MEEN 432 –Automotive Engineering

Fall 2026

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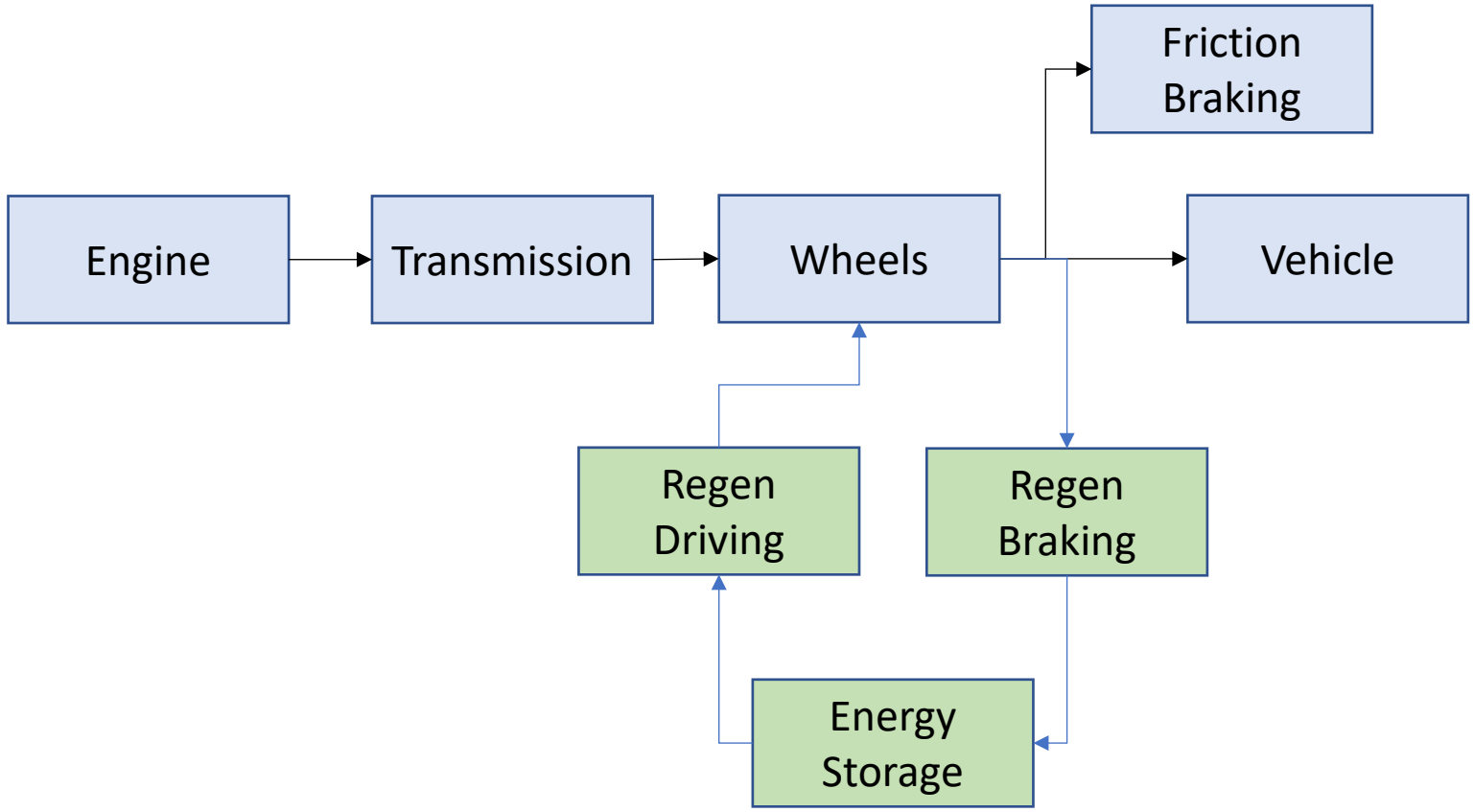
Lecture 13: Energy Storage Devices

- Electro-chemical, Electrical Storage
- Kinetic Storage
- Hydraulic Storage

Regeneration



- We saw the dramatic capability to improve drive cycle energy efficiency by using regeneration
- A critical ingredient is the Energy Storage System

Electric / Electrochemical Storage

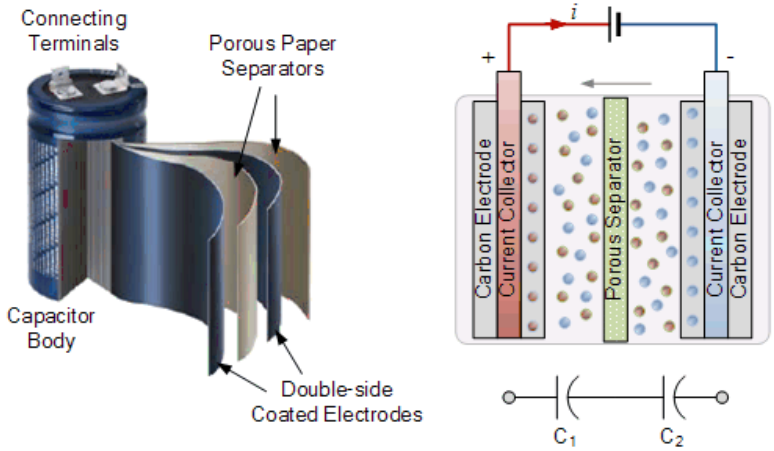
- Electrochemical – You have already seen this – the Batteries
- Ultracapacitors
  - Essentially “capacitors” but designed to have higher capacity, and power density

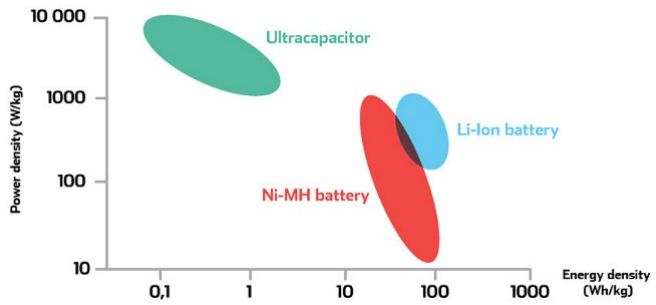
	Ultracapacitor	Battery
Discharge Time	1-30 sec	0.3-3 hrs
Charge Time	1-30 sec	1-5 hrs
Life Cycle	>500,000	500-2000
Efficiency	90-95%	70-85%
Power Density	1000-2000 w/kg	50-200 w/kg
Energy Density	1-10 Wh/kg	
Operating Temp.	-40 – 70°C	0 – 60°C

Up to 250+ Wh/kg for Li Ion

Table 1: Ultracapacitor battery comparison

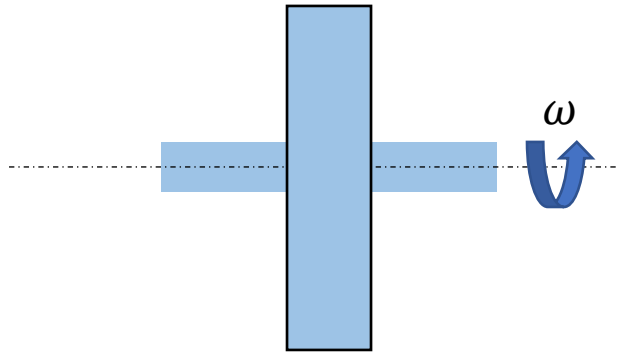
Glavin, M.E., & Hurley, W.G. (2007). Ultracapacitor/ battery hybrid for solar energy storage. 2007 42nd International Universities Power Engineering Conference, 791-795.





Kinetic Storage

- Kinetic Energy Storage
  - $KE = \frac{1}{2} I\ \omega^2$
  - Energy Stored = $\Delta KE = \frac{1}{2} I\ (\omega_2^2 - \omega_1^2)$
- One way to increase stored energy: operate the flywheel at high speeds.
  - Operational speed range from 10,000 rpm to even 100,000 rpm
  - High speeds → friction is a challenge
    - Special bearing designs (e.g. magnetic, contactless bearings)
    - Low pressure (vacuum) operation



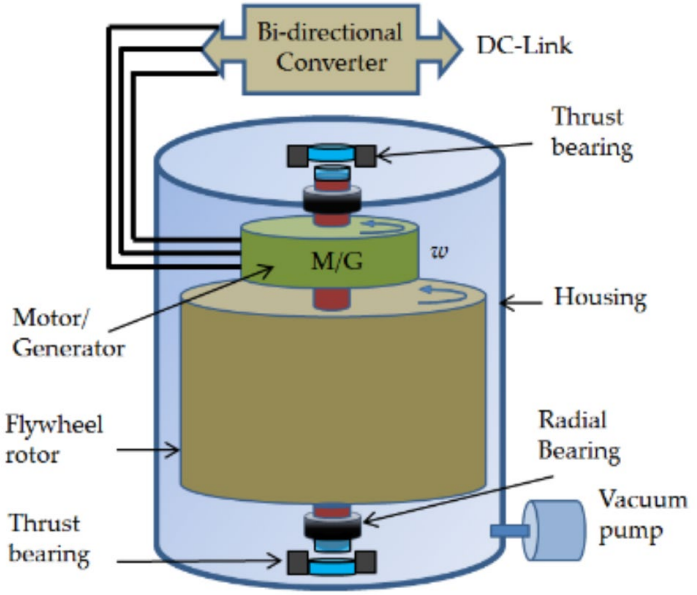


Figure 1. Structure and components of a flywheel.

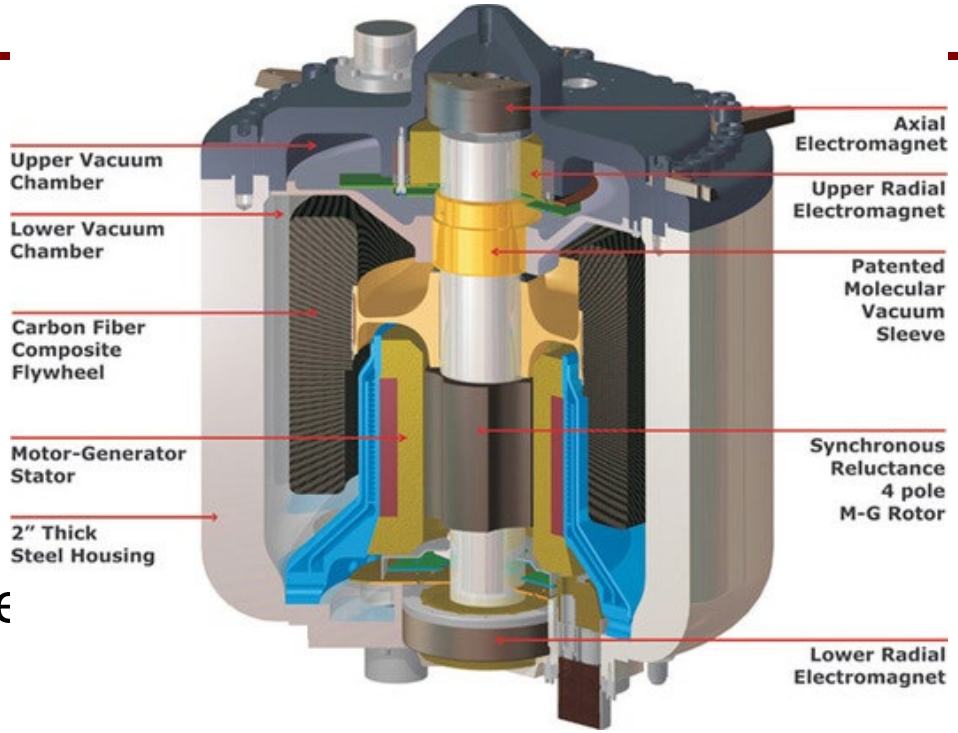
Kinetic Storage

- Another way to increase stored energy: Increase inertia I
- Inertia for a cylinder of height h, radius r , and density ρ is:
  - $I = \frac{1}{2}mr^2 = \frac{\pi}{2}\rho h\, r^4$
  - ➔ to increase inertia, we could either increase the height or the radius.
    - More impactful to increase the radius
    - However, increasing radius has another consequence on the structural integrity of the flywheel:
    - Maximum stress in the cylinder due to centrifugal forces occur at the extremities:
      - $\sigma_{max} = k\rho\omega^2 r^2$ where k is a geometry factor, that depends on the shape of the cylinder (for e.g., solid vs. hollow cylinder)
    - We require that $\sigma_{max} \leq \sigma_{matl}$ where σ_{matl} is the acceptable stress that the material can tolerate before failure

Kinetic Storage

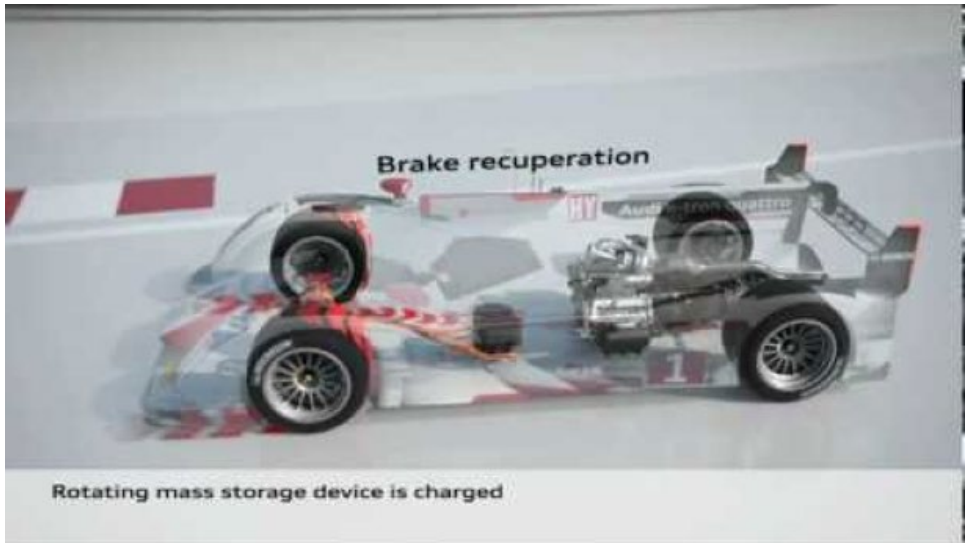
- $E = \frac{1}{2} I\omega^2 = \frac{1}{2}\frac{\pi}{2}\rho h\, r^4\omega^2 = \frac{\pi}{4k} hr^2\sigma_{max}$
  - $\leq \frac{\pi}{4k} hr^2\sigma_{matl}$
- Recognizing that $m = \rho\pi r^2 h\, k_2$ where k_2 is another geometry factor, we have
  - $\frac{E}{m} \leq \frac{1}{4kk_2}\sigma_{matl}$ i.e. Energy Density is limited by the material properties!
- Similarly, with $V = \pi r^2 h$, we have $\frac{E}{V} \leq \frac{1}{4k}\sigma_{matl}$

  i.e. Volume Density is also limited by the material properties

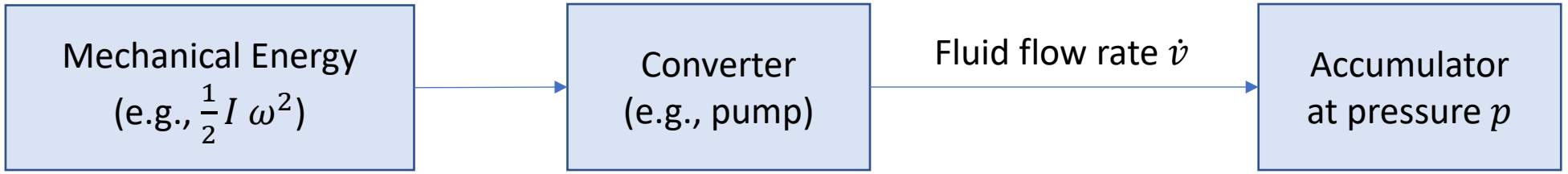


Kinetic Storage

- Flywheels not just theoretical concepts explored in R&D Labs.
  - They have been used for utility scale applications (~20 MW)
  - Also used in automotive applications:
    - The Audi R-18 e-tron quattro has a flywheel regenerative braking system (called the "recuperative braking system")
      - Race car, and won the 2014 Leman's endurance challenge!!
    - This is a "parallel mild hybrid"



Hydraulic Energy



- Instead of storing energy as Kinetic Energy, it is also possible to store energy as potential energy – as compressed fluid
- Rate of accumulation of energy = $p\ \dot{v}$, Or $\Delta E = \int_{v_{min}}^{v_{max}} p\ dv$
- The pressure usually changes during the course of the filling (depends on the design of the system). A "rough" estimate of the storage capacity would be $p_{max} v_{max}$
- Hydraulic Energy Storage Operation

Hydraulic Energy

- Inside EPA - The Hydraulic Hybrid
- How Heavy Duty Series Hydraulic Hybrid Vehicles (HHVs) Work