Energy Transmission and Storage

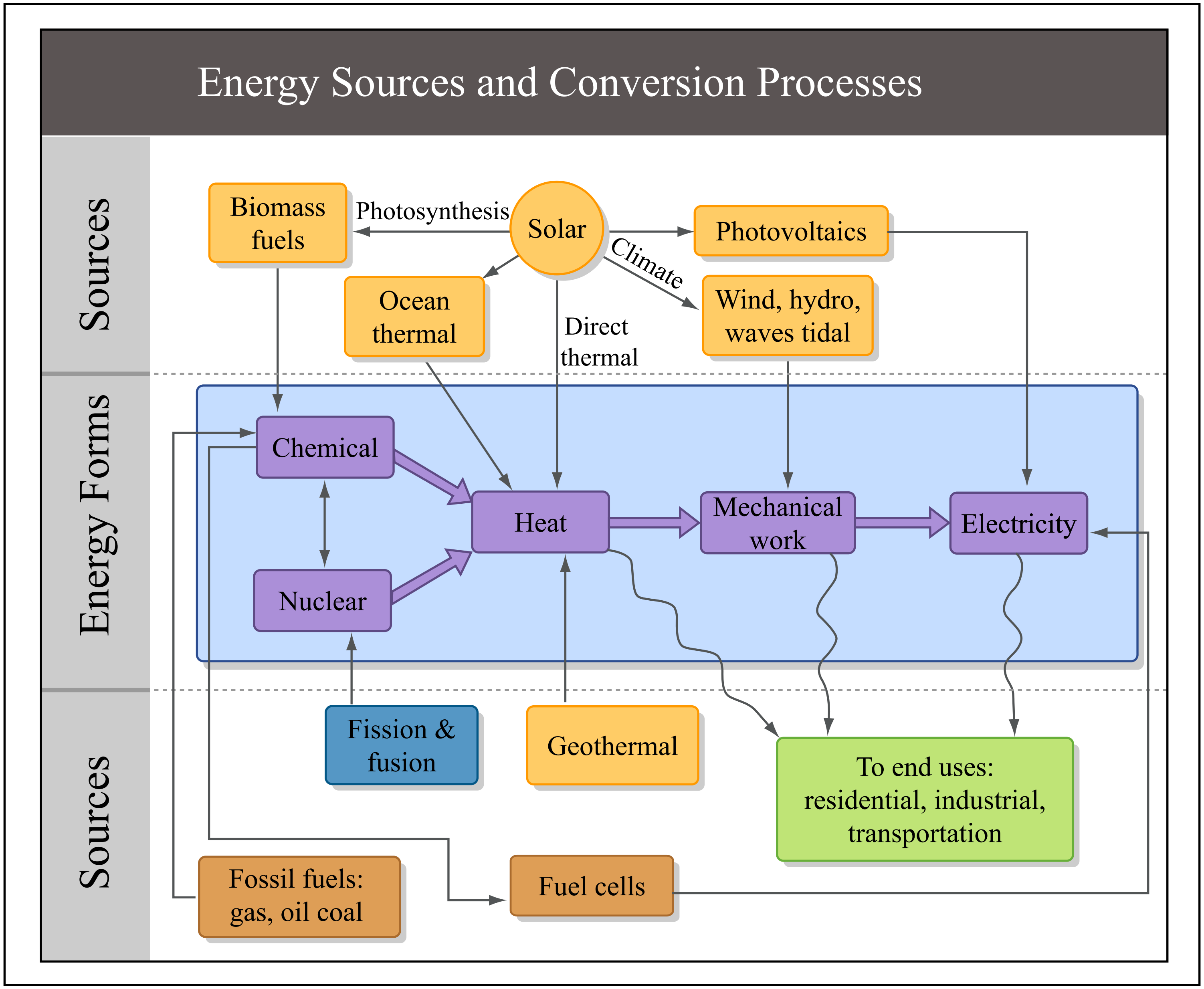
Sustainable Energy
9/23/2010

text readings in Chapter 16
Sections 16.1-16.3, 16.6-16.7

Sustainable Energy – Chapter 16
Storage, Transportation, and Distribution of Energy

Energy Storage – outline of topics

- Why do we need storage?
- Demand and scale requirements
- Technology options
- Performance factors and metrics
- Economic considerations and status
- Storage for Hybrid Electric Vehicles
- Environmental and sustainability issues



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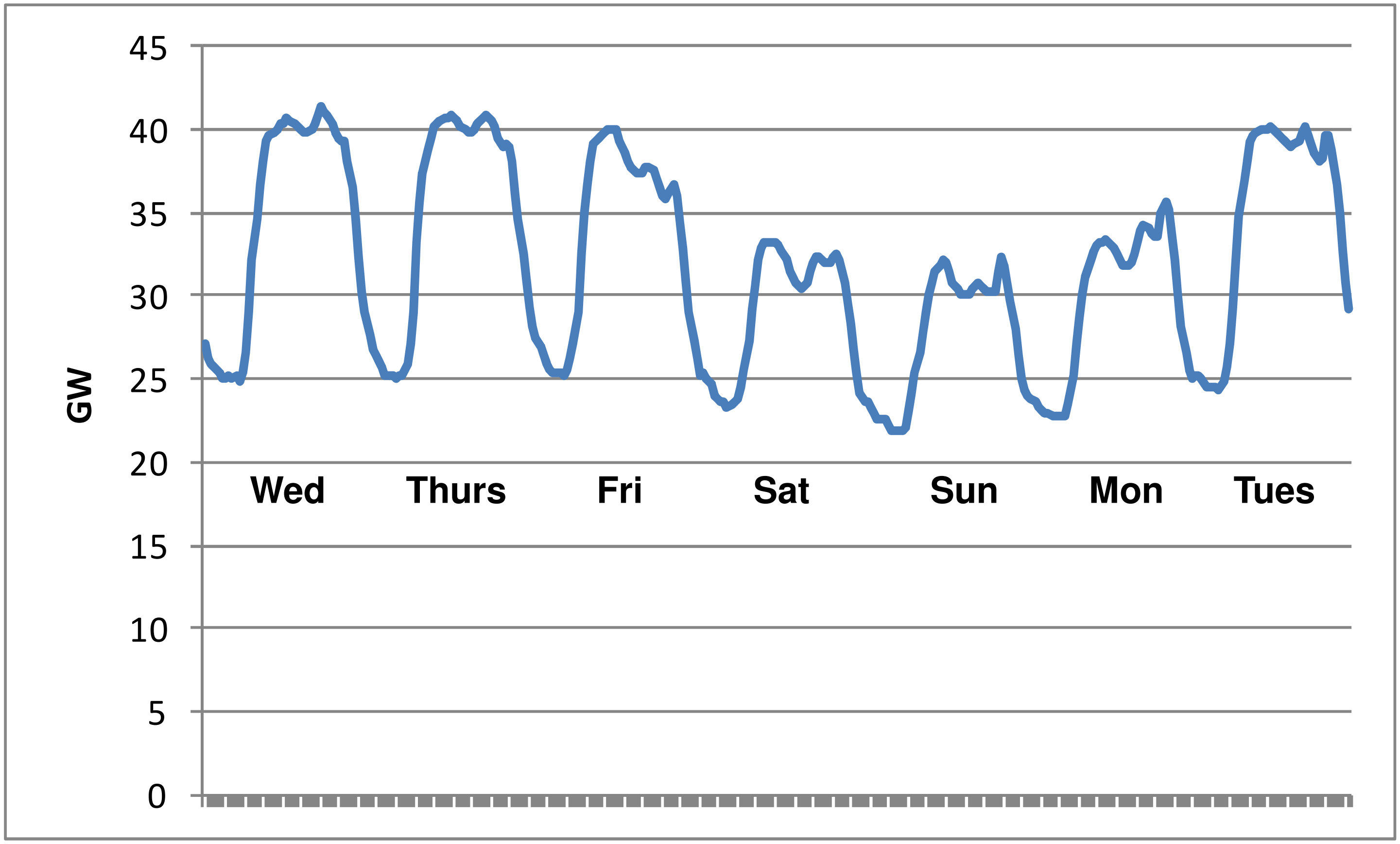
Motivation for storage

- Variations in Energy Demand
- Variations in Energy Supply
- Interruptions in Energy Supply
- Transmission Congestion
- Demand for Portable Energy
- Efficiency of Energy Systems
- Energy Recovery

Variations in Energy Demand



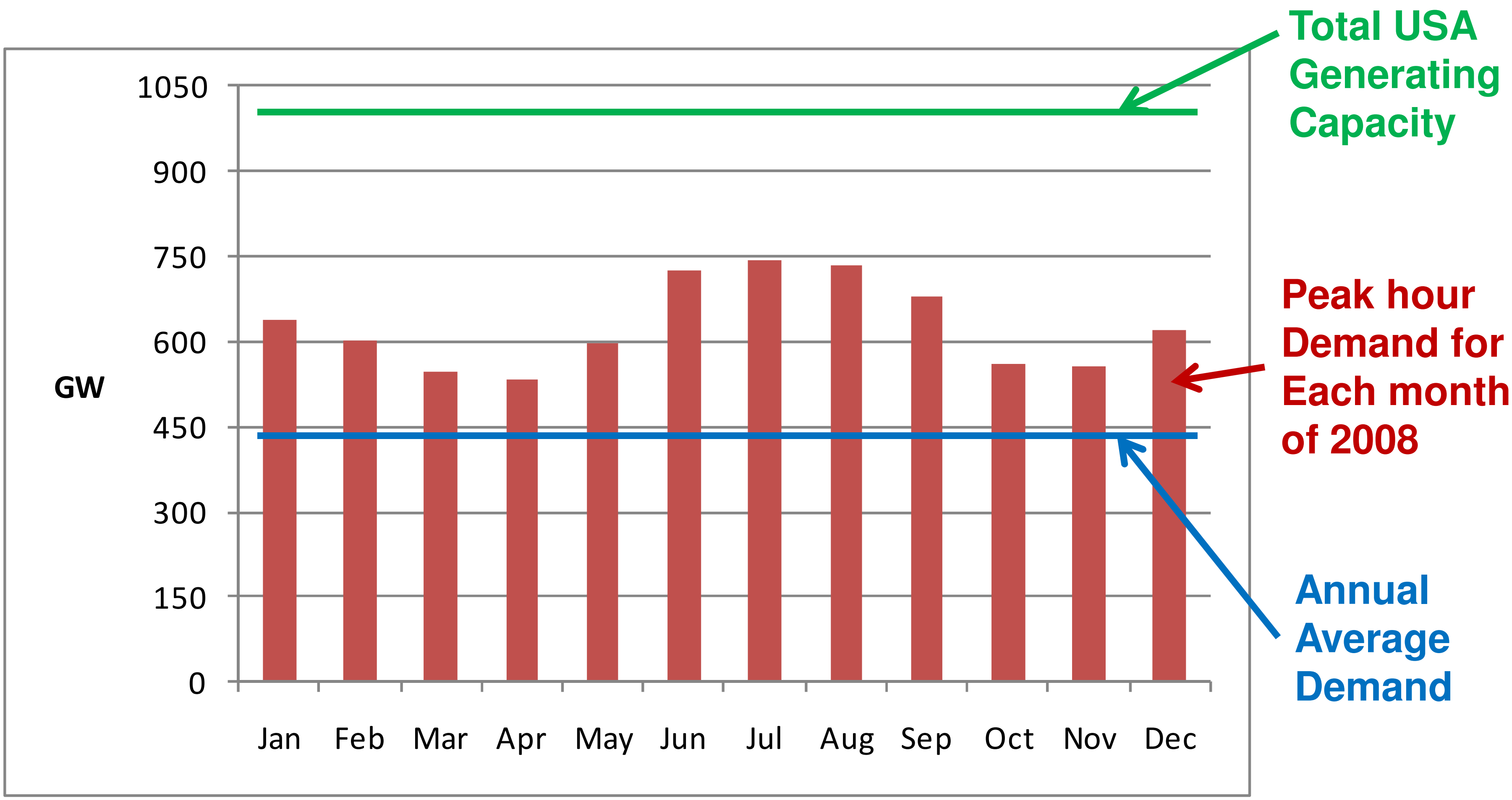
Diurnal variations for UK electricity demand in the last week of August 2010

Source: NationalGrid

Options to Manage Supply & Demand

- Excess capacity plus dispatch system
- Demand management
- Energy storage

Variations in Energy Demand



Source: EIA 2008

Variations in Energy Supply

Example: Nevada Solar One hourly net electricity output

Image removed due to copyright restrictions. Please see slide 36 in Cohen, Gilbert. "Solargenix Energy: The Natural Power for Good." Las Vegas, NV: IEEE, May 16, 2006.

Interruptions in Energy Supply

- Cost to USA from poor power quality $119 to $188 billion/year (EPRI)
- Global market for Uninterruptable Power Supply, UPS systems, is $7 billion/year

Baxter, Richard. *Energy Storage: A Nontechnical Guide*. Tulsa, OK: PennWell, 2006. ISBN: 9781593700270.

Motivation for storage

- Variations in Energy Demand
- Variations in Energy Supply
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Reality Today

- Not much energy storage in US electricity supply system
  - Pumped storage is only 2% of entire generating capacity
- USA system uses excess capacity and dispatch to meet demand
  - Installed capacity is more than twice the average demand
- Lack of storage impedes large-scale deployment of intermittent sources
  - Requires redundancy by conventional power plants

Storage demand requirements – a multiscale challenge

- Electric power
  - for grid 10 to 1000 MW hrs on diurnal and seasonal cycles
  - for non-grid distributed power 10 W to 100 MW
    - battery back up for PV solar and wind, hybrid vehicles
    - farm pumping and other remote applications
    - low-head hydro storage
- UPS systems – kW to MW for seconds to hours
- Thermal energy applications – kW to MW
  - heating and cooling in buildings
  - passive – solar residential
  - active systems – hot water and ice storage
  - industrial process heating – 100 kWh to 100 MWh

Storage technology options and modes

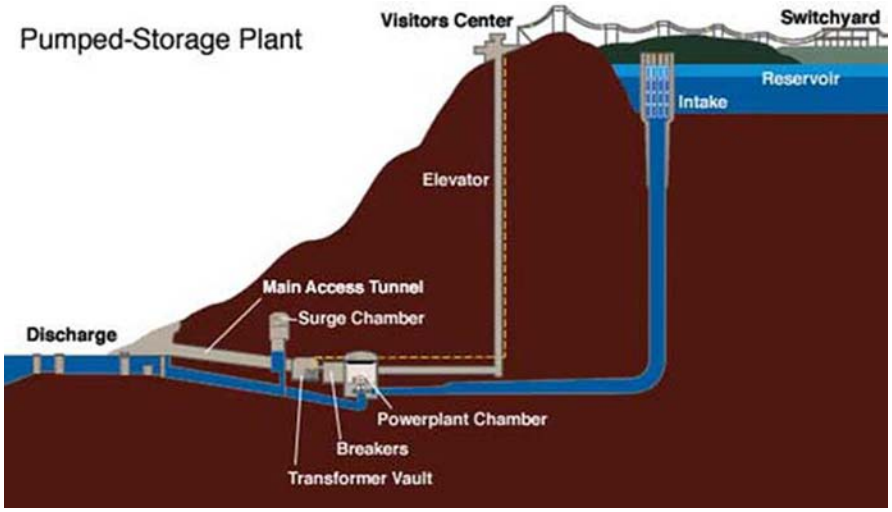
- Potential energy (pumped hydro, compressed air, springs)
- Kinetic energy (mechanical flywheels)
- Thermal energy without phase change
  - passive (adobe) and active (water)
- Thermal energy with phase change (ice, molten salts, steam)
- Chemical energy (hydrogen, methane, gasoline, coal, oil)
- Electrochemical energy (batteries, flow cells)
- Electrostatic energy (capacitors)
- Electromagnetic energy (superconducting magnets)

Pumped Hydro is the conventional large-scale storage option. More than 20 GW capacity in USA today.

Pumped Storage

Advantages:
- Low Cost
- Scale

Disadvantages:
- Siting
- Large footprint



Images from TVA and Adrian Pingstone on Wikimedia Commons.

S. van der Linden / Energy 31 (2006) 3446–3457

Compressed Air electricity storage starting to be deployed at 10+ MW scale

Modern CAES Cycle

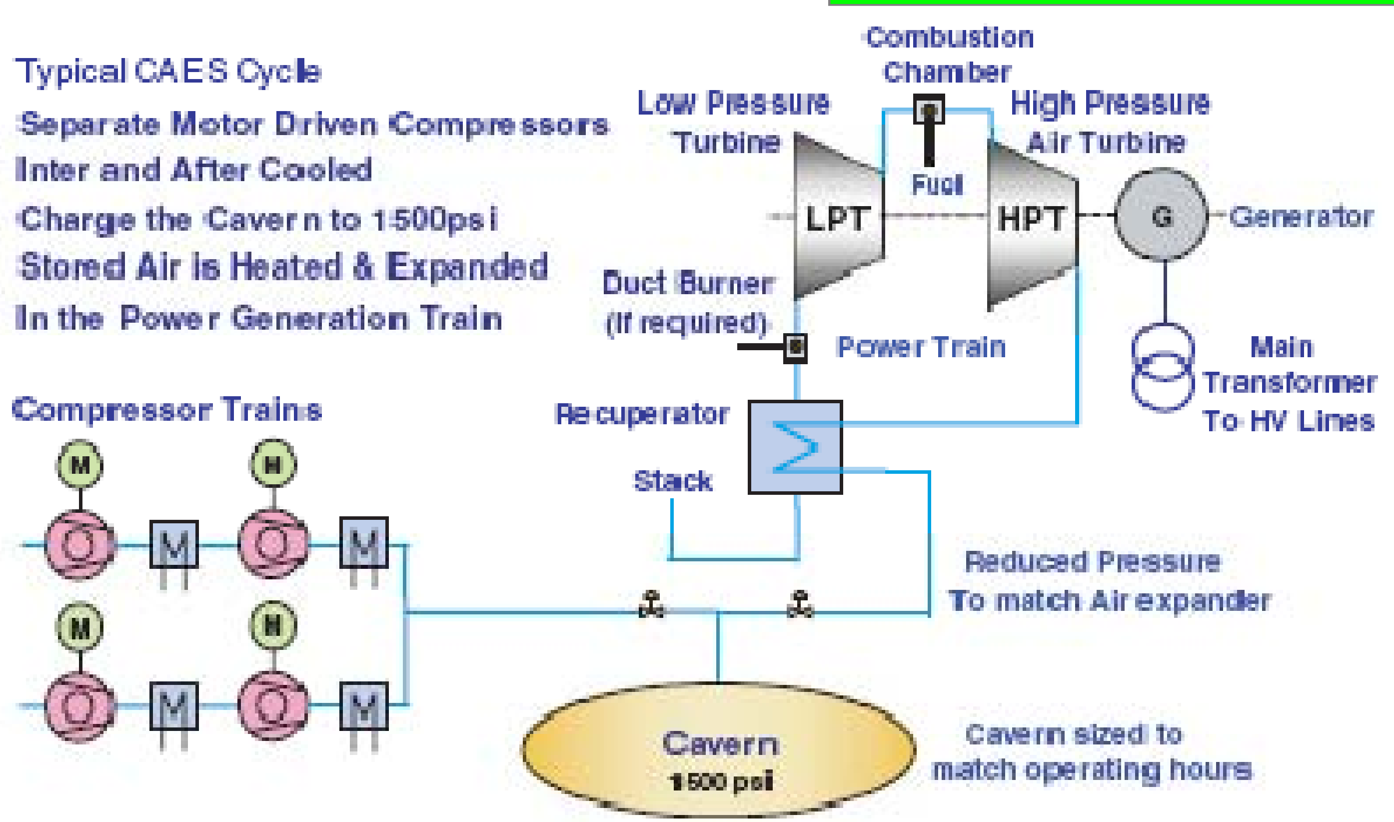


Fig. 1. CAES basic cycle. *Source:* Alstom Power.

Electric energy storage at kW scale: Lead-Acid Batteries

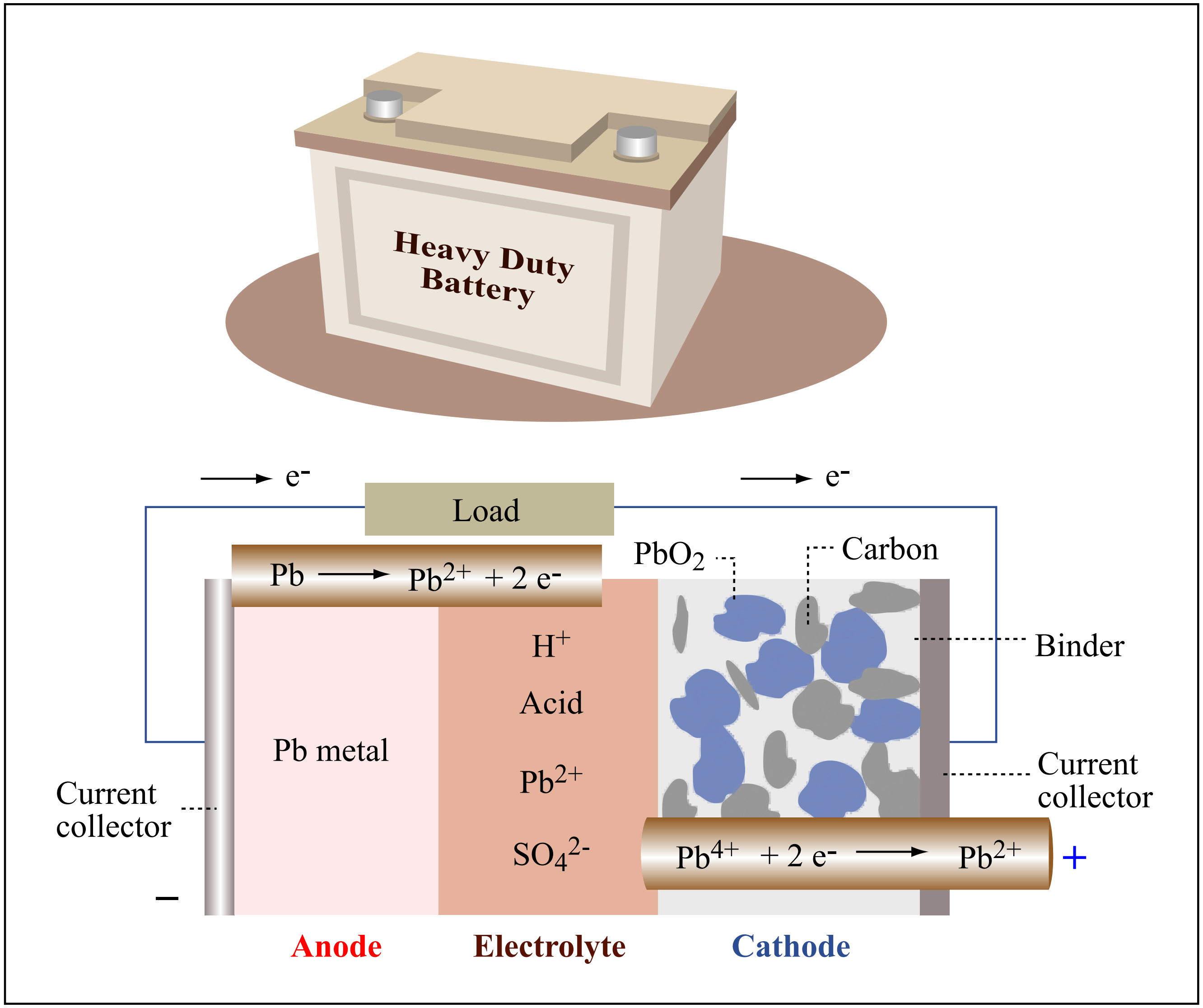


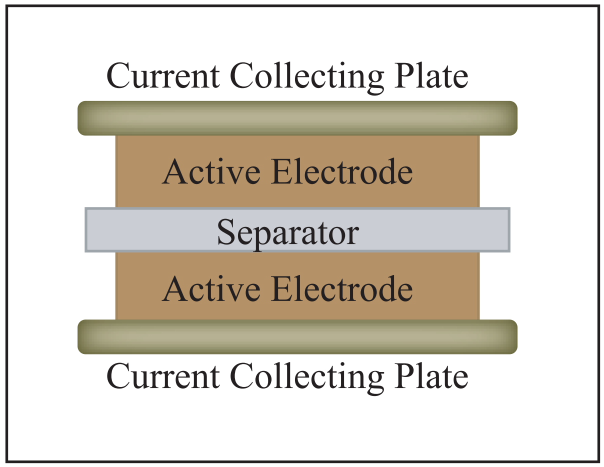
Image by MIT OpenCourseWare. Adapted from Donald Sadoway.

Flywheel Technology:
High Power Density but Low Specific Energy

Image of POWERTHRU Flywheel removed due to copyright restrictions.

Pentadyne GTX Flywheel

Supercapacitor:
High Power Density but Low Specific Energy



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Opportunities:
- Increased effective area
- Enhanced dielectric materials

Superconducting Magnetic Energy Storage (SMES): High Power Density but very expensive

Diagram of American Superconductor's D-SMES system removed due to copyright restrictions.

Advantages:
• Very high efficiency – 95%

Disadvantages:
• Very high Costs

American Superconductor

Performance factors for energy storage systems

- energy capture rate and efficiency
- discharge rate and efficiency
- dispatchability and load following characteristics
- scale flexibility
- durability – cycle lifetime
- mass and volume requirements – footprint of both weight and volume
- safety – risks of fire, explosion, toxicity
- ease of materials recycling and recovery

Performance factors for energy storage systems

- energy capture rate and efficiency
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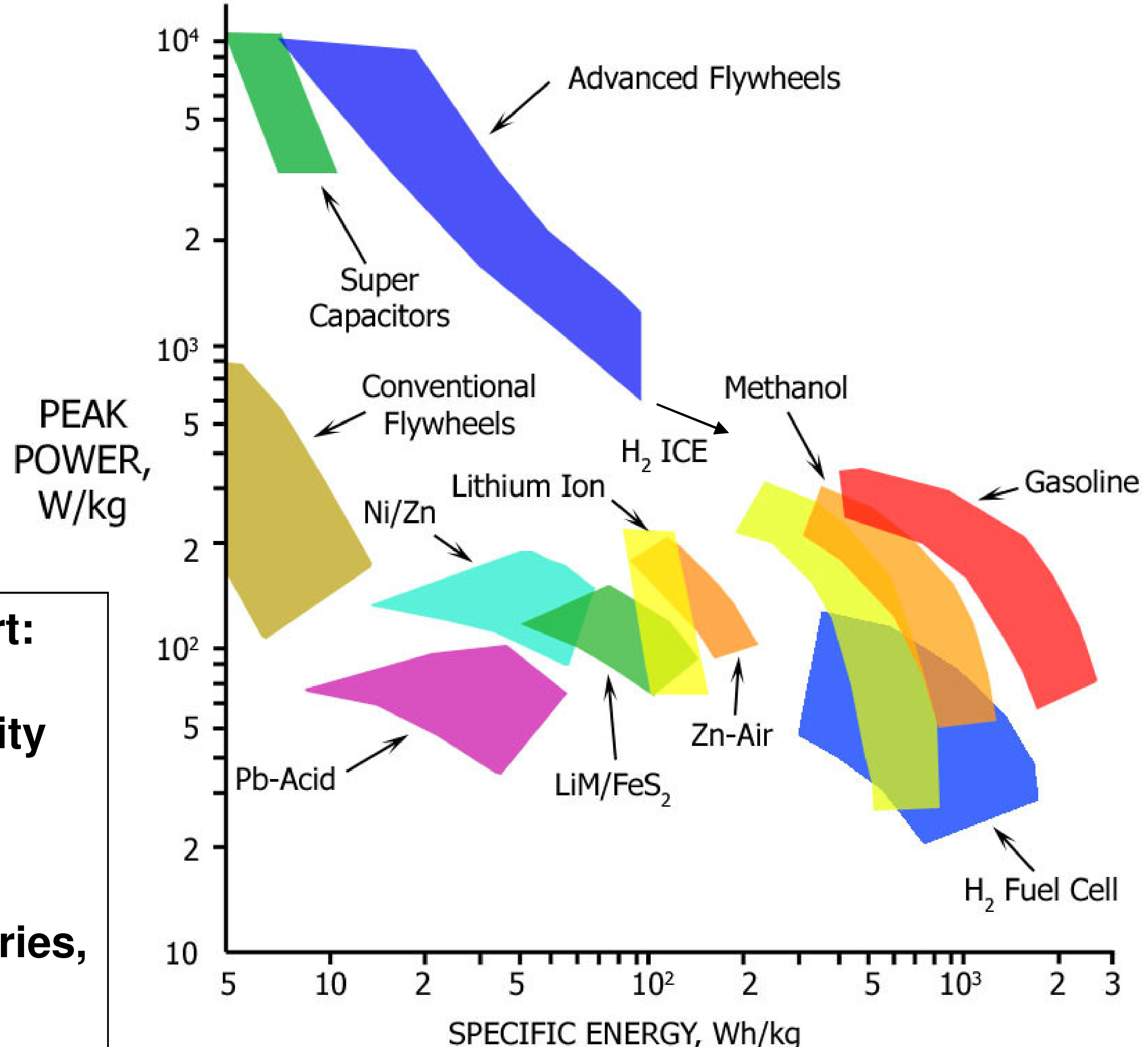
Energy and power density are both important!!

Comparing Storage Technologies – Ragone Plot



Omitted from chart:

Low Energy-Density Storage for Large Stationary Applications: Hydro, Flow Batteries, Compressed Air

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	Kinetic	30-360	Transport
Thermal	Enthalpy (sensible + latent)	Water (100-40^oC) – 250 Rock (250-50^oC) – 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	Supercapacitors	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

Energy storage costs and status

- Capital versus operating costs
- Current commercial systems
  - pumped hydro (widely deployed: more than 20 GWe USA capacity)
  - thermal energy storage (water, ice, passive systems common)
  - chemical energy storage (natural gas, petroleum, solid fuels)
  - batteries – 1 W to 100 kW scale now common for lead acid
- future systems – near term
  - flywheels
  - supercapacitors
  - compressed air
  - Improved batteries Li-ion polymer
- future systems – long term
  - hydrogen storage for vehicles and distributed power
  - SMES
  - Advanced batteries and fuel cells

Cost projections for energy storage systems

System	Typical Size Range MWe	$/kWe	$/kWh
Pumped hydropower	100-1000	600-1000	10-15
Batteries Lead acid Nickel metal hydride Li-ion	 0.5–100 0.5-50 0.5-50	 100-200 200-400 200-400	 150-300 300 500
Mechanical flywheels	1-10	200-500	100-800
Compressed air energy storage (CAES)	50-1,000	500-1,000	10-15
Superconducting magnetic energy storage (SMES)	10-1,000	300-1,000	300-3,000
Supercapacitors	1-10	300	3,600

Storage Challenges for Hybrid Electric Vehicles (HEV)

Photo by IFCAR on Wikimedia Commons.

Energy Storage for an HEV

- Batteries
  - Lead-acid
  - Lithium-ion
  - Nickel-metal hydride
- Ultracapacitors
- Flywheels

Energy Storage in HEV's: Technical Challenges

- Low Specific Energy: Batteries are Heavy!
- Cycling Lifetime
  - Many batteries lose capacity on each charge/discharge
  - Can ameliorate by not charging/discharging all the way
- Power Density
  - Existing batteries limit ability to absorb energy from regenerative braking
  - Opportunities for super capacitors or flywheels
- Charging battery-only vehicles rapidly

Environmental issues for energy storage

- Land use
  - inundation caused by hydro projects
  - thermal (hot/cold) island local effects
  - underground storage systems have special geotechnical requirements to insure safe operation
- Materials toxicity disposal and recycle – e.g. batteries
- Durability and lifetime of entire system
- Emissions during manufacture and operation

Relevance of energy storage to sustainability

- Essential for effective use of intermittent renewable energy resources – including solar, wind, biomass, and hydro
- Storage can provide quality energy when it is needed
- Critical for high efficiency hybrid ICE/electric and fuel cell vehicles
- Full life cycle environmental impacts must be considered in tradeoffs -- especially for pumped hydro and batteries
- Continuing advances in technology and deployment will lower costs to enable broader participation for electric and thermal storage at scales from 10 W to 100 kW for seconds to 100 hours
- Major innovations are needed for new systems to have an impact at largest scale (> 100 MW, >5 GWh)

Energy Transmission – outline of topics

- Options and costs
- Infrastructure and scale
- Issues

Graph removed due to copyright restrictions. Please see Fig. 16.7 in Tester, Jefferson W., et al. *Sustainable Energy: Choosing Among Options*. MIT Press, 2005. ISBN: 9780262201537.

There are many options for energy transport:

- **For electricity -- we have**
  - **wires (AC and DC)**
- **For fossil fuels gas/oil/coal we have --**
  - **pipelines**
  - **trains**
  - **trucks**
  - **ships**
- **For hot or cold water, steam we have --**
  - **pipelines**

Costs scale with directly with distance; $0.20-$0.60/bbl/1000 mi for oil; 10x more for electricity & coal. Transport very significant cost for coal & gas far from markets. LNG affordable to ship by sea, but very expensive to liquefy in first place.

USA Energy Transport Infrastructure is large and deeply entrenched

400,000+ miles of gas and oil pipelines
160,000+ miles of high voltage transmission lines

Image by SystemF92 on Flickr.

Image by jrawle on Flickr.

Energy transmission – scale and performance

- Scale of energy transmission is Enormous!
  - 250,000 mi of gas pipelines of various sizes in the US supply about 30 EJ per year
  - supertankers carry 200,000 to 300,000 ton (1.4 to 2.1 million bbl of oil) payloads long distances very efficiently -- 2000+ miles
  - Oil pipelines can extend for long distances (1000 or more miles) and have high capacity

    e.g. max flow of 2.1 million bbl per day of crude over 900 miles in 1988 from Prudhoe Bay to Valdez, Alaska
  - 160,000+ miles of electric transmission lines in the US >250 kW
  - a unit train carries 100,000+ tons of coal.
- Many options, but costs, energy consumption increase with distance

- Environmental Impacts

  -Oil Spills
- Security, Political, and Right-of-Way issues

Additional transmission issues

- **Security/Politics**
  - Russian gas pipelines to Europe
  - How to get Caspian oil to market?
  - Many places in world rely on a single pipeline.
  - NIMBY concerns about shipping nuclear materials.
- Pipelines, LNG, Electric Grid, Rail require **huge upfront capital investments**
  - Investors taking a lot of risk, want guarantees
  - Supply resource must last many years
- Often hard, expensive to **secure right-of-way**
  - To add new power lines or rail into cities
  - May not be worth it for small projects.
  - Complex regulations and permitting for electric utilities, pipeline operations, rail.

Assessing Storage/Transmission Issues for New Energy Options: Stranded Gas

– Efficiency:

$\eta_{gas\text{-}to\text{-}LNG}(1\text{-}k_{ship}d_{ship})(1\text{-}k_{pipe}d_{pipe})\eta_{gas\text{-}to\text{-}electricity}(1\text{-}k_{wire}d_{wire})$

– Economics: net present value!

Cost: NPV of LNG plant, terminals, ships, pipeline, power plant, transmission lines, plus cost of the gas, plus operating/maintenance

Revenue: NPV of the electricity

Size of resource is crucial: need many years of revenue to pay back the capital costs

Assessing Storage/Transmission Issues for New Energy Options: Biomass

- Efficiency:

  $(1\text{-}k_{truck}d_{truck})\eta_{biomass\text{-}to\text{-}fuel}(1\text{-}k_{pipe}d_{pipe})$

Can dramatically improve efficiency by locating conversion plant next to waste heat source, but large losses in trucking biomass to this location.

- Economics:
  - *Cost:* NPV of conversion plant, trucks, pipeline, labor to collect biomass.

  NOTE: will conversion plant be used year-round? If so, how to store the biomass from the harvest? If not, low utilization rate of conversion plant.

  Revenue: NPV of delivered fuel stream

Energy storage and transmission – summary

- 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, supercapacitors, and SMES)
- Importance of both power and energy density (weight and/or volume) e.g. Ragone plot of specific power versus specific energy
- Transmission many options but costs increase with distance while performance decreases
- Environmental Impacts and sustainability issues

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