Green Electronics Part IA

3. Electrical Energy Storage
Methods of Energy Storage

• “Irreversible Chemical Storage”
  • Petrol/Gasoline (C-based)
  • Fuel Cells (H2-based)

• Potential Gravitational Energy
  • Pumped Hydro-electricity

• Kinetic Energy
  • Flywheels

• Reversible Chemical Storage “Batteries”
  • Lead Acid
  • Ni-metal hydride
  • Li-ion

• Electronic Charge Storage
  • Dielectric Capacitors “Capacitors”
  • Electrolytic Capacitors
  • Electro-chemical Capacitors “Super- or Ultra-Capacitors”
Pumped Hydro Energy Storage

• Energy Stored:
  • Mass*gravity*height
  • $g = 10, \ E = 10 \, \text{J/(m-kg)}$

• Racoon Mountain:
  • $h = 70\, \text{m}$,
  • $m = 54 \times 10^9 \, \text{kg} \ (1000\, \text{kg/m}^3; \ 1\, \text{km} \times 1\, \text{km} \times 54\, \text{m})$
  • $E = 38\, \text{TJ} = 10\, \text{GWh} = 6 \, \text{hours at 1.6GW}$

• Up conversion & down conversion loss
• Only useful where Nature is particularly friendly
Mechanical Flywheels

- Energy Stored
  - Mass $M = 100\,\text{kg}$
  - Radius $R = 0.3\,\text{m}$
  - Angular velocity
    - $\omega = 20,000\,\text{rpm} = 2090\,\text{rad/s}$
    - $1\,\text{rpm} = \frac{2\pi}{60}\,\text{s}$
  - Geometric factor ($k = 1/2$)
    - Circular hoop $k = 1$
    - Solid sphere (earth) $k = 2/5$
    - Solid disk (wheel) $k = 1/2$
  - $E = 9.8\,\text{MJ} = 2.7\,\text{kWh}$

- Regenerative Braking
- KERS: kinetic energy recovery system
  - F1 battery version not flywheel

$$E = \frac{I\omega^2}{2} \quad I = kmR^2$$
Energy Storage considerations

- Energy $U$ [J, Wh], Energy density $u$ [Wh/kg, Wh/cm$^3$]
- Power $P$ [Js$^{-1}$, W], Power density $p$ [W/kg, W/cm$^3$]
- Active time [s,h,days]
- Stand by time [s, h, days]
- Cost [$], [Wh/$]
- Environmental considerations
- Cyclability

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>radio-active Pu, Pm</td>
<td>1.00E+06</td>
<td>10</td>
<td>1.00E+05</td>
<td>100 years</td>
<td>very high</td>
<td>very bad</td>
</tr>
<tr>
<td>Fossil Fuels</td>
<td>1000</td>
<td>100</td>
<td>1.00E+01</td>
<td>1 year</td>
<td>low</td>
<td>bad</td>
</tr>
<tr>
<td>Fuel Cells</td>
<td>100</td>
<td>100</td>
<td>1.00E+00</td>
<td>1 year</td>
<td>high</td>
<td>good</td>
</tr>
<tr>
<td>Lead Acid Battery</td>
<td>10</td>
<td>10</td>
<td>1.00E+00</td>
<td>100 days</td>
<td>low</td>
<td>bad</td>
</tr>
<tr>
<td>Li-ion battery</td>
<td>100</td>
<td>100</td>
<td>1.00E+00</td>
<td>100 days</td>
<td>high</td>
<td>neutral</td>
</tr>
<tr>
<td>Supercapacitors</td>
<td>1</td>
<td>1000</td>
<td>1.00E-03</td>
<td>1 day</td>
<td>high</td>
<td>neutral</td>
</tr>
<tr>
<td>Capacitors</td>
<td>0.1</td>
<td>1.00E+06</td>
<td>1.00E-07</td>
<td>1s</td>
<td>very high</td>
<td>neutral</td>
</tr>
</tbody>
</table>
Energy Storage: Figure of Merit

- Ragone plot: Energy density [kJ/kg, Wh/kg] vs Power density [W/kg]
- Time to discharge $T[h] = \frac{\text{Energy}[\text{Wh}]}{\text{Power}[\text{W}]}$
Electrical Energy Storage

• Large scale (ON GRID)
  • Chemical Energy Storage
    • Direct conversion from chemical energy to electrical energy (to motion)
      • Extremely efficient operation
      • Instead of chemical energy to heat to motion (very inefficient and limited by Carnot cycle)
    • Fuel Cells
    • Batteries

• Small scale (OFF GRID)
  • Charge Storage
    • Capacitors
    • Supercapacitors
Fuel Cells

- Fuel Cell: electrochemical energy generation system

<table>
<thead>
<tr>
<th>name</th>
<th>Negative electrode oxidation</th>
<th>Positive Electrode reduction</th>
<th>ion</th>
<th>electrolyte</th>
<th>solvent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Cell</td>
<td>H2</td>
<td>O2</td>
<td>H⁺</td>
<td>KOH</td>
<td>water</td>
</tr>
</tbody>
</table>

\[
2H_2 \rightarrow 4H^{1+} + 4e \\
O_2 + 4e \rightarrow 2O^{2-} \\
4H^+ + 2O^{2-} \rightarrow 2H_2O \\
H \rightarrow H^{1+} + e \\
O + 2e \rightarrow O^{2-} \\
2H_2 + O_2 \rightarrow 2H_2O
\]
Fuel Cells

• Where do we get the Hydrogen from?
  • Geological processes
    • Energy source!
    • Hydrothermal vents, Ophiolite rock
    • No effective/efficient method (yet!)
• Electrolysis of Water
  • Energy Carrier
  • Might be interesting if energy input is solar!
    • Concurrent desalination?!
  • Essentially a remote battery!
    • (electrolysis is exactly reverse of fuel cell)

Toyota Mirai: on sale now!
Batteries

- **Battery**: electrochemical energy storage system
- Reduction & Oxidation at both interfaces
- Liquid electrolyte
  - Ions move through the electrolyte
- Separator/Membrane to prevent electronic conduction
  - Electrons move through the external circuit

<table>
<thead>
<tr>
<th>Name</th>
<th>Negative Electrode</th>
<th>Positive Electrode</th>
<th>Ion</th>
<th>Electrolyte</th>
<th>Solvent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead-Acid</td>
<td>Pb</td>
<td>Pb</td>
<td>H⁺</td>
<td>H₂SO₄</td>
<td>water</td>
</tr>
<tr>
<td>Alkaline</td>
<td>Mn</td>
<td>Zn</td>
<td>OH⁻</td>
<td>KOH</td>
<td>water</td>
</tr>
<tr>
<td>Li-ion</td>
<td>Li</td>
<td>Co</td>
<td>Li⁺</td>
<td>LiPF₆</td>
<td>organic</td>
</tr>
<tr>
<td>Metal Hydride</td>
<td>H</td>
<td>Ni</td>
<td>OH⁻</td>
<td>KOH</td>
<td>water</td>
</tr>
</tbody>
</table>
Battery Equations (discharging)

- **Lead-acid:**
  
  \[ Pb(s) + HSO_4^- \rightarrow PbSO_4(s) + H^+(aq.) + 2e^- \]
  \[ PbO_2(s) + HSO_4^- + 3H^+(aq.) + 2e^- \rightarrow PbSO_4(s) + 2H_2O(l) \]

- **Li-ion:**
  
  \[ LiC_6 \rightarrow Li^+(aq.) + e^- + C_6 \]
  \[ CoO_2(s) + Li^+(aq.) + e^- \rightarrow LiCoO_2(s) \]

- **Ni-MH**
  
  \[ OH^-(aq.) + MH \rightarrow H_2O + M + e^- \]
  \[ NiO(OH) + H_2O + e^- \rightarrow Ni(OH)_2 + OH^-(aq.) \]

- **intercalation:** large amount of small ions: Li in LiC6 or Hydrogen in MH
Battery Considerations

- High Energy density
  - light elements: H or Li
  - but Pb(s), H(g), Li(g)
  - Intercalation: store H or Li within the lattice of another material
    - Li in Graphite: LiC₆
    - H in LaNi₅ or NdCo₅: Metal Hydride MH

- Power Density (maximum/effective)
- Cyclability (rechargeable, how many times?)
- Cost, Durability, Safety, Toxicity,
- Temperature behaviour
  (chemical reactions much more sensitive than electrostatic)
Battery for Grid storage

- Southern California
  - 396 battery stacks
  - Energy: 60MWh
  - Power: 15000 kW (or homes)
  - Time: 4h
Battery Operation: Lead Acid

- **Lead Acid**
  - Low energy density (both weight/volume)
  - Cheap

- **Charging:**
  - Formation of Pb (cathode)
  - Formation of PbO2 (anode)
  - Sulphuric acid into the electrolyte

- **Discharging:**
  - Removal of Sulphuric acid from electrolyte
  - Formation of Lead Sulphate at both electrodes
Battery Operation: Ni-Metal Hydride

- Ni-MH
  - Good energy density
  - Relatively Cheap
  - Memory effect (needs to be fully charged & discharged)
  - High self discharge rate
  - Replaced by Li ion batteries
Battery Operation: Lithium Ion

- Lithium Ion
  - Excellent energy density
  - Good Power density
  - Expensive
  - Does not like to be fully charged & discharged
  - Electrolyte flammable

Nissan Leaf

Iphone: charging strategy

- Fast Charge
- Slow trickle charge
mpoweruk.com: Li ion battery behaviour at different temperature

- Constant voltage during discharge
  - Li-ion=3.6V, Pb acid=2V, Ni-MH=1.5V
- Temperature behaviour
  - Operating range
- Self discharge
  - Storage time
Battery: Specific Energy

\[ U = \int_{0}^{Q} V \, dq = V_{\text{cell}} \int_{0}^{Q} dq = Q V_{\text{cell}} \]
\[ Q[C] = \frac{z e}{\text{atom}} \]
\[ e = 1.6 \times 10^{-9} \text{ C} \]
\[ Q[C / g] = \frac{z e}{M[g]} = \frac{z e N_a}{(m_{an} + m_{ca})} \]
\[ N_a = 6.0 \times 10^{23} / \text{mol} \]
\[ Q[C / kg] = \frac{z e}{M[kg]} = \frac{z e}{(m_{an} + m_{ca})} m_{\text{proton}} \]
\[ m_{\text{proton}} = m_{\text{neutron}} = 1.6 \times 10^{-27} \text{ kg} \]

<table>
<thead>
<tr>
<th>Battery</th>
<th>( z )</th>
<th>m(anode)</th>
<th>m(cathode)</th>
<th>Q[C/g]</th>
<th>Vcell</th>
<th>( u ) [J/g]</th>
<th>( u ) [kWh/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb-acid</td>
<td>2</td>
<td>Pb=207</td>
<td>Pb=207</td>
<td>463</td>
<td>2</td>
<td>928</td>
<td>0.26</td>
</tr>
<tr>
<td>Ni-MH</td>
<td>1</td>
<td>H=1</td>
<td>Ni=59</td>
<td>1655</td>
<td>1.5</td>
<td>2483</td>
<td>0.69</td>
</tr>
<tr>
<td>Li-ion</td>
<td>1</td>
<td>Li=7</td>
<td>Co=59</td>
<td>1455</td>
<td>3.6</td>
<td>5238</td>
<td>1.46</td>
</tr>
</tbody>
</table>

- Experimental specific energy Li-ion: 0.07-0.27 kWh/kg
- Cobalt oxide, not Cobalt; Li Carbide, not Li; Weight of the solvent
Home Battery

- DC power storage (before DC to AC inverter)
- Tesla Powerwall
  - £2000
  - Li ion battery: Mn-Co
    - So far so good
  - Energy: 7.0kWh
    - American household 30kWh/day,
    - European household with Gas central heating/cooking 3kWh/day
  - Power: 3.3kW
    - One kettle or washing machine or clothes/hair dryer or oven
  - Weight=100kg
    - Better have a strong wall
  - Size: 1.3m x .9m x 0.2m
    - Rephrase: It is the wall!
  - “Net zero”
    - Still connected to the grid: (give and take)
Home Battery

- Sonnenbattery Eco 6
  - £2000
  - Li ion battery
    - Li-Fe-Phosphate
  - Energy: 6.0kWh
  - Power: 3kW
  - Weight: 200kg
  - Size: 1.6m x .6m x 0.4m
  - Cyclability: 10000
Capacitor

- Parallel Plate: metal/dielectric/metal

\[ U = \int_0^Q V dq = \int_0^Q \frac{dQ}{C} = \frac{Q^2}{2C} = \frac{CV^2}{2} \]

\[ C = \frac{Q}{V} = \frac{Q \varepsilon_0 A}{Q d} = \frac{\varepsilon_0 \varepsilon_r A}{d} \]

\[ u = \frac{U}{Vol} = \frac{U}{Ad} = \frac{\varepsilon_0 \varepsilon_r E^2}{2} \]

\[ \varepsilon_0 = 8.85 \times 10^{-12} \text{ Fm}^{-1} \]

- Dielectric breakdown
  - Max Field/Voltage limited
  - Energy density: low

\[ u(Mica) = 0.061 \text{ Wh/l} \]

<table>
<thead>
<tr>
<th>material</th>
<th>( \varepsilon_r )</th>
<th>( E_{bd}[\text{V/\mu m}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>air</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>paper</td>
<td>3</td>
<td>50</td>
</tr>
<tr>
<td>PTFE</td>
<td>2</td>
<td>60</td>
</tr>
<tr>
<td>MICA</td>
<td>5</td>
<td>100</td>
</tr>
</tbody>
</table>
Capacitor

- **Series Resistance**
  - Very small in normal capacitor
  - Power density: very high
- **Leakage Current**
  - Energy dissipates with time
  - Energy only stored for 100s

\[
Q = CV_{emf}e^{-t/RC} \quad t = RC \ln 2
\]

\[
C = \frac{\varepsilon_0 A}{d} \quad R = \rho \frac{d}{A} = \frac{d}{\sigma A} \quad RC = \frac{\varepsilon_0}{\sigma}
\]

<table>
<thead>
<tr>
<th>material</th>
<th>(\sigma[/\Omega m])</th>
<th>(T [s])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor</td>
<td>10^8</td>
<td>10^{-19}</td>
</tr>
<tr>
<td>Semiconductor (doped)</td>
<td>10^3</td>
<td>10^{-14}</td>
</tr>
<tr>
<td>Semiconductor (pure)</td>
<td>10^{-3}</td>
<td>10^{-8}</td>
</tr>
<tr>
<td>Insulator</td>
<td>10^{-13}</td>
<td>100</td>
</tr>
</tbody>
</table>
Electrolytic Capacitor

- Parallel Plate: metal/metal oxide/electrolyte
  - Metal oxide formed by anodic oxidation
    - Typically Al/Al2O3 or Ta/Ta2O5
    - Distance d < 1nm, breakdown self-limiting
  - Roughened Metal electrode
    - Area A many times higher

\[ C = \frac{\varepsilon_0 \varepsilon_r A}{d} \]

\[ A_{\text{electrode}} \neq A_{\text{capacitor}} \]

<table>
<thead>
<tr>
<th>material</th>
<th>(\varepsilon_r)</th>
<th>(E_{bd} [V/\mu m])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al2O3</td>
<td>10</td>
<td>1000</td>
</tr>
<tr>
<td>Ta2O5</td>
<td>25</td>
<td>600</td>
</tr>
<tr>
<td>PTFE</td>
<td>2</td>
<td>60</td>
</tr>
<tr>
<td>MICA</td>
<td>5</td>
<td>100</td>
</tr>
</tbody>
</table>

\[ u(\text{EC}) = 120 \text{Wh/l} \]

But Volume = Vol(Al2O3) only: bad approximation
Ultra Capacitors: Electric-double layer Capacitor

- Electrostatic
- Single layer of molecules as “dielectric”
  - d=1nm
- Porous Activated Carbon as electrode:
  - Extremely large Area

\[ U = \frac{CV^2}{2} \]
\[ C = \frac{\varepsilon_0 \varepsilon_r A}{d} \]

- High Capacitance
  - High energy density
- High R series
  - Reasonable power density
  - Discharge time [seconds]
- Low R leakage
  - Longer storage time
Super-capacitor

- Combination of capacitive and electrochemical storage
- Electric double-layer capacitor $EDLC = \text{Electrolytic capacitor}$
- Pseudo Capacitance $PC = \text{Electrochemical battery}$

$$U = U_{EDLC} + U_{PC}$$

$$U_{PC} = r U_{EDLC}$$

$$U = U_{EDLC} (1 + r)$$

$r \approx 0.1 - 10$
Electrical Energy Storage: Summary

• Fuel Cells
• Batteries
• Capacitors

Ragone plot of energy density versus power density