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
- **electric** — e

- **macro level — global scale**
  
  $E = 1$ to $1000$ quad = $10^{15}$ BTU $\approx 1$ exajoule = $10^{18}$ J

  (today’s global energy consumption = 400 quads/year $\approx 15$ 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

<table>
<thead>
<tr>
<th>Item</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>food</td>
<td>250 kcal/candy bar</td>
</tr>
<tr>
<td>average daily requirement</td>
<td>2000-3000 kcal/day = 100 W</td>
</tr>
<tr>
<td>human heart</td>
<td>2 W</td>
</tr>
<tr>
<td>running</td>
<td>500 W</td>
</tr>
<tr>
<td>1 horsepower</td>
<td>750 W</td>
</tr>
<tr>
<td>757 jet plane</td>
<td>1 – 10 MW</td>
</tr>
<tr>
<td>automobile</td>
<td>100 -160kW</td>
</tr>
<tr>
<td>space shuttle</td>
<td>1 GW</td>
</tr>
<tr>
<td>Typical electric generating plant</td>
<td>1000 MW</td>
</tr>
<tr>
<td>1 wind turbine</td>
<td>1-3 MW</td>
</tr>
<tr>
<td>laptop computer</td>
<td>10 W</td>
</tr>
<tr>
<td>cell phone</td>
<td>2 W</td>
</tr>
</tbody>
</table>

US energy consumption per year

100 quads or Q=100,000,000,000,000,000,000,000,000 J or 3.5 TW

Worldwide energy consumption per year

400 quads or Q =400,000,000,000,000,000,000,000,000,000 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
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
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 degrade the efficiency of energy conversion and reduce work/power producing potential

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 \( \frac{dT}{dx} \)
  - concentration \( \frac{dC}{dx} \)
  - pressure \( \frac{dP}{dx} \)
  - chemical potential \( \frac{d\mu}{dx} \)

- Rates depend on characteristic resistances that relate directly to transport properties, e.g.
  - thermal conductivities
  - molecular diffusivities
  - permeabilities
  - viscosities
1. Global rate laws can be used to characterize rates, e.g.
\[
\text{rate} = \frac{dC_i}{dt} = k \{[C_1]^{n_1} [C_2]^{n_2} [C_3]^{n_3} \ldots \}
\]
where
- \(C_i\) = chemical species \(i\)
- \(n_i\) = stoichiometric coefficient in reaction
  (+ for products and – for reactants)
- \(k\) = rate constant = \(A \exp\left( - \frac{E_a}{RT}\right)\)
- \(n_i\) = 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

- \( \text{CH}_4 + 3 \text{O}_2 = \text{CO}_2 + 2 \text{H}_2\text{O} \) – natural gas
- \( \text{C}_8\text{H}_{12} + 11\text{O}_2 = 8 \text{CO}_2 + 6 \text{H}_2\text{O} \) – gasoline
- \( \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 = 6 \text{CO}_2 + 6 \text{H}_2\text{O} \) – cellulosic biomass

Hydrogen production

- \( \text{CH}_4 + \text{H}_2\text{O} = \text{CO} + 3\text{H}_2 \) – steam reforming of methane
- \( \text{CO} + \text{H}_2\text{O} = \text{CO}_2 + \text{H}_2 \) – water gas shift reaction

Hydrogen fuel cell

- \( \text{H}_2 + \frac{1}{2} \text{O}_2 = \text{H}_2\text{O} + \text{electricity} \) – 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

<table>
<thead>
<tr>
<th>Mode</th>
<th>Primary Energy Type</th>
<th>Characteristic Energy Density kJ/kg</th>
<th>Application Sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumped Hydropower</td>
<td>Potential</td>
<td>1 (100m head)</td>
<td>Electric</td>
</tr>
<tr>
<td>Compressed Air Energy Storage</td>
<td>Potential</td>
<td>15,000 in kJ/m³</td>
<td>Electric</td>
</tr>
<tr>
<td>Flywheels</td>
<td>Kinchi</td>
<td>30-360</td>
<td>Transport</td>
</tr>
<tr>
<td>Thermal</td>
<td>Enthalpy (sensible + latent)</td>
<td>Water (100-40°C) – 250 Rock (250-50°C) – 180 Salt (latent) – 300</td>
<td>Buildings</td>
</tr>
<tr>
<td>Fossil Fuels</td>
<td>Reaction Enthalpy</td>
<td>Oil – 42,000 Coal – 32,000</td>
<td>Transport, Electric, Industrial, Buildings</td>
</tr>
<tr>
<td>Biomass</td>
<td>Reaction Enthalpy</td>
<td>Drywood – 15,000</td>
<td>Transport, Electric, Industrial, Building</td>
</tr>
<tr>
<td>Batteries</td>
<td>Electrochemical</td>
<td>Lead acid – 60-180 Nickel Metal hydride – 370 Li-ion – 400-600 Li-pdgmer ~ 1,400</td>
<td>Transport, Buildings</td>
</tr>
<tr>
<td>Superconducting Magnetic Energy Storage (SMES)</td>
<td>Electromagnetic</td>
<td>100 – 10,000</td>
<td>Electric</td>
</tr>
<tr>
<td>Supercapacitors</td>
<td>Electrostatic</td>
<td>18 – 36</td>
<td>Transport</td>
</tr>
</tbody>
</table>
# Energy Storage Technology Characteristics

<table>
<thead>
<tr>
<th></th>
<th>Pumped Hydro</th>
<th>CAES(^{(a)})</th>
<th>Flywheels</th>
<th>Thermal</th>
<th>Batteries</th>
<th>Supercapacitors</th>
<th>SMES(^{(b)})</th>
</tr>
</thead>
</table>
| **Energy Range**        | 1.8 X 10^6–  
36 X 10^6 MJ | 180,000–  
18 X 10^6 MJ | 1–18,000 MJ | 1–100 MJ | 1800–  
180,000 MJ | 1–10 MJ | 1800– 5.4 X 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 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.