Energy Transfer, Conversion and Storage Toolbox 5

Sustainable Energy
J.W. Tester

1. Multiple scales of energy
2. Energy sources and properties
3. Energy flows and balances
4. Chemical reactions and kinetics
5. Energy transport phenomena and rates
6. Energy storage revisited
7. Discussion of example problems

Energy Transfer, Conversion and Storage Toolbox 5

Suggested text readings

- Chapter 1, sections 1.2
- Chapter 2, sections 2.1 and 2.2, esp Table 2.1
- Chapter 3, all sections 3.1- 3.8
- Chapter 16, sections 16.1, 16.3

1. Multiple scales of energy

Energy *E* (in BTU, joules(J) or cal)
Power *P* = *dE/dt* (BTU/hr, Watts(W))
thermal – t or th or electric - e

- **macro level** – **global scale**

  E = 1 to 1000 quad = 10^{15} BTU ≈ 1 exajoule = 10^{18} J
  (today's global energy consumption = 400 quads/year ≈ 15 TW)

- **meso level** – process or central station power plant level

  E = 10000 to 1 million BTU or 1,000 kJ to 100,000 kJ
  P = 100 KW t or e to 1000 MW t or e

- **micro level** – eg. individual buildings or vehicles

  E = 1 – 10000 BTU to 1000 J to 10 kJ
  P = 1 Watt (W) to 100 kW

Energy rate scaling

- ❑ food - ---------------------------------- 250 kcal/candy bar
- ❑ average daily requirement ---------- 2000-3000 kcal/day = 100 W
- ❑ human heart -------------------------------- 2 W
- ❑ running -- 500 W
- ❑ 1 horsepower ----------------------------------- 750 W
- ❑ 757 jet plane ---------------------------------- 1 – 10 MW
- ❑ automobile ------------------------------------ 100 -160kW
- ❑ space shuttle ----------------------------------- 1 GW
- ❑ Typical electric generating plant ---------- 1000 MW
- ❑ 1 wind turbine -------------------------------- 1-3 MW
- ❑ laptop computer ----------------------------- 10 W
- ❑ cell phone ------------------------------------- 2 W

US energy consumption per year -----------
100 quads or Q=100,000,000,000,000,000,000 J or 3.5 TW

Worldwide energy consumption per year ------
400 quads or Q =400,000,000,000,000,000,000 J or 15 TW

2. Energy sources and properties

- Potential
- Kinetic
- Gravitational
- Elastic strain
- Thermal
  - sensible heat
  - latent heat
- Chemical
  - stored in chemical bonds
- Electrochemical
- Electrostatic
- Electromagnetic
- Nuclear fission and fusion

Energy conversion

- Laws of Thermodynamics provide limits
- Heat and work are not the same
- Maximum work output (or minimum work input) only occurs in idealized reversible processes
- All real processes are irreversible
- Losses always occur to the degrade the efficiency of energy conversion and reduce work/power producing potential

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In other words – You can't win or even break even in the real world

Energy conversion

- Laws of Thermodynamics provide performance limits for reversible processes
    - for heat to work/power conversion, e.g. Carnot
    - for work to work conversion, e.g. zero current fuel cell operation
- Thermodynamics characterizes equilibrium and quasi-static processes but tells us nothing about rates
- Rates are governed by constitutive laws that link gradients and transport properties

Energy Flows and Balances

- **Energy flow or transfer by**
  - ❑ sensible heat transfer by temperature gradients (conduction, convection, radiation)
  - ❑ latent heat transfer via phase change
  - ❑ mass transfer -- diffusive or convective
  - ❑ momentum transfer – KE-PE energy exchange
  - ❑ chemical reaction – enthalpy and free energy
  - ❑ work transfer – compressive, electrochemical, etc.
- **Energy balances**
  - ❑ overall conservation law

    input – output = accumulation
  - ❑ boundary fluxes – heat and work
  - ❑ internal accumulation or depletion to *E*
  - ❑ steady state versus transient processes –

Transport rate processes in general

- **Constitutive laws exist to characterize rates, e.g.**
  heat transfer – Fourier's law
  mass transfer – Fick's law
  momentum transfer – Navier-Stokes equations
- **Rates depend on gradients, e.g.**
  - temperature dT/dx
  - concentration dC_i/dx
  - pressure dP/dx
  - chemical potential $d\mu_i/dx$
- **Rates depend on characteristic resistances that relate directly to transport properties, e.g.**
  - thermal conductivities
  - molecular diffusivities
  - permeabilities
  - viscosities

Rates of chemical reactions - $\Sigma \nu_i C_i = 0$

1. Global rate laws can be used to characterize rates, e.g.

   rate = $dC_i/dt = k\,\{[C_1]^{n1}\ [C_2]^{n2}\ [C_3]^{n3} \ldots\}$ where

   C_i = chemical species *i*

   ν_I = stoichiometric coefficient in reaction
   (+ for products and – for reactants)

   k = rate constant = $A \exp(-E_a/RT)$

   n_i = reaction order

   E_a = activation energy, J/ mol

   R + gas constant = 4.186 J/ mol K

   T = temperature, K
2. Heat or thermal energy can be released or absorbed by chemical reactions,
   exothermic ($\Delta H_{rxn} < 0$) or endothermic ($\Delta H_{rxn} > 0$)
3. Reaction conversion is limited by chemical equilibrium some are favorably shifted toward desired products while others are unfavorable
4. Reaction rates can be accelerated by catalysts

Several Important Chemical Reactions

Fuel combustion

- $CH_4 + 3 O_2 = CO_2 + 2 H_2O$ – natural gas
- $C_8H_{12} + 11O_2 = 8 CO_2 + 6 H_2O$ – gasoline
- $C_6H_{12}O_6 + 6O_2 = 6 CO_2 + 6 H_2O$– cellulosic biomass

Hydrogen production

- $CH_4 + H_2O = CO + 3H_2$ – steam reforming of methane
- $CO + H_2O = CO_2 + H_2$ – water gas shift reaction

Hydrogen fuel cell

- $H_2 + \frac{1}{2} O_2 = H_2O$ + electricity – overall reaction

Energy storage (continued)

- ❑ Range of energy storage
  - from watts to megawatts
  - e.g. from small batteries to pumped hydropower
- ❑ Modes of energy storage
  - potential energy (pumped hydro , CAES)
  - kinetic (mechanical flywheels)
  - thermal (sensible and latent heat)
  - chemical (heats of reaction and combustion for biomass, fossil, hydrogen, etc.)
  - electrical (electrochemical, electrostatic, electromagnetic batteries, fuel cells, super capacitors, and SMES)
- ❑ Power density versus energy density (weight and volume)
- ❑ Ragone plot of specific power versus specific energy
- ❑ Typical costs

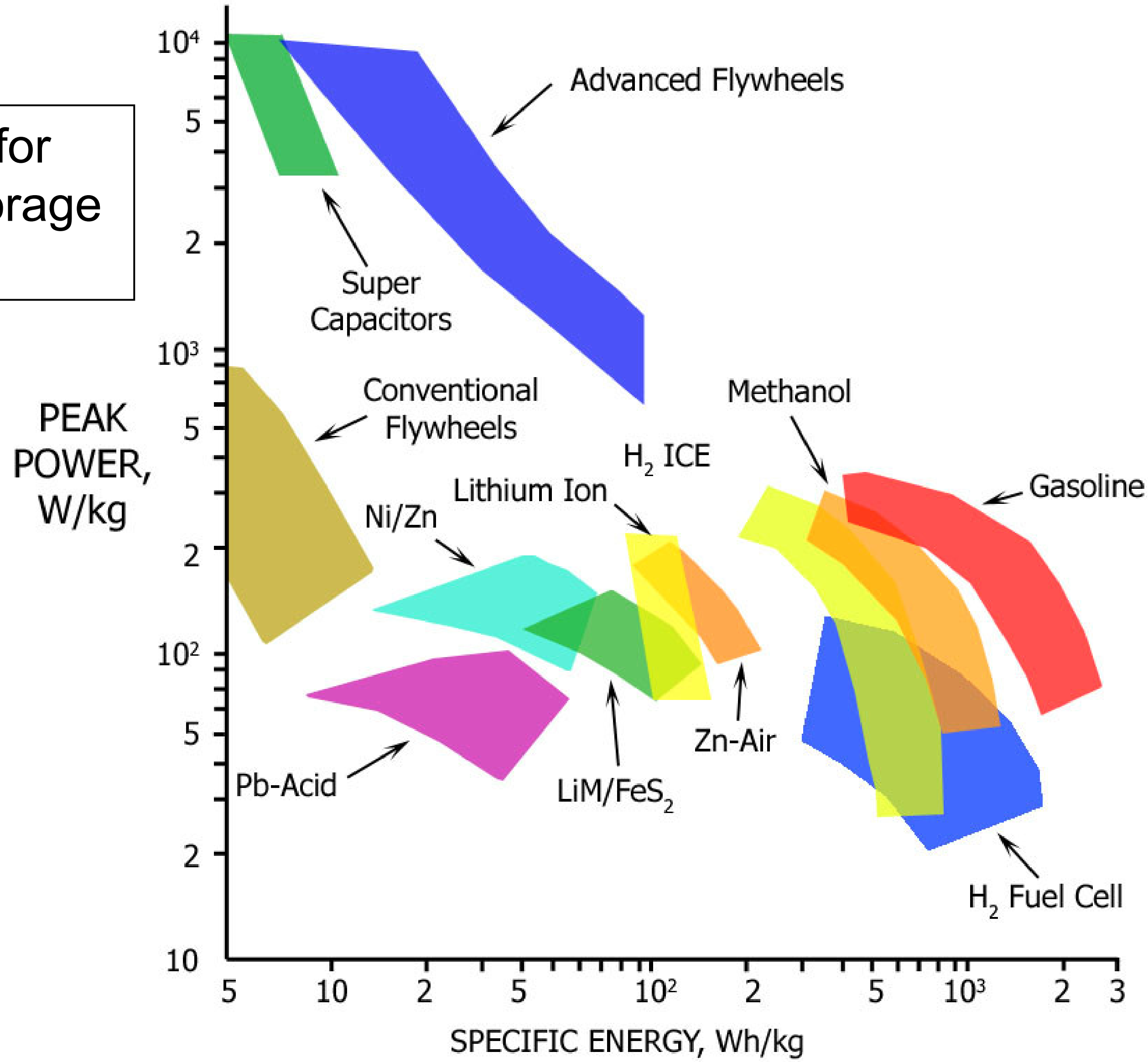
Energy storage in general

Mode	Primary Energy Type	Characteristic Energy Density kJ/kg	Application Sector
Pumped Hydropower	Potential	1 (100m head)	Electric
Compressed Air Energy Storage	Potential	15,000 in kJ/m^3	Electric
Flywheels	Kinchi	30-360	Transport
Thermal	Enthalpy (sensible + latent)	Water (100-40^{o}C) – 250 Rock (250-50^{o}C) – 180 Salt (latent) – 300	Buildings
Fossil Fuels	Reaction Enthalpy	Oil – 42,000 Coal – 32,000	Transport, Electric, Industrial, Buildings
Biomass	Reaction Enthalpy	Drywood – 15,000	Transport, Electric, Industrial, Building
Batteries	Electrochemical	Lead acid – 60-180 Nickel Metal hydride – 370 Li-ion – 400-600 Li-pdgmer ~ 1,400	Transport, Buildings
Superconducting Magnetic Energy Storage (SMES)	Electromagnetic	100 – 10,000	Electric
Supercapacitors	Electrostatic	18 – 36	Transport

Energy Storage Technology Characteristics

	Pumped Hydro	CAES (a)	Flywheels	Thermal	Batteries	Supercapicitors	SMES(b)
Energy Range	1.8×10^6– 36×10^6 MJ	180,000– 18×10^6 MJ	1–18,000 MJ	1–100 MJ	1800– 180,000 MJ	1–10 MJ	1800– 5.4×10^6 MJ
Power Range	100–1000 MWe	100–100 MWe	1–10 MWe	0.1 to 10 MWe	0.1 to 10 MWe	0.1-10 MWe	10–1000 MWe
Overall Cycle Efficiency©	64–80%	60–70%	~90%	~80–90%	~75%	~90%	~95%
Charge/Discharge Time	Hours	Hours	Minutes	Hours	Hours	Seconds	Minutes to Hours
Cycle Life	?10,000	?10,000	?10,000	>10,000	?2,000	>100,000	?10,000
Footprint/Unit Size	Large if above ground	Moderate if under ground	Small	Moderate	Small	Small	Large
Siting Ease	Difficult	Difficult to moderate	N/A	Easy	N/A	N/A	Unknown
Maturity	Mature	Early stage of development	Under development	Mature	Lead acid mature, others under development	Available	Early R&D stage, under development

Ragone Plot for comparing storage technologies



A few questions for our recitation discussion

1. "Sustainable transport" -- If we stacked all the cars and trucks in the world on top of one another, how far could would it extend into space?
2. Is 2 better than 1" -- What is the relative improvement in energy efficiency that results when you replace a single pane conventional glass window with a double pane, low E glass?
3. "Sustainable hydro" How much water flow does the Niagara Falls hydroelectric plant require?
4. "Bio-Mass" versus "Cape Wind" in MA -- If we produce all of the state's electricity by growing and burning trees, how much land area is needed? If we chose off shore wind power at the Cape how many windmills are needed?
5. "Batteries for families" What weight of lead acid batteries are needed to power a family sized electric car with a range of 200 miles. You can assume that the power needed is 50 hp for speed up to 60 mph with regenerative on board flywheel storage for additional acceleration when needed.

A few questions for your homework on PS 4

1. "Oil versus water" -- How does a good geothermal well compare with a good oil well flowing at 10,000 bbl per day?
2. "Hydrogen versus gasoline" -- If the US converts to a hydrogen economy to replace its current energy system, how much natural gas would be needed per year to produce the hydrogen required for all our transportation fuels? Currently US transport consumes about 40 quads/year in energy and the worldwide production rate of natural gas is 90 trillion SCF per year.