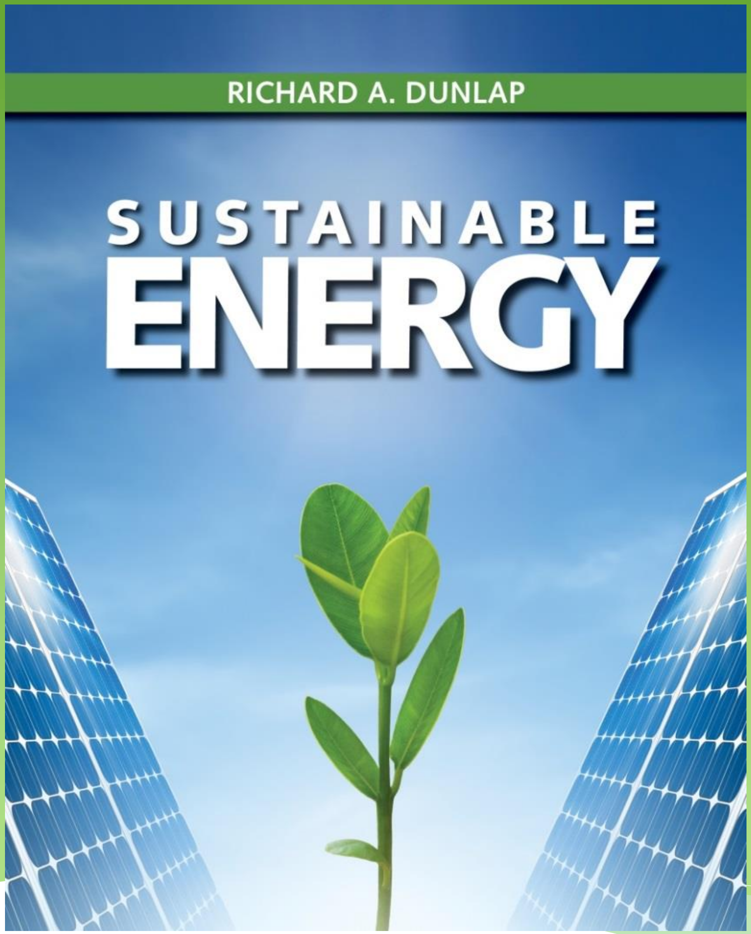
Sustainable Energy



Chapter 18

- Energy Storage

CENGAGE Learning

Learning Objectives

- The need for energy storage.
- Pumped hydroelectric storage and its use.
- The properties of compressed air.
- The use of compressed air for energy storage.
- Energy storage capabilities of flywheels and the relevance of materials properties.
- Properties of superconductors and the history of their development.

Energy storage

Energy storage is necessary because energy is not always produced

- when it is needed
- where it is needed

This is particularly true for many alternative sources of energy.

Types of energy storage

- Residential thermal energy storage (covered in Chapter 8)
- Batteries (covered in Chapter 19)
- Hydrogen (covered in Chapter 20)
- Other large scale electricity storage methods (covered in this chapter)

Supply and demand

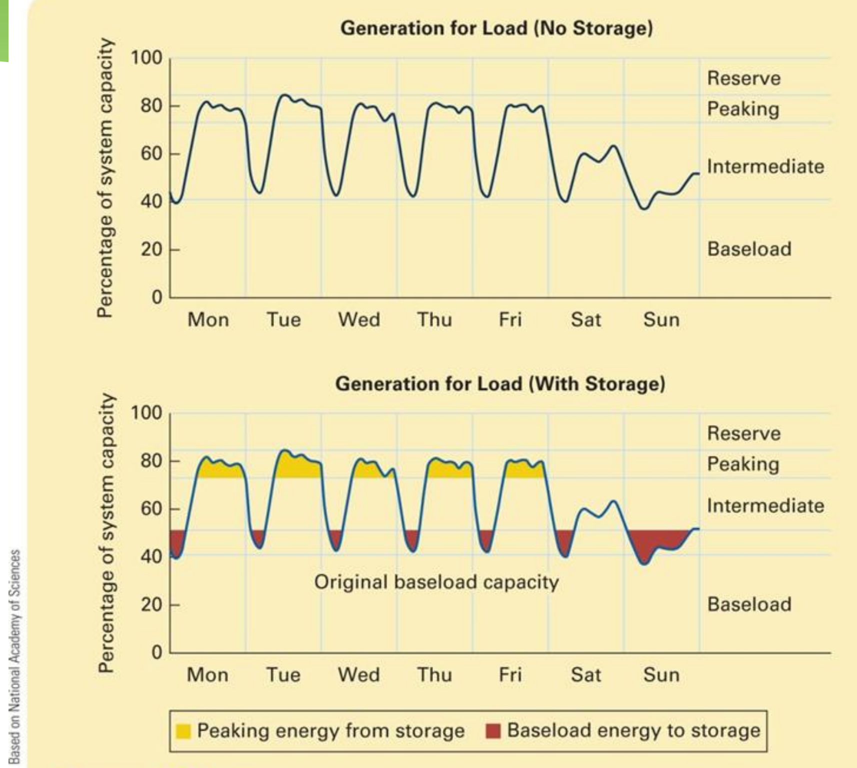


Figure 18.1: Typical electricity demand throughout the week. Daily variations are seen during weekdays as well as variations between weekdays and the weekend.

Typical electricity demand throughout the week showing periods of storage during low demand and periods of stored energy use during peak demand

Methods of energy storage

- Pumped hydroelectric
- Compressed air
- Flywheels
- Superconducting Magnetic Energy Storage (SMES)

Pumped hydroelectric storage

Water is pumped to an elevated reservoir during periods of low demand using excess electricity and electricity is generated from the potential energy of the water during periods of high demand.

Analysis of pumped hydroelectric power

Potential energy of water in reservoir is

$$E = mgh \qquad (18.1)$$

Power generated in terms of flow rate, dV/dt,

$$P = \frac{dE}{dt} = gh\frac{dm}{dt} = \rho gh\frac{dV}{dt} \qquad (18.2)$$

It is preferable to have high head and low flow rate (rather than vice versa) because this minimizes the size of the penstock and maximizes the energy per unit mass of water.

Schematic of pumped hydroelectric facility

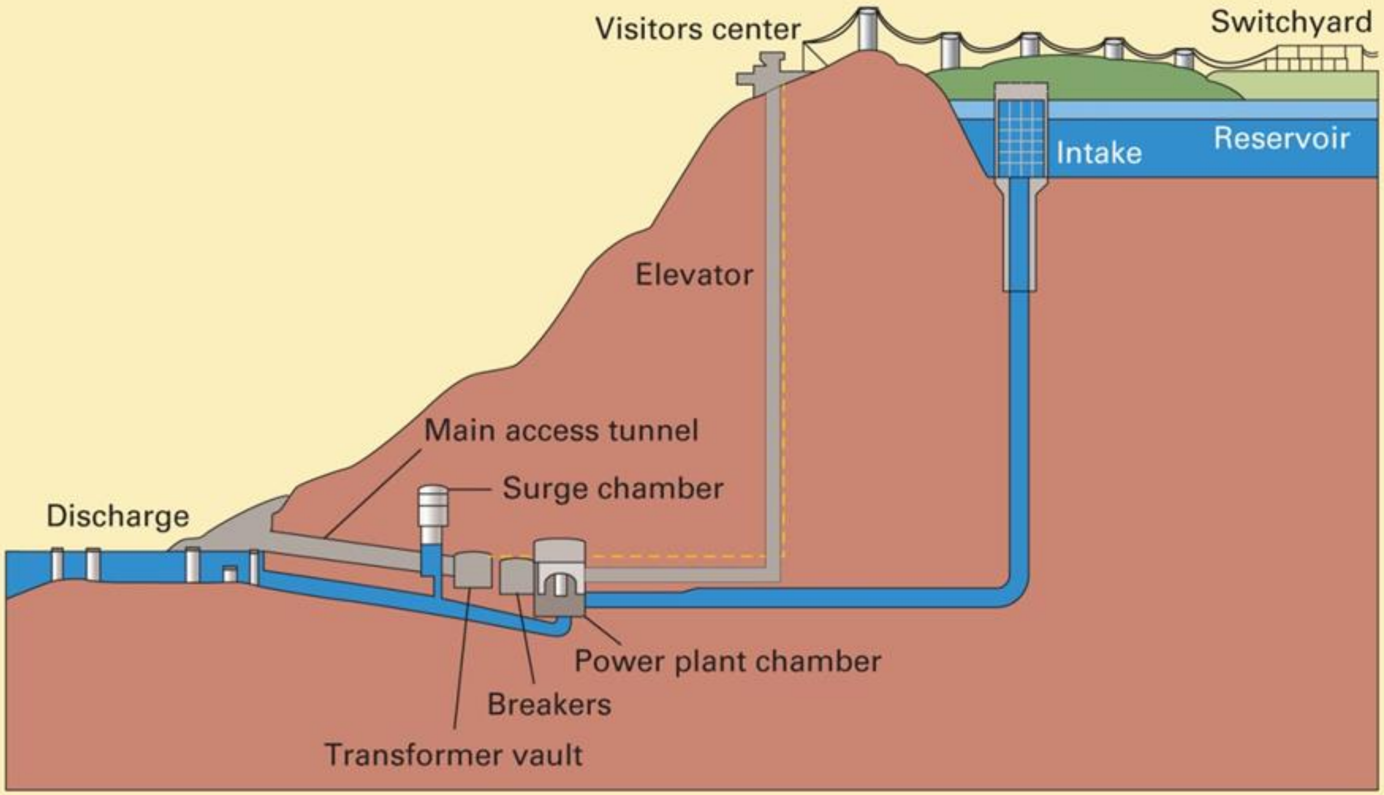


Figure 18.2: Diagram of pumped hydroelectric facility.

Based on http://www.tva.gov/power/pumpstorart.htm, http://large.stanford.edu/courses/2010/ph240/boysen2/images/f2big.gif, http://www.consumersenergy.com/uploadedImages/CEWEB/OUR_COMPANY/Electricity/Pumped_Storage/how-the-ludington-pumped-storage-facility-works.gif?n=2055

Use of pumped hydroelectric power

Most common method of storing large amounts of electrical energy for the grid

Does not have to be associated with traditional hydroelectric generation.

Ideal for storage for variable alternative technologies

Largest facility is in Bath County, VA
Maximum capacity 2772 MW_e for up to 11 hours

Advantages of pumped hydroelectric power

Advantages

- Large capacity
- High efficiency (about 80% overall)
- Reliable technology
- Low maintenance
- Quick response to demand
- Long storage time

Disadvantages

- High infrastructure cost
- Appropriate geography required

Compressed air energy storage

Excess electricity can be used to run pumps to compress air during low demand periods and the compressed air can be used to run turbines to generate electricity during high demand periods.

Analysis of compressed air energy storage

Energy available in compressed air for initial and final pressures P_i and P_f,

$$E = nRT \cdot \ln\left(\frac{P_f}{P_i}\right) \quad (18.3)$$

Approximate energy per unit volume in kJ/m^3 is

$$E/V = 100 \cdot \ln\left(\frac{P_f}{P_i}\right) \quad (18.4)$$

Requirements for compressed air energy storage

Requires a large container of chamber capable of withstanding high pressure

Most practical containers are underground caverns such as former salt mines

Schematic of compressed air facility

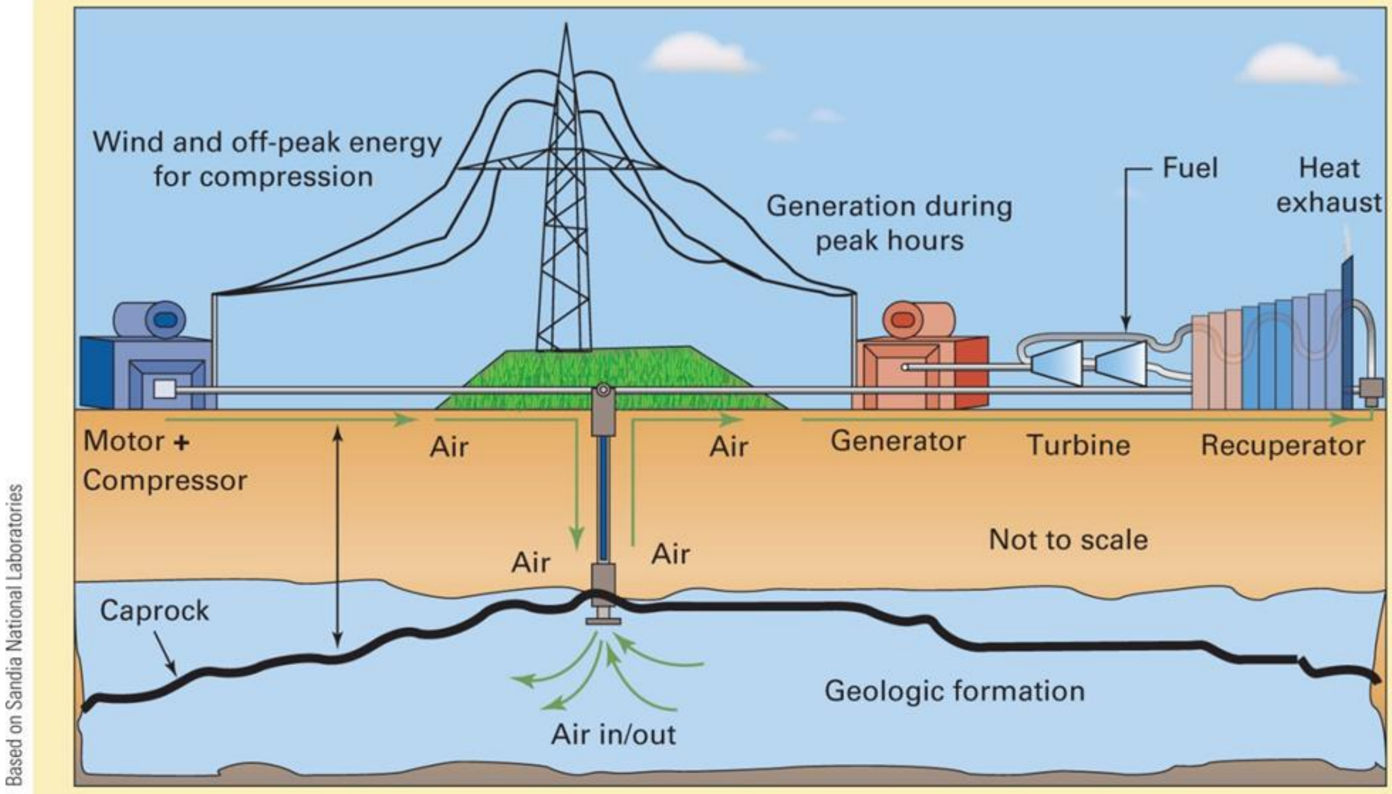


Figure 18.3: Schematic of typical large-scale compressed air energy storage system.

Compressed air energy storage facilities

Two major facilities exist worldwide

- Huntorf, Germany 290 MW_e capacity
- McIntosh, Alabama 110 MW_e capacity

Huntorf compressed air facility

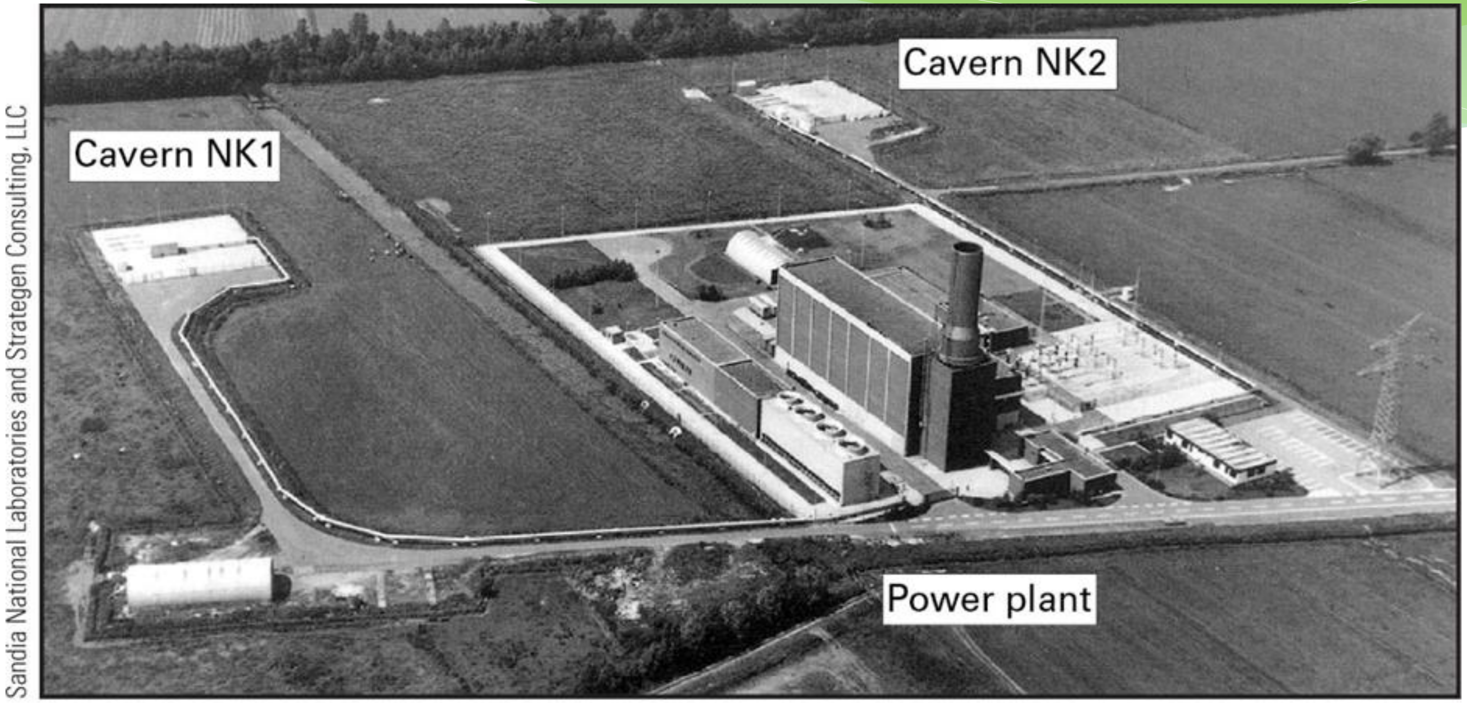


Figure 18.4: Huntorf compressed air energy storage facility.

Flywheels

Rotating objects have energy associated with their rotational motion

$$E = \frac{1}{2} I\omega^2 \qquad (18.6)$$

where I is the moment of inertia and ω is the angular frequency.

Stored energy can be maximized if I is large and/or if ω is large.

Moment of inertia

The moment of inertia of an object depends on its mass, its dimensions and its geometry. For a cylindrically symmetric object

$$I = kmr^2 \qquad (18.8)$$

The constant *k* for some simple geometries is shown.

Table 18.1: Constants, *k*, from equation 18.5 for different geometries.

geometry	*k*
disk	1/2
ring	1
solid sphere	2/5
spherical shell	2/3

Example of flywheel energy

A disk of steel with a diameter of 0.85 m and a mass of 400 kg rotates at an angular frequency of 40 s^{-1}.

This is a good description of a wheel on a freight train traveling at 100 km/h.

The rotational energy content of this disk is sufficient to light a 60 W light bulb for about an hour.

Storing a reasonable amount of energy would require a very large flywheel rotating at a very high frequency.

Ideal flywheel geometry

The table shows that a ring gives the best value of k and represents a common flywheel design.

The maximum rotational frequency of a flywheel will be limited by the strength of the flywheel material.

Practical limits for a flywheel energy storage capacity is probably in the range of 100 kWh, much less than pumped hydroelectric or compressed air.

Characteristics of flywheel energy storage

Advantages
- Compact
- Efficient

Disadvantages
- Minimal capacity
- Losses due to friction (~1% per hour)

Potential uses

- Short term backup to even out power fluctuations due to variability of alternative energy sources

Superconducting Magnetic Energy Storage (SMES)

Electric current can circulate indefinitely in a superconducting coil without loss.

Electrical energy can be stored by injecting current into the superconducting coil and extracting it as needed.

Energy storage in a coil

The energy stored in a current circulating in a coil is

$$E = \frac{1}{2} L I^2 \tag{18.12}$$

The inductance of the coil is

$$L = f r N^2 \tag{18.13}$$

where the geometry factor f is

$$f = \frac{3.9 \times 10^{-5}}{\left[9 + \frac{10l}{r}\right]} \mathrm{J/(m \cdot A^2)} \tag{18.14}$$

Superconductivity and magnetism

The superconductivity of a material can be destroyed by temperature or a magnetic field.

Type I superconductors undergo a transition from the superconducting to the normal state as a function of temperature and magnetic field.

Type II superconductors undergo a transition from the superconducting state to a mixed state and then to a normal state.

Magnetic field can result from current flowing through superconductor.

Critical temperatures and fields for Type I and type II superconductors

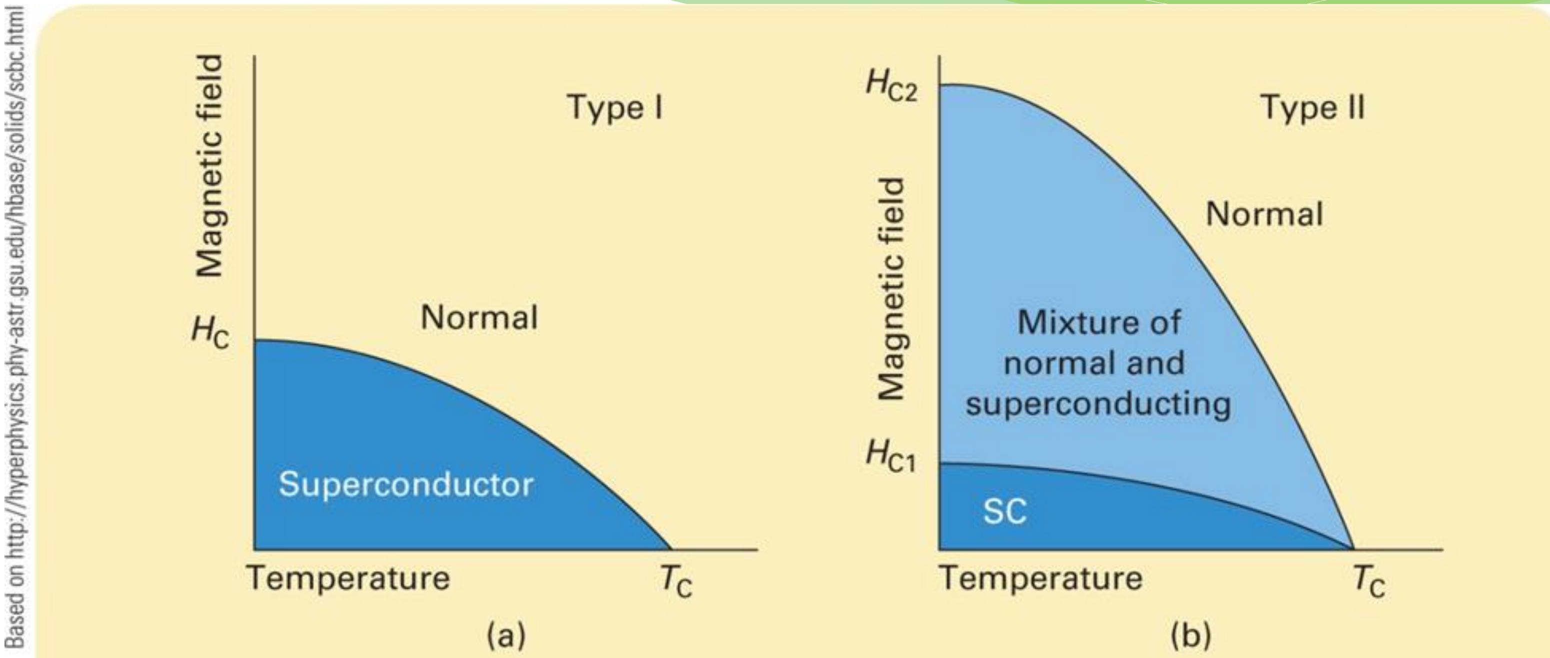


Figure 18.8: Temperature dependence of the critical field in (a) Type I superconductors and (b) Type II superconductors.

High temperature superconductors

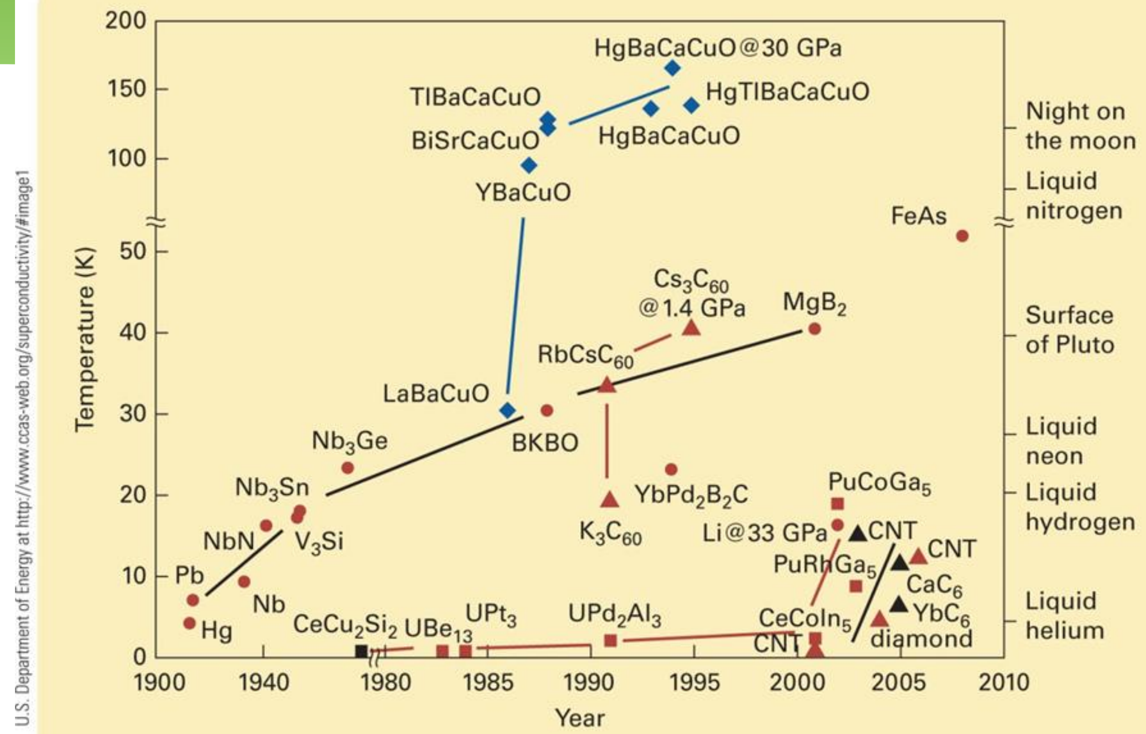


Figure 18.7: Progress in increasing T_C for superconductors. The symbols represent different classes of materials: carbon compounds (triangles), rare earth and actinide compounds (squares), perovskites (diamonds), and transition metal and alkali compounds (circles).

First discovered in 1986, critical temperature has increased since then

Critical properties of some superconductors

Table 18.3: Properties of some superconducting materials. (T = tesla)

material	type	T_C (K)	$H_C(0)$ (T)	$H_{C2}(0)$ (T)
Sn	I	3.7	0.03	—
Pd	I	7.2	0.08	—
Nb	II	9.3	—	0.4
NbTi	II	10	—	12
Nb_3Sn	II	18	—	25
$YBa_2Cu_3O_7$ (YBCO)	II	93	—	168
$Bi_2Sr_2Ca_2Cu_3O_{10}$ (BSCCO)	II	110	—	200

High temperature superconductors have high critical temperature and critical field

Prototype SMES systems

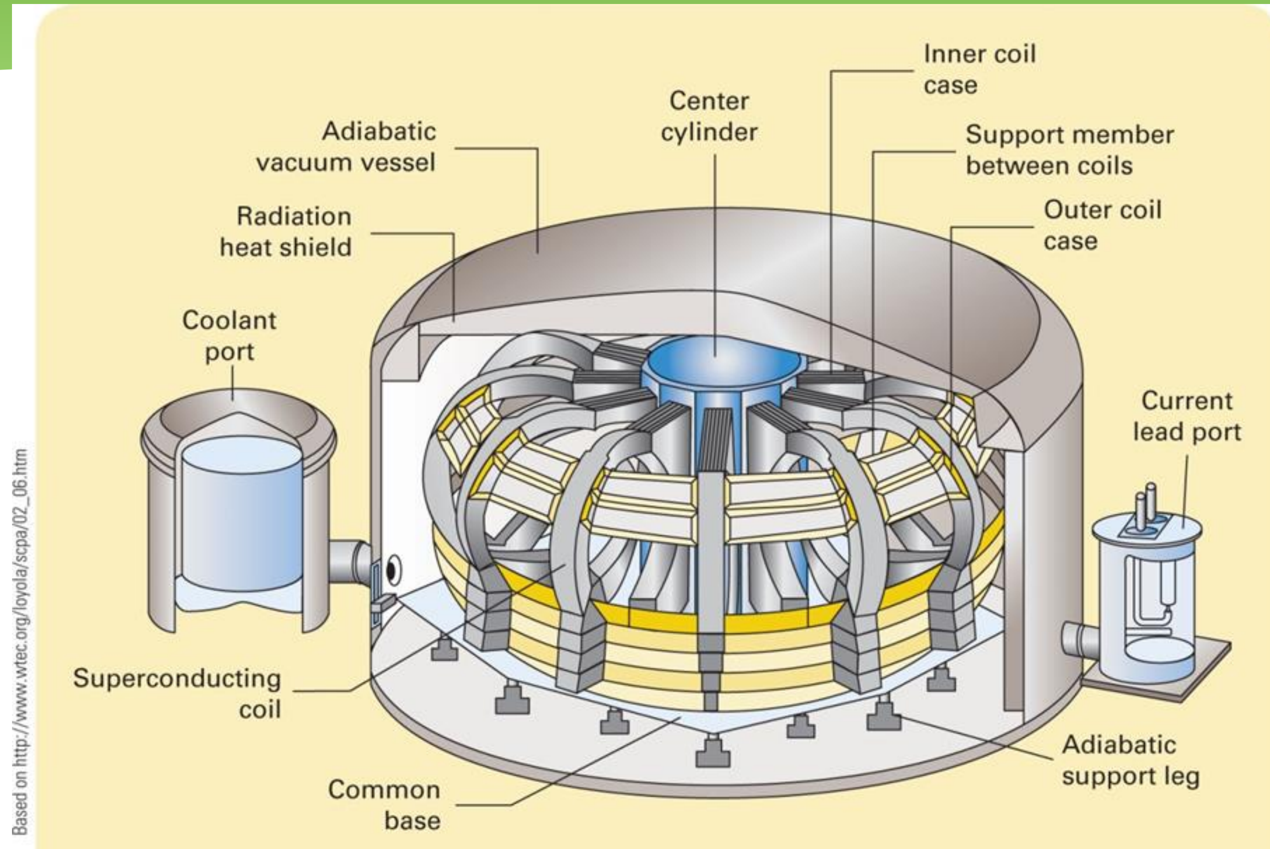


Figure 18.9: Design of a SMES system for grid stabilization.

Have found applications for grid stabilization

Summary

- Energy storage is important to satisfy grid demand fluctuations
- Pumped hydroelectric is the most commonly used method for large scale grid storage
- Compressed air energy storage is also a viable technique that has been utilized
- Flywheels can store energy, but on a smaller scale than pumped hydroelectric or compressed air
- Flywheels are most applicable for stabilizing short term grid fluctuations
- A superconducting current can store energy
- High critical temperatures and high critical magnetic fields are desirable characteristics of a superconductor for energy storage
- SMES has found applications for grid stabilization