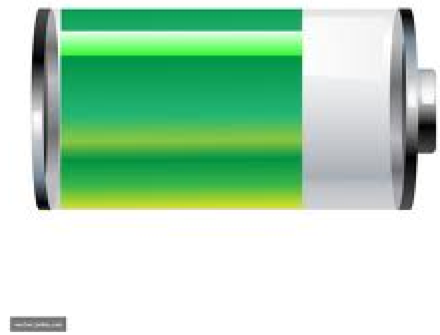




- Cost of TE addition is minimal: Electricity cost ~ $0.25/W_p$
- Uses commercially available evacuated tube collector
- Does not require any tracking
- Increases the capital utilization of SWH all year round

Solar PV or CSP?

+

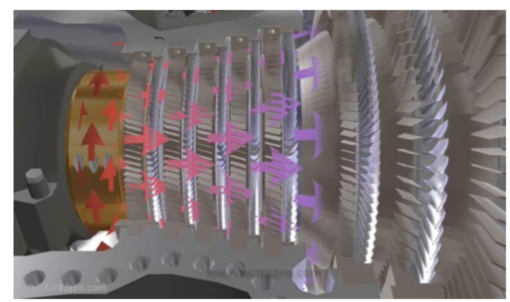


= Higher LCOE

+

Thermal storage

+



= Lower LCOE possible!

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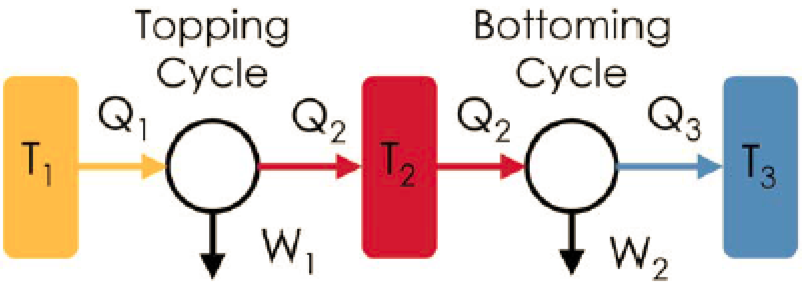
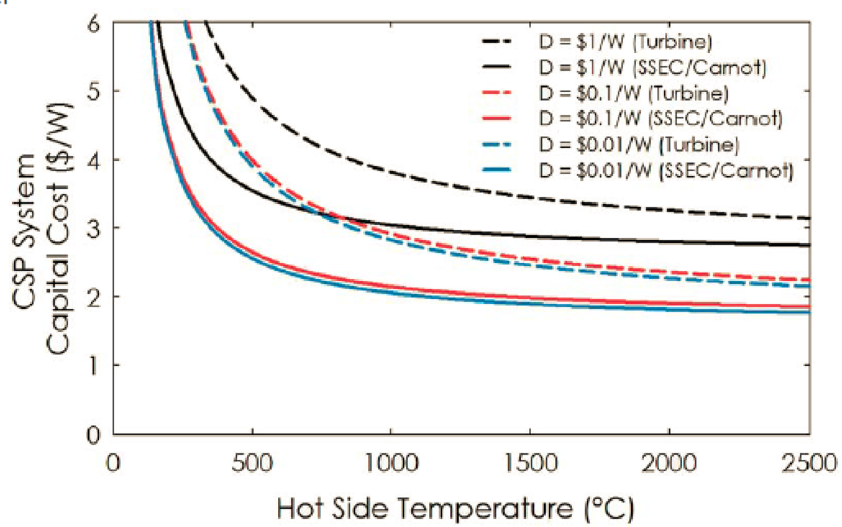
Cite this: DOI: 10.1039/c4ee00288a

The prospect of high temperature solid state energy conversion to reduce the cost of concentrated solar power

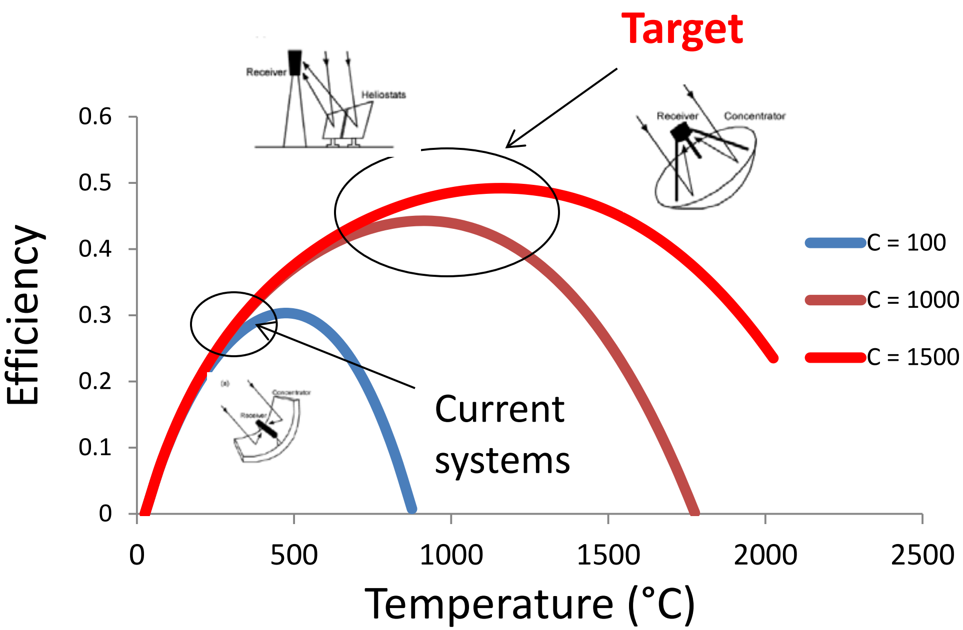
Asegun Henry*[a] and Ravi Prasher[b]

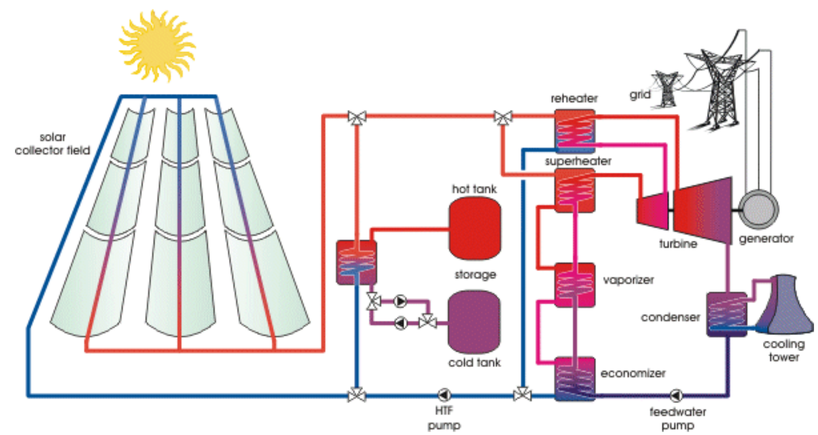




Similar principles can be applied for fossil generators as well

High-Temperature applications: CSP





	Storage Cost ($/kWh$_t$)
SOA	80-120
Target	**15**

SOA:

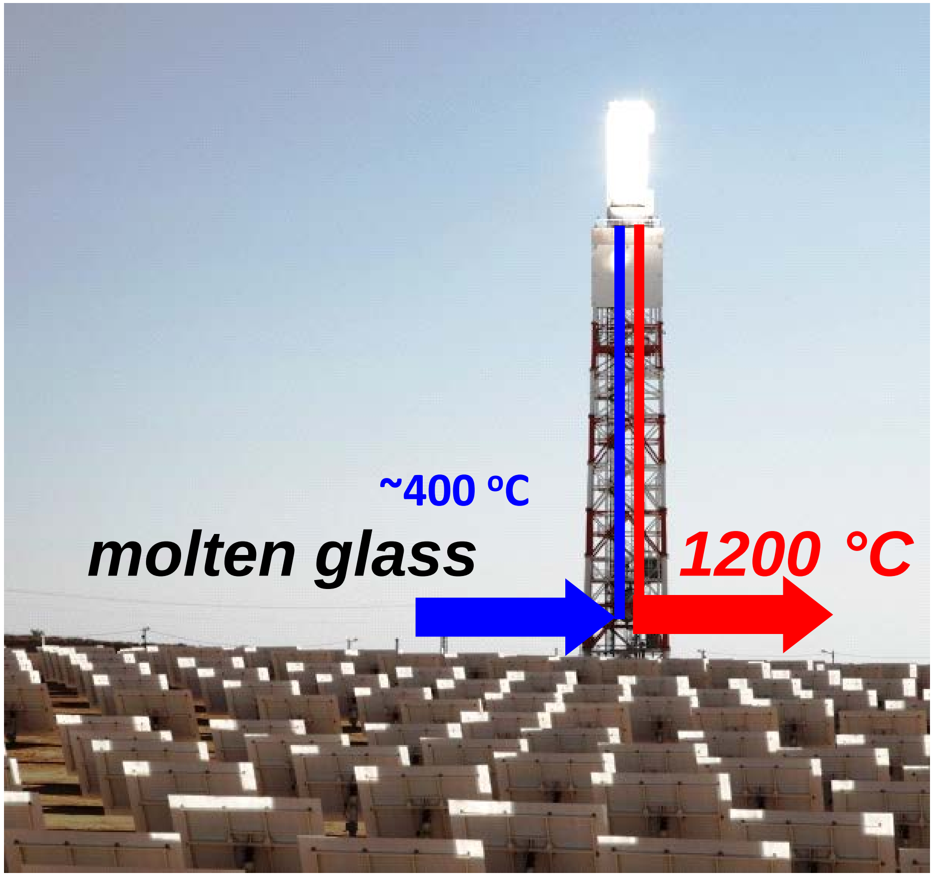
•3 fluids: Oil, Molten salt, Steam

•Molten salt

•Sensible storage

•ΔT = 100 °C (290 – 300 °C)

Novel Approaches



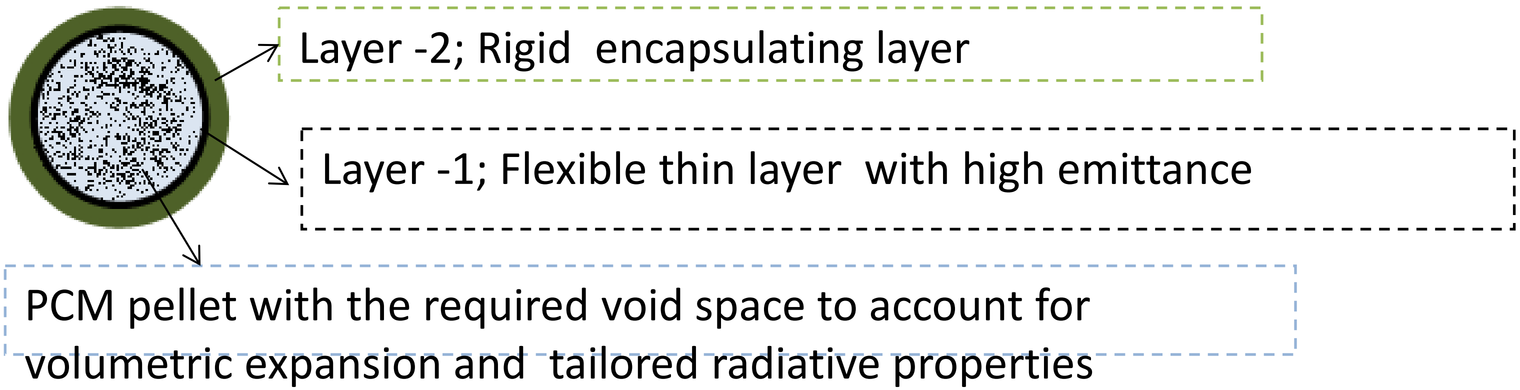
Halotechnics, Inc

Low viscosity molten glass instead of molten salt s thermal storage for solar generation

Phase Change Materials with Enhanced Radiation Heat Transfer

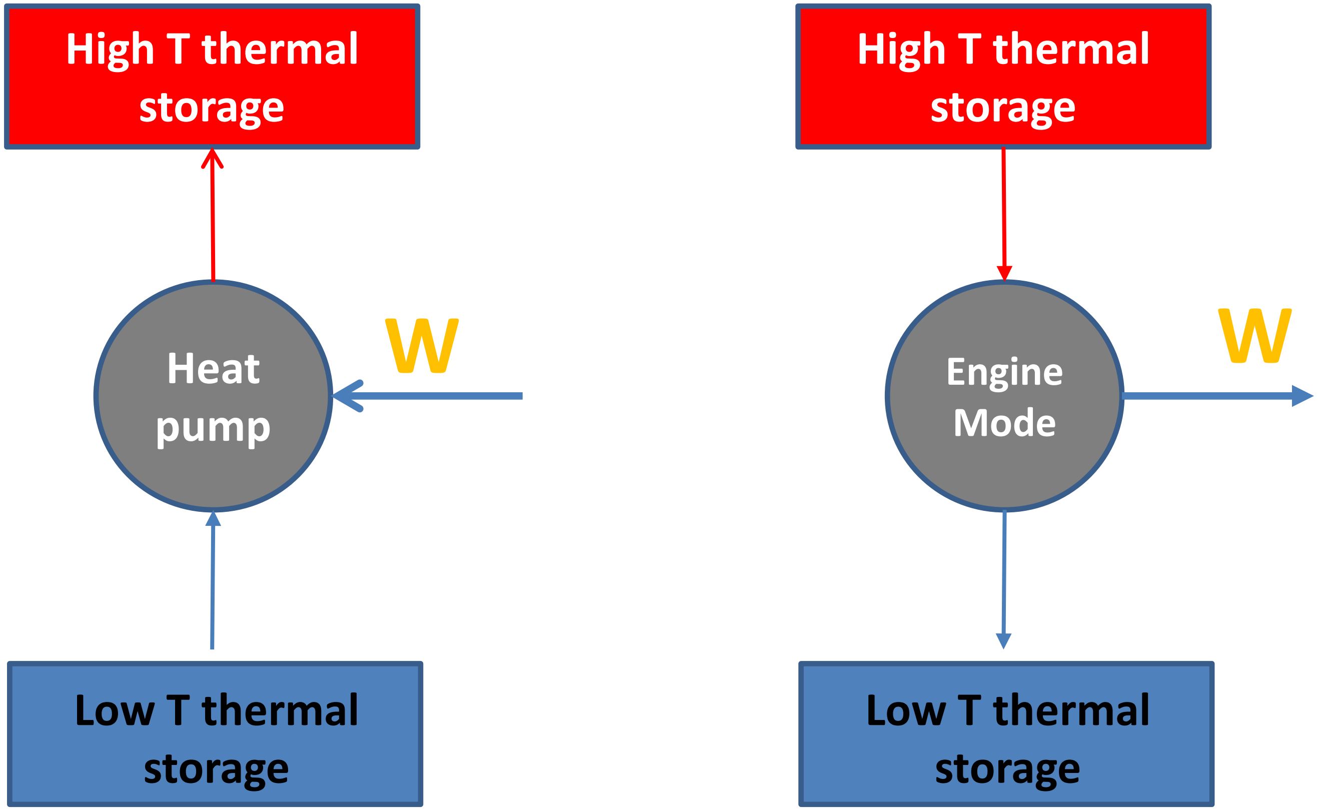
Dr. Yogi Goswami / University of South Florida

- Use of high temperature PCMs with tailored radiative properties
- Encapsulating the tailored PCM using an electroless deposition technique



Low Cost Electroless Encapsulation of High Temperature PCMs with Uniquely Tailored Heat Transfer Characteristics

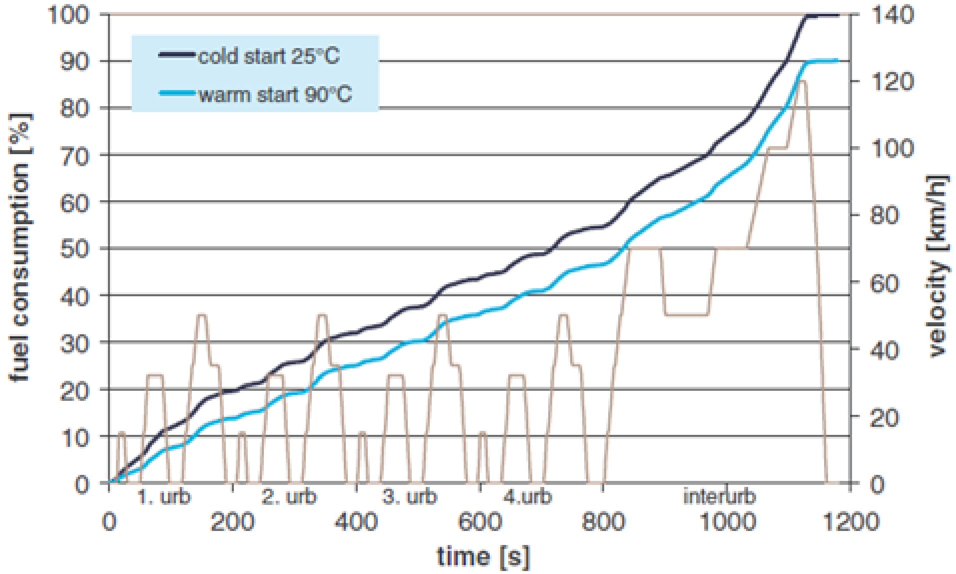
Thermal Storage to Store Electricity



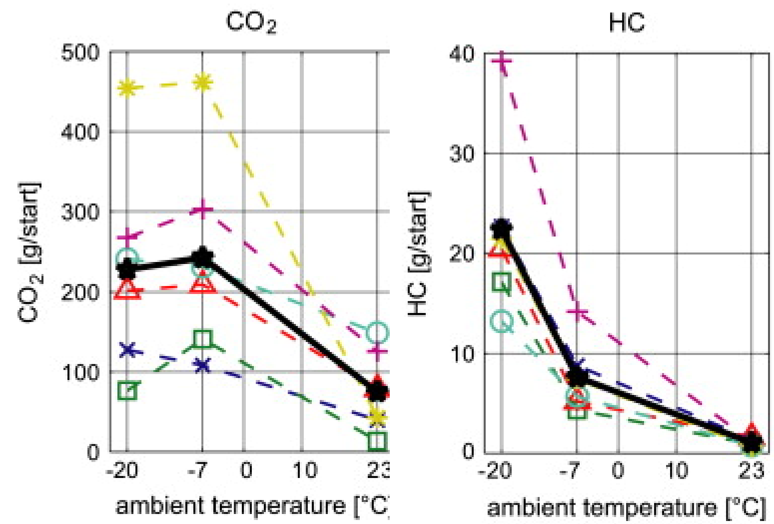
This can potentially enable electrical storage with cost of pumped hydro but geographically independent

References: 1) http://www.isentropic.co.uk/our-phes-technology 2) Prof. Robert Laughlin, Nobel Laureate, Stanford University

Thermal Management of IC Vehicles



Warm start fuel consumption reduction potential of a midsize gasoline passenger car in NEDC (1.urb = first urban cycle, interurb = interurban cycle)



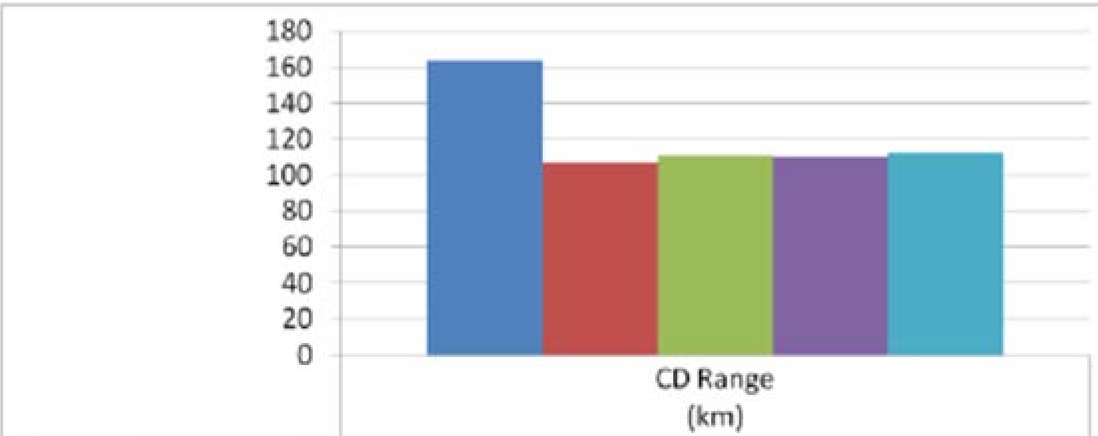
Weilenmann, et al., Atmospheric Environment, 43, 2419 (2009)

A Systematic Analysis of CO2-Reduction by an Optimized Heat Supply during Vehicle Warm-up

Klaas Kunze, Stefan Wolff, Irina Lade and Johann Tonhauser
BMW Group

Cold Start of IC vehicles increases fuel consumption and GHG emissions

Thermal Management of Electric Vehicles



	CD Range (km)
No Climate Control	163.79
Heat	106.98
Heat (preconditioned)	111.14
AC	110.22
AC (preconditioned)	112.06

Climate control of the cabin can decrease the range of EVs by as much as 40%


NREL

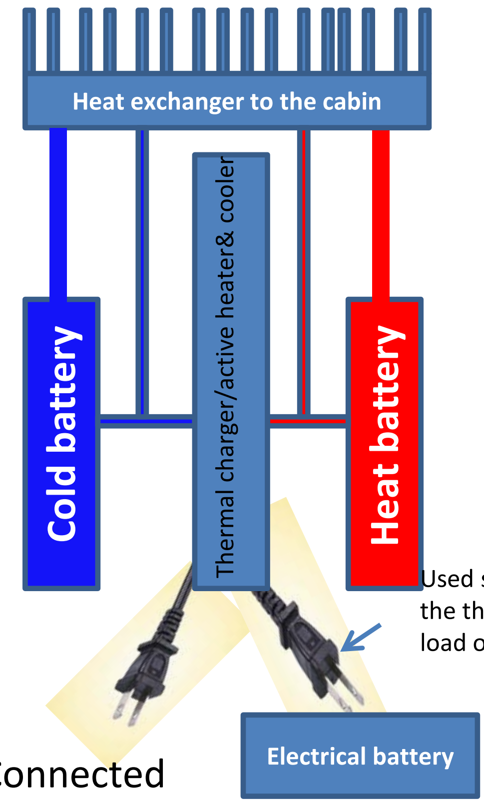
Analysis of Off-Board Powered Thermal Preconditioning in Electric Drive Vehicles

Preprint

Robb A. Barnitt, Aaron D. Brooker, Laurie Ramroth, John Rugh, and Kandler A. Smith

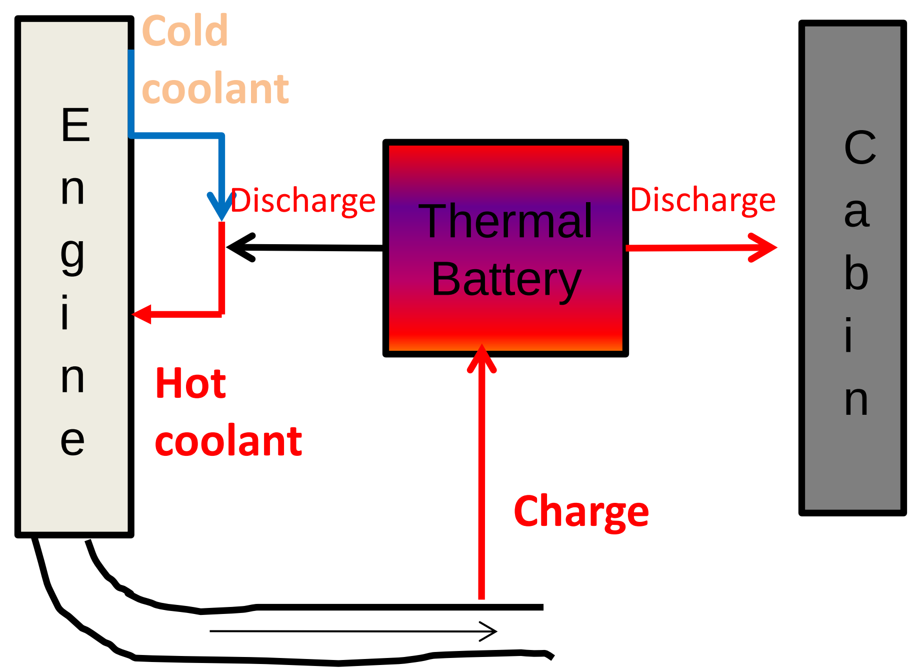
Presented at the 25th World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition Shenzhen, China November 5 – 9, 2010

Thermal Storage for ICV and EV



Used sometimes in conjunction with the thermal battery to provide peak load or in case of emergency

Connected to the wall plug in garage



Exhaust ~ 400 – 500 ºC

Other Thermal Components

All Solid Heat
Exchanger

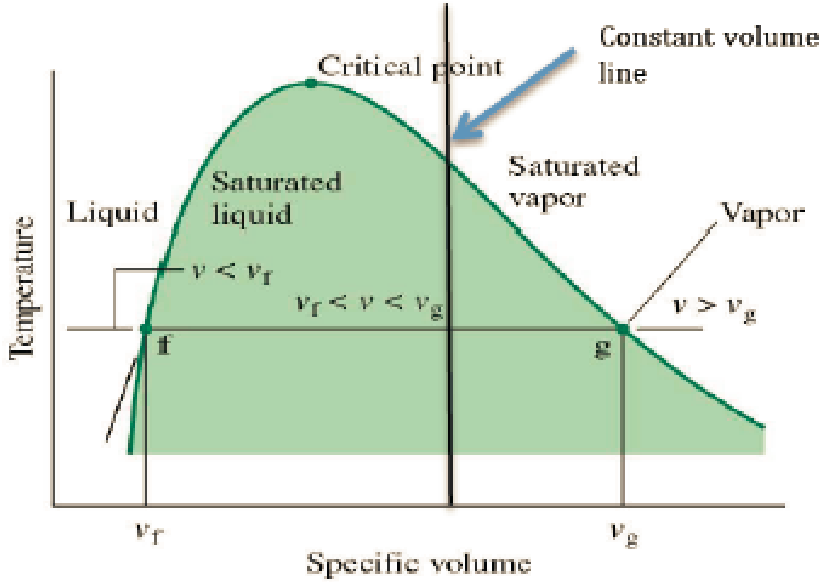
Long-distance
Heat Transport

Switchable
Insulation
(thermal diode)

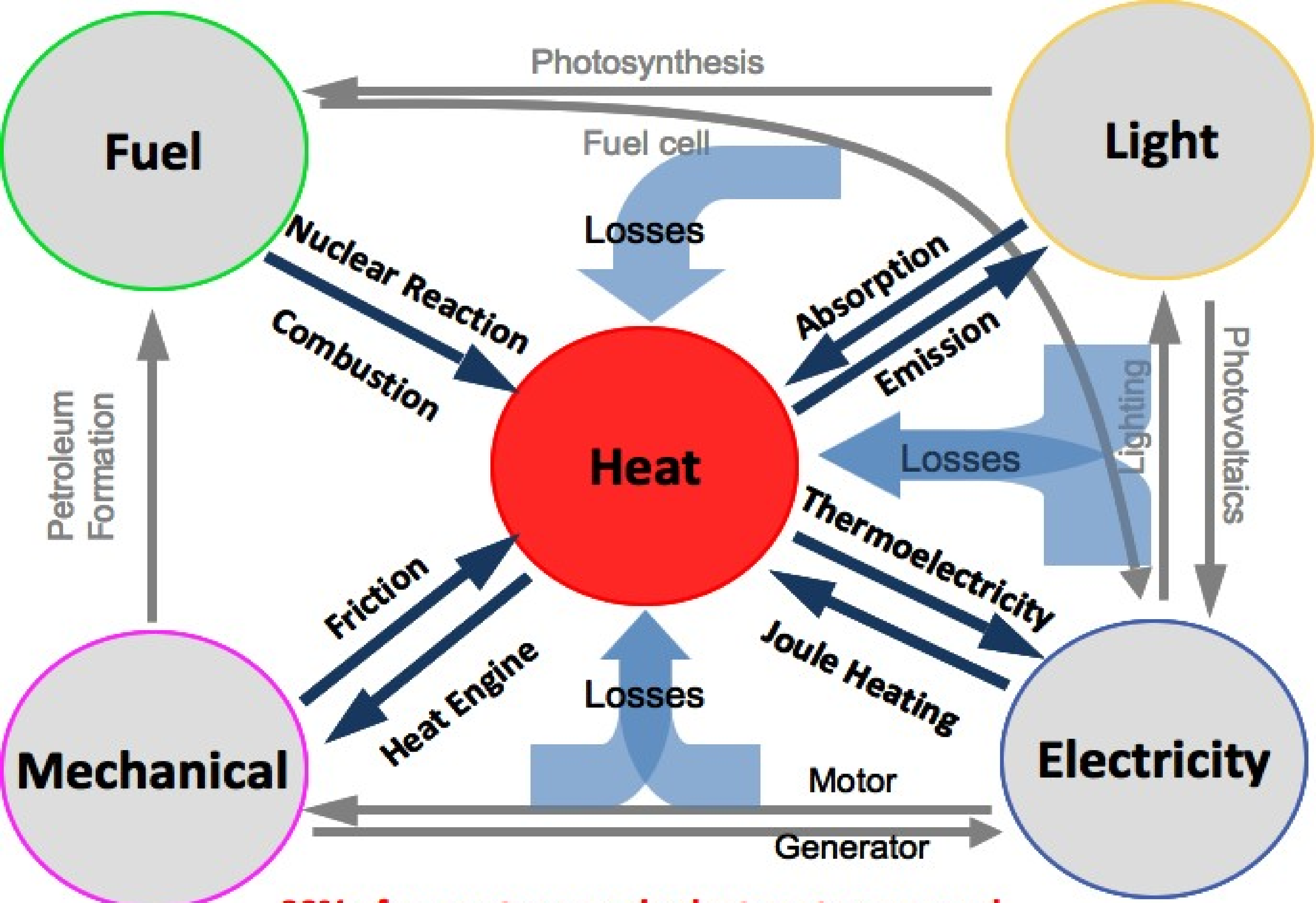
Back Up

Thermal Energy Storage with Supercritical Fluids

Dr. Richard Wirz / UCLA & Dr. Gani Ganapathi/JPL



Energy density ~ 2 – 3x of PCM

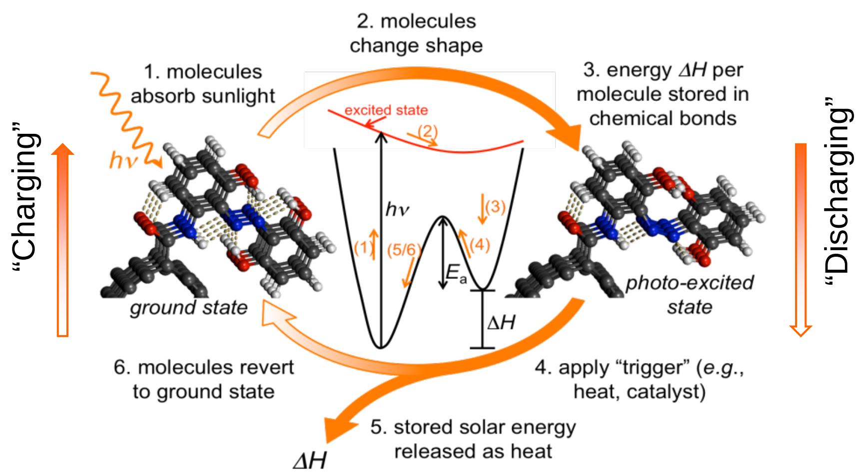


90% of current energy budget centers around Heat conversion, transmission, and storage

Courtesy: Arun Majumdar

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

Grossman, MIT



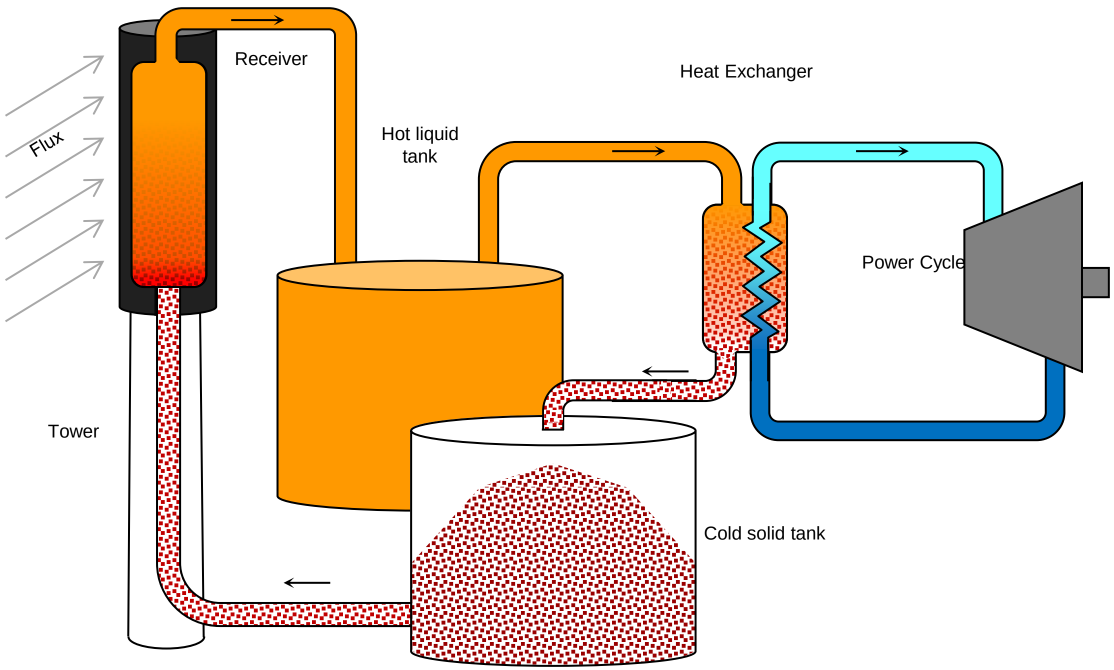
Transportable like a fuel…

…rechargeable like a battery.

Energy density similar to a Li-Ion battery

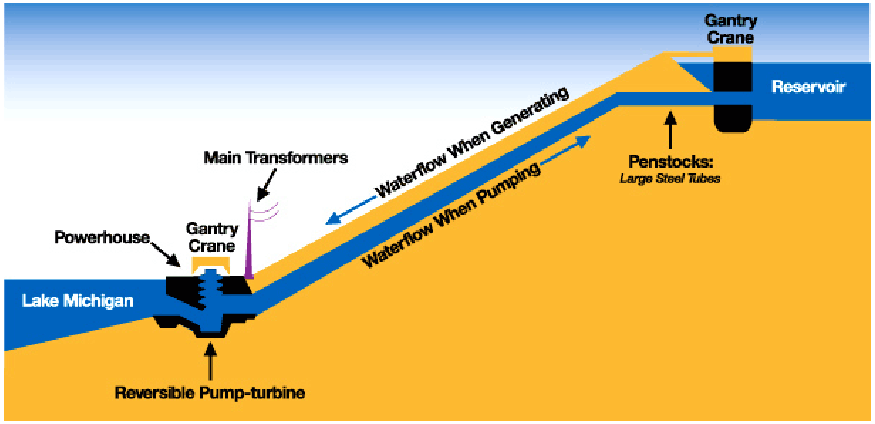
High Efficiency Solar-Electric Conversion Power Tower

Abengoa Solar Inc.



Metallic heat transfer fluid and storage

Utility Scale Electricity Storage



Both pumped hydro or compressed air storage is geographically limited

Cost of Pumped hydro but geographically independent storage: Is it possible?

Thermal storage demonstrated at utility scale
Can we use it for electricity storage?