High Density Thermal Energy Storage

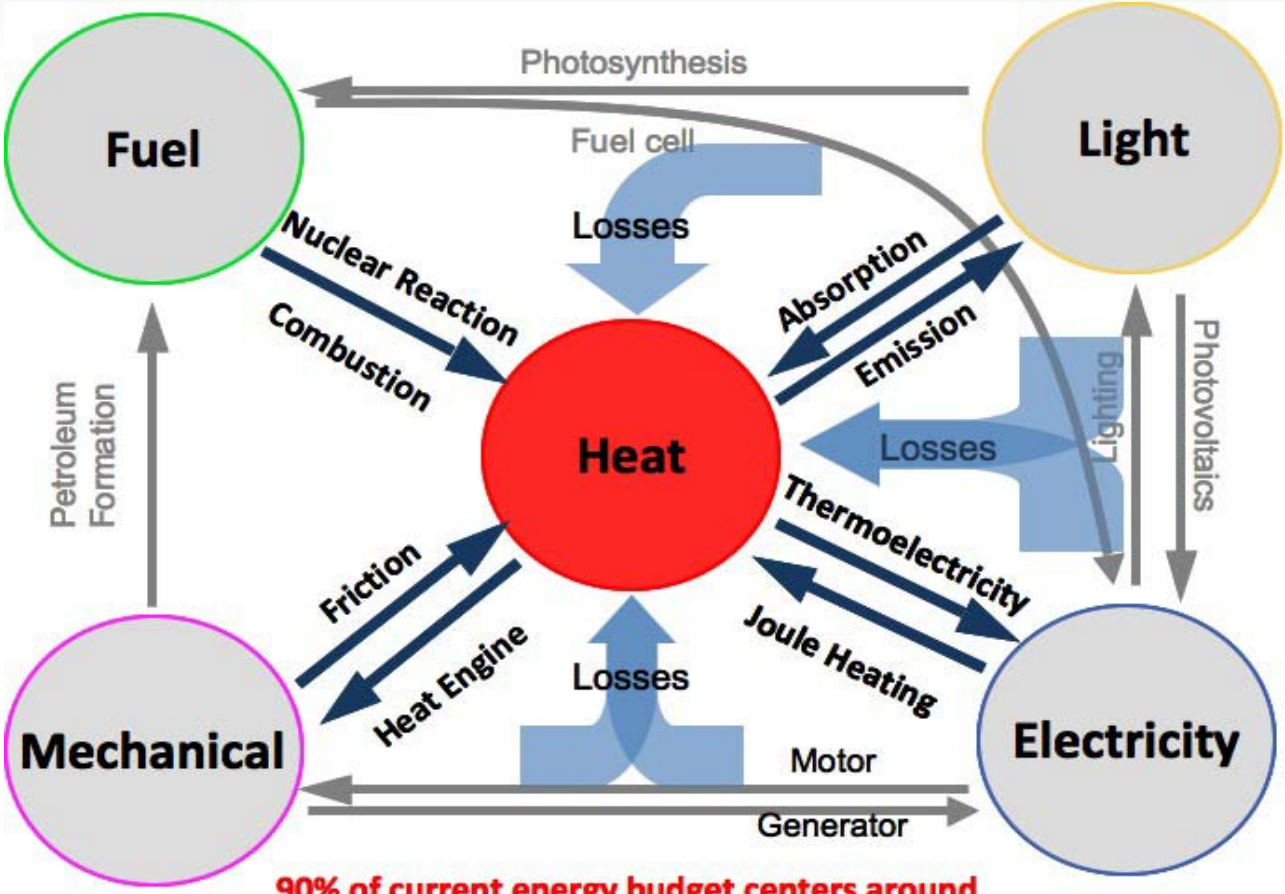
Workshop held on Jan 31, 2011

Ravi Prasher

02/28/2011

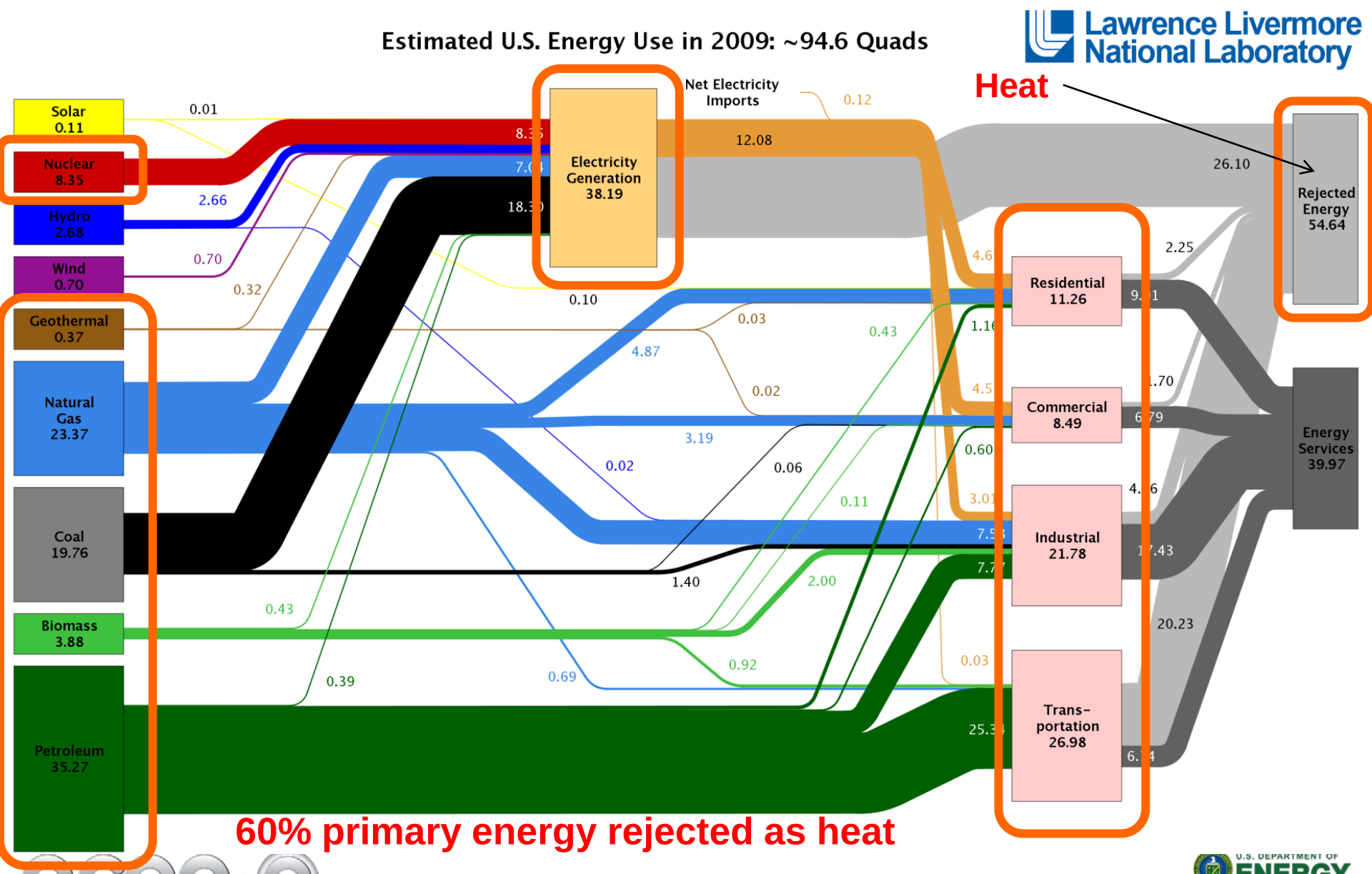
Goals of the Workshop

- Brainstorming among scientists and engineers
- Identify most promising applications of thermal energy storage
- To develop new ideas and identify the most promising R&D pathways for thermal energy storage



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

US Energy Diagram



Applications of Thermal Storage

Buildings

Dramatically reduce building energy consumption by storing and redeploying heat or cold to match building loads

Solar Thermal Power Generation

Enable widespread deployment of solar thermal power by firming and extending the time window of output power generation

Industrial waste heat capture and storage

Dramatically reduce industrial energy consumption by storing and redeploying waste heat for processing and manufacturing

Applications of Thermal Storage

PHEV/EV: Thermal battery for thermal management and cabin conditioning

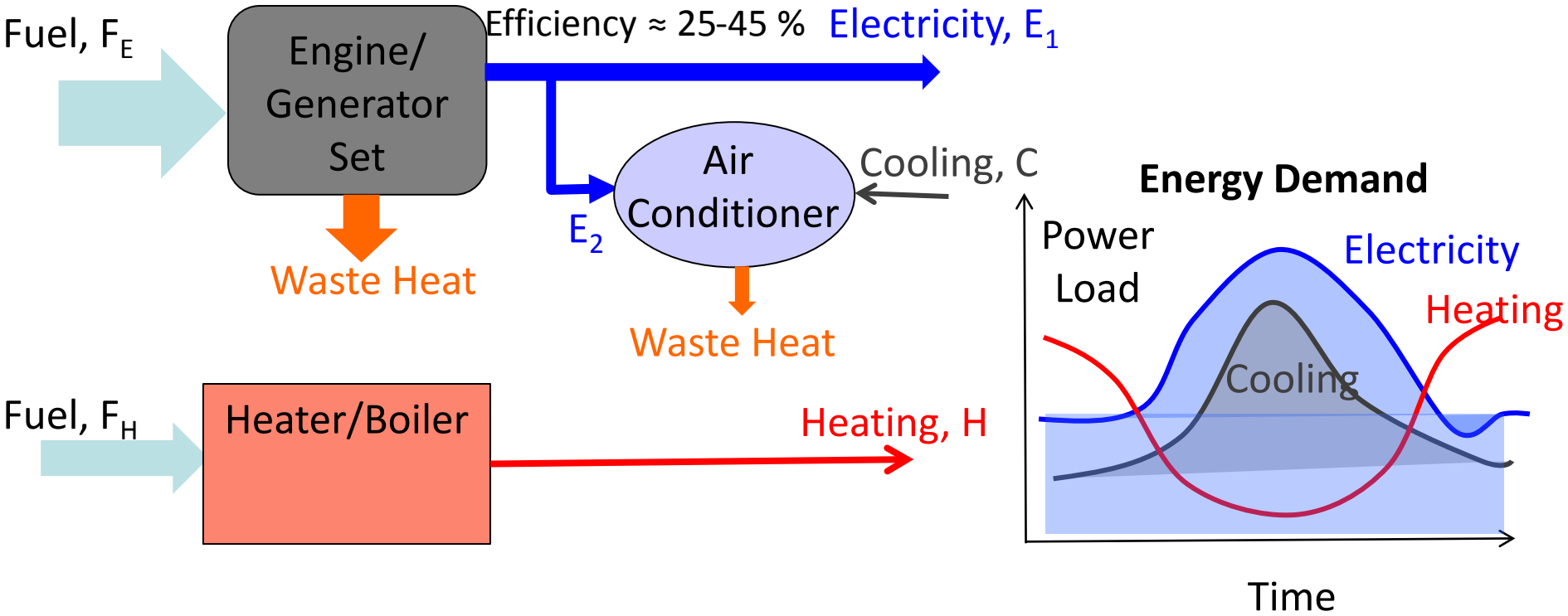
Nuclear: Heat storage for peak power

Grid-level electricity storage: High-temperature thermal storage + subsequent conversion by engines at < $100/kWhr

Refrigerated trucks and LNG Transport

Efficient use of heat in carbon capture plants

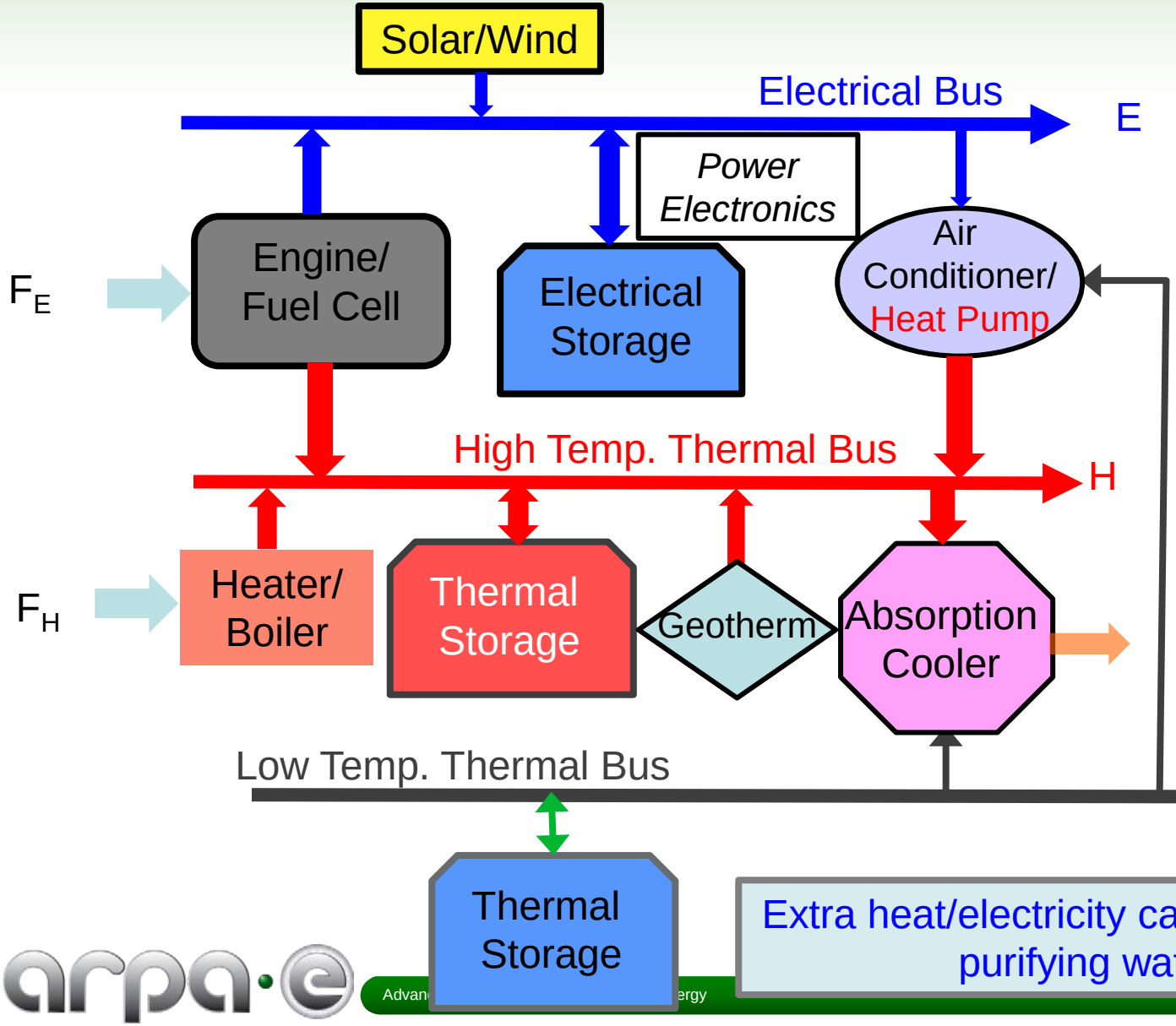
Current System Architecture



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

Integrated Energy Supply Systems:

New Systems Architecture



Performance Goal: Minimize F by at least 25%

Technical Challenge: Operating System (Software) & Sensors-Actuators (Hardware) for Optimal Operation

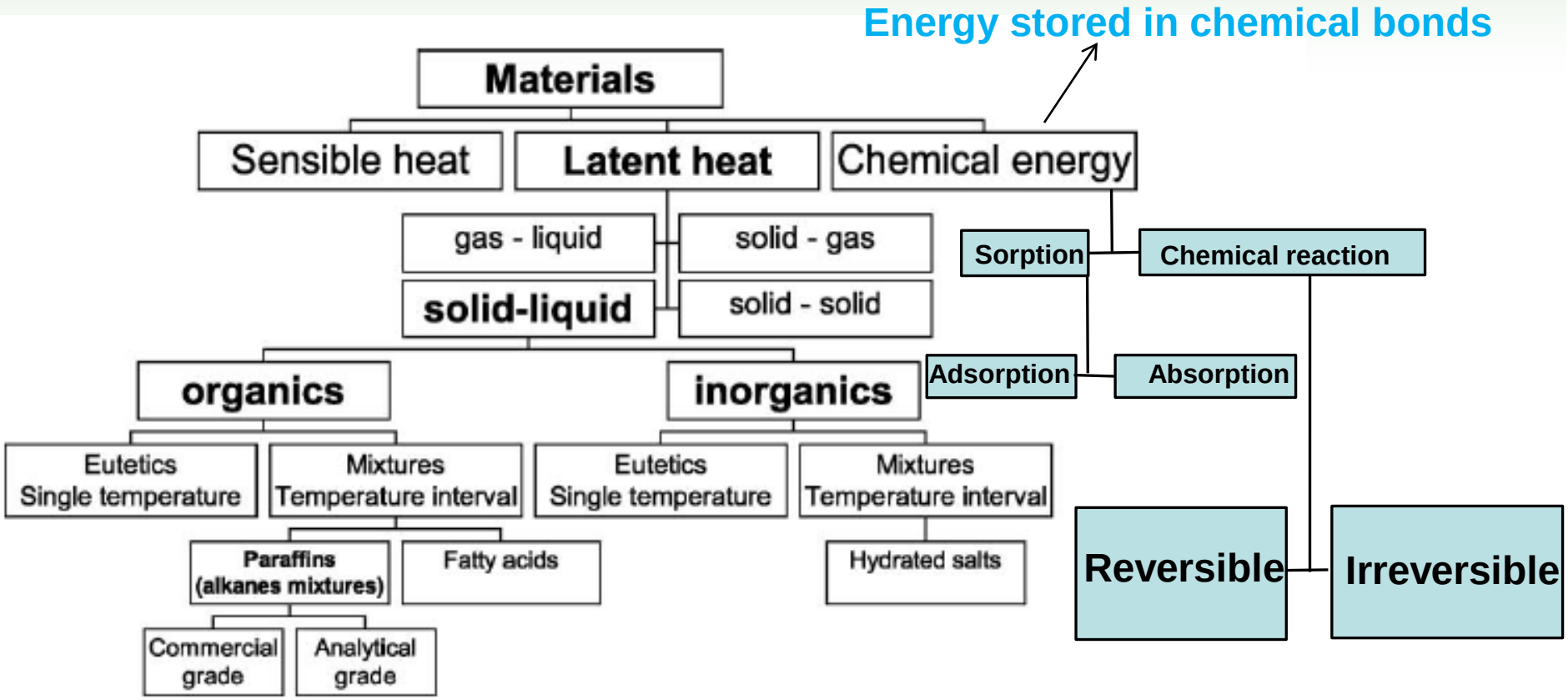
Extra heat/electricity can be used for purifying water

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

Types of Thermal Energy Storage

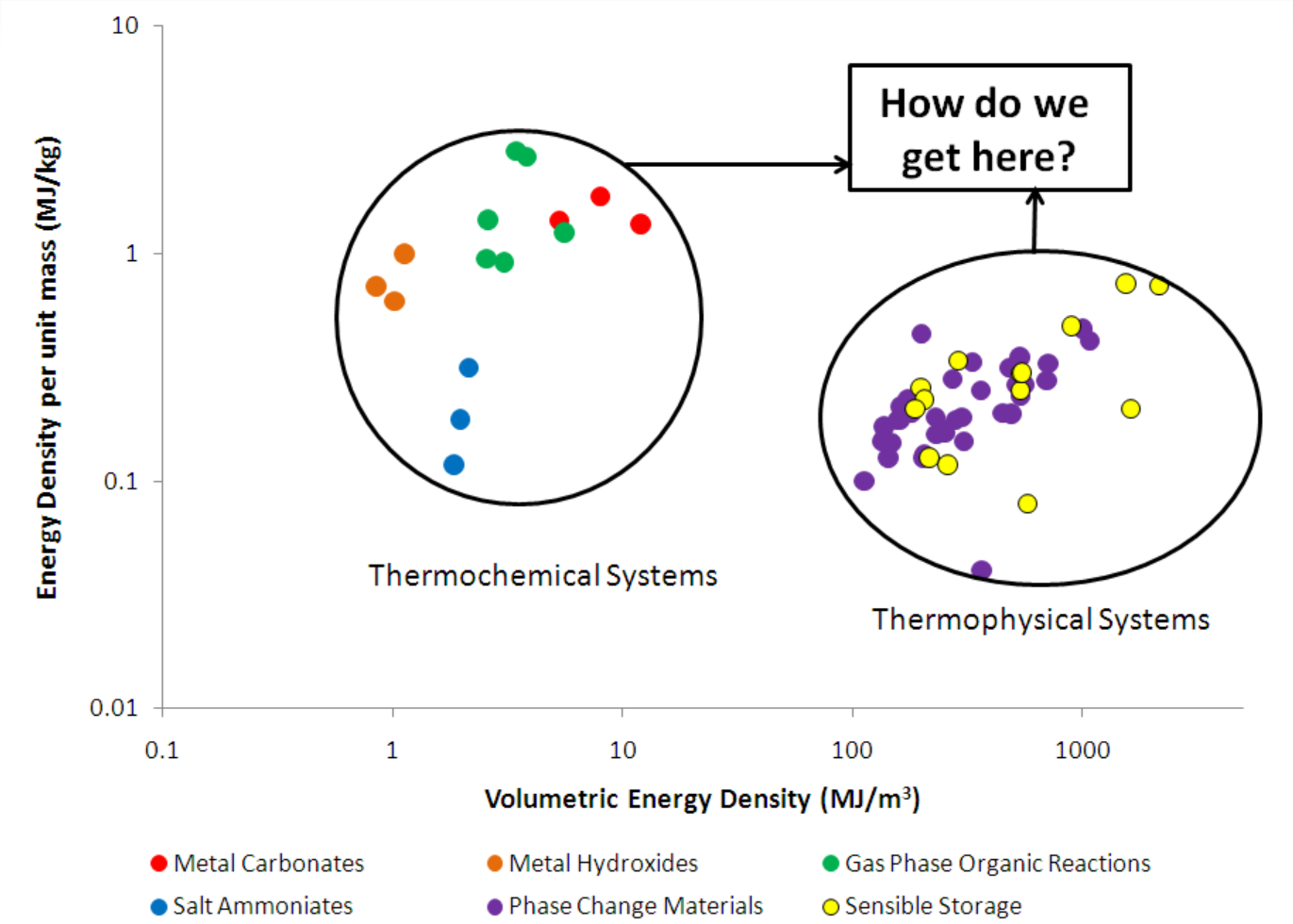


B. Zalba et al. / Applied Thermal Engineering 23 (2003) 251–283

Key Issues for Thermal Storage

- **Time Shift**: Electricity and heat demand do not always coincide
- **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

Thermophysical Versus Thermochemical Storage



Science-Engineering Partnership for Thermal Energy Storage

Can we tune and control interplay between ΔH, ΔS, ρ, $\Delta\rho$, effusivity in the presence of engineering constraints of cost, toxicity, reliability, …. ?

- Chemical reactions
  - ✧ Gas (hydrogen, methane,…) storage technology for thermal storage
  - ✧ Binding of gases/liquids with ionic liquids or metalorganic frameworks (MOFs)
- Magnetic dipoles
- Electric monopoles – ions in solution/plasma
- Electric dipoles

Thermal Storage Workshop Participants

Basic science
- Chemists
- Physicist
- Materials

Engineering
- Chemical
- Thermal
- Mechanical
- Materials
- System designer

Applications
- Nuclear
- CSP
- Buildings
- Automotive
- High temperature

65 attendees from Academia, National Labs, Industry & Government

Workshop Agenda Overview

Brief Technical Talks

Arun Majumdar (ARPA-E)
"Thermal Energy Storage"

Yukitaka Kato (Tokyo Institute of Technology)
"Thermochemical Energy Storage: Possibility of Chemical Heat Pump Technologies "

Anoop Mathur (Terrafore)
"Concentrating Solar Thermal Energy Storage"

Charles Forsberg (MIT)
"Thermal Energy Storage Systems for Peak Electricity from Nuclear Energy"

Reuel Shinnar (CUNY)
"High Density Thermal Storage for Power Plants: High Efficiency – Low Cost"

Morning Breakout Sessions

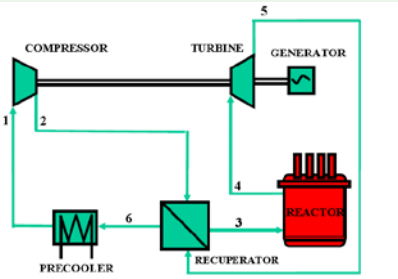
- **ThermoPhysical Storage**
- **ThermoChemical Storage**
- **Thermal Storage for Nuclear Energy**

Afternoon Breakout Sessions – *Systems and Applications*

- **High Temperature Systems**
- **Low Temperature Systems**
- **Alternate Applications of Thermal Storage**

High Impact Applications Identified

Synergy between Solar and High-Temp Nuclear



Increase in efficiency > 50% compared to current systems (T ~ 300- 400 ºc)

CHP systems in buildings

Reduces primary consumption ~ 25%

PHEV & EV

Increase EV range by ~ 40%

Scale

<100 ºC | **~ 500 ºC** | **> 800 ºC**

Temperature

System Level Perspective to Thermal Storage

Material based spec = $\dfrac{\Delta H_{out}}{\Delta H_{in}}$

System based spec:

$$\frac{\Delta G_{out}}{\Delta G_{in}} = \frac{\Delta H_{out} - T_{amb}\Delta S_{out}}{\Delta H_{in} - T_{amb}\Delta S_{in}}$$

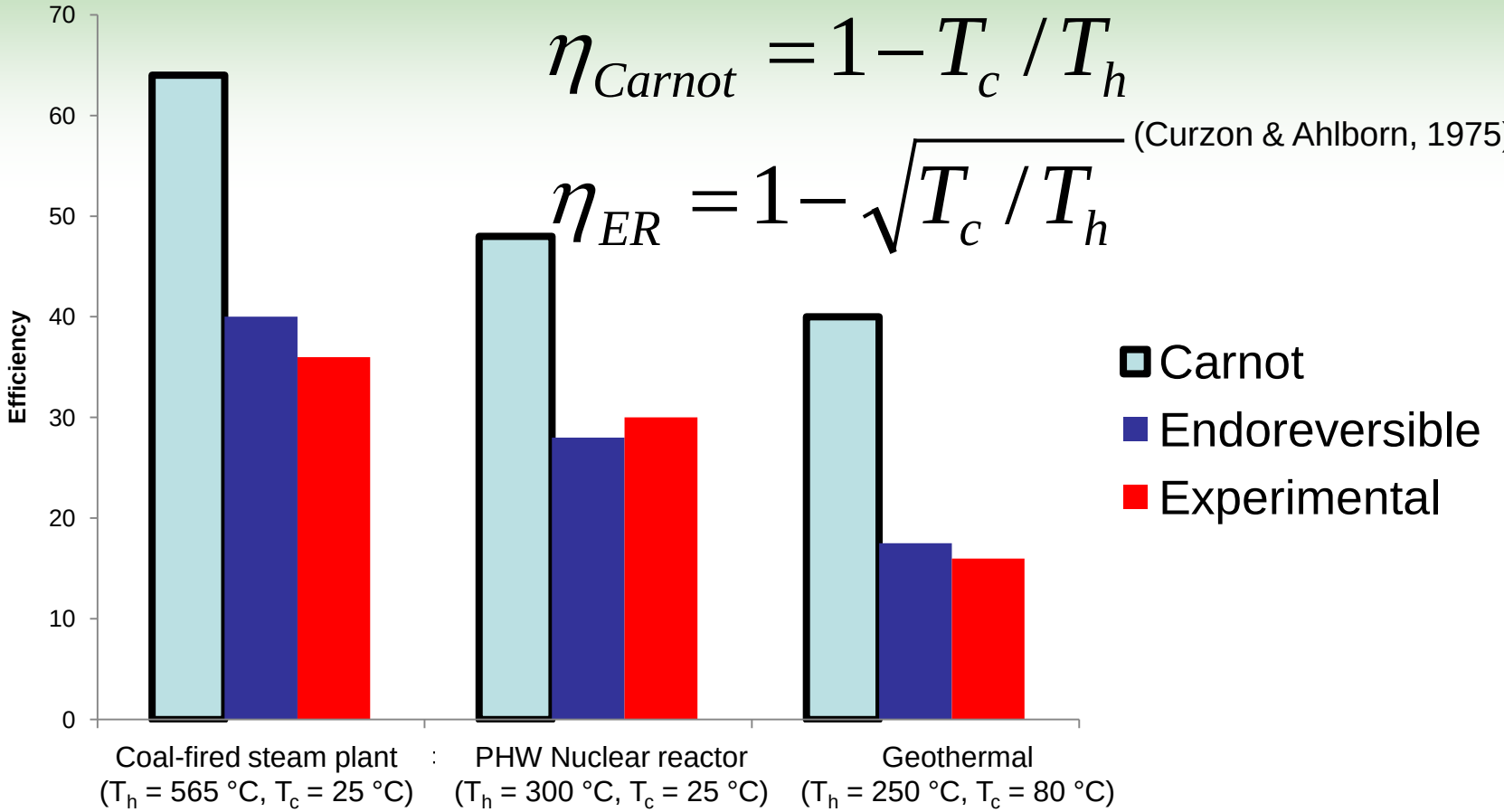
Exergy based spec also accounts for the inefficiencies due to heat exchanger

Thermodynamic Efficiency

$$\eta_{Carnot} = 1 - T_c / T_h$$

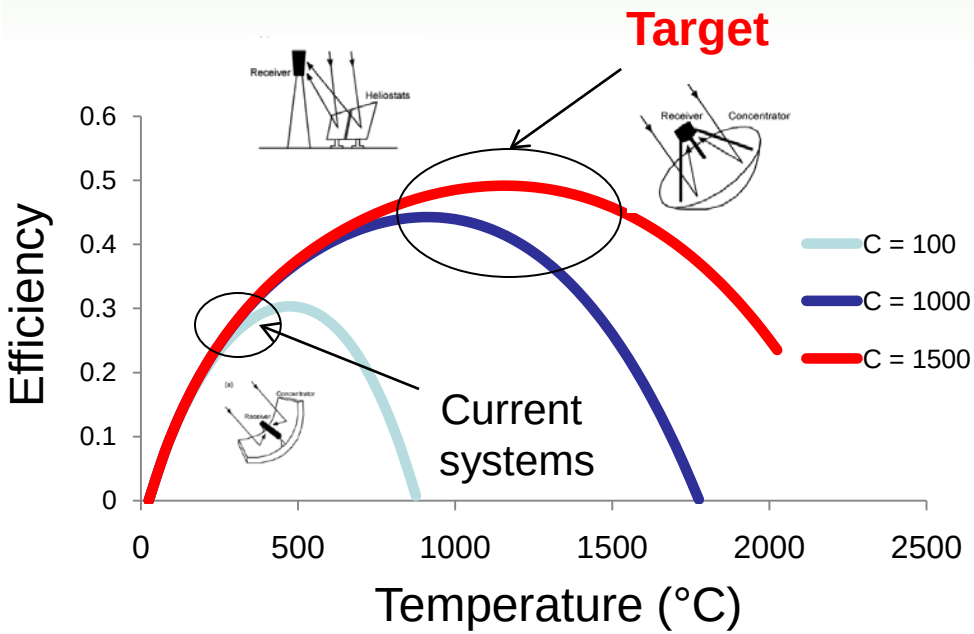
$$\eta_{ER} = 1 - \sqrt{T_c / T_h}$$

(Curzon & Ahlborn, 1975)



- Endoreversible efficiency derived for maximum power limited by heat transfer
- Match with actual data is purely empirical
- Should be used only for studies to understand trends

High-Temperature Applications: CSP



$$\eta_{collector} = \frac{IC\alpha - \varepsilon\sigma T^4}{IC}$$

$$\eta_{ER} = 1 - \sqrt{T_c / T_h}$$

$$\eta_{solar-electrical} = \eta_{collector} \times \eta_{ER}$$

- **LCOE of CSP without subsidy ~ 18 cents/kWh (Blair et al., NREL, 2008)**
- **Storage can increase capacity factor from ~ 20% to ~75%**

Synergy between CSP & Gen 4 Nuclear Reactors

- Gen 4 nuclear reactors are targeting temperature > 800 °C
  - Thermal storage can be used in Nuclear plants to meet peaking requirements using Brayton cycle

- Gen4 reactors plan to use He Brayton or Supercritical CO_2 cycle
  - Supercritical CO_2 cycle can have efficiencies greater than Ideal gas cycles due to real gas effects (fluid is near critical point before the compressor)
  - Brayton cycle can be potentially used for CSP (Craig S. Turchi, NREL, 2009)

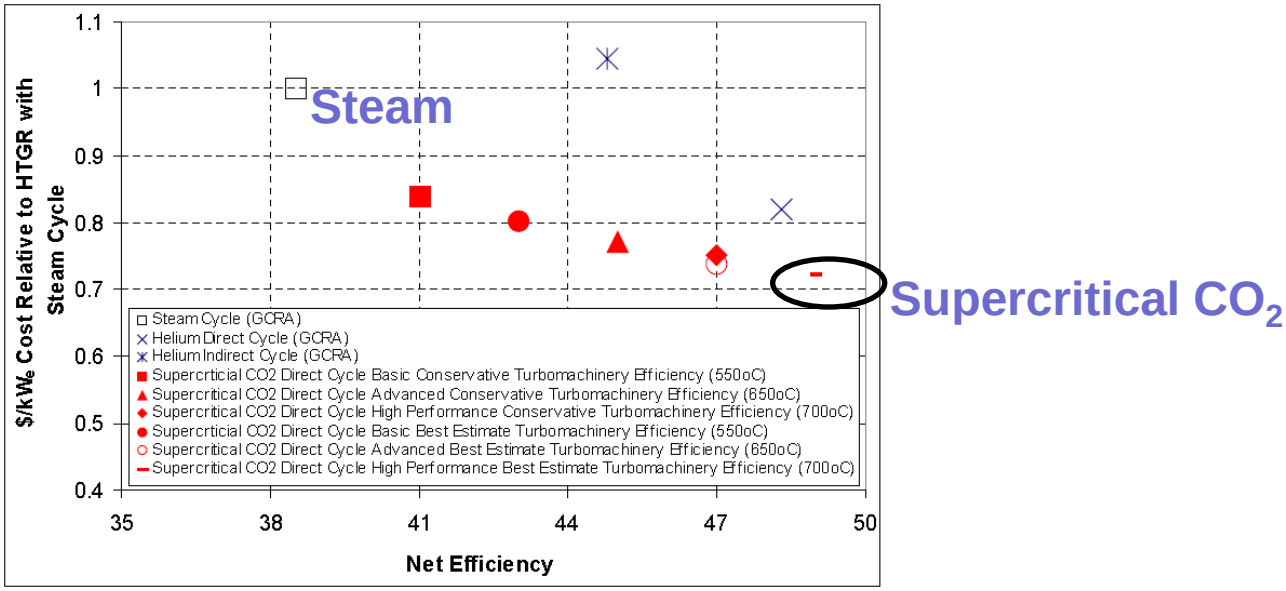


Figure 8.1 Net efficiency and relative costs for different power cycles

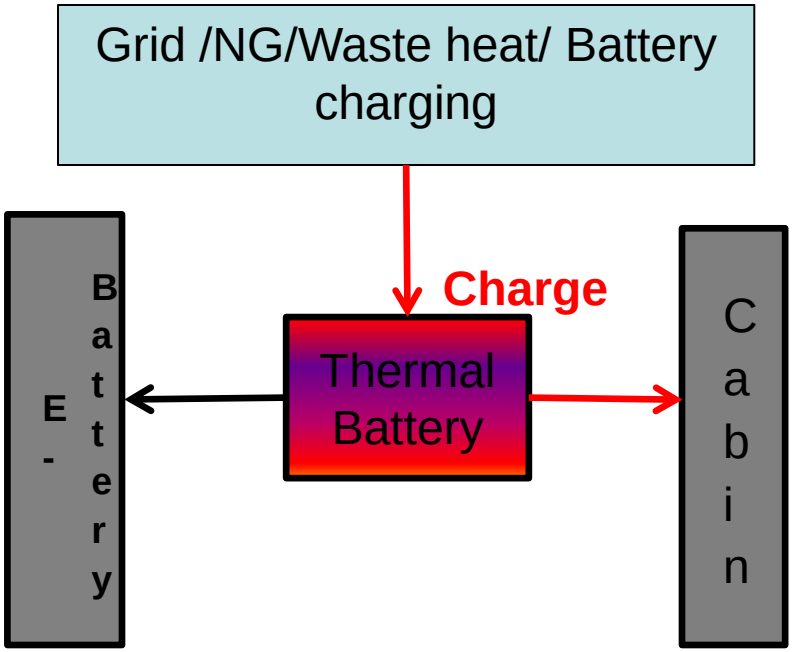
Source: Dostal, V., PhD Thesis: "A Supercritical CarbonDioxide Cycle for Next Generation Nuclear Reactors," MIT, 2004

Low- Medium Temperature: Effect of Climate Control on PHEV and EV

- Best example of combined heat and power: heating of cabin of IC engine vehicle (**heating is free**)
- Fully electrified light duty fleet will require > 1 Quad for heating
- Power consumption in EV ~ 6 KW @ 40 miles/hr and 13 KW @ 60 miles/hr (Source: Tesla)

Mode	Peak load (kW)	Steady state load (kW)
A/C	3.9	2.1
Heat	6.0	2.0

Barnitt et al., NREL, 2010



Heating and cooling will reduce the mileage of PHEV and EV by 5 -40%

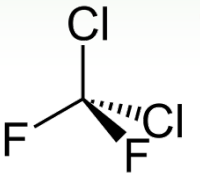
An Example of Chemistry-Engineering Partnership that Changed the Course of Energy & Environmental History

Stratospheric sink for chlorofluoromethanes : chlorine atomc-atalysed destruction of ozone

Mario J. Molina & F. S. Rowland

Department of Chemistry, University of California, Irvine, California 92664

Nature Vol. 249 June 28 1974



CFC-12; R-12

Large losses of total ozone in Antarctica reveal seasonal ClO_x/NO_x interaction

NATURE VOL. 315 16 MAY 1985

J. C. Farman, B. G. Gardiner & J. D. Shanklin

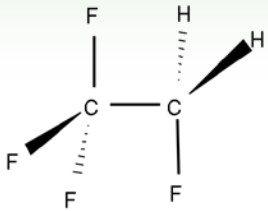
British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge CB3 0ET, UK

Vienna Convention for the Protection of the Ozone Layer: 1985

Montreal Protocol on Substances That Deplete the Ozone Layer: Initiated Sept. 16, 1987, enacted Jan. 1, 1989.

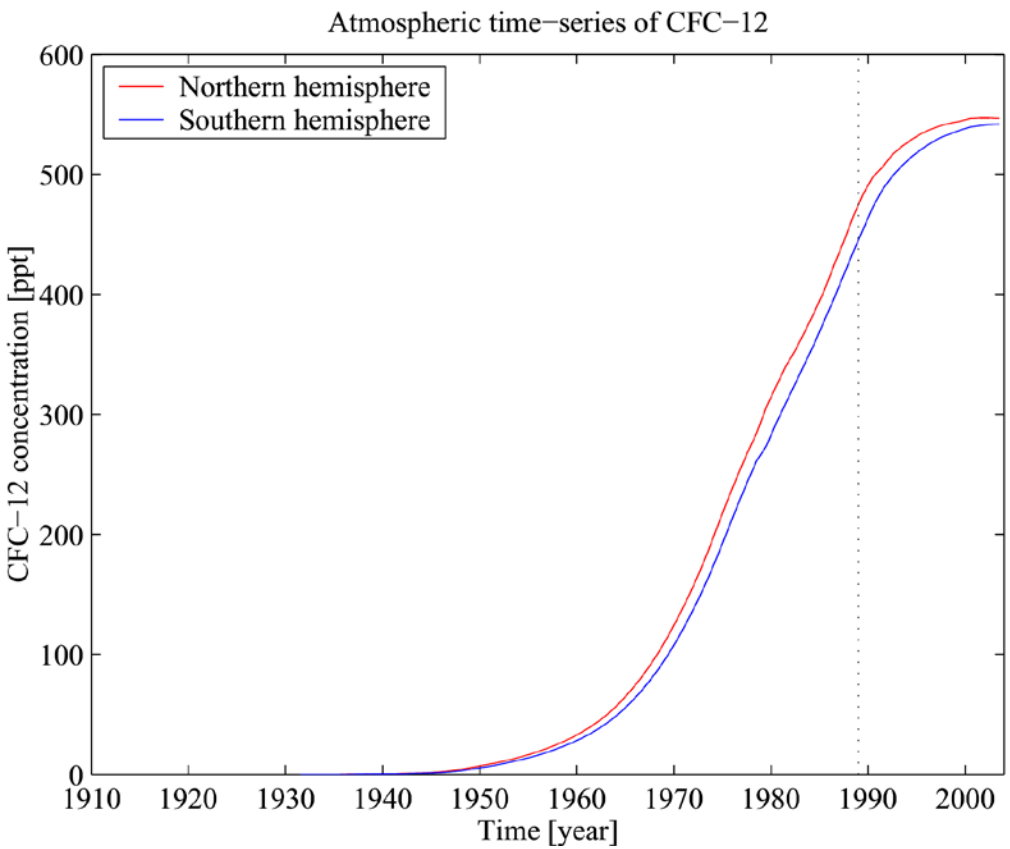
Mario Molina, F. Sherwood Rowland, Paul Crutzen – 1995 Nobel Prize in Chemistry

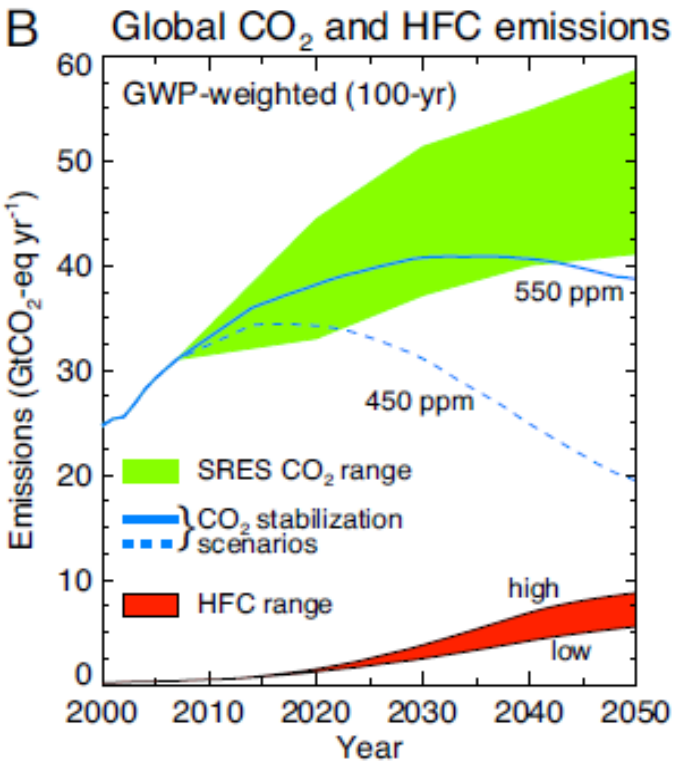
Development of HFCs for Air-Conditioning & Refrigeration



1,1,1,2-Tetrafluoroethane, R-134a

Started being used in early 1990s

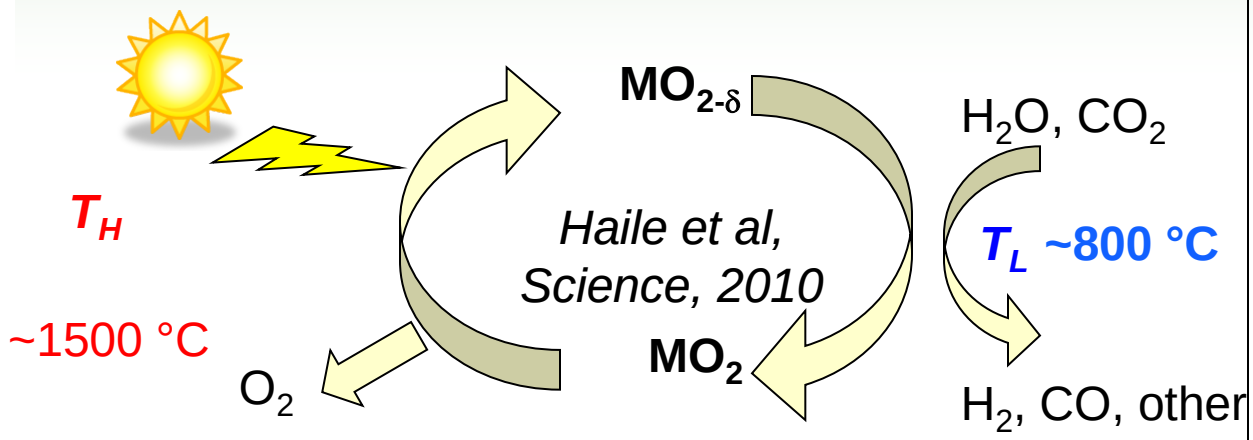




Velders et al, PNAS 106, 10949 (2009

New/Cross-Disciplinary Science & Technology

Thermo-chemical storage: Fuel Production



Direct thermolysis of water = 4000 °C

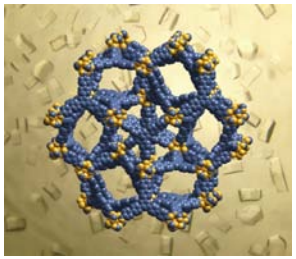
T = 890 °C

$CaCO_3$ <--> $CaO + CO_2$

T = 1300 °C

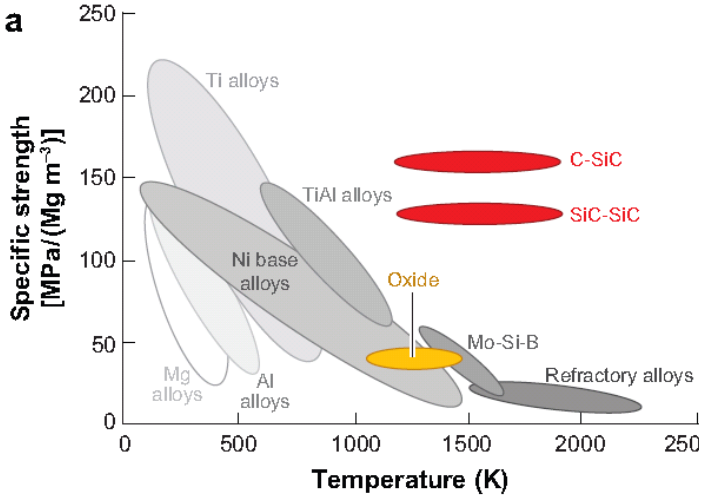
$BaCO_3$ <--> $BaO + CO_2$

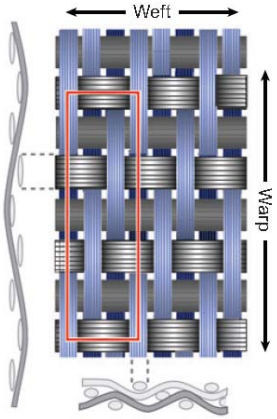
Volumetric density < 10 MJ/m^3



Volumetric density ~ 100 MJ/m^3

Storing Gaseous phase in MOFs

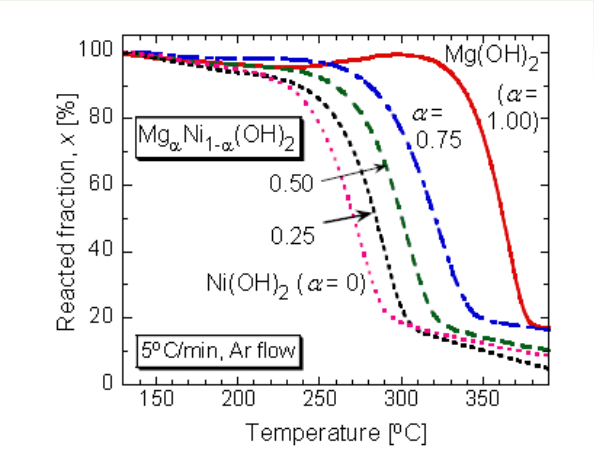




High temperature ceramic composites developed for rocket engines
(Marshell & Cox, 2008)

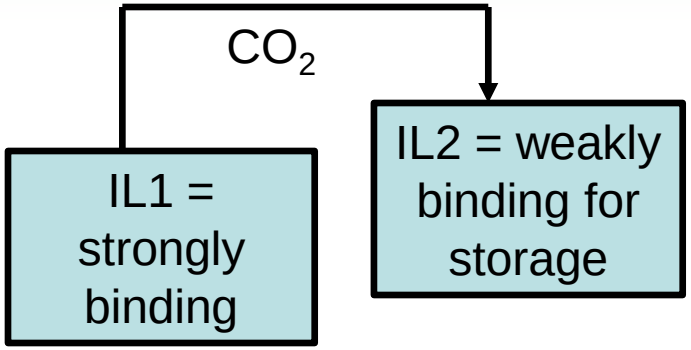
New/Cross-Disciplinary Science & Technology

SOA: Thermochemical storage density < 10 MJ/m^3 (due to gaseous phase)



Effect of molecular mixing (Kato et al., 2007)

Using binding energy of IL with Ionic liquids



ΔH ~150 MJ/m^3

Workshop Output Report

Visit: www.arpa-e.energy.gov

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Click: "Past Workshops"

High Density Thermal Energy Storage

Monday, January 31, 2011

ARPA-E recently held an event in its public workshop series – "High Density Thermal Energy Storage," on January 31, 2011, in Arlington, Va. Thermal energy transport and conversion play a very significant role in more than 90% of energy technologies. Approximately two thirds of thermal energy is wasted.Thermal energy storage can significantly reduce this waste and enhance the efficiency of energy delivery and consumption. Applications range from low temperature cold storage to high temperature nu...

Read More Workshop Output

Q & A

Please submit your questions on the note cards.

www.arpa-e.energy.gov