John Andrews & Nick Jelley

Lecture 10:

Electricity and energy storage

Electric power generation

Electric generators convert **rotational kinetic energy** into **electrical energy**.

By Faraday's laws of electromagnetic induction, an **alternating current** I arises when a loop of wire rotates in a magnetic field B, given by

$$I = (NBA\omega/R)\sin\omega t$$

where N = no. of turns of wire, A = cross-sectional area of loop, R = resistance, ω = angular velocity.

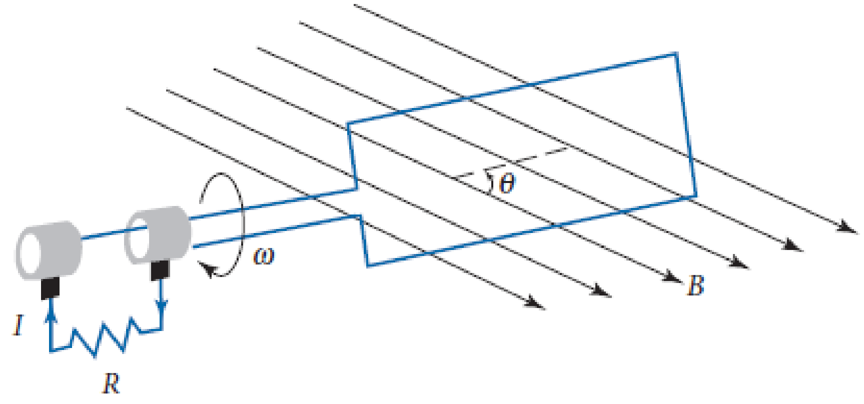


Fig. 10.1 Loop rotating in a uniform magnetic field.

In a **power station**, the generator consists of coils mounted on rotating shaft (= **rotor**), connected to turbine. Rotor surrounded by stationary coils wound around iron core (= **stator**).

Frequency of generation (50 Hz in Europe, 60 Hz in N & S America) set high enough to avoid flickering of electric lights.

OXFORD UNIVERSITY PRESS

Electricity transmission

Electricity is usually generated as **3-phase current**, which delivers constant power through a resistive load and requires only about **75% of the material** to conduct the same power as single phase.

For transmission over large distances, the **transmission voltage** is chosen such as to minimise the loss of power by the resistance of the transmission line.

For a wire of cross-sectional area *A*, length *L*, resistivity *ρ*, conducting a current *I* at an operational voltage *V*, the fractional loss of power is

$$\frac{\Delta P}{P} = \rho \frac{I}{A} \frac{L}{V}$$

Hence, the transmission voltage needs to be **as large as possible**.

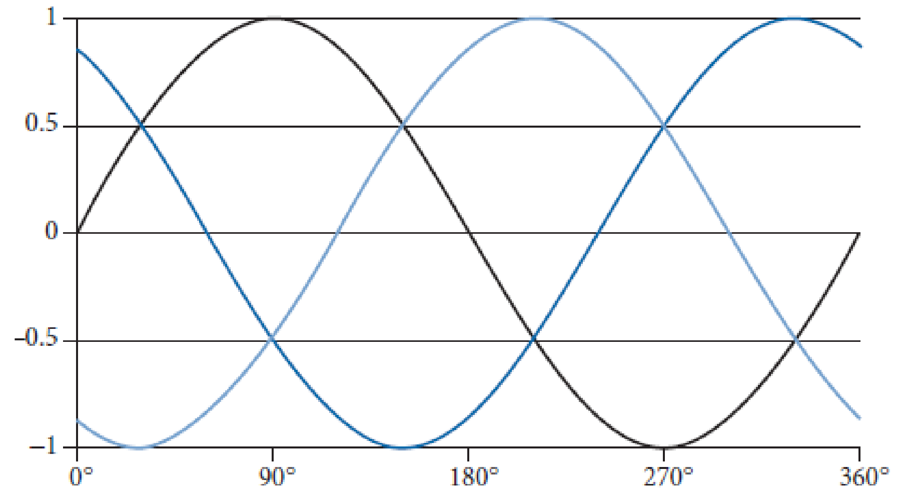


Fig. 10.2 Three-phase current.

The upper limit for the transmission voltage is determined by the **electrical breakdown strength** of air, around 3 x 10^6 Vm^{-1} for dry air, but lower in wet conditions.

The total power loss for national grids is typically **5-10%**.

Electricity transmission

Transformers

Power stations generate at around 18-20 kV. **Transformers** are used to step up the voltage for transmission over long distances.

Transformers consist of two coils, wrapped around a common iron core, with fewer turns N_1 on the primary side (low voltage) than the number N_2 on the secondary side (high voltage). The ratio of the voltages is given by

$$\frac{V_2}{V_1} = \frac{N_2}{N_1}$$

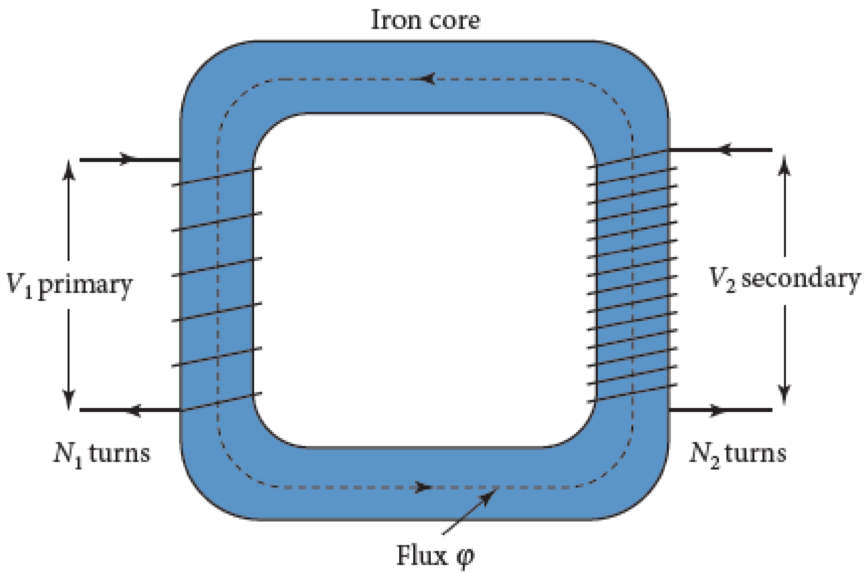


Fig. 10.3 Transformer.

HVAC or HVDC transmission?

HVAC transmission lines produce reactive currents, which need to be controlled by extra components. HVDC has lower resistive and corona losses, which offset the cost of converters at each end of the line. Hence, **HVAC** for distances up to a few hundred kilometres and **HVDC** for longer distances.

Grid systems

National grids

Power plants are usually part of a **national grid** of high voltage transmission lines and substations, linked to a central control unit.

Minimising the total **cost** and ensuring **stability** of the system are priorities.

Super grids

Super grids are networks which transmit power over very large distances from variable sources, such as wind and solar power, where conditions are favourable. Costs are high and obtaining planning permission can be difficult.

Smart grids

Smart grids are networks that use **digital communication** between consumers and the providers, which

- enable small generators to supply electricity to the national grid
- allow customers to time their electricity consumption to when power is cheaper
- enable providers to control plant (e.g. a refrigerator or a heating system

Fig. 10.4 Possible HVDC grid for transmitting solar energy across the USA.
Source: DOE2007.

Energy storage

Energy storage is useful

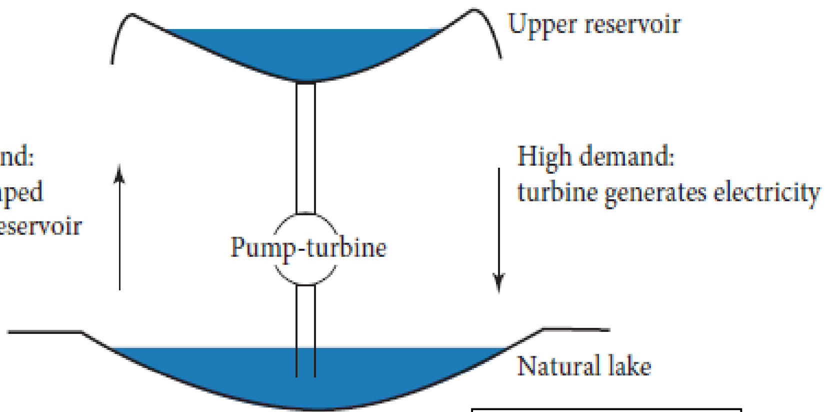
- in coping during periods of **peak demand** and avoiding using costly peaking power plants
- in coping with **unexpected losses** in capacity
- in smoothing fluctuations due to variable sources like wind and solar

Time scales range from seconds to several hours, to several days or months

Energy storage options:

- Pumped storage of water
- Compressed air storage
- Thermal storage
- Flywheels
- Batteries
- Synthesis of low-carbon fuels e.g, H_2 by electrolysis of water
- Fuel cells

Pumped storage



$$P = \eta \rho g h Q$$

Fig. 10.5 The Okinawa pumped storage plant in Japan.
Source: Agency of Natural Resources and Energy Japan.

Pumped storage plants PSP)

Water pumped from low level to high reservoir:

- provides largest and most cost-effective form of large energy storage (>95%)
- can respond to sudden increases in demand
- 145 GW of PSP capacity installed in 2015

Dinorwig PSP (Wales)

Storage capacity 7.8 GWh; delivers 317 MW within 16 seconds from rest.

OXFORD UNIVERSITY PRESS

Compressed air and flywheels

Compressed Air Energy Storage (CAES)

Consider n moles of air and assume $pV = nRT$
If air is compressed from V_1 to V_2 , work done

$$dW = -p\,dV = -(nRT/V)\,dV$$

Integrating, $W = p_1V_1 \ln(V_1/V_2)$

Typical energy density ~1 MJ/m^3

Large underground caverns provide huge energy storage capabilities, but

- significant **heat losses** (~50%)
- R&D on **adiabatic** CAES e.g. ADELE project
- **salt caverns** naturally seal under pressure.
- **public concern** over accidental releases of compressed air.

Flywheels

(Flywheel on car provides kinetic energy to keep the engine turning between piston strokes.)

Modern materials - plastics, epoxies and carbon fibres - light and very strong.

Kinetic energy/unit mass of uniform disc of radius *a*, mass *m*, angular velocity ω is

$$T/m = (1/4)\,a^2\omega^2$$

ω_{max} is determined by max. tensile stress of material $\sigma_{max.}$ **Less dense materials** have larger storage capacity.

Storage capacity ~ 15 MWh for 100 tonne flywheel.

Thermal storage

- In buildings, **solar heat** absorbed by material during the day provides heating at night when it is emitted. Can be extended to seasonal stores.
- **Ice storage**: ice can be made when energy is cheap and the temperature low and used to cool a building in summer.
- **Liquified air**: can be stored in well-insulated cryogenic containers. Energy is provide by pressurizing and vaporizing the air. The superheated air passes through a turbine generator, and if waste heat is used, ~70% efficiency can be obtained.
- In principle possible to store electrical energy by using an engine to pump heat from one reservoir to another and then recover it by running the system in reverse.

  Maximum heat that ejected at T_2, when work ***W* pumps heat** from T_1 to T, is

  $$Q = W \times T / (T_2 - T_1)$$

  while the maximum work from a heat engine with Q flowing in at temperature T_2 and with heat ejected at temperature T_1 is

  $$Q \times (T_2 - T_1)/T_2 = W$$

  Difficulty is keeping overall efficiency high. Energy density might be ~40 kWh m^{-3} but making it cost-effective has yet to be demonstrated.

Batteries

Volta's battery (1800)

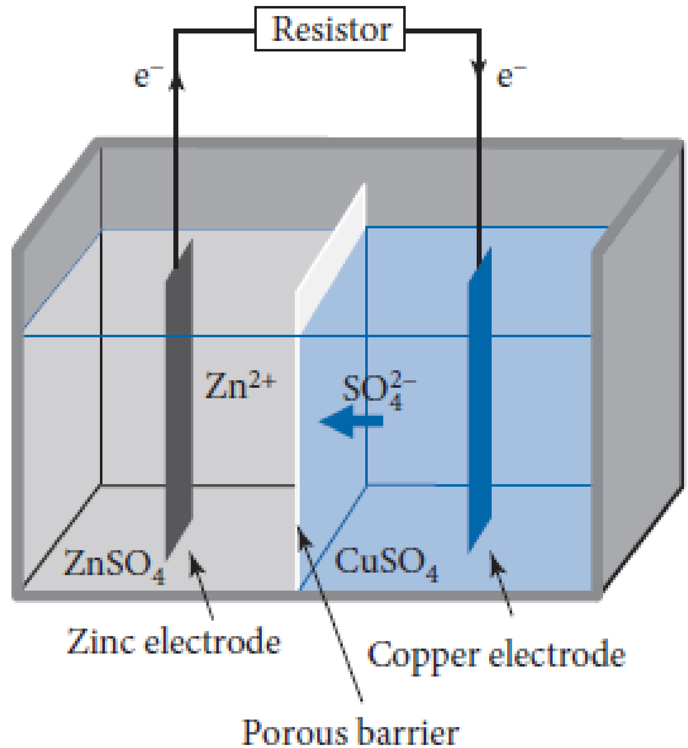
First battery. Zinc and silver electrodes, salt electrolyte. Standard potential = 0.76 V. Not reversible.

Daniell cell (1836). Consisted of

2 half-cells, one for **oxidation** and one for **reduction**, with

- **zinc electrode** in zinc sulfate solution
- **copper electrode** in copper sulfate solution,
- separated by **porous barrier**, allows ions to pass through.

Open circuit voltage V^0 = **standard potential** = 1.1 V



When circuit is closed, electrons flow via external circuit from zinc electrode to copper electrode. At electrodes,

$Zn \rightarrow Zn^{++} + 2e^-$ (oxidation)
$Cu^{++} + 2e^- \rightarrow Cu$ (reduction)

Lead-acid battery

Lead acid battery (1859)

First practicable rechargeable battery

Lead anode and lead oxide cathode in sulfuric acid electrolyte.

Open circuit voltage $V^0 = 2.0$ V (0.356V at anode, 1.685V at cathode)

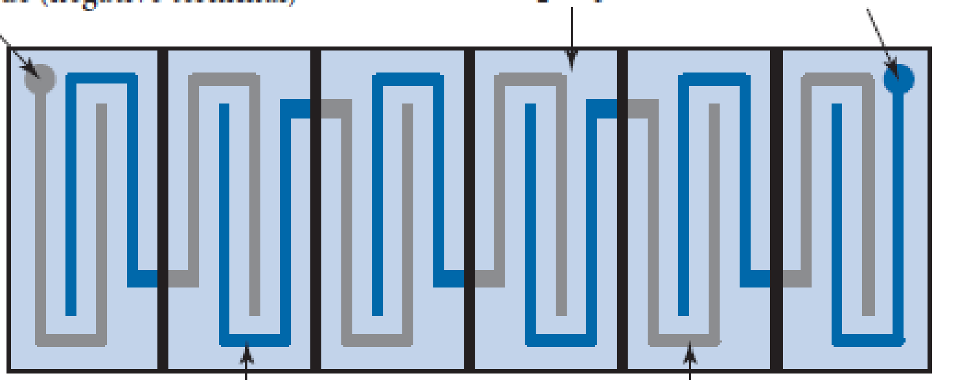


Fig. 10.8 Lead-acid battery with six cells: output voltage ~12 V.

Reactions:

$Pb + H_2SO_4 \rightarrow PbSO_4 + 2H^+ + 2e^-$ (at anode)

$PbO_2 + 2H^+ + 2e^- + H_2SO_4 \rightarrow PbSO_4 + 2H_2O$ (at cathode)

Low energy density (~ 20-30 Wh kg^{-1}) but can provide large currents. Rechargeable ~300 times, and 95% of lead-acid batteries are recycled in Europe and USA.

Lithium Ion Battery

Lithium-ion battery

- High energy density and standard potential - ~200 Wh kg^{-1} and 3.7V
- Problem that lithium is chemically very reactive was overcome by Goodenough (1980) through **intercalation** – a reversible process which move lithium ions in to or out of graphite without damaging it.
- Costs have fallen and Li-ion batteries are now being used for load-balancing on grid (Germany, 2015).
- R&D ongoing to improve safety and to decrease their charging time to less a tenth of an hour for electric vehicles (≡ >10C)
- Development of electric vehicles is increasing demand for lithium-ion batteries and costs are falling through ‘learning’

Standard Potentials

Half-reaction	Standard potential
$Li^+ + e^- \rightarrow Li$	−3.04
$K^+ + e^- \rightarrow K$	−2.93
$Ca^{++} + 2e^- \rightarrow Ca$	−2.87
$Na^+ + e^- \rightarrow Na$	−2.71
$Zn^{++} + 2e^- \rightarrow Zn$	−0.76
$V^{+++} + e^- \rightarrow V^{++}$	−0.26
$2H^+ + 2e^- \rightarrow H_2$	+0.00
$Cu^{++} + 2e^- \rightarrow Cu$	+0.34
$Ag^+ + e^- \rightarrow Ag$	+0.80
$2H^+ + VO_2{}^+ + e^- \rightarrow VO^{++} + H_2O$	+1.00
$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$	+1.23
$Cl_2 + 2e^- \rightarrow 2Cl^-$	+1.36

Flow batteries

- **Flow batteries** store energy in electrolyte rather than in the electrodes, so capacity is limited only by volume of electrolyte.
- High efficiency, many discharge cycles.
- Most common type is the vanadium redox flow battery. Vanadium is expensive, so cheaper materials are being researched.

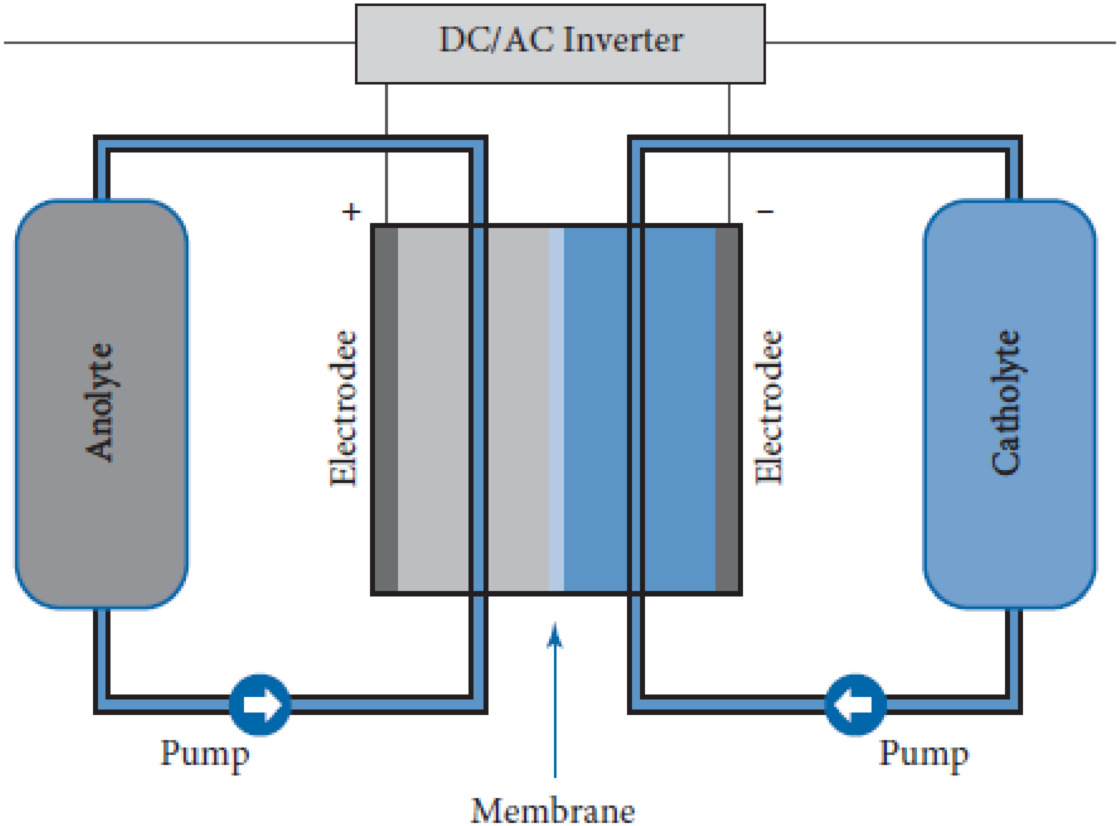


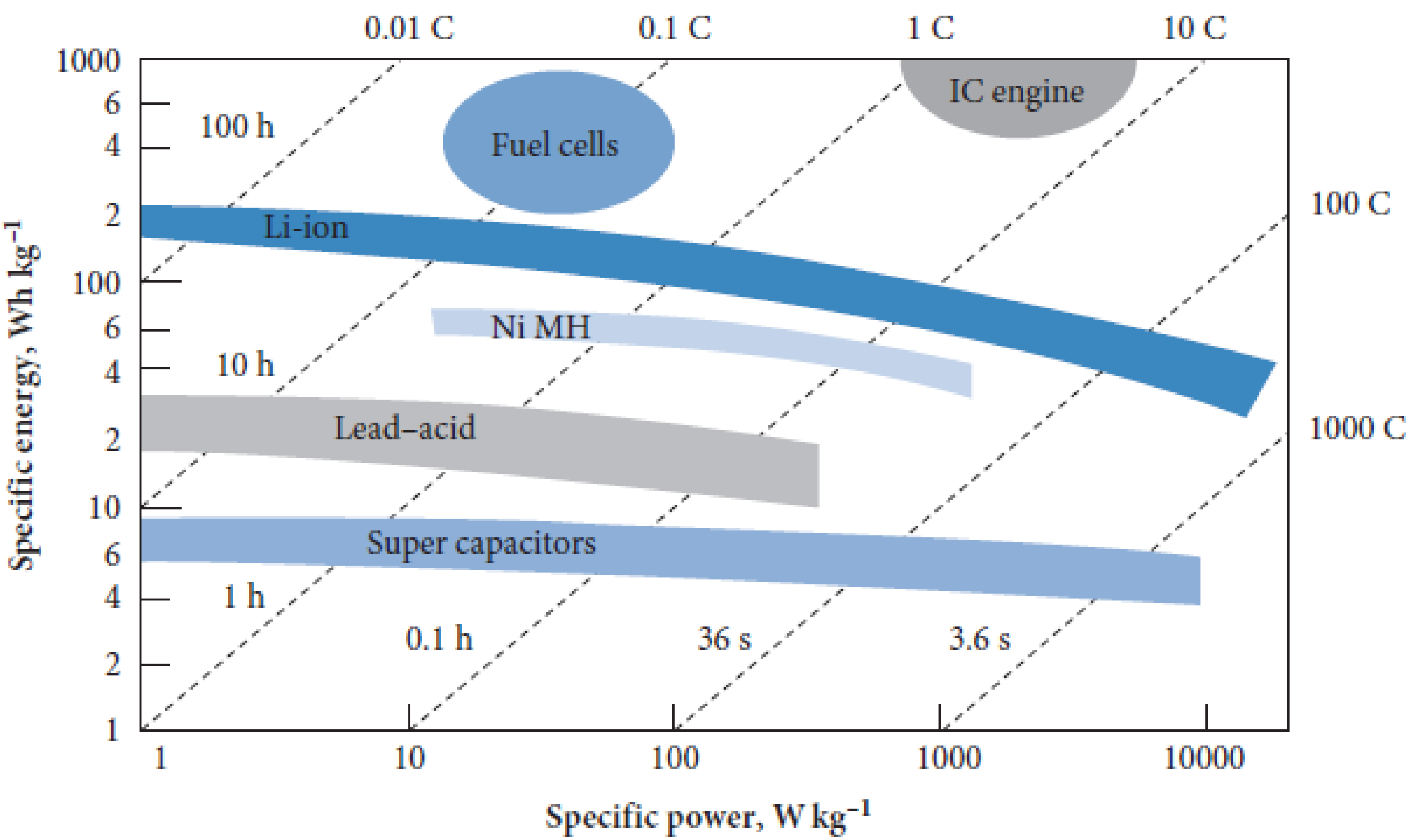
Fig. 10.9 Schematic of a flow battery.

$$\text{Anode}: V^{++} \rightarrow V^{+++} + e^- \qquad \text{Cathode}: 2H^+ + VO_2^+ + e^- \rightarrow VO^{++} + H_2O$$

Ragone Plot

The **Ragone plot** provides a way of comparing different batteries and supercapacitors in terms of their

- **specific energy** (stored energy per unit mass)
- **specific power** (deliverable power per unit mass.)



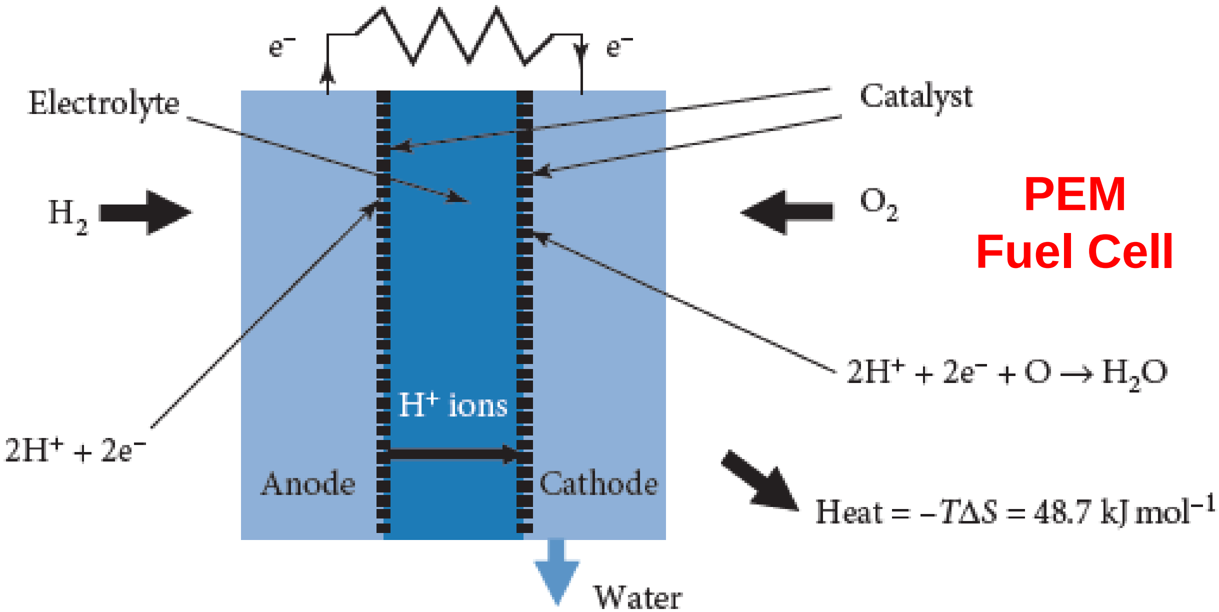
The **driving range** of a vehicle is roughly proportional to its **specific energy**, whereas the **speed capability** is nearly proportional to its **specific power.**

OXFORD UNIVERSITY PRESS

Fuel cells

Fuel cells

- **generate electricity** by combining hydrogen and oxygen to make water hydrogen (= **opposite of electrolysis**).
- **Catalysts** are used to speed up the reactions at the electrodes.
- A fuel cell is not a heat engine operating in closed cycle, so the Carnot limit to efficiency does not apply. **Typical efficiency ~ 50%**



PEM Fuel Cell

Fuel cells are suitable for vehicles; they give an increased range compared with current battery EVs and fast refuelling. They can provide both heat and electricity overall efficiency ~80%, are vibration-free, quiet and reliable.

Becoming more cost-competitive, but require **low-carbon** hydrogen generation and hydrogen **storage**

Hydrogen production and energy storage capacity of fuels

Hydrogen can be produced

(a) by **electrolysis** of water,
(b) by reacting hydrocarbons with steam (**reforming**),
(c) from biomass.

Finding a **compact method of storing hydrogen** is a major challenge (compression and metal hydrides provide only limited storage)

Fuel/store	Wh litre^{-1}	Wh kg^{-1}	Fuel/store	Wh litre^{-1}	Wh kg^{-1}
Diesel	9950	11 890	Liquid H_2	1400	1900
Petrol	8990	12 070	H_2 (34.5 MPa)	600	1800
Dry wood	2720$^{\$}$	5430	Hydride*	400	400
Ethanol	5910	7490	NaNiCl$^{\$\$}$	160	100
Methanol	4430	5580	Lead–acid	70	30
Coal	5500	6500	Li-ion	500	200

*300 °C; $^{\$}$density 0.5 kg litre^{-1}; $^{\$\$}$known as a ZEBRA battery.

Key Points

- **Long distance** electricity transmission requires high voltages, either HVDC or HVAC.

- To accommodate significantly more **wind and solar power**, national grids will need to be more **responsive to fluctuations** in supply and incorporate **energy storage**

- **Pumped storage** is the dominant (>95%) means of energy storage,

- **Li-ion** and other types of batteries are likely to become increasingly used by electricity grids

- The cost of Li-ion batteries is expected to be **below $100 per kWh by 2030**, which will help the transition from fossil fuel to electric vehicles.

- Fuel cells provide carbon-free electricity with very low emissions and efficiencies of around 50%, and also CHP, but **low-carbon** production of hydrogen is required.

OXFORD
UNIVERSITY PRESS